School of Civil and Mechanical Engineering

Integrated Spatial Technology Framework for Greenhouse Gas Mitigation in Grain Production in Western Australia

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DECLARATION

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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ABSTRACT

Agriculture contributes to environmental degradation through practices such as land use change, loss of biodiversity, increased soil salinity, acidification eutrophication and soil erosion, amongst others, all of which are problems throughout Australia. Furthermore, agriculture is one of the major sources of greenhouse gas emissions (GHGs) which include soil nitrous oxide (N_2O) emissions from fertiliser application and methane (CH_4) from pasture production. An increase in agricultural production and export is expected to further contribute to a related increase in the emission of GHGs. For example, the GHG emissions from the use and production of agro-chemicals are contributing to climate change.

The medium to long-term consequences of agricultural practices on climate change are being addressed by researchers on a global scale. Research has included the use (and not exclusively) of geographical information systems (GIS) and life cycle assessment (LCA) tools in agriculture, to cleaner production (CP) methods and precision farming approaches, and monitoring of N_2O emissions in farming systems. There is a gap in the current literature concerning the integration of LCA, remote sensing (RS) and GIS as a tool for use in agriculture. It is therefore proposed that LCA, RS and GIS be integrated in order to develop a comprehensive framework that will not only aid the existing LCA tool but also develop strategic climate change mitigation options.

The primary objective for this greenhouse gas research was to develop a framework, particularly for cropping industries, that could identify the farm management practice (FMP) for a particular soil type and agro-ecological zone, in a specific time frame (2010–2011), with the highest GHG emissions (the hotspot) using GIS, LCA and RS at the farm paddock level. The development of the framework will enable specific CP methods to be identified, which could be used as mitigation strategies at the farm level.

A total of 24 paddocks were selected for the study from an initial allocation of 44 paddocks provided by the Department of Food and Agriculture Western Australia (DAFWA) from a current crop sequencing project that had been operating since June 2010. The paddocks were selected by registering the paddock co-ordinates on RS

images uploaded into the GIS, and selecting those falling within the image boundaries. Thereafter, desktop studies and fieldwork were used to identify the FMPs employed and data was gathered pertaining to the development of the LCA. The GHG analysis consisted of the four phases proposed by ISO 14040–14044 and included goal and scope definition, inventory analysis, impact assessment and interpretation. The functional unit selected was the GHG emissions generated from the production of one tonne of grain. The LCA focused on two stages of agricultural production (pre-farm and on-farm stages) and the carbon footprint, ignoring other environmental impact categories, and hence, the LCA was considered to be a streamlined LCA (SLCA).

Data consisted of information supplied by DAFWA, data collected through personal communications, internet sites, scientific articles and literature. The carbon footprint for each paddock was calculated based on data obtained from DAFWA and relevant literature, and then the results uploaded into the GIS where the RS images were located. These results were then added as layers to the GIS to create images showing the hotspots. The images were then used to identify cleaner production methods that could be theoretically applied as mitigation strategies. The mitigation strategy results obtained from the CP methods provide alternative farm management practices which could be employed to aid the reduction of the GHG emissions per paddock.

The development of the IST framework was successful in identifying hotspots on the paddocks. It also showed that the user could select chosen variables for the generation of an image to display different FMPs, which could identify the hotspot and highlight potential mitigation measures. Finally, the framework developed in this study allows users to test the impact of a number of different alternatives on the environment prior to actual FMP being initiated.

PUBLICATIONS RELATING TO THIS THESIS

JOURNAL PUBLICATION

Engelbrecht, D., Biswas, W.K. & Ahmad, W. (2013). An evaluation of integrated spatial technology framework for greenhouse gas mitigation in grain production in Western Australia. *Journal of Cleaner Production, 57*, 69-78.

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MEDIA CONVERAGE

Towie, N. (2013). Software zeros in on carbon pollution. Science network of Western Australia, 26 July 2013. Website: http://sciencewa.net.au/topics/agriculture/item/2296-software-zeros-in-on-carbon-pollution/2296-software-zeros-in-on-carbon-pollution

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ABBREVIATIONS

ABARE	Australian Bureau of Agriculture and Resource Economics
ABS	Australian Bureau of Statistics
ACCU	Australian carbon credit units
ACRES	Australian Centre for Remote Sensing
AGEIS	Australian Greenhouse Emissions Information System
AEP	Agriculture emissions projections
AGDA	Australian Government Department of Agriculture
AOI	Area of interest
APH	Australia Parliament House
APVMA	Australian Pesticides and Veterinary Medicines Authority
ASC	Australian soil classification
ASRIS	Australian soil atlas
AUD	Australian dollar
BOM	Bureau of Meteorology
CEF	Country Education Foundation of Australia
CER	Clean Energy Regulator
CFI	Carbon Farming Initiative
CLAN	Climate Change in Agriculture and Natural Resource Management
COAG	Council of Australian Governments
CMM	Covariance matrix method
CP	Cleaner production
CPM	Carbon pricing mechanism
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
DAFWA	Department of Agriculture and Food of Western Australia
DAP	Diammonium phosphate
DCCEE	Department of Climate Change and Energy Efficiency

DEPI	Department of Environment and Primary Industries
DFAT	Department of Foreign Affairs and Trade
DM	Dry matter
DN	Digital number
DOS	Dark object subtraction
DSE	Direct soil emissions
EPA	Environmental Protection Agency
ERF	Emissions Reduction Fund
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
FMP	Farm management practices
GDP	Gross domestic product
GGA	Grower Group Alliance
GHG	Greenhouse gases
GIS	Geographical information systems
GRDC	Grains Research and Development Corporation
GWP	Global warming potential
HMM	Histogram minimum method
ICSM	Intergovernmental Committee on Surveying and Mapping
IFAD	International Fund for Agriculture Development
IPCC	Intergovernmental Panel on Climate Change
ISE	Indirect soil emissions
IST	Integrated spatial technology
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LULUCF	Land use, land use change and forestry
MAP	Monoammonium phosphate

MLA	Meat and Livestock Australia
MOP	Muriate of potash
MSDS	Material safety data sheet
N-fertilisers	Nitrogenous fertilisers
NASA	National Aeronautics and Space Administration
NDVI	Normalised difference vegetation index
NFF	National Farmers Federation
NGGI	National Greenhouse Gas Inventory
NIEC	National Inventory by Economic Sector
NIR	National Inventory Report
OECD	Organisation for Economic Co-operation and Development
RMIT	Royal Melbourne Institute of Technology
RS	Remote sensing
SD	Standard deviations
SOM	Soil organic matter
UAN	Urea ammonium nitrate
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change
UTM	Universal Transverse Mercator
USD	United States dollar
WANTFA	Western Australian No-Tillage Farmers Association
WFP	United Nations World Food Programme
WHO	World Health Organization
WTO	World Trade Organization
WWF	World Wildlife Fund

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CHAPTER 1
INTRODUCTION

This thesis aims to develop an approach which integrates life cycle assessment (LCA), remote sensing (RS) and geographical information systems (GIS) to mitigate greenhouse gas (GHG) emissions from Western Australian grain industries. This chapter introduces the research problem, the rationale of the study, the research design, the study area, and the aims, objectives, scope and structure of the thesis.

1.1 OVERVIEW

Food security has been defined by the Food and Agriculture Organization of the United Nations (FAO) as:

> *existing when all people, at all times, have physical and economic access to sufficient safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life.* (FAO), 2014)

The FAO furthermore states that agricultural productivity needs to increase by 60% in 2050 compared to 2006, in a sustainable way, in order to reduce poverty and feed the world population (FAO, United Nations World Food Programme (WFP) and International Fund for Agriculture Development (IFAD), 2015). In 1990 – 1992 there was an estimated 1,010 million undernourished people in the world compared to an estimated 795 million for 2014–16. Global agricultural productivity tripled between 1961 and 2011 as the global population rose by 126% and global cereal production increased by 200% on harvestable fields that only increased by 8%. However, more recently there has been a decline in agricultural yields due to factors such as limited water availability and the farming of marginal agricultural land, resulting in farmers being placed under additional pressure (FAO, 2014; FAO, IFAD & WFP, 2015; Lee, Edmeades, De Nys, McDonald & Janssen, 2014).

Recent climate changes have the potential to transform the agricultural sector and in turn place agricultural productivity under pressure; even a 2°C rise in global temperatures will destabilise current farming systems (Lee et al., 2014; Vermeulen et al., 2012). The fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC) noted that climate change is having a negative impact on agriculture

(IPCC, 2014a) and Lee et al. (2014) stated that the impact of climate change on agriculture is location specific. To combat the effect of climate change on agriculture, it is recommended by the FAO (2014) and Lee et al. (2014) that farmers respond to local and regional needs and vulnerabilities by developing and implementing mitigation and adaptation strategies. These strategies could focus on aspects such as policy development, livestock and crop management, land management and education (Lee et al., 2014; Matthews, Rivington, Muhammed, Newton & Hallett, 2013).

Agriculture is a key sector globally, contributing approximately 14.5% of climate altering GHG in 2010 (Engelbrecht, Biswas & Ahmad, 2013; FAO, 2014). The major GHG emissions from agriculture are soil nitrous oxide (N_2O), methane (CH_4) from animal husbandry and carbon dioxide (CO_2) from fertilisation products and urea hydrolysis emissions (Biswas, Graham, Kelly & John, 2010). In 2010 Australia was ranked 12th in the world, generating 1.5% of the global total of 37,928 Mt carbon dioxide equivalents (CO_2-e) and furthermore the agricultural sector emitted 18% of the national GHG emissions, of which 61% was CH_4 and 39% was N_2O (The shift project (TSP)), 2015). Garnaut (2008) highlights that Australia's level of exposure and sensitivity to the impact of climate change are high and agricultural productivity could be affected by changes in water availability, water quality and rising temperatures. In order to sustain agricultural productivity, evaluate the environmental impact of the agricultural productivity and increase the efficiency of the agriculture and livestock sectors, the entire Australian agricultural sector will be required to investigate different options for production (Biswas et al., 2010; NGGI, 2010a). This is particularly necessary due to its dependency on agricultural export commodities, which are expected to increase in the next few years, and the need to comply with 'green and clean' agreements imposed by the World Trade Organisation (WTO) and some Organisation for Economic Co-operation and Development (OECD) countries (Biswas, John, Batt & Noonan, 2011). Section 299(1)(f) of the Australian Corporations Law requires that companies that operate under any environmental legislation must report on their environmental performance (Ridley, 2001). Retailers are reacting to this pressure for 'clean and green' products by requiring their suppliers to verify that the food they purchase is safe and, increasingly, produced in an environmentally sustainable manner (Newton, 2007).

1.2 RESEARCH PROBLEM AND RATIONALE

National and international literature reviews have focused on aspects such as the use of LCA, GIS and RS as tools for agricultural management. For example, LCA was used to determine the implications of farm management practices, investigating things such as N_2O emissions from fertilisers, pesticides (Barton & Biswas, 2008; Barton, Butterbach-Bahl, Kiese, and Murphy, 2011; Climate Change in Agriculture and Natural Resource Management (CLAN), 2006; GRDC, 2011), CH_4 emissions from livestock, CO_2 emissions from farm machinery use and from vegetation sinks, and the manufacture of products such as corn chips following the production of maize (Grant & Beer, 2008). Hennessy et al., (2007) investigated the influence of soil type, rainfall and crop management practices on GHG emissions.

GIS, in turn, have been used to model GHG emissions from Chinese rice paddies (Yao, Wen, Xunhua, Shenghui, & Yongqiang, 2006), and to assess the annual direct biogenic GHG emissions from European agriculture (Freibauer, 2003). Both GIS and RS have useful characterisation tools for agro-ecosystem land use planning (Choudhury, Chakraborty, Santra, & Parihar, 2006).

No literature reviewed to date has considered integrating LCA, RS and GIS to identify environmentally problematic areas for mitigation strategies. Furthermore, all of the aforementioned research projects were conducted at research stations which are not representative of diversified agro-ecological zones or the topography of broader farming areas, and do not represent a regional environmental management strategy or plan (Engelbrecht et al., 2013).

This research therefore explores a mechanism integrating these three tools (LCA, GIS and RS) into an integrated spatial technology (IST) approach, hereafter referred to as the IST. The IST will be formulated in such a way that it is able to identify the emissions hotspot on a farm and allow the decision-maker to investigate and subsequently select GHG mitigation options based on cleaner production (CP) strategies. Historically regular LCA's include several environmental impacts such as global warming, acidification, eutrophication and human health (Curran, 2006), however this research, using an LCA approach, will only focus on the climate change impact category by defining the GHG emissions from the system studied.

The following research questions will be addressed during the study to address and select appropriate mitigation measures:

- Which inputs or processes in grain production (cereal cropping) can cause the biggest carbon footprint?
- Which mitigating strategies are appropriate for reducing carbon footprints in the wheatbelt of south-western Australia?
- Which mitigation strategies will be the most effective for the environmental management of the grain industries in the wheatbelt of south-western Australia?

1.3 AIM AND OBJECTIVES

The aim of this research will be the development of an approach (IST) that can assist with the quantification of a farm’s carbon footprint to identify areas of concern (hotspots). This approach will endeavour to integrate LCA, GIS and RS into the IST that will ultimately be used to identify appropriate mitigation methods based on CP strategies.

To achieve this aim the research will be focused around five objectives.

1.3.1 Objective 1: To identify the study area in GIS using geographical co-ordinates and RS

The initial study area transversed the wheatbelt of Western Australia from the northernmost to the southernmost parts. The dataset obtained from the Department of Agriculture and Food, Western Australia (DAFWA) defined the study area and consisted of the contact details of the farmers and the co-ordinates of 44 paddocks that were selected for inclusion in this research. As only two satellite images were available for this research, the study area needed to be redefined.

For the definition of the final dataset, the objective was to ascertain whether the scope of the research could be limited to a smaller area by using GIS and the satellite imagery. This smaller area was to include only the areas within the boundaries of the satellite images, which would identify each individual paddock using geographical co-ordinates and demarcate the area of each paddock for easy recognition.

1.3.2 Objective 2: To calculate the carbon footprints of individual paddocks of south-western Australian farms using an LCA-approach

The literature reviewed indicated that LCA had been used successfully in many agricultural applications to calculate the CO_2-e (carbon footprints) from inputs and outputs within the farming system. As only the pre-farm and on-farm stages until harvesting were included and only the climate change impact category was considered, this research was deemed to be a limited focus LCA (Finkbeiner, Tan, Raimbult, 2011).

This research thus set out to determine whether it was possible to calculate the carbon footprints of individual paddocks and farms by using an LCA approach, using the same methodology as for a full LCA. The LCA methodology as defined by the International Organization of Standardization (ISO) ISO 14000-14044 (Curran, 2013; ISO, 2006; Sauer, 2012) consists of goal and scope definition, the compilation of a life cycle inventory (LCI), the life cycle impact assessment (LCIA) and the interpretation of results.

1.3.3 Objective 3: To identify the hotspots on each paddock for different farms utilising LCA, RS and GIS through an integrated approach

LCA, RS and GIS tools have been used to identify the hotspots in paddocks under a variety of agricultural systems, either on their own or used in conjunction with other tools. However, a review of the literature revealed that LCA appeared to dominate as it is able to generate tables and graphs that are visual and therefore easy to understand and interpret. LCA has also been employed as a comparative tool wherein one farming system is easily compared to another. By contrast, GIS and RS are visual representations of spatial variables that enable users to identify topographical aspects that are included in analyses. By integrating the three tools, the research project sets out to present the hotspot, as calculated in LCA, in a visual manner showing its relationship to other features including soil, rainfall and climate zone, thus enabling decision-makers and farmers to make quick and comprehensive decisions based on these LCA outputs (Towie, 2013). Furthermore, LCA will be used in GIS as an IST, in order to compare specific practices and be able to propose the best, most appropriate alternatives. The program interface that will assist in the automatic transfer of LCA data to GIS to produce visual representation is beyond the scope of this research.

1.3.4 Objective 4: To propose mitigation measures based on CP strategies for each paddock and farm

CP strategies concentrate on mitigating GHG emissions at the source through input substitution, good housekeeping, technology modification, product modification and recycling and reuse. Historically, the literature shows that CP strategies have been applied successfully to industries in the energy sector, and some literature has recommended the inclusion of the same in agriculture.

The research undertakes to identify the source of agricultural GHG emissions and then propose the best CP strategy for the mitigation of GHG emissions at both a farm and paddock level. The economic implications of the use of CP strategies are beyond the scope of this research. The mitigation strategies have been theoretically based on information gathered from refereed literature and authentic government documents on both local and international CP, and suited to local climatic conditions and farming practices.

1.3.5 Objective 5: To present the integrated tools as a product that can be used by farmers, the industry and academic institutions alike

Adaptation and mitigation has been a primary focus of agricultural research in the face of climate change, as GHG emissions from the agricultural sector are major contributors to climate change, especially in Australia. To combat climate change, farmers are expected to reduce GHG emissions from their farms by implementing mitigation measures and adapting their farm management practices. A user-friendly tool for the farmers was not found when reviewing literature, although different methods exist wherein the industry and academic institutions are able to identify the areas within the agricultural cycle generating the most GHGs.

As a new tool, the IST is targeted at the identification of hotspots at both the paddock and farm scales. Furthermore, it aims to allow for the selection of mitigation measures that are then remodelled within the IST to allow the user to make comparisons with the original results, based on visual representation. As a simple, quick and easy to use tool, the purpose of the IST is to focus on farmers who have limited time at their disposal. Whilst it is beyond the scope of the current research, further research will enable the development of an application that can be downloaded onto a 'tablet computer' or a 'smart phone'. This application will enable farmers to input their variables into the IST and then generate their carbon footprint, on site, to determine appropriate mitigation measures (Towie, 2013).

1.4 RESEARCH DESIGN AND METHODOLOGY

The development of the IST methodology encompassed four key stages. In the first stage the remotely sensed data from satellite images were uploaded as input into a GIS. In the second stage an LCA approach was used to calculate the carbon footprint of the crops grown on the paddocks and farms, as identified in the study. Then in the third stage the carbon footprints were uploaded into the GIS application and images were created using the LCA results and GIS. Finally CP strategies were identified which could mitigate the GHG emissions from the farms.

At the outset, DAFWA provided basic data consisting of climate details, farm management practices and geographical co-ordinates for 44 paddocks from seven grower groups throughout the agricultural regions of the Western Australian wheatbelt. In order to select the paddocks for inclusion in the study (falling within the boundaries of the aerial photography), the geographical co-ordinates were superimposed on the available satellite imagery in GIS. The final sample consisted of 24 paddocks from eight farms in two grower groups, namely the Western Australian No-Tillage Farmers Association (WANTFA) and the Liebe Group. The farming system forming part of the research was the dry temperate system, which is characterised by hot, dry summers and cool, wet winters. Despite the poor soils and low rainfall in Western Australia (Engelbrecht et al., 2013), the state produced 40–50% of the annual grains for Australia in 2012/13, with the growth of wheat, barley and lupins concentrated in the wheatbelt area. Wheat is the major crop grown in Western Australia contributing about 70% of Western Australian grain production and 50% of the annual wheat production for Australia (Paterson & Wilkinson, 2015; Wilkinson, 2015).

To initiate the second stage, both quantitative and qualitative data were collected through site visits, participatory research, interviews, questionnaires, and telephonic and email communications. The participants included farmers, industry and academic professionals and product suppliers/formulators. The interpretation of the data was complemented with a review of literature from credible sources such as journal articles, published books, conference proceedings and websites of internationally recognised stature. The second stage involved the use of LCA methodology, proposed by ISO 14040-14044, wherein the goal and scope of the project were defined, a LCI compiled, the LCIA conducted and the results interpreted. At the outset, the functional unit selected was the GHG emissions generated from the production of one tonne of a crop from the paddock over two crop growing seasons, 2010 and 2011. For the development of an inventory, the data obtained from DAFWA were separated into pre-farm[1] and on-farm[2] stages for each paddock. The inventory lists quantified all the inputs and outputs in terms of one tonne of crop production, in Microsoft Excel (hereafter referred to as Excel) format. Thereafter, the inputs and outputs were converted to carbon footprints in Excel by multiplying with the corresponding emission factors and global warming potentials (GWP).

In the third stage, the total carbon footprint values as calculated were incorporated into the GIS image to provide the user with a visual representation of the hotspots during the annual farming cycle for the selected years.

Finally after integrating the three tools, mitigation measures were selected by identifying appropriate CP strategies and re-running the carbon footprint calculation in Excel with theoretical data. The mitigation measures and CP strategies were selected by reviewing literature from journal articles, published books and reliable websites.

[1] Pre-farm processes: agro-chemical production, chemical transportation, farm machinery production.
[2] On-farm processes: farm machinery operation, direct soil emissions, indirect soil emissions, emissions from stubble burning and emissions from grazing.

To summarise, this research included a participatory approach with the farmers wherein qualitative and quantitative data were obtained. The methodology used for the analysis of the data was based on an LCA approach which was integrated into RS and GIS, culminating in the identification of mitigation measures to address the paddock hotspots.

1.5 THESIS OUTLINE

This research thesis consists of eight chapters as presented in Figure 1.1. Chapter 1 introduces the significance, goal, objectives and scope of the research, as well as the approach taken to achieve the research objectives.

Chapter 2 reviews the standing body of knowledge with respect to climate change, the effect of agriculture on climate change, and the current Australian situation with regard to climate change, agriculture, the management of agriculture and legislation pertaining to agriculture and climate change. It concludes with a section on environmental management tools as to how LCA, RS and GIS have been used in agricultural modelling to identify the research gap.

Chapter 3 discusses IST approach based on the review in Chapter 2, the principal sampling and data collection methods and how the data capture methods were expressed with specific reference to LCA, RS and GIS. Thereafter, the data processing methods are described and the method of integration is further expanded upon.

Chapter 4 presents the study area and data inclusions and exclusions, and the goal and scope of the research design. The compilation of the LCI for all selected farming stages and paddocks is also included in this chapter. The chapter concludes with statistical analyses of selected LCI variables including inputs and outputs.

Chapter 5 interprets the results of the LCIA using tables and graphs in a logical manner. It focuses on identifying the hotspots on a paddock at farm level utilising LCI, and finally discusses these hotspots.

Chapter 6 presents the results of the integration of LCA into GIS and gives a visual representation of different IST images. The chapter also compares the results obtained in Chapter 5 pertaining to hotspots with those identified in the IST, for agreement and consistency.

Chapter 7 identifies relevant CP strategies and recommends usable mechanisms, at a paddock and farm level, for the mitigation of GHG emissions.

Chapter 8 presents the synthesis, recommendations and conclusions and discusses the outcomes of the objectives proposed in the previous section of this chapter. Recommendations for future research are made and finally conclusions are drawn by integrating the information from the entire study.

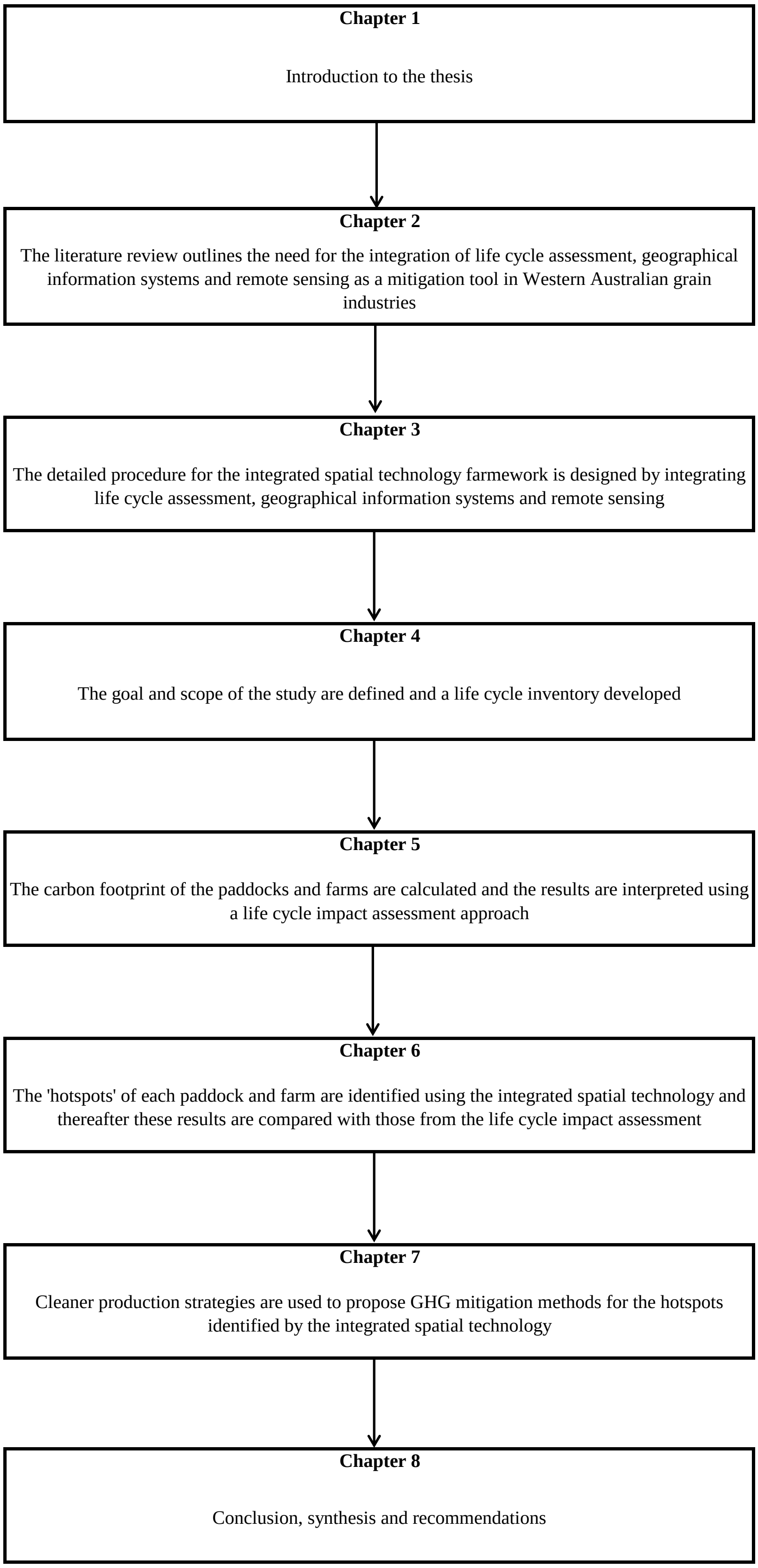

Figure 1.1. Thesis outline covered by the eight chapters

In summary, this chapter has given a brief overview of the current literature and has presented the research problem and rationale for the study. The objectives of the research have been articulated and the research design and methodology succinctly summarised.

Chapter 2 will provide a theoretical background to the study by highlighting the main findings from a critical evaluation of the literature. Furthermore, gaps in the reviewed literature will be highlighted.

CHAPTER 2
LITERATURE REVIEW

This chapter critically reviews agriculture and climate change, specifically for Western Australia, and then highlights legislation and methodologies used to manage climate change including the concept of integrating different tools. National and international literature was reviewed to determine the research gap required for integration of three environmental management tools, including geographical information systems (GIS), life cycle assessment (LCA) and remote sensing (RS) for mitigating greenhouse gas (GHG) emissions.

2.1 THE GREENHOUSE EFFECT AND CLIMATE CHANGE

Historically there is evidence that the global climate system varies naturally over large time scales. Prior to the Industrial Revolution in the 1700s, climate change was explained by changes in solar energy, volcanic eruptions and natural changes in greenhouse gases (GHGs). Since the mid-20th century, evidence suggests that variation in climate cannot be attributed solely to natural causes but also to human activities (Environmental Protection Agency (EPA), 2014a; International Panel on Climate Change (IPCC), 2007a), which include, amongst others, the burning of fossil fuels, agriculture and land-use change (Landcare, 2005).

The atmosphere surrounding planet Earth consists of five different layers, namely the troposphere (0–10 km), the stratosphere (10–30 km), mesosphere (30–50 km), thermosphere (50–400 km) and the exosphere (>400 km) (National Aeronautics and Space Administration (NASA), 2014a). The troposphere is the lowest layer and the closest to Earth, containing the majority of atmospheric water vapour or moisture, and is the layer where most of the world's weather takes place. The stratosphere is the layer above the troposphere and contains the world's ozone, which absorbs the ultraviolet radiation from the sun. It is a very stable layer and is almost completely free of clouds and weather. The next and coldest layer is the mesosphere. The fourth layer is the thermosphere or the 'heat sphere'. Although this layer would feel cold for humans due to the few molecules present, these few molecules are heated to extraordinary temperatures (in excess of 1000°C) by the sun. Greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and carbon monoxide (CO) are found here and are stratified according to their molecular masses. The exosphere is the upper limit of Earth's atmosphere and is made up of very thin air, primarily hydrogen and helium (NASA, 2014a). There are several mechanisms by which the atmosphere of the earth protects and sustains life on Earth. Amongst others it provides oxygen (O_2) for respiration, absorbs dangerous radiation from the sun, retains heat radiating from the earth for warmth, protects the Earth from objects falling from outer space, supplies CO_2 for photosynthesis and causes 'weather' (ScienceTerrific.com, 2014).

The Sun provides energy in the form of sunlight and when it reaches the Earth's surface, some is absorbed by the surface of the Earth, providing heat, and some is reflected back to the atmosphere as infrared light. In the atmosphere this infrared light is either absorbed by GHGs or escapes into outer space. If absorbed by the GHGs it may be reflected back to Earth's surface warming the atmosphere and subsequently the planet even more. This is known as the greenhouse effect (Bureau of Meteorology (BOM), 2014a; Environmental Protection Agency (EPA), 2014b; Department of Environment, 2014a). These greenhouse gases (GHGs) are primarily made up of water vapour, CO_2, N_2O, CH_4 and ozone (O_3). Currently the balance of these GHGs in the atmosphere has been disrupted by anthropogenic activities, such as the burning of fossil fuels (coal, oil, natural gas), land clearing and agriculture. This has initiated an increase in the overall concentration of GHGs, resulting in increased heat radiation, which is known as the enhanced greenhouse effect (BOM, 2014a; EPA, 2014b; Department of Environment, 2014a). More commonly the enhanced greenhouse effect is referred to as climate change or global warming. Throughout this literature review the term climate change will be used, and is defined by the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) as:

> *the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity* (Intergovernmental Panel on Climate Change (IPCC), 2014b).

> *a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods* (IPCC, 2014b).

Both definitions are in agreement that the changes that are occurring in the global climate can be attributed to both anthropogenic (direct and indirect) and natural causes. They furthermore state that these changes take place over extended periods of time.

Each GHG has different radiative properties which determine the length of time that they remain in the atmosphere and also their ability to trap heat. As CO_2 is considered to be the most important anthropogenic GHG, all GHGs are converted to carbon dioxide equivalents (CO_2-e) for comparative purposes. According to the IPCC (IPCC, 2007a) CO_2-e emissions are:

> *the amount of CO_2 emission that would cause the same time-integrated radiative forcing over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs* (IPCC, 2007a).

The calculation of the CO_2-e requires the product of the global warming potential (GWP) for each GHG and its emissions to be determined. The United States Environmental Protection Agency (US EPA) defines the GWP of a GHG as the measure of the total energy that a gas absorbs over a particular period of time (usually 100 years), compared to CO_2 (EPA, 2014c). The change in energy in the atmosphere due to GHG emissions is known as the radiative forcing. A positive forcing warms the troposphere and a negative forcing cools it down. Different time scales are used to measure the cumulative chronic effects of GHGs on climate such as 20, 50, 100 and 500 year horizons (IPCC, 2007a). However, long horizons such as 500 years are subject to significant uncertainties in the decay rate of CO_2, and shorter horizons such as 20 and 50 years represent the maximum response to temperature. The IPCC found that the 100 year horizon provided the most balanced representation of the various time scales for the maximum rate of response of temperature, thus it is currently the most commonly used horizon (IPCC, 2007a).

Currently the GWPs of CO_2, N_2O and CH_4 are 1, 298 and 25, respectively (IPCC, 2007a). Hence, 1 kg of N_2O has the same effect as 298 kg of CO_2 on climate change and 1 kg of CH_4 is equivalent to 25 kg of CO_2, over 100 years (IPCC, 2007a). The Australian Parliament House (APH) (2014a) reports atmospheric concentrations of CO_2 to be higher than ever before recorded, largely as a result of fossil fuel consumption, agriculture and land clearing, and predicts that the average temperature of the Earth will increase by 5.8°C in the next 100 years (APH, 2014a).

There are many indicators of climate change mentioned by the IPCC working group including changes in surface temperatures, atmospheric water vapour, precipitation, severe events, glaciers, ocean and land ice and sea-level (Cubasch et al., 2013). Furthermore, the IPCC confirms that the global climate has changed over the last 50 years and will continue to change. An increase of 0.2°C per decade has been projected for the next two decades, and a rise of 1.5–4.5°C by the year 2100 (Engelbrecht et al., 2013; IPCC, 2007b).

Climate change poses challenges for all sectors of the Australian economy, but will most affect those sectors dependent on natural resources, such as agriculture. Water availability, water and soil quality, and the incidence of pests, weeds and diseases are among the factors that will be affected by climate change, which in turn will affect crop yield and quality. In addition to being affected, agriculture contributes to the change in climate by contributing to GHG emissions (Anwar et al., 2015).

2.2 CLIMATE CHANGE AND AGRICULTURE

Food security needs to be ensured with minimal environmental degradation and associated GHG emissions. According to the World Health Organization (WHO), food security will exist when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life (World Health Organization

(WHO, 2014). The Food and Agriculture Organization of the United Nations (FAO) forecasts a world population in excess of nine billion people by 2050. To meet global nutritional and food demands, the production of food is required to increase by 60–70% from its 2005–2007 levels (Food and Agriculture Organization of the United Nations (FAO), United Nations World Food Programme (WFP) and International Fund for Agriculture Development (IFAD), (FAO, WFP & IFAD, 2012). However, agricultural productivity has been falling and greater fluctuations in crop yields and local food supplies are expected in the face of climate change (Darwin, 2004; Huang & Wang, 2014). The FAO and other researchers agree that fluctuations in crop yields will not be uniform across the entire globe but will vary according to regional temperatures, precipitation, soil types and agronomic practices (Darwin, 2004; Fleischer, Mendelsohn, & Dinar, 2011; FAO, WFP and IFAD, 2012; Huang, von Lampe, & van Tongeren, 2011; Huang & Wang; 2014).

According to the IPCC, the world land area currently dedicated to agriculture is 40–50%, with significant amounts of CO_2, N_2O and CH_4 being released into the atmosphere (Smith et al., 2007), accounting for 14% of total global anthropogenic GHG emissions in 2004 (Figure 2.1) (IPCC, 2007a). In 2005, the N_2O and CH_4 emissions from agriculture accounted for approximately 60% and 50% of the total global N_2O and CH_4 emissions, respectively. The net flux of CO_2 was considered to be balanced although there were large exchanges of CO_2 between the atmosphere and agricultural lands (Smith et al., 2007). Overall, agricultural GHGs originate from the use and production of agrochemicals, such as fertilisers, and other agricultural inputs and farm machinery operations (Anderson, 2009; Engelbrecht et al., 2013; Ugalde, Brungs, Kaebernick, McGregor, & Slattery, 2007). Specifically, the generation of N_2O occurs when the nitrogen (N) in soils and excreta is transformed by microbial action, and is often enhanced when available N exceeds plant requirements, especially under wet conditions (Oenema et al., 2005; Smith et al., 2007). Barton et al. (2014), state that the nitrification process in soil is carried out by ammonia-oxidising bacteria and ammonia-oxidising archaea, whereas the denitrification process can be carried out by different taxonomic groups. Nitrification is the oxidation of ammonia (NH_3) to nitrate (NO_3) via hydroxylamine (NH_2OH) and nitrite (NO_2) in a two-step process. Denitrification is the reduction of NO_3^- to di-nitrogen gas (N_2) under anaerobic conditions, with N_2O and nitric oxide

(NO^-) as intermediary gaseous products. This bacterial activity varies with climate and soil, thus influencing soil N_2O emissions. For example, in the case of Western Australia's semi-arid climate, the soil N_2O-N emission is 50 times lower than the IPCC value (Barton, Butterbach-Bahl, Kiese, & Murphy, 2010). When organic materials decompose in anaerobic conditions, CH_4 is produced and CO_2 is released from microbial decay or the burning of plant litter and soil organic matter (Smith et al., 2007).

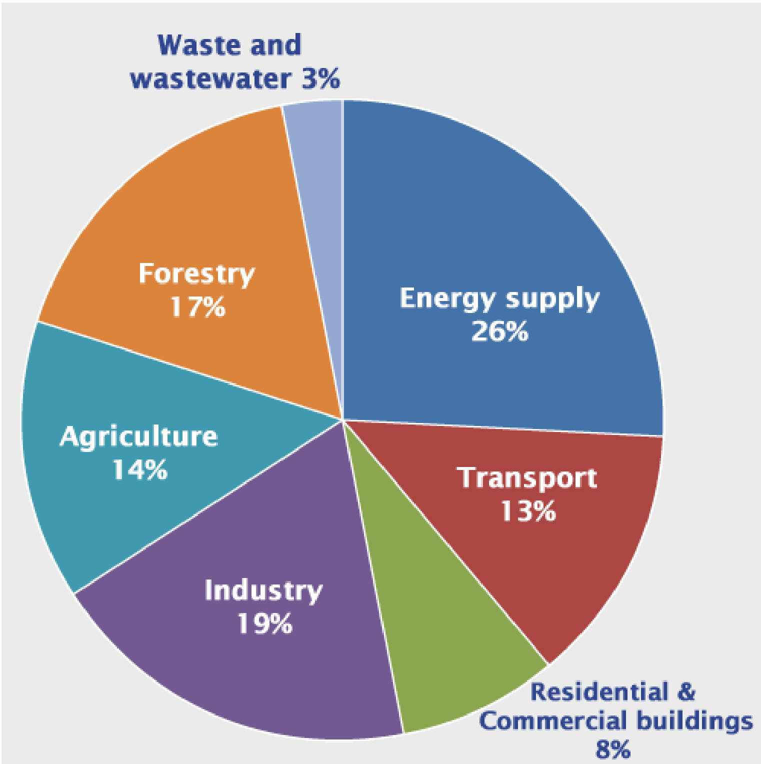

Figure 2.1. Global anthropogenic GHG emissions in terms of CO_2-e, per sector for 2004 (IPCC, 2007b)

The two main strategies recognised by de Bruin & Dellink, (2011), Liebig, Franzluebbers, & Follett, (2011), and the IPCC (2007a) for addressing GHG emissions associated with climate change are adaptation and mitigation. These strategies can be used in conjunction with each other or individually to exercise a measure of control over the impacts resulting from climate change.

2.2.1 Adapting to climate change

Adaptation refers to the development and adjustment of ecological, social or economic systems to minimise potential damage associated with climate change. It is essential as the global population grows, creating a demand for agricultural products and increased competition for natural resources (de Bruin & Dellink, 2011; Liebig et al., 2011). Adaptations to enable the agriculture sector to better respond to climate change, as summarised by the IPCC, (2007a), Huang & Wang (2014), Liebig et al. (2011) and Matthews et al. (2013), include options and strategies to manage all aspects of agricultural systems such as crop, vegetation, water, soil, livestock and chemical applications. However, adaptation strategies specific to a country's climate and social status need to be identified (Kiem & Austin, 2013).

Feola, Lerner, Jain, Montefrio & Nicholas, (2015) focused on five case studies (Mexico, Colombia, California, India and the Philippines) and found that social and biophysical conditions influenced the adaptation of farmers to other alternatives, although the combination of social and biophysical conditions was dependent on the context of the farm management practice (FMP). They stated that it was important to understand the behaviour of farmers in attempting to produce food sustainably under increasing pressure. For example, in California decision-making is an individual process, whereas in Colombia social networks influence the farmers. In India, however, the weather variability, market price and groundwater depletion are drivers of behaviour and determined whether cropping strategies would be altered. It was found that farmers would respond to the driver imposing the greatest risk (e.g. drought) at that time, and would hope that they had made the correct decision thereafter (Feola et al., 2015). In Australia, farmers are driven by profitability and are sceptical about the causes of climate change (Kiem & Austin; 2013).

In Switzerland an LCA approach with an economic focus was used to determine the environmental consequences if farmers adapted to climate change. The results were region-specific and showed that GHG emissions could increase or decrease under different conditions (Tendall & Gaillard, 2015). This furthermore implies that there is a need to improve farming systems, focusing on the regional situation, by changing FMP whilst concentrating on climate change adaptation and mitigation. The authors concluded by stating that if farmers continued with a 'business as usual' approach and did not adapt, region-specific productivity and eco-efficiency would decrease (Tendall & Gaillard, 2015).

Huang & Wang (2014) suggested that educating farmers about the overuse of fertilisers and training them to adapt their FMP would result in the potential to reduce N_2O emissions from the Chinese agricultural system by 30%. They stated furthermore that adopting improved irrigation could reduce the CH_4 emissions from the rice paddies. In addition, the authors recommended sequestering soil carbon by preserving existing soil carbon stocks by improving the rotation of grazing animals, limiting animal numbers on degraded lands, using fallow and crop rotation systems, focusing on minimum or low tillage, applying organic fertilisers and acquiring low energy use machines (Huang & Wang, 2014). Another study by Wang, Huang and Yang (2014) focused on the impact of climate change on China's agriculture and stated that for China's agricultural sector to take advantage of the changing temperatures and rainfall, the government needed to adopt actions such as acquiring improved technology and improving infrastructure. It was furthermore suggested that farmers would need to adapt with regard to sowing dates, crop cultivars and water saving strategies.

Three studies were reviewed to ascertain the opinion of Australian farmers on climate change. In a study by Donnelly, Mercer, Dickson, & Wu (2009), 1,000 primary producers were included as part of a national survey, of which 27% did not accept that climate change was human induced and still had to be proven, and 64% were against a carbon trading scheme. In addition, many felt that climate change and mitigation warranted no more attention than any other challenge they were facing, which included financial burdens, labour shortages and declining profitability. Evans, Storer, & Wardell-Johnson (2011) surveyed 411 farmers in a south-western Australian project to ascertain their opinions on climate change, and inferred that although the general consensus is that Australians are innovative, the farmers are not. They showed that 37% of the respondents would try alternatives, 36% would follow suit if the methods were proven, and 27% would be slow to adapt. They also found that 36% of the participants believed that climate change was occurring, 24% thought it was human induced, 43% viewed it as a threat to their communities and 33% believed it was a threat to their businesses. A study in South Australia which included 300 participants showed that equal numbers accepted, rejected or were not sure that climate change was occurring. Those who rejected climate change also felt that the variation in climate was due to natural cycles (Raymond & Spoehr, 2012). Yet, in contrast to the diverging beliefs, Raymond & Spoehr (2012) found that farmers had implemented adaptation methods to counteract decreased productivity.

As Australian farmers have previously adapted their FMPs, they have been successful in providing agricultural products for national use and export purposes whilst facing harsh climatic conditions (Bell, Stirling, & Pankhurst, 2007; Bennett, Kingwell, & George, 2002; Engelbrecht et al., 2013). Yet, as the world climate continues to change, Australia's responsibility to adapt to alternative and improved FMPs increases. Researchers such as Bell et al., (2007) and Bennett et al. (2002) claim that Australian farmers are not averse to using new technology or implementing research findings and innovation to increase sustainability, productivity and profit.

The next section will focus on adaptation methods for crop and croplands, vegetation; pests, diseases and weeds; soil; chemical applications, water, pasture and energy management, mainly focusing on conservation agriculture (CA) methods used in Australia, as CA has become a widely adopted practice (Kirkegaard, Christen, Krupinsky, & Layzell, 2008).

2.2.1.1 Crop and cropland management

Due to climate change, crop yields may decline due to faster crop maturation, less available water, erratic weather and new pests and diseases (Matthews et al., 2013). The large range of existing crops, make it imperative for farmers to investigate alternative methods of managing croplands (Kirkegaard et al., 2014; Matthews et al., 2013).

New crop management practices include adopting conservation agriculture (CA), which encompasses zero/minimum till, permanent residue cover, diverse rotations and livestock management from cropped land (Australian Government, 2014a; Kirkegaard et al., 2014; Northern Territory Government (NTGov), 2015). Oliver, Ashton, Hodges, & Mackinnon (2009) continue by stating that countries like Australia and Brazil benefit from adopting CA, but this is not the case in Africa where productivity is considered the primary task of agriculture. In Australia the adoption of CA farming methods has been driven by the need to achieve a balance between agricultural productivity and agricultural resources (Llewellyn, D'Emden, & Kuehne, 2012; NTGov, 2015).

Generally the literature reviewed supported CA due to the reduction in GHGs, increase in soil organic content (SOC) and increase in yields observed when some or all of the abovementioned practices were employed (Barton, Murphy, & Butterbach-Bahl, 2013; Gaudin, Janovicek, Deen, & Hooker, 2015; Kirkegaard et al., 2008; Krupinksy et al., 2006; Maraseni & Cockfield, 2011).

- **Tillage**

Tillage is a management variable that may enhance or retard emissions of GHG from agriculture. Advantages of adopting minimum/no-tillage are reduced soil erosion, lower fuel costs, higher long term productivity, better water quality, greater soil moisture and improved water infiltration (D'Emden, Rick, Llewellyn, & Burton, 2006). However, the potential for soils to sequester carbon was reported as being 0.3–0.4 Mg C/ha/yr for Europe, Australia, America and Canada (Sheehy, Regina, Alakukku, & Six, 2015), and it should be remembered that although the SOC can be increased, the ability of the soil to store C is limited. If the soil is not managed properly, the sequestered C will be released into the atmosphere over a number of years (De Gryze, Lee, Ogle, Paustian, & Six, 2011). The disadvantages of not tilling include an increased incidence of pests, diseases and weeds, the increased use of herbicides to eradicate the weeds, the associated GHG emissions from the use of herbicides, and increasing herbicide resistance (Baldock, Wheeler, McKenzie, & McBrateny, 2012; Bell et al., 2007; Chatskikh & Olesen, 2007; Chauhan, Singh, & Mahajan, 2012; D'Emden et al., 2006; Llewelyn et al., 2012; Seguin et al., 2007; Ugalde et al., 2007b). The use of tillage methods has the advantage of reducing compaction, reducing the incidence of weeds, increasing water movement and reducing run-off, but at the same time it reduces the SOC which affects the balance of soil micro-organisms (Chatskikh & Olesen, 2007; Chauhan et al., 2012). The current research has assessed the GHG emissions from grains produced under no and minimum tillage conditions taking into account the aforementioned variables (see Chapter 5). As GHG emissions from soil are generally low, the anticipated reduction of GHGs from tillage practices is expected to be from the reduced chemical applications and the use of improved farm machinery (Ugalde et al, 2007).

The literature review highlighted different views on the adoption of no-tillage practices. Research by Pannell, Llewellyn, & Corbeels (2014) found that the major determinant of adopting no-tillage methods in developing countries was due to labour and machinery cost-saving, and not due to conservation awareness. The authors found that in India’s Haryana state, no-tillage was adopted by 34% of farmers and 19% in Pakistan’s Punjab.

In Australia, approximately 90% of farmers have adopted minimum or no-tillage methods covering a range of practices from direct drilling to deep ploughing, with only one pass and minimal soil disturbance (Oliver et al., 2009; Seguin et al., 2007). The adoption of these practices was dependent on factors such as rainfall variation, farm characteristics and personal preferences. For example, in areas with high rainfall, minimum/no-tillage practices were more frequently adopted over the longer term, soil health as a farm characteristic was an important determinant, and the more educated a farmer was in terms of conservation agriculture, the more readily it was adopted. Western Australian farmers adopted the practices earlier than the rest of Australia (D’Emden et al., 2006).

- **Residue cover**

The practice of retaining stubble (above-ground plant residue remaining in the field after harvesting) by mulching, slashing or left standing has increased (Krupinsky et al., 2006; Llewelyn et al., 2012). Over time, stubble improves water infiltration, moisture retention, soil fertility and biological activity, reduces runoff, saves labour and input at seeding and improves air quality through decreased burning practices. (Scott, Podmore, Burns, Bowden, & McMaster, 2013; Ugalde et al, 2007b). The treatment of the stubble and the decomposition rate from harvest to the next sowing period determines the condition and amount of stubble remaining at sowing, when the seeds are placed between the rows of stubble. Practices employed to reduce the stubble load before sowing (ideally less than four tonnes per hectare of dry matter) include grazing, paddock burn, windrow burning, or a combination of these (Grains Research and Development Corporation (GRDC), 2011a; Ugalde et al, 2007b). During grazing, livestock (generally cattle and sheep) feed on the remaining stubble for a period of time sufficient to reduce and anchor the stubble load to the farmer's requirements, before being moved to another paddock (GRDC, 2011a). The practice of burning is declining but is still used where weeds proliferate and are hard to eradicate (GRDC, 2011a; White & van Rees, 2011). The burning of stubble generated 148 Gg (or 0.17% of the agricultural GHG emissions) of N_2O and 238 Gg (or 0.28% of the agricultural GHG emissions) of CH_4.in Australia in 2013 (National Inventory Report (NIR), 2013a). The CO_2 released during combustion is photosynthesised by plants in the following growing season, thus this GHG is not considered during GHG accounting (GRDC, 2011a; White & van Rees, 2011). In the current research, as explained in Chapter 5, the influence of stubble burning, and grazing during the fallow land period on the overall GHG emissions has been taken into account.

- **Crop rotation and species diversity**

The use of crop rotation was initially suggested by the IPCC in 2007 (IPCC, 2007b), as the roots of crops are able to affect the surrounding soil by increasing soil nutrient turnover and thus affect the soil organic and nutrient status. In addition, nutrients from fertilisers or biological fixation can be stored in the soil organic matter for subsequent crop use (Lehuger et al., 2011). The rotation of the land to different crops may disrupt the growth cycles of diseases, pests and weeds, which in turn alters the amount and types of chemicals used, resulting in a decreased chance of resistance developing for the chemicals (Chauhan et al., 2012; Kirkegaard et al, 2008; Luo, Bellotti, Williams, & Wang, 2009). Crop rotations that included the use of legumes as a natural fertiliser showed that, although dependent on the type and growing conditions of the legume, residual N increased in the soil profile (Barton et al., 2014; Chauhan, 2012; Krupinsky et al., 2006; Luo et al., 2009; Oliver et al., 2009; Philippot & Hallin, 2011; Rochecouste, Dargusch, Cameron, & Smith, 2015). Furthermore, the decomposing crop stubble from preceding growing seasons brought additional benefits such as increased soil organic content (SOC) and increased yields (Lal, 2004; Lehuger et al., 2011; Malhi, Nyborg, Solberg, Dyck, & Puurveen, 2011). Increased SOC decreases the loss of soil through erosion and promotes the decrease of soil GHG emissions (Lal, 2004; Lehuger et al., 2011). In this research, legume grain rotation has been considered as one of the GHG mitigation strategies for grain production, where the production of N fertiliser has been found to be a hotspot (see Chapter 7).

When incorporating perennial pastures in the rotation, Hochman et al. (2013) found that weed proliferation was reduced and soil structure and soil fertility were enhanced, however the livestock increased the enteric CH_4 emissions (Biswas, 2015; Hochman et al., 2013). However, on comparing different farming practices in northern Australia, Hochman, Prestwidge, & Carberry (2014), found that the whole farming system needed to be evaluated and not only a part of it, to ascertain whether crop rotations were beneficial. The study highlighted that FMP had a large role to play in optimising crop rotation benefits. The research by Lehuger et al. (2011) in a study conducted in Western Europe is in agreement, showing that eliminating the use of N fertilisers led to a substantial loss of C that was not compensated for by lower GHG emissions. Gan, Liang, Wang & McConkey, (2011) found that the crop yield of wheat increased after oilseeds or pulses had been harvested, however the cropping of a legume reduced the SOC and N losses when compared to cereals. Disadvantages from continuously cultivating the same crop species may result in an increase in specific diseases, pests and weed species. Additionally, the repeated use of chemicals to combat these pests may result in the development of chemical resistance and immunity (Chauhan et al., 2012; Kirkegaard et al., 2008;).

Wang, Liu, Asseng, Macadam, & Yu (2015) state that farmers should respond to changes in environmental conditions by choosing the most favourable crops, cultivars, and cropping systems suitable to their soil type. Chapter 5 investigates the implications of GHG emissions due to FMPs by farmers in south-western Australia’s changing climate.

2.2.1.2 Vegetation management

Since early European settlement, about 75% of land in Australia has been converted for human use, with 13% used for agriculture and the remaining 62% for a variety of other functions. The native vegetation of Australia is diverse, complex and has unique features. About 85% of the plant species in Australia are endemic to the continent. Currently, most of the remaining native vegetation (more than 224 million hectares) is found on agricultural land, with farmers playing a crucial role in the management thereof (Harris-Adams, Townsend, & Lawson, 2012). On agricultural land, native vegetation is required to maintain biodiversity and soil health, provide natural pastures and shelter for stock and for soil stabilisation and erosion control and the management of salinity (Harris-Adams et al., 2012). Native vegetation can contribute to the natural environment by maintaining crucial soil functions and aiding with the cleansing of air and filtering of water and to climate change mitigation and adaptation (Council of Australian Governments (COAG), 2012; Harris-Adams et al., 2012). Crucial soil functions maintained by native vegetation include the removal of heavy metals, adding binding materials as debris, increasing the soil carbon through decomposition, and restoring the soil microbial communities which then improves the soil health through biological processes (Baah-Acheamfour, Carlyle, Bork, & Chang, 2014; Kabas et al., 2012).

Harris-Adams et al. (2012) state that managing native vegetation in Australia for production and conservation benefits can be challenging. Whilst managing this land, farmers often encounter threats to the native vegetation including the loss, fragmentation and degradation of habitat, unsustainable use of natural resources, invasive species, changes to the aquatic environment and water flows, inappropriate fire regimes, urban development, lack of valuation of the environment and climate change (COAG, 2012).

Landcare (2005) suggests that planting new trees and shrubs and protecting existing vegetation will reduce greenhouse emissions through carbon sequestration and the preservation of existing carbon stores. The improved management of native vegetation is considered a high priority by COAG (2012).

2.2.1.3 Pest, disease and weed management

It is well known that pests, diseases and weeds can cause havoc in agricultural systems, thus it is imperative that farmers continue focusing on alternative methods for the control thereof (Dang , Seymour, Walker, Bell, & Freebairn, 2015; Flower, Cordingly, Ward, & Weeks, 2012; Nash & Hoffman, 2012).

The management of pests, diseases and weeds targets the damage to crops by pests (weeds and invertebrates) that carry viruses and spread diseases as well as those that cause damage in the establishment phase. For example, direct damage of crops by pests is a risk for canola growers and the viruses transmitted by aphids are a concern for wheat growers (Nash & Hoffman, 2012). Due to variability in temperatures and rainfall, the incidence of pests varies from year to year. Other methods such as lower reliance on tillage and stubble retention have increased specific pest populations. For example in Victoria, Australia, smuts and bunts in the cereal crops increased when the climate became favourable for breeding. Tillage, in contrast, has the ability to bury seeds and pathogens in the soil and subsequently kill them (Dang et al., 2015; Nash & Hoffman, 2012). Traditionally the eradication of pests has been dependent on the use of chemicals (herbicides, fungicides, insecticides, pesticides), however due to societal pressure, greater control is being exercised over these use of these chemicals. Added to the societal pressure is the development of both crop and pest resistance to the chemicals that have always been used, thus alternative strategies have been investigated and farmers have starting adapting to these alternatives (Dang et al., 2015; Nash & Hoffman, 2012).

A Western Australian study by Doole & Weetman (2009) found that the use of ungrazed pasture fallows was an effective means of controlling weed populations. Mixed farming systems, soil tillage, crop rotations, the use of selective chemicals and the cultivation of new crops were highlighted as other successful approaches to managing pests, disease and weeds (Dang et al., 2015, Doole & Weetman, 2009; Nash & Hoffman, 2012). However Nash & Hoffman (2012) state that pest, disease and weed management, which is beneficial to both the environment and the farmer, needs to be adapted to take into consideration the changing climate, agronomic practices, landscape use, societal concerns and economic matters. In this thesis, the GHG implications of pest control mechanisms in south-western Australia's semi-arid climate are adequately covered in Chapters 5 and 6.

2.2.1.4 Soil management

The FAO (2014b) states that healthy soil has the capacity to function as a living system comprising a diverse community of organisms that help control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots, recycle plants nutrients, and improve soil structure for optimal water and nutrient holding capacities Well-structured, healthy soils are important for agricultural production and sustainability purposes. The ability of soil to provide water and nutrients to agricultural produce is considered the soil productivity and is generally measured in terms of crop yield per millimetre of available water (Baldock et al., 2012; Bennett et al., 2002; Department of Agriculture and Food of Western Australia (DAFWA), 2014).

Changes in soil moisture, soil structure, organic matter content, cation exchange capacity and pH due to tillage, soil management or climate changes may have an influence on the emission or sequestration of GHGs from soil (Baldock et al., 2012; Bell et al., 2007; Rochecouste et al., 2015). Tillage, soil management and climate change are three factors that cannot be divorced from each other if the soil health needs to be maintained or improved. Interacting with each other they have the capacity to improve the soil organic matter (SOM) due to increased yields, which are optimised when sufficient water for the crop is available. Poor soil structure cannot provide the required nutrients, water holding capacity or ideal micro-organism community and furthermore each crop requires an ideal (different) pH to take full advantage of soil health and thereby increase in yield (Asseng, Thomas, McIntosh, Alves, & Khimashia, 2012, Baldock et al., 2012; Bell et al., 2007; Browne, Kingwell, Behrendt & Eckard, 2013; Rochecouste et al., 2015).

The management of soils can either reduce or increase the emissions of CO_2, N_2O and CH_4 from the soils into the environment (Baldock et al., 2012). Soil emissions are separated into direct soil emissions (CO_2 from urea hydrolysis, CO_2 from liming, N_2O from fertiliser, CH_4 from the soil) and indirect soil emissions (N_2O-N from leaching and runoff, N_2O-N from NH_3 volatilisation) (IPCC, 2007b). The soils of Australia have been placed into 38 groups depending on the texture, structure, subsurface, subsoil and substrate properties of the soil (Isbell, 1996; Moore, 2001). Western Australia has a wide variety of soils that show a high degree of weathering, laterisation, low fertility and a coarse texture. They are among the oldest in the world and are low in nutrients such as nitrogen and phosphorus (Moore, 2001; Steffan, Sims, & Walcott, 2011).

In the wheatbelt area of Western Australia, farmers plant crops in predominantly infertile shallow, sandy duplex soils and deep sands (Ludwig & Asseng, 2006; Moore, 2001). The application of nutrients in the form of fertilisers and lime, amongst other chemicals, has overcome many limitations to produce higher yielding crops (Baldock et al., 2012). As the soils in Western Australia are not naturally arable, it is important to manage the health of the soil and in so doing reduce the GHGs originating directly or indirectly from the soil (Landcare, 2005; Ugalde et al., 2007). The GHG implications of liming and claying in south-western Australia's grain production are further investigated in Chapters 5 and 6. Other factors influencing crop yield include the type of soil, the availability of water, temperature variances and location (Ludwig & Asseng, 2006).

2.2.1.5 Fertiliser management

The primary producers in Australia successfully operate in one of the world's most hostile agricultural environments characterised by a high degree of climate variability and soils that exhibit a general deficiency of N and P (Madinhire, Mugwindiri, & Mbohwa, 2015; Steffan et al., 2011). For intensive cropping systems in Australia to be productive, adequate amounts of N need to be applied to increase the fertility of the soil, as fertilisers (Gregorich, Janzen, Helgason, & Ellert, 2015). The Department of Agriculture for Australia defines a fertiliser as a growth enhancer or regulator that aids plant growth, which in Australia is grouped in one of three main categories, namely chemical (synthetic) fertiliser, mined fertiliser or organic fertiliser. Chemical fertilisers are produced artificially, mined fertilisers are natural, non-organic and are mined from the earth, and organic fertilisers are of aquatic animal, terrestrial animal, avian or microbial origin (Australia Government Department of Agriculture (AGDA), 2015a). If fertilisers are not applied efficiently, according to plant demands, they can be lost to the environment as ammonia emissions, nitrate leaching and runoff and emissions of nitrous oxide (Gregorich et al., 2015) and at the same time affect the yield of the crop (Liu et al., 2015).

The application of synthetic N-fertilisers to agricultural soils is one of the key causes of N_2O emissions in Australia and represents around 3% of total national GHG emissions (Australian Bureau of Standards (ABS), 2015). Other sources of N_2O loss include legumes, livestock excreta and cultivation, however the NIR (2012) states that agricultural soils are the greatest source. In 2011–12, fertiliser was applied to 46.7 million hectares of land in Australia, of which Western Australia contributed 18.2 million hectares, the highest of all the Australian states (39% of all fertilised land in Australia) (Australian Bureau of Statistics (ABS), 2015). New South Wales farmers applied fertiliser to 21% of Australian agricultural fertilised land (ABS, 2015). The current research has thus endeavoured to investigate the GHG implications of N-fertiliser applications in south-western Australia's farming systems (see Chapter 5).

Factors such as soil type, temperature, soil moisture, application rates, placement of fertiliser, time of application, crop type and FMP all play a role in the N_2O emissions generated from the use of fertilisers (Smith et al., 2007).

Landcare (2005) recommends using adaptation strategies to improve the efficiency of fertiliser use in Australia, such as determining the nitrogen requirements of the crop based on residual soil nitrogen content and the yield goals for the crop to be planted, the application of other nutrients which can facilitate the uptake of the N-fertiliser, the use of application methods where the fertiliser is placed close to the roots, and the appropriate timing of applications.

The correct application rate and type of fertiliser is imperative in optimising the yield as the yield can be compromised if the application is too high or low. In addition, if the application of the N-fertiliser is too high, the loss of N via direct and indirect pathways can occur. Incorrect fertiliser use can also affect the quality of the grain harvested (Arregui et al., 2006; Kim et al., 2015; Wang & Dalal, 2015). Soil testing could be effectively used by farmers to ascertain which soil variables should be addressed and they can then focus on addressing the identified deficiencies (Arregui et al., 2006; Stuart, Schewe, & McDermott, 2014). Crop rotation has been shown to be an effective method of fixing N in the soil for it to be available to crops in later years (Barton, Thamo, Engelbrecht, & Biswas, 2014; De Gryze et al., 2011; Stuart et al., 2014). Legume based crops have been studied extensively and have been found to be a good rotation alternative. However, authors such as De Gryze et al. (2011) and Stuart et al. (2014) state that it is important to consider more than one rotation as all rotations will contribute to N_2O emissions.

All researchers are in agreement that reducing the GHG emissions from N-fertiliser is no easy task. For example, adopting no-tillage mechanisms may lead to a reduction in N_2O emissions but other environmental impacts such as increased pests could require pesticide applications, which in turn could increase other GHG emissions. It is therefore imperative that the whole farming system be considered in adopting alternative management practices (Arregui et al., 2006; Kim et al., 2015; Lehuger et al., 2011; Wang & Dalal, 2015).

2.2.1.6 Water management

Climate change and drought, coupled with the competition between industries, environment and recreation, for water, all have an impact on global water resources. Agricultural drought is defined by the National Aeronautics and Space Administration (NASA) (2014b) as "insufficient soil moisture to meet the needs of a particular crop at a particular time". NASA (2014b) continues by stating that a deficit of rainfall over cropping areas during specific periods of the growth cycle could lead to underdeveloped crops with reduced yields.

Current statistics show variation in the average annual rainfall throughout Australia, with most of the provinces receiving less than the average of 300 mm. Rainfall in the south-western part of Australia has been predicted to decline even more (Steffan et al., 2011). Climate change will be responsible for further precipitation alterations in Western Australia causing a higher incidence of agricultural drought, thus improved water management is required.

One way of adapting to low rainfall to maintain harvest productivity is by making use of irrigation methods (Jamali, Quayle, & Baldock, 2015; Kirby, Bark, Connor, Qureshi, & Keyworth, 2014; Mushtaq, Maraseni, & Reardon-Smith, 2013; Mushtaq & Moghaddasi, 2011). About 18% of the world's countries now use irrigation (Smith et al., 2007) and it has been successfully used in countries such as Pakistan, Turkey, South Africa, the United States and Australia (Kirby et al., 2014).

In the face of climate change and ongoing drought, the reduction in seasonal water allocation and less environmental water is a problem for irrigators (Kirby et al., 2014), and thus Landcare (2005) suggests that less water be used per unit of product. In reducing water use the energy required for pumping is reduced and thus the CO_2 emissions. In addition, Landcare (2005) also focuses on the avoidance of waterlogging to avoid denitrification and the associated loss of N as N_2O. Other adaptation strategies for water management include monitoring of water requirements and irrigating according to crop need, improving drainage and selecting more water efficient crops (Mustaq & Moghaddasi, 2011). Irrigation is associated with high fertiliser applications that increase the N_2O emissions from the soil and high energy use which further elevates farm GHG emissions.

However, as with all of the adaptation strategies considered, water management should be integrated with the whole farming system, as by altering one aspect to decrease GHG emissions can lead to other inputs then increasing the GHG emissions from the system.

In Australia, researchers have focused on how to maintain crop yields, optimise the use of water and energy and at the same time focus on the environmental impact of irrigation (Jamali et al, 2015; Mushtaq et al., 2013; Mushtaq & Moghaddasi, 2011). A study in New South Wales, Australia (Mushtaq et al., 2013) tested three scenarios (full irrigation, limited irrigation, no irrigation) to determine the effect of reducing water on the crops. The authors found that when no irrigation was applied the crop area and yield decreased as well as the cropping area. When the water supply was restricted, they inferred that environmental savings could be made in the form of reduced water applications and energy use per unit of yield, as the additional water and energy could be used to extend the cropping area and in that way the productivity of the farm could increase. In Western Australia, irrigated agriculture accounts for 35% of the state's water use (Department of Water, 2015), however the study area of this current research only assessed the GHG emissions from rainfed crops, as none of the paddocks analysed were irrigated.

2.2.1.7 Pasture management

Rainfed mixed crop-livestock farming systems are a major part of the world's land use and agricultural production, producing about half of the world's beef, a third of its sheep-meat and half of its milk (Bell & Moore, 2012; Steffan et al., 2011). As the winter temperatures in Australia are relatively mild, livestock are bred successfully as they are able to graze all year on native pastures, improved pastures, forage pastures and crop stubbles/residues (Wolfe, 2009). In 2010, crop-livestock enterprises occupied about a third of the agricultural land (Bell & Moore, 2012; Steffan et al., 2011). However, the production of livestock in Australia is dependent on international export and the domestic market (Bell & Moore, 2012; Steffan et al., 2011).

The largest contributor of GHGs in Australian agriculture is the emission of CH_4 from livestock, originating from the decomposition of excreta as well as from enteric fermentation (Table 2.4) (Biswas et al., 2010; NIR, 2012; White & van Rees, 2011). Enteric CH_4 is produced by microbes during the anaerobic digestion process when the plant material is broken down into simple fatty acids, CO_2 and CH_4. The fatty acids are absorbed into the bloodstream and the gases are eliminated through eructation and exhalation. Undigested food and microbial cells pass through the digestive tract for elimination as dung or urine. The type of digestive tract, age and weight of the animal and the quality of the feed consumed all play a role in the digestive process (Biswas et al., 2010; Eckard, 2007; NIR, 2012, 2013a; White & van Rees, 2011). Manure (dung and urine) produces CH_4 during decomposition under anaerobic conditions, when stored or handled. Less CH_4 is produced aerobically when the manure is left in the field, than when manure is stored under anaerobic conditions (NIR, 2012, 2013a). The N in the manure is converted to N_2O under aerobic conditions through nitrification and denitrification.

Suggestions for the reduction of CH_4 from livestock focus on breeding, feeding, dietary supplementation and manure management (Biswas et al., 2010; de Boer et al., 2011; Department of Agriculture, Fisheries and Forestry (DAFF), 2013; Eckard, 2007, Garnett, 2011; Meat and Livestock Australia (MLA), 2014). Breeding focuses on improving the productivity of each animal by giving attention to milk production, growth rate, fertility and feed conversion. If these aspects are optimised, the overall GHG emissions per animal are reduced and the output units (milk, meat and wool, amongst others) are increased. Feeding requirements are addressed by giving higher quality feed to the livestock to improve digestibility, which in turn reduces GHGs from the enteric fermentation process. When added as a supplement to the feed, tannins and oilseeds have the ability to alter the digestive process, inhibiting CH_4 production by reducing the availability of hydrogen in the digestive tract (tannins), and inhibiting the methanogens and protozoa responsible for the production of CH_4 (oilseeds). CH_4 is produced by anaerobic processes during the storage and management of manure (de Boer, 2011; Eckard, 2007; Garnett, 2011, Smith et al., 2007). The management of manure includes reducing the time of storage of manure, movement of the animals away from areas where frequent urination takes place, and the management of litter either by more frequently replacing it or eliminating its use (de Boer, 2011; Eckard, 2007; Garnett, 2011).

However, Garnett (2009) and Eckard (2007) state that even if all of the breeding, feeding, supplementation and manure management methods are able to mitigate GHGs from livestock production, other environmental impacts could increase, so these analyses should all be made in the context of each specific farming system.

2.2.1.7 Energy management

The abundance of natural energy sources in Australia contributes to the country's economic prosperity. Natural energy resources include an estimated 38% of uranium resources, 9% of coal resources and 2% of natural gas resources in the world. In 2008–2009, energy exports in Australia reached nearly 14,000 petajoules (PJ). Australia is the world's 20th largest consumer of energy and 15th in terms of per capita energy use. As the Australian economy and population grow, the demand for energy is on the rise (Australian Bureau of Agriculture and Resource Economics (ABARE), 2010).

In 2008–2009 Australia used a total of 2,797 PJ of energy and in 2009–2010 a total of 2,824 PJ. For both these periods the energy use for agriculture ranked the second lowest, just before water supply and waste services (Table 2.1).

Table 2.1. Energy use by industry for 2008–2009 and 2009–2010 (ABARE, 2010)

Industry	Energy use 2008–2009 (PJ)	Energy use 2009–2010 (PJ)
Manufacturing	1,041	1,034
Transport	531	544
Mining	519	543
Commercial and services	433	429
Construction	144	144
Agriculture	107	109
Water supply and waste services	22	21
Total	2,797	2,824

Note: One petajoule (PJ) – 1,000,000 gigajoules (GJ).

The use of energy on farms includes the use of electricy and fuel. In Australia farmers have adapted to more efficient energy uses by adopting more efficient diesel powered machinery and energy conserving tillage practices, resizing equipment to more appropriate dimensions, and employing energy saving technology for irrigation. By improving the efficiency of energy use on farms, GHG emissions can be reduced (Landcare, 2005; Sloan, Sipe, & Dodson, 2014).

Adaptation strategies are generally effective immediately and could increase yields or reduce the vulnerability of crops to climate variability in the same growing season. Furthermore, as farming methods adapt to climate change, benefits could increase over time and the negative impacts of climate change on human activities and ecosystems could be minimised (IPCC, 2007a; Tubiello & Fischer, 2007). However, limitations include financial, technological, political, social, institutional and cultural constraints, which could affect both the implementation and effectiveness of adaptation (IPCC, 2007a; Matthews et al.., 2013).

2.2.2 Mitigation

Both Liebig et al. (2011) and the IPCC (2007a) agree that climate change mitigation refers to anthropogenic efforts that aim to reduce or prevent the emissions of GHGs from the source (United Nations Environment Programme (UNEP), 2014a). The general consensus is that mitigation focuses on a global level when compared to adaptation, which is said to focus on national or local sources of emissions (Laukkonen et al., 2009; Shaw, Burch, Kristensen, Robinson, & Dale 2014; Tol, 2005). However Laukkonen et al. (2009) maintain that mitigation can and should be executed at all levels, be it local, national or international, and in affirmation the IPCC state that adaptation and mitigation can work together (IPCC, 2007a).

Reddy (2015) highlights the fact that all is not yet known about GHGs and climate change, and continues by stating that although GHG emissions may be reduced, there are also distinct disadvantages in implementing mitigation methods. As with adaptation, mitigation is constrained by the availability of funding for different technologies, as no one technology can address all mitigation measures, and there is also a lack of funding for implementing actions and plans (Huang & Wang, 2014; IPCC, 2007a; Tubiello & Fischer, 2007). Research by Blandford, Gaasland, & Vårdal (2014) and Franks & Hadinham (2012) shows that in mitigating GHGs on a farm there is usually a trade-off between high productivity and lower GHG emissions, i.e. high productivity is usually associated with high levels of GHG emissions. Barton et al. (2014) showed that an opportunity cost would be incurred when a lupin-wheat rotation was grown, in that the GHG emissions would be reduced considerably but the financial saving was small. The financial saving would however be determined by the cost of the inputs into the system. In agreement with these statements, Laukkonen et al. (2009) argued that mitigation and adaptation can work together at some levels but are contradictory at others. Synergies could include properly designed biomass production, formation of protected areas, land management, energy use in buildings, and forestry, whereas trade-offs may increase GHG emissions due to increased consumption of energy (IPCC, 2007a). However, mitigation measures are required in agriculture to make a significant contribution to the reduction of GHGs (Darwin, 2004). In addition, mitigation could mean using new technologies and renewable energies, making older equipment more energy efficient, changing management practices or changing consumer behaviour (UNEP, 2014a). Overall the benefits of mitigation will not necessarily be immediate, as with adaptation, but are more near-term and long-term benefits (IPCC, 2007a).

The following table (Table 2.2) broadly suggests areas in which GHGs could be reduced in the agricultural sector as well as giving a few examples of mitigation strategies. However, these mitigation strategies may vary within regions, FMPs and agro-ecological zones. Chapter 7 presents the mitigation strategies specifically applicable for south-western Australia’s grain production systems.

Table 2.2. Recommended mitigation strategies for agriculture

Mitigation	Examples	References
Enhance soil C sequestration	Maintain plant residues on the soil surface	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Drain water from rice paddies	EPA, 2015; Reddy, 2015
	Improve crop and grazing land management	De Boer, 2011; Reddy, 2015
	Minimise soil disturbance and erosion	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Cultivate crops with deep root systems	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
Improve N-use efficiency	Make use of cover crops, legumes and nitrification inhibitors	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Better timing, placement and prediction of N requirements	Editorial, 2005; EPA, 2015; Reddy, 2015
	Use soil tests to determine residual N	Liebig et al., 2011; Reddy, 2015
Increase ruminant digestion efficiency	Improve feeding practices and use of dietary amendments	De Boer et al., 2011; Eckard, 2007; EPA, 2015; Liebig et al., 2011; Reddy, 2015
Capture GHG emissions from manure and other wastes	Manage manure/excreta	Liebig et al., 2011; Reddy, 2015
	Capture GHG emissions from excreta and other wastes and use as an energy source	EPA, 2015; Liebig et al., 2011; Reddy, 2015
Reduce fuel consumption	Limit number of field passes by farm machinery	Bennett et al., 2002; Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Implement efficient irrigation practices	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Decrease fuel consumption	Editorial, 2005; Liebig et al., 2011; Reddy, 2015
	Decrease land preparation	Editorial, 2005; Liebig et al., 2011; Reddy, 2015

On considering the previous table (Table 2.2) it is clear that the mitigation practices listed here are closely related to the adaptation methods described in the previous section. The foregoing discussion shows that by adapting alternative FMP, GHG emissions can be mitigated. However, the discussion also shows that a whole system approach needs to be adopted as altering one aspect in the FMP will have an impact on all GHG emissions, either positively or negatively. The IPCC supports this deduction by stating that “no one single technology can provide all of the mitigation potential in one sector” (IPCC, 2007a).

Cleaner production (CP) is the mitigation strategy that will be considered as part of this research as it can be holistically applied in the agricultural sector. Furthermore, by introducing both mitigation and CP strategies into all facets of agriculture, especially grain production, the GHG emissions resulting from agricultural inputs and outputs could be reduced (Engelbrecht et al., 2013).

CP is an integrated preventative environmental strategy, amongst others, that is embodied in mitigation and focuses on preventing waste and emissions rather than dealing with them once they have been generated (UNEP, 2011; United Nations Industrial Development Organization (UNIDO), 2015; van Berkel, 2002). Furthermore it concentrates on processes, products and services to increase efficiency and reduce risks to humans and the environment (Biswas et al., 2010; van Berkel, 2002, 2007). The benefits of CP can reduce risks to the environment and humans by decreasing waste, recovering valuable by-products, improving environmental performance, increasing resource productivity, increasing efficiency, lowering energy consumption and reducing overall costs (Khan, 2008; van Berkel, 2011; Madanhire et al., 2015).

Five key CP prevention practices that are considered applicable to agriculture and this project are discussed in full in Chapter 7 and include:

- product modification (on-site processing),
- input substitution (use of alternatives),
- technology modification,
- good housekeeping (reduction of energy, raw materials etc.),
- recycling and reuse (packing material, water) (Biswas et al., 2011; Engelbrecht et al., 2013; van Berkel, 2011).

The IPCC consider it important to establish a working relationship between adaptation and mitigation to realise the benefits of reducing GHG over a long term period. Adaptation can reduce sensitivity to climate change while mitigation can reduce the exposure to climate change (IPCC, 2007a).

2.3 MANAGING GLOBAL CLIMATE CHANGE

The increasing pressure on agriculture to provide food for the growing world population has highlighted the importance of improved management of the carbon footprint (or life cycle GHG emissions) generated during production (Biswas et al., 2010; Engelbrecht et al., 2013; National Greenhouse Gas Inventory (NGGI), 2010b). Consequently farmers may respond to climate change either by adapting to the unavoidable changes occurring or by attempting to reduce climate change by introducing mitigation measures. Given that changes in the climate are specific to each country or region (Huang et al., 2011), no uniform global management scheme can be devised. It is therefore necessary for a variety of schemes or actions to exist which specifically cater to individual situations (Arregui et al., 2006; Kim et al., 2015; Lehuger et al., 2011; Wang & Dalal, 2015).

On a global level there is an extensive range of governance and policy responses to the climate change issue, some of which are listed here (APH, 2010).

- **International Action**
    - The United Nations Framework Convention on Climate Change (UNFCCC)
    - Kyoto Protocol
    - IPCC
    - Montreal Protocol on substances that deplete the ozone layer

The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) collectively established the Intergovernmental Panel on Climate Change (IPCC) in 1988. The aim of the IPCC was to provide the world with a clear scientific view on the current state of climate change and its potential impact. Today the IPCC is the leading international body assessing climate change under the auspices of the United Nations (UN) (IPCC, 2014c).

In December 1997 during the 3rd meeting of the UNFCCC in Kyoto, Japan, the Kyoto Protocol was negotiated and came into force on 16 February 2005. The Marrakesh Accords contain the detailed rules for the implementation of the Kyoto Protocol. On signing and ratifying the Kyoto Protocol, countries legally agreed to reduce emissions from six GHGs, namely CO_2, N_2O, CH_4, sulphur hexafluoride, hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs), compared to 1990 emissions. Each country was assigned a specific reduction target, for example 8% for the European Union, 7% for the USA, and 6% for Japan (Kyoto, 2014; UNFCCC, 2014). Australia is permitted an increase of 8% and Iceland 10%. Overall the global reduction target is 5.2% (Kyoto, 2014; UNFCCC, 2014).

Most countries are participating in cooperative actions that derive from the 1992 United Nations Framework Convention on Climate Change and the 1997 Kyoto Protocol (APH, 2010), some of which are summarised briefly below.

- **Foreign Government Action**
    - New Zealand Climate Change
    - Government of Canada Climate Change
    - Environmental Protection Authority (USA)
    - Centre for Science and Environment (India)

The national governments of some countries have undertaken detailed reviews and studies and have subsequently developed policies and actions to specifically react to their own individual climate change scenarios (APH, 2010). The foreign government actions will not be discussed herein, as it is beyond the scope of this project, but some that are applicable to Australia are included.

- **Domestic Action (Australia-specific)**
    - Territory and municipal services (Australian Capital Territory)
    - Department of Environment and Climate Change (New South Wales)
    - Natural Environment, Resources and the Arts (Northern Territory)
    - Queensland Climate Change Strategy (Queensland)
    - Tackling Climate Change in South Australia (South Australia)
    - Living Environment Programme (Tasmania)
    - Department of Sustainability and Environment (Victoria)
    - Department of Environment and Conservation (Western Australia)

At various levels of state and territory governments in Australia, policies and actions have been developed to respond to climate change (APH, 2010).

2.4 THE AUSTRALIAN SITUATION

This section reviews climate change in Australia, including the management of agriculture in Western Australian and Australian legislation. Western Australia is highlighted as this project focuses on agriculture in south-western Australia. The other states and territories are not of lesser importance, but are not included in the scope of the project and will thus not be examined.

2.4.1 Background

Australia, the lowest and flattest continent in the world and second driest (after Antarctica), has been divided administratively into six states and two territories (ABS, 2014; Australian Government, 2014b; Steffan et al., 2011). The six states, namely Western Australia, New South Wales, Queensland, South Australia, Tasmania and Victoria, each have their own constitution, whereas the two territories, the Australian Capital Territory and the Northern Territory, have limited self-governance (Australian Government, 2013).

The landmass of Australia is about 7,692,024 km^2 (Australian Government, 2014b), with Western Australia being the largest state covering an area of 2,529,875 km^2 (Geoscience Australia, 2010). Australia has several climatic zones ranging from tropical rainforests, deserts and cool temperate forests to snow covered mountains (Carbon neutral, 2011; Australian Government, 2014b). The summers are mostly hot with temperatures exceeding 30°C, winters are warm in the north and cooler in the south. The climate in Western Australia shows many extremes, for example, tropical in the north and dry temperate in the south. The average temperatures for Western Australia vary between 15–31°C in the summer and 9–18°C in the winter (Geoscience Australia, 2010). Figure 2.2 shows the average daily mean temperatures over Australia for the period 1961–1990 (BOM, 2014b).

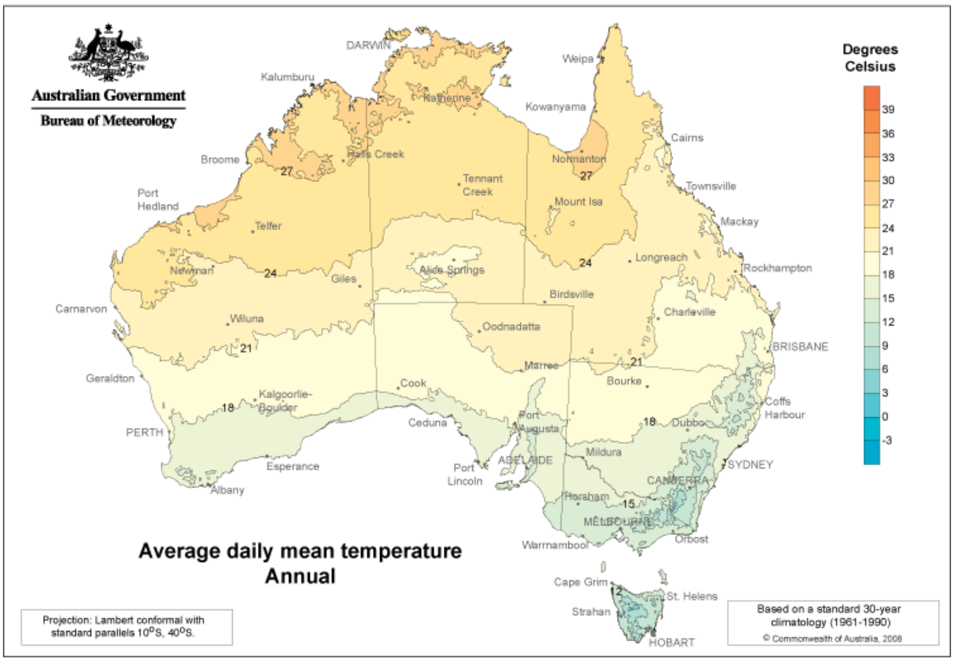

Figure 2.2. Average daily mean temperature (annual) (BOM, 2014b)

Australian rainfall varies seasonally, with winter rainfall occurring in the south and summer rains in the north in some areas, whilst other areas have rain throughout the year. Western Australia is characterised by two rainfall patterns due to the large area of the state (WAClimate, 2014) (Figure 2.3).

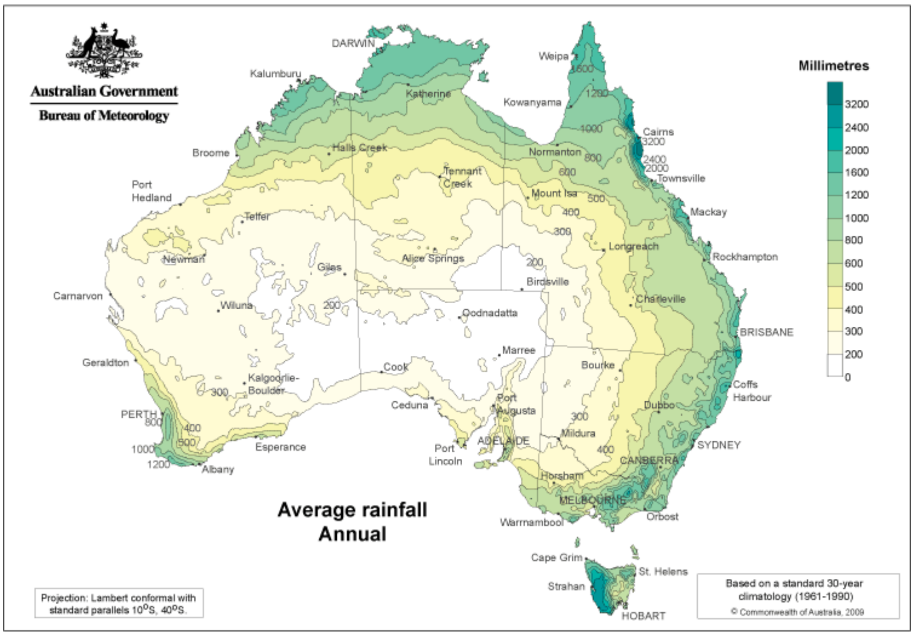

Figure 2.3. Average annual rainfall 1961–1990 (BOM, 2014b)

Australian soils have been classified into 14 different groups according to their soil profile, soil properties and vegetation type (Figure 2.4) (Australian Soil Resources Information System (ASRIS), 2014; DAFF, 2012). Soils provide clean water, sustain terrestrial biodiversity, regulate filtering contaminants, reduce dust levels and absorb organic waste in thriving ecosystems (DAFF, 2012). The productivity of soil is largely determined by the maintenance of good soil health and moisture content, which in turn determines the FMP employed by the farmers (DAFF, 2012). Crop yield and farm productivity can be optimised by soil nutrient testing and the application of fertiliser to rectify the balance of depleted nutrients (Moore, 2001), particularly nitrogen, phosphorus and recently potassium (ABS, 2012). Although soils used for agriculture in Australia are geologically old and deeply weathered with some containing high concentrations of salt, agricultural production has been successful (DAFF, 2012).

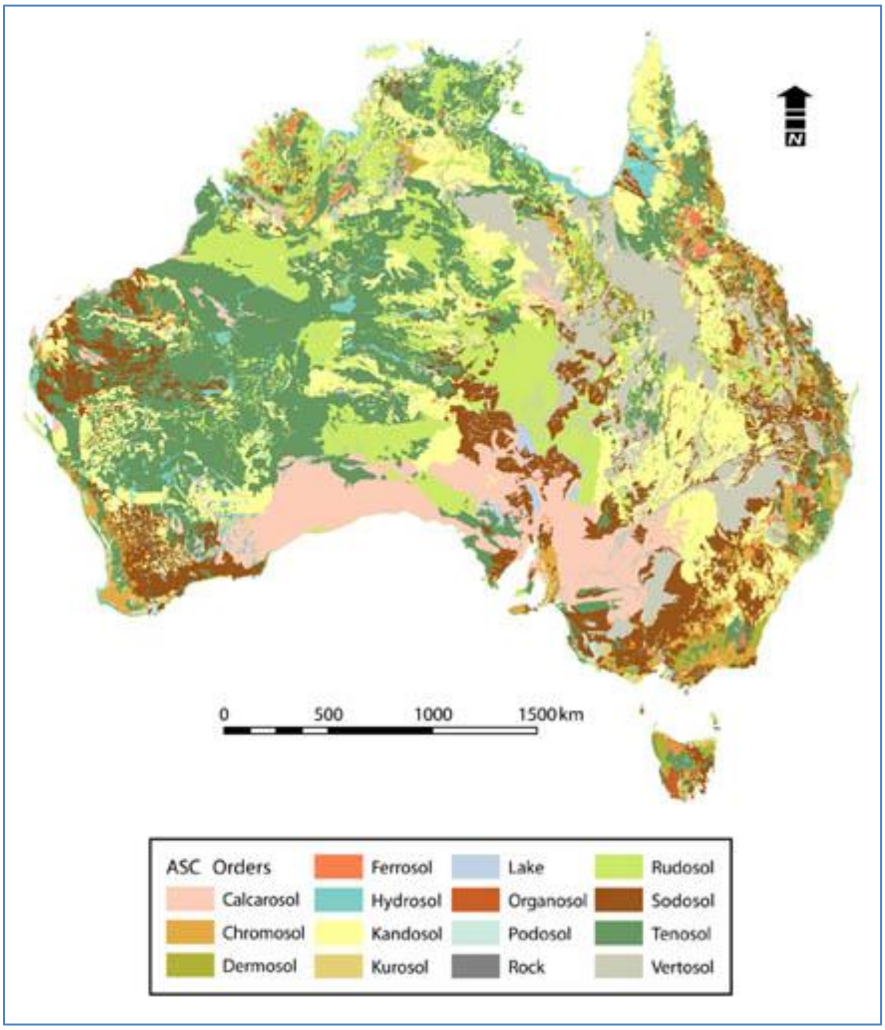

Figure 2.4. Map of Australia showing the different soil types (ASRIS, 2014)

2.4.2 Overview of agriculture in Australia

Agriculture in Australia has increased at an average rate of 2.8% from 1974 to 2004. In 2013 agriculture contributed to about 4% (Index Mundi, 2013) of the gross domestic product (GDP) of Australia and employed around 307,000 people in 2010–11 (National Farmers Federation (NFF), 2014). During 2007–2013 around two-thirds of agricultural products were exported, accounting for about 15.5–18% of the total Australian exports across all sectors. Grains and oilseed export accounted for 24% of the agricultural exports (Australian Government Department of Agriculture (AGDA), 2015b; Department of Foreign Affairs and Trade (DFAT), 2015; Gunasekera, Tulloh, Ford, & Heyhoe, 2008; NFF, 2015).

Grain produced in Australia is of international standard due to the high quality and production reliability (NFF, 2014). Western Australia is one of the major cropping areas of Australia, growing a variety of grains, predominantly wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and lupins (*Lupinus angustifolius*) (Steffan et al., 2011). As stated in section 1.4, Western Australia produces 40–50% of the annual grains for Australia (Biswas et al., 2008; Engelbrecht et al, 2013; Paterson & Wilkinson, 2015). The cultivation of these grains is concentrated in the south-west corner of Australia as shown in Figure 2.5 (green shaded region), known as the wheatbelt area, comprising approximately 197,300 km^2 (8% of the state).

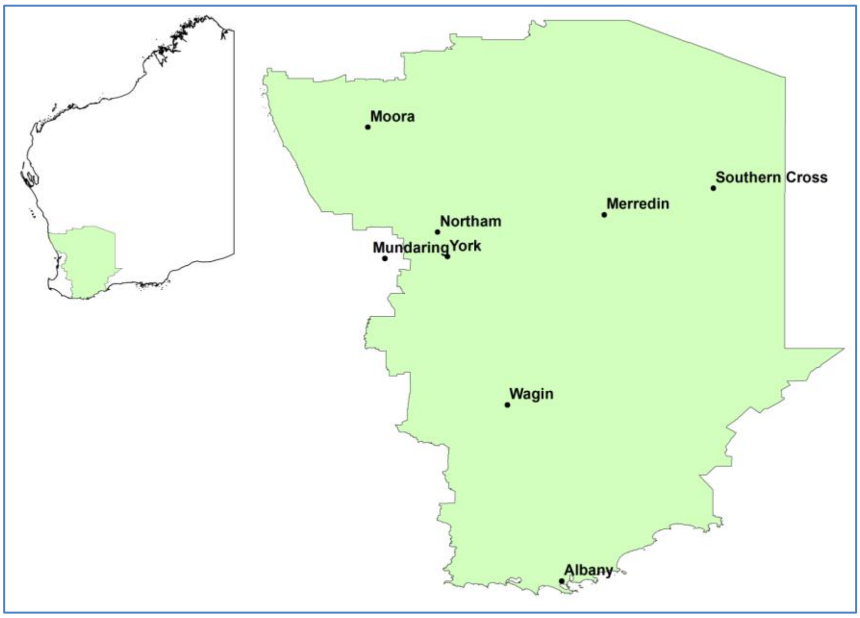

Figure 2.5. Map of Western Australia showing the position and extent of the wheat belt as a green polygon (Trestrail, Martin, New, Corrie, & Frakes, 2013)

The wheatbelt of Western Australia is divided into 55 local government areas or shires which are further subdivided into smaller areas of land comprised of buildings and land used for growing crops and rearing animals, namely a farm. Each farm is subdivided into paddocks[1] which are enclosed by a fence or defined by a natural boundary, with neighbouring paddocks on the same farm often used for entirely different purposes. An estimated 13,478,518 hectares of this land belonged to farmers in 2010–11 (Engelbrecht et al., 2013; Trestrail et al., 2013). Furthermore, in Western Australia, five groups of highly organised farmers initiated a system in 1990 (known as the 'Decade of Landcare') in which researchers and agribusiness companies convened with the farmers to focus on local issues specific to a region. They were organised according to agro-ecological zones and FMP across five regions, namely Northern Agricultural Region, Central Wheatbelt, Swan, South-west Region and South Coast Region (Gianatti & Llewellyn, 2003, 2006; Grower Group Alliance (GGA), 2014). These grower groups enabled government and non-government agencies to channel information, funding and services to the farming community and also to receive information from them. Each of these grower groups had its own objectives and an individual approach to agriculture (Gianatti & Carmody, 2006; Taylor, 2013). Currently there are 42 grower groups in Western Australia and approximately 4,078 members (individuals and businesses) (GGA, 2014).

In 2010–11 wheat accounted for 31% of the gross agricultural production in the Western Australian wheatbelt, wool, sheep and lambs accounted for 16% each (48% in total), canola for 8% and mixed grains for 8%. Mixed grain and livestock farms were the most common, making up 85% of the total farming area in Western Australia (Trestrail et al., 2013).

[1] Universally a paddock is defined as a small, usually enclosed field near a stable or barn for pasturing or exercising animals. In Australia and New Zealand a paddock is a piece of fenced in (enclosed) land that may be used for any purpose (Free, 2014; Ref, 2014).

2.4.3. Climate change in Australia

In Australia temperatures have increased by 0.9°C since 1910 and average rainfall has increased slightly since 1900, with the largest increase over the north-west, and decreases over the south-west since 1970. Across large parts of Australia the fire season is longer and the fire weather is more extreme (since 1970) and the incidence of heatwaves has also increased since 1950 (Commonwealth Scientific and Industrial Research Organisation (CSIRO), 2014a; IPCC, 2007b). Further changes are expected to precipitation patterns, sea levels could rise and weather related disasters could become more frequent and severe (APH, 2014a; Carbon neutral, 2011; CSIRO, 2014a; DAFF, 2014).

The changes in the Australian climate are consistent with global changes and the State of the Climate Report (CSIRO, 2014a) suggests that not all changes are due to natural variabilities but are also due to human induced climate change.

Due to climate related differences over the vast area and agro-ecological zones of the nation the effects of climate change will manifest in different ways in different states (Pittock, 2003; Steffan et al., 2011). Figure 2.6 summarises the projections for Australia reported by CSIRO (2014a) based on data received from BOM.

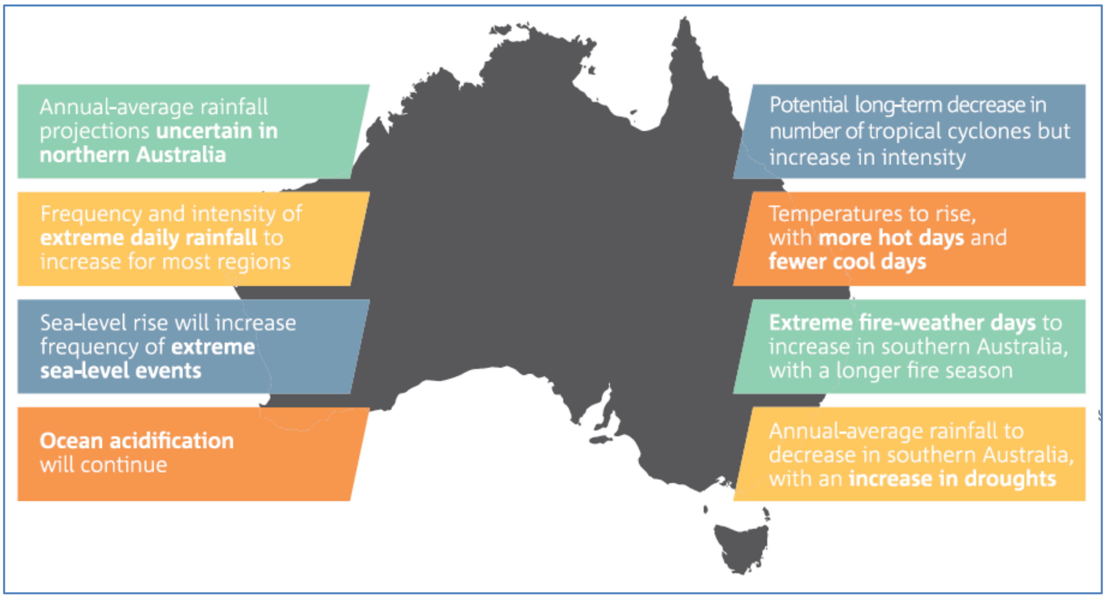

Figure 2.6. Long term effects of climate change on Australia (CSIRO, 2014a)

The major effects of climate change, focusing on agriculture in south-western Australia, include:

- It will become warmer than what it is currently, especially in the south. Average annual temperatures are expected to rise by 0.4–2.0°C and 1–6°C by 2030 and 2070, respectively (Foster, 2007). This will be advantageous as the incidence of frost will decrease and yield could increase as a result of increasing CO_2 levels in the atmosphere, however the higher CO_2 levels could affect the grain protein negatively. Some insects and pests flourish under warmer conditions and could become a nuisance (Bennett et al., 2002).
- The average annual winter rainfall is expected to decrease by as much as 15% over the south-western wheatbelt of Western Australia by 2030 and 30% by 2070 (Ludwig & Asseng, 2006). This means the growing season would start later, the growing season would be short and the grain yields would decrease (Bennett et al., 2002).
- As the temperature increases the evaporation rates are expected to increase, consequently disrupting the water balance (Foster, 2007) and affecting the yield (Bennett et al., 2002).
- Grain production in Western Australia is predicted to decrease by 9% and 14% by 2030 and 2070 respectively, mainly due to a decrease in rainfall (Gunasekera et al., 2007).
- More frequent extreme weather events will cause stock and crop losses (Bennett et al., 2002).

In combatting climate change and the effects it can have on agriculture, as outlined above, Laukkonen et al., (2009) stress the importance of developing a methodology and a tool that can be used to combat climate change.

2.4.4 GHG emissions from agriculture in Australia

In 2012, Australia was the seventh largest user of natural resources in the world after Qatar, Kuwait, UAE, Denmark, the USA and Belgium, one of the top 20 polluting countries, and the largest per capita emitter of GHGs (Australian Greenhouse Emissions Information System, (AGEIS), 2014; World Wildlife Fund (WWF), 2012). Australia was ranked eighth highest GHG polluting country in 2010 (AGEIS, 2014) and 17th in May 2015 (Bulletin, 2015). In 2013 the GHG emissions from Australia totalled 538.0 Mt CO_2-e, an increase of 1.2% from 1990 (531.6 Mt CO_2-e) (AGEIS, 2014). Furthermore, the per capita emissions increased by 25.2% from 1990 to September 2014 (NGGI, 2014).

Figure 2.7 illustrates the GHG emissions in terms of CO_2-e for each Australian state for 2000 and 2013. Here it can be seen that the state emitting the most CO_2-e for both years was Queensland, then New South Wales, followed by Victoria and Western Australia in fourth place. The Australian Capital Territory and the external territories both emitted insignificant amounts of CO_2-e and were thus excluded from this graph (Department of Environment, 2013).

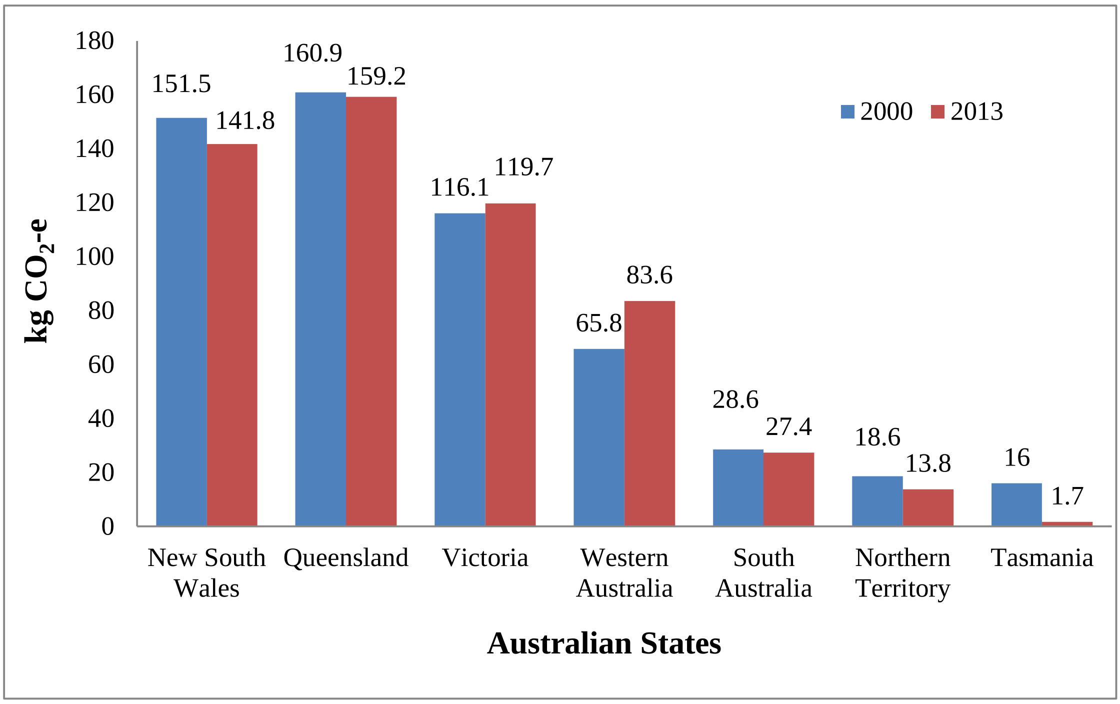

Figure 2.7. National greenhouse gas inventory total, carbon dioxide equivalent per state for 2010 and 2013 (Department of Environment, 2013)

The overall GHG emissions for Queensland decreased by 1.7% (including land use, land use change and forestry (LULUCF)) from 2010 to 2013, with the three sectors (decreasing magnitude), stationary energy, agriculture and LULUCF generating the highest GHGs in 2013(Figure2.7). New South Wales showed a reduction in GHGs of 9.7% from 2000 to 2013 with stationary energy, transportation and agriculture manifesting as the highest emitters in 2013. Victoria and Western Australia showed increases by 3.6% and 17.8% respectively in GHG emissions from 2000 to 2013. Stationary energy, followed by transportation and agriculture, were the highest emitters in both Victoria and Western Australia for 2013 (National Inventory by Economic Sector (NIEC), 2013). Therefore, further investigation is warranted into the possibilities of reducing GHG emissions from Western Australia, and this current research particularly focuses on the agricultural sector using an integrated spatial technology approach as illustrated in Chapter 3.

Of all economic sectors in Australia, agriculture, forestry and fisheries generated the second highest tonnage of carbon dioxide equivalents, accounting for 30.0% of the total emissions in 2013, following electricity, gas and water supply which contributed to 34.9% of the national GHG emissions for 2013 (Figure 2.8) (AGEIS, 2014; NIEC, 2013). Overall, agricultural emissions were reduced by 3.8% from 2012 to 2013 and 53.2% from 1990 to 2013 (NIEC, 2013).

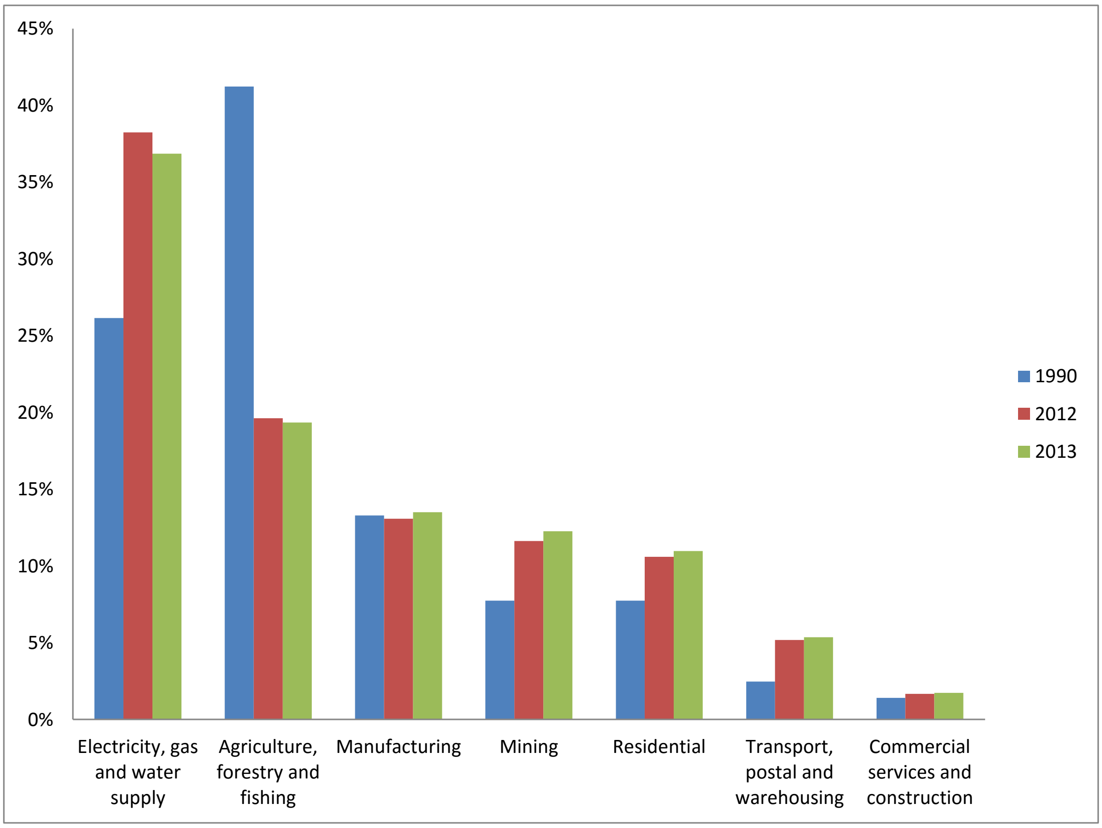

Figure 2.8. Percentage representations of the carbon dioxide equivalent emissions per economic sector in Australia for 1990, 2012 and 2013 (NIEC, 2013)

The sources of the agricultural GHG emissions quantified in the National Inventory Report (NIR) include enteric fermentation, manure management, rice cultivation, field burning, savanna burning and agricultural soils (Table 2.3). Table 2.3 presents the GHG emissions from agriculture by source for 2010, 2012 and 2013 for Australia (NIR, 2012, 2013) and shows that the two highest sources of GHGs were from enteric emissions from livestock (64–67%) followed by the GHG emissions from agricultural soils (17–18%). As a result, a number of Australian organisations such as GRDC and DAFF provided research funding for mitigating GHG emissions from the agricultural sector (AGDA, 2015c; GRDC, 2010). In 2013 enteric emissions produced 66.3% of the total agricultural GHG emissions and agricultural soils 17.4% (Table 2.3). The results presented in the NIR are calculated using IPCC default methodologies and emissions factors, as well as some country specific methodologies (IPCC, 2006; NIR, 2013a). Full details of the methodology used are documented in the NIR (NIR, 2013a).

Table 2.3. Agricultural GHG emissions by source for 2010 and 2012 (NIR, 2012; 2013a)

Source	2010	2012	2013
As percentage of total agricultural GHG emissions for Australia			
Enteric fermentation	67%	64.3%	66.3%
Manure management	4%	3.7%	3.9%
Rice cultivation and field burning	0.6%	1.0%	0.7%
Savanna burning	11%	13.4%	10.8%
Agricultural soils	17%	17.5%	17.4%
Total for agriculture (Mt CO_2-e) (excluding LULUCF)	86.4	87.4	85.0

The National Inventory Report further states that the agricultural sector is the dominant national source of CH_4 and N_2O, accounting for 78.2% and 19.4% respectively of the national agricultural emissions in 2013 (Table 2.4).

Table 2.4. Agricultural GHG emissions by gas for 2013 (NIR, 2013a)

Details	CO_2 as Mt of CO_2-e	CH_4 as Mt of CO_2-e	N_2O as Mt of CO_2-e	Total as Mt of CO_2-e
National GHG emissions across all sectors	403.5	111.8	23.8	549.5
Agricultural sector GHG emissions for Australia	2.0	66.5	16.5	85.0
Agricultural sector GHG emissions for Western Australia	0.7	7.3	2.9	10.9

In 2013 enteric emissions were the greatest source of CH_4 which contributed to 66.3% of the total (85.0 Mt) agricultural emissions, agricultural soils generated the most N_2O (15.5% of the agricultural emissions), and urea application contributed the most CO_2 emissions (1.5% of the agricultural emissions) (Table 2.5) (NIR, 2013a).

Table 2.5. Agricultural sector CO_2-e emissions, 2013 (NIR, 2013a)

Greenhouse gas source and sink categories	CO_2-e emissions (Gg) (1 000 t)			
	CO_2	CH_4	N_2O	Total
Enteric fermentation	NA	56,375	NA	56,375
Manure management	NA	2,422	887	3,308
Rice cultivation	NA	556	NA	556
Agricultural soils	NA	NA	13,160	13,160
Prescribed burning of savannas	NA	6,868	2,331	9,199
Field burning of agricultural residues	NA	238	148	385
Liming	761	NA	NA	761
Urea application	1278	NA	NA	1,278
Total for agriculture	2 039	66 459	16 526	85 024

Accounting for 16% (86.5 million tonnes (Mt) CO_2-e) of the total national GHG emissions in 2010, 16.1% (87.4 Mt CO_2-e) in 2012 (NIR, 2012) and 15.7% (83.6 Mt CO_2-e) for 2013 (excluding LULUCF), the GHG emissions for Western Australia in 2013 were 4.0% lower than the 1990 base year Australian GHG emissions of 86.5 Mt CO_2-e for agriculture (Department of Climate Change and Energy Efficiency (DCCEE), 2012; NGGI, 2012; NIR, 2013a), and 29.3% higher than the Western Australian base year emissions for agriculture (59.1 Mt CO_2-e).

Western Australian agriculture was ranked as the fourth highest GHG (as CO_2-e) emitter for the state after electricity, mining and manufacturing (in descending order according to the highest GHG emitter) in 2013. In the Western Australia agricultural sector, 66.9% of the agricultural emissions were from CH_4, 26.7% from N_2O and 6.4% from CO_2 (NIR, 2013a). Therefore, investigation is warranted into the identification of hotspots or the FMPs causing the most GHG emissions in Western Australian agricultural sector, in order to enable farmers to reduce GHG emissions.

From the foregoing discussion it can be seen that the CH_4 and N_2O emissions from agriculture, both in Western Australia specifically and Australia generally, contribute the most to the nation's overall GHG emissions (NIR, 2013a). The largest contributors to GHG emissions in agriculture are the sectors related to enteric fermentation and agricultural soils. The main agricultural activity responsible for the generation of N_2O emissions is the application of fertilisers on crop land (NGGI, 2013).

2.4.5 Australian legislation and the management of climate change

As stated in section 2.3, a variety of policies have been developed so far for the global management of climate change and the reduction of GHGs. This section will specifically focus on legislation pertaining to the agricultural sector in Australia, namely the Kyoto protocol, the *Clean Energy Act 2011* (Cth) of Australia, the Emissions Reduction Fund and the Carbon Farming Initiative (CFI) of Australia.

2.4.5.1 Kyoto Protocol

The Australian Government signed the Kyoto Protocol on 24 April 1998, which was ratified on 12 December 2007 with Australia committed to stabilise its emissions for 2008–2012 at no more than 108% (574.1 Mt) of its 1990 (base year) emissions level (Department of the Environment, 2014) of 531.6 Mt (AGEIS, 2014). Under the Kyoto Protocol, national GHG emissions are quantified by IPCC sectors, namely energy, industrial processes, agriculture and waste. Further subdivisions exist for each of these sectors. For example, agriculture is subdivided into enteric fermentation, manure management, rice cultivation, agricultural soils, prescribed burning of savannas and field burning of agricultural (Department of the Environment, 2014), and the more recent additions, urea application and liming (NIR, 2013a).

As the country's emissions had increased by 9% from 1990 to 2007, action was required to bring about a reduction in these emissions (IPCC, 2007a). The second commitment period for the Kyoto Protocol commenced on 1 January 2013, and will end in 2020. The quantified emission limitation or reduction objective for Australia for this timeframe is 99.5% of the 1990 levels, which equates to a total carbon budget for the eight years of 4,626 Mt or an average of 578 Mt per year (Department of Environment, 2012). Currently in Australia, national emissions are projected to be 24% (690 Mt CO_2-e) above 2000 levels for 2020 and agricultural emissions are projected to be 0.4% below the 1990 level (86 Mt CO_2-e per year), for the period 2013–2020 and 94 Mt CO_2-e in 2020. The decline in agricultural emissions can be attributed to drought which led to a decline in animal populations, thus reducing the emissions from livestock, a large contributor of CH_4. Overall, however, the national GHG emissions are projected to reach 690 Mt CO_2-e or 24% above 2000 levels if Australia does not take appropriate action (Agriculture Emissions Projections (AEP), 2014; DCCEE, 2010 (Table 2.3 emissions by source for 2010 and 2012).

To enable the parties of the Kyoto Protocol to reach their targets, they are given the choice of either reducing their GHG emissions or increasing their removal sinks, or both (APH, 2010). Australia undertakes to meet its targets by applying domestic policies and legislation, which include amongst others the *Clean Energy Act 2011*

(Cth), the emissions reduction fund (ERF) and the carbon farming initiative (Department of Environment, 2012).

2.4.5.2 *Clean Energy Act 2011* (Cth)

In July 2012, the Australian government commenced with carbon pricing by introducing the *Clean Energy Act 2011* (Cth) (Commonwealth of Australia (Cth)), which was later repealed in July 2014 (Carbon Pricing Mechanism (CPM), 2014). This act was aimed at responding to climate change impact by reducing environmental pollution and driving the transformation of the Australian economy for a clean energy future (Country Education Foundation of Australia (CEF), 2011; Engelbrecht et al., 2013).

The four elements of the Act, of which this project only focuses on the first and fourth element (although the act has been repealed), included 1) carbon pricing scheme, 2) renewable energy, 3) energy efficiency and 4) action on the land. To address the first element, putting a price on carbon pollution, there were three separate targets for emissions reduction to meet Australia's obligations (APH, 2014b; CEF, 2011):

- 5% reduction in carbon pollution from 2000 levels by 2020 and up to 15–25% depending on the scale of global action (UNFCCC, 2014)
- restricting national emissions to an average of 108% of 1990 levels from 2008–2012 (Kyoto, 2014; UNFCCC, 2014)
- Long-term target of reducing Australia's net GHG to 80% below 2000 levels by 2050 (Clean Energy Bill, 2014; CEF, 2011).

As the agriculture, forestry and land sectors were not required to pay any taxes on agricultural emissions but have an important role to play in reducing carbon pollution, the Carbon Farming Initiative (CFI) was devised. The CFI encourages farmers to voluntarily participate in reducing carbon pollution using approved methodologies (CEF, 2011).

2.4.5.3 Emissions Reduction Fund

In June 2014 a bill was presented to the government for the implementation of the Emissions Reduction Fund (ERF). The ERF is the centrepiece of the Direct Action Plan (DAP) and focuses on the development of programmes and methodologies that will enable Australia to meet its emissions reduction target of five percent below 2000 levels by 2020. The ERF will provide an incentive for businesses, land owners, state and local governments, community organisations and individuals to adopt new practices and technologies which reduce their emissions below a baseline to sell their CO_2 abatement back to the Government (Clean Energy Regulator (CER), 2014; Emissions Reduction Fund (ERF), 2014). This will include business activities as well as farming practices. As part of the ERF, the CFI bill was amended and included therein to enable individuals and entities to be issued with Australian carbon credit units (ACCUs) through activities that store carbon or reduce greenhouse gas emissions on the land (CER, 2014; ERF, 2014).

2.4.5.4 Carbon Farming Initiative

The CFI has been designed for farmers and landholders to generate ACCUs and sell these credits in the carbon market (nationally and internationally). Each carbon credit represents one tonne of CO_2-e (Carbon Farming Initiative (CFI), 2012; Engelbrecht et al., 2013). This is achieved by implementing projects that fall into one of two categories – emissions avoidance, where greenhouse gas emissions are prevented from entering the atmosphere, and sequestration, where carbon is stored on the land (CER, 2014). Furthermore, the CFI encourages landscape rehabilitation by offering incentives to rural communities to support sustainable farming (CFI, 2012).

Activities identified in the Kyoto Protocol for which compliance ACCUs are earned and which are applicable to the national targets include reforestation, forest management and native forest protection, savanna fire management; landfill gas recovery, manure management, management of methane from livestock, and the management of soil carbon and biochar (CFI, 2014).

As national agricultural emissions accounted for 17% of the total GHGs for 2013, the reduction of emissions from agriculture in Australia is imperative. Focus should especially be given to reducing N_2O and CH_4 since agriculture is the highest emitter of N_2O and CH_4 of all national industries (Table 2.4 and Table 2.5) (NGGI, 2013). As the worldwide population increases and more pressure is applied to increase food production, these emissions are projected to increase and therefore the development of additional and alternative methodologies becomes paramount. New options should focus on enabling farmers to identify and manage their carbon footprints and in turn generate tradeable carbon credits (Engelbrecht et al., 2013). Areas that have previously been identified and are currently managed by some farmers include sustainable management of cropland and pastures (GRDC, 2011a). Ideally there is no one system that will work for all farms, as the soils, environmental conditions and the financial positions of farmers differ. It is therefore crucial for each farmer to identify individual strategies for overcoming problems and improving the efficiency of the farm (Anderson, 2009; NTGov, 2015).

2.5 TOOLS CURRENTLY EMPLOYED TO MONITOR CLIMATE CHANGE AND GREENHOUSE GAS EMISSIONS

The following section will highlight the use of remote sensing, geographical information systems and life cycle assessment tools that are currently used in the monitoring and mitigation of GHGs in agriculture.

2.5.1 Remote sensing

Remote sensing is defined as the science and art of obtaining information or data about various objects (targets) on the Earth with the help of a device placed on board a number of aerial and space-borne platforms (Engelbrecht et al., 2013; Lillesand, Kiefer, & Chipman, 2004; NASA, 2014c). The data that is received is translated into digital images that are made up of small squares or pixels. These pixels represent the reflected light energy from the object in either a scale of grey or as a colour and enable the user to identify and categorise the image by class, type, substance and spatial distribution (Lillesand et al., 2004; Mather, 2006; NASA, 2014c). For example, using the normalised difference vegetation index (NDVI),[2] different plant species can be identified in an image after being sensed remotely, as the wavelengths

[2] NDVI is an index which measures the difference resulting between the visible light absorbed during photosynthesis by live green vegetation, and the reflected solar energy (near infrared) scattered by the plant. It indicates the photosynthetic capacity of the land surface cover (Lillesand et al., 2004; Mather, 2006).

radiated (in different hues of red) by different types of green vegetation differ according to the various shades of green. The clarity of the received image depends on the quality of the image received by the sensor on board the platform. If the resolution of the sensor is high the image clarity will be better than for that of a low resolution. High resolution images allow for more accurate identification of an object (Lillesand et al., 2004; Mather, 2006; NASA, 2014c).

All remotely sensed images acquired will contain deficiencies and flaws which can be removed from the image by applying pre-processing techniques which may include:

- atmospheric path corrections in which the scattering and/or absorption of the electromagnetic radiation by particles in the atmosphere is eliminated (Field Guide, 1999; Lillesand et al., 2004; Mather, 2006);
- image rectification and registration during which geometric distortions are removed (Lillesand et al., 2004);
- image enhancement which focuses on improving the features of the raw, remotely sensed data (Field Guide, 1999; Lillesand et al., 2004);
- image classification in which the pixels are categorised into, for example, land cover themes of classes (Field Guide, 1999; Lillesand et al., 2004; Mather, 2006).

Remote sensing has been used worldwide in various different agricultural applications since the early 1970s (Mulla, 2013), focusing on aspects such as crop identification, crop yield (Mo et al., 2005; Peña-Barragán, Ngugi, Plant, & Six, 2011), crop nutrient detection (Goel et al., 2003; Nigon, et al., 2015; Schlemmer et al., 2013, Tilling et al., 2007; Yang, Everitt, & Murden, 2011), water stress (Nigon et al., 2015; Tilling et al., 2007), weed infestations (Cavalli, Laneve, Fusilli, Pignatti, & Santini, 2009; Goel et al., 2003) and soil properties (Mulder, de Bruin, Schaepman, & Mayr, 2011), amongst others. In Australia RS was used to discriminate between crops in New South Wales (Van Niel & McVicar, 2004). In Western Australia, Suganuma et al. (2006) examined the structure of the soil and estimated the woodland biomass using GIS, while Lawley, Lewis, Clarke, & Ostendorf (2015) found that RS methods were able to monitor vegetation condition, and when combined with detailed ecological site-based data could improve monitoring and thereby answer ecological questions.

Seelan, Laguette, Casady, & Seielstad (2003) also found that RS had not been embraced in agriculture due to the availability of images, the cost of the images, the ignorance associated with the application of the RS images and the inability (of the farmers/users) to analyse the images. Seelan et al. (2003) also stated that RS software was usually developed in isolation and thus there were normally compatibility issues with other geospatial software.

Lillesand et al. (2004) and CSIRO (2014b) mention various other applications for which RS has been used successfully, including the identification and mapping of invasive species, the identification of crop damage due to pests and disease, monitoring of wind erosion, prediction of soil salinity, monitoring of waterlogging, monitoring of the condition of remnant vegetation and monitoring of rangeland condition.

2.5.2 Geographical information systems

GIS is a tool that has been used for capturing, editing and analysing multi-layered environmental and ancillary data layers along with its geographic location and temporal variation (Lillesand et al., 2004). The components of a GIS are the computer system, the software, data management procedures, analysis procedures and the user (Lillesand et al., 2004; Mather, 2006). Spatial data, which includes geographical positioning and the connection thereof with non-spatial data, are entered into the GIS as thematic layers. The thematic layers could represent features over a specific area such as rainfall, soil types, temperatures or crop type. Each feature represented may be demarcated as a point, a line or a polygon. Points are used to show, for example, the positioning of the farmhouse, a line would represent a river on the farm and a polygon could establish the area in which a specific crop is grown (Lillesand et al., 2004; Mather, 2006). The output created by the GIS enables the user to visualise, question, analyse, and interpret data to understand relationships, patterns, and trends in the form of maps, globe reports and charts (Environmental Systems Research Institute (ESRI), 2014).

A large body of knowledge exists with respect to the use of GIS and GIS integrated with RS for use in agriculture. The following are only a few examples of the literature reviewed.

Using GIS and environmental properties such as lithology material, soil typology, hydrology, hydrogeology, topography and some biotic factors, a methodology was successfully developed by de Paz, Sánchez, & Visconti (2006) to evaluate and map the physical, chemical and biological soil degradation in agriculture. Mendas & Delali (2012) successfully designed a tool to determine the suitability of land for agriculture using GIS. Using field-based data and georeferenced maps they were able to generate images which they stated were easy to interpret, could be digitally processed and easily updated. Crop productivity, evapotranspiration rates, rainfall, irrigation boundaries and locations of meteorological stations were modelled by Todorovic & Steduto (2003), waterlogging after Monsoon rains in south Asia were mapped by Chowdary et al. (2008), and the extent of global productivity and the impact of global warming were analysed by Tan & Shibasaki (2003).

Chhabra, Manjunath, & Panigrahy (2010) successfully integrated GIS and RS to map soil types in the Indo-Gangetic plains in India, and thereafter used the integration to estimate the use of N-fertilisers and the loss of N. After integrating RS and GIS to study the extent of global wetland changes due to the expansion of agriculture Rebelo, Finlayson, & Nagabhatla (2009) concluded that although they could identify variation in the extent of the wetland over time, the assessment and mapping of wetlands and landcover change needed further development. Bharathkumar & Mohammed-Aslam (2015) successfully integrated GIS and RS to map crop suitability and crop production in India, using NDVI and supervised classification methods. Using field data, RS and GIS, Oikonomidis, Dimogianni, Kazakis, & Voudouris (2015) set out to map the hydrology and groundwater potentiality of the study area. At the conclusion of the study, in which they ascertained that groundwater mapping was possible using RS and GIS, they stated that field data needed to be kept up to date for accurate images to be created. The extent of pesticide exposure and the effect on human health was examined in a study by VoPham et al. (2015) in which both RS and GIS were used to create thematic maps. They found that the estimation of pesticide exposure could be classified using RS images and then used in epidemiological studies to ascertain the location where the individuals were located. Limitations to their research included not having images for the entire research period, misclassification of crops and inaccuracies of NDVI data due to soil reflectance discrepancies. El Nahry, Ali, & El Baroudy (2011) contrasted precision farming methods[3] with traditional agriculture to investigate water use and nutrient applications in Egypt. The results showed that both of the FMPs could be modelled using RS and GIS, and used to identify where the FMPs were functioning optimally.

Navarro, Bryan, Marinoni, Eady, & Halog (2013) successfully used GIS to create a map of the GHGs and energy requirements for agricultural fertiliser and pesticide production in Australia, and enabled linkages between the production and GHG emissions to be analysed. Dresen & Jandewerth (2012) targeted the integration of the LCI datasets, from the production and emissions of upgraded biogas, directly into GIS to determine the biogas potentials coupled with GHG balances. The current research has integrated GIS with LCA for assessing GHG emissions from agricultural section, with a particular focus on grains (see Chapter 6).

2.5.3 Life cycle assessment

LCA is a decision-making tool for the systematic evaluation of the environmental impact of a product or service system through all stages of its life cycle such as raw material acquisition, through production and use to waste management. It is used to evaluate and implement opportunities to bring about environmental improvements by comparing existing products and developing new products (ISO, 2006). During an LCA all life stages from a product are considered to be interdependent on each other, thus enabling resulting cumulative impacts to be evaluated (Curran, 2006).

[3] Precision farming involves studying and managing variations within a field that can affect agricultural productivity. It makes use of information technologies from multiple sources to derive data that will affect the decision of the farmer (El Nahry et al., 2011).

There are four stages to an LCA (Biswas et al., 2008; Curran, 2006; Engelbrecht et al., 2013; Gunady, Biswas, Solah & James, 2012; ISO 2006; Solah & James, 2012; UNEP, 2014b) as follows:

1. **Goal and scope definition** – this stage of the LCA defines the product and services to be assessed, a functional unit for comparative purposes is selected and the level of detail is defined (UNEP, 2014b).
2. **Life cycle inventory (LCI)** – during the LCI the energy and raw materials used, the emissions to the atmosphere, water and land, for the entire life cycle of a product, process or activity are quantified and related to the functional unit (Curran, 2006; UNEP, 2014b).
3. **Life cycle impact assessment (LCIA)** – during the LCIA the effects of the resource use and the emissions generated are grouped and quantified into a limited number of impact categories which may then be weighted for importance (UNEP, 2014b).
4. **Interpretation** – this is the last stage of the LCA and is used to systematically identify, quantify, check and evaluate the information from the LCI and LCIA, and communicate these effectively (Curran, 2006; UNEP, 2014b).

Two ways of performing LCAs are by making use of either an attributional (retrospective) or a consequential (prospective) LCA. Attributional LCA (ALCA) focuses on describing the environmentally relevant physical flows to and from a life cycle and its subsystems, whereas consequential LCA (CLCA) aims to describe how environmentally relevant flows will change in response to possible decisions (Ekvall, Tillman, & Molander, 2005; Finnvedin et al., 2009; Tillman, 2000). Although Ekvall et al. (2005) state that ALCA is generally used for learning purposes and marketing and CLCA is used for decision-making, both can be used together. Furthermore CLCA focuses on the consequences of decisions and ALCA aids with identifying the areas within the system that ideally should be avoided (Ekvall et al., 2005; Finnveden et al., 2009; Tillman, 2000). In addition, Tillman (2000) implies that ALCA should be used when no decision is clear or when the ALCA and CLCA do not deliver a clear differentiation required for decision-making. The current research considered attributional LCA as the system boundary is limited to grain production only and the purpose is to discern GHG mitigation potential from pre- and on-farm stages.

As full LCAs are labour and cost intensive and may include impacts that are not within the scope of the study, the explicit definition of the included and excluded boundaries is needed for simplification of the LCA. According to the Society of Environmental Toxicology and Chemistry (SETAC) it is possible to take only the necessary stages of the product life cycle into account. In doing so an alternative LCA methodology is not applied, but rather a more definite manner of specifying the boundaries and data needs of a study (Todd & Curran, 1999; Curran, 2006). By limiting the boundaries all of the abovementioned stages of the full LCA are included, however the LCA focuses more on limiting the scope of the study (Todd & Curran, 1999).

LCA has been used extensively in the agricultural sector (Table 2.6). Aspects such as N_2O emissions from nitrogen fertiliser applications and production, methane emissions from livestock, CO_2 emissions arising from agricultural energy use, CO_2 emissions from vegetation sinks and the manufacture of products such as corn chips following the production of maize have been investigated locally (Barton & Biswas, 2008; Biswas et al., 2010; Grant & Beer, 2008; GRDC, 2011a) and internationally (Hasler, Bröring, Omta, & Olfs, 2015; Meisterling, Samaras, & Schweizer, 2009; Thomassen, van Calker, Smits, Iepema, & de Boer (2008). Additional literature reviewed shows that eco-efficient crop rotations can be designed on completing a LCA of crop combinations, however the crops were not individually analysed as the project leaders felt that the large number of crops would be too time consuming in terms of data collection (Nemecek et al., 2015).

The literature reviewed included a local study conducted by Grant & Beer (2008), in which an LCA was completed focusing on the pre-farm, on-farm and post-farm processes of the supply chain in the manufacture of corn chips. The emissions measured were CO_2, N_2O and CH_4 and the sequestration of CO_2. All other emissions were ignored. The SCLA was used to establish which of the inputs generated the most GHG emissions, the amount of N remaining in the soil and which FMP produced the highest GHG emissions (Grant & Beer, 2008). The global warming potentials of wheat, sheep meat and wool production in Victoria, Australia were assessed using an LCA approach. In the study, the emissions of CO_2, N_2O and CH_4 from these products were converted to CO_2-e and then compared to ascertain which of them had the highest GWP. The authors found that enteric CH_4 from livestock digestion, CH_4 from the decomposition of manure and N_2O emissions from the application of fertiliser to wheat were the most significant in terms of GHG emissions (Biswas et al., 2010). In estimating the total GHGs emitted during the production of rain-fed wheat from a farm in south-western Australia, Biswas et al. (2008) used LCA as a tool. The study quantified the GHG emissions of wheat from pre-farm through on-farm to post-farm processes. In the study the focus was limited to the emissions of CO_2, N_2O and CH_4. The pre-farm stage emitted the highest concentration of GHGs followed by the on-farm (Biswas et al., 2008). None of the studies quantified GHG emissions from different tillage methods, different fertilisers or crop rotations.

Internationally, LCA research in the US by Meisterling et al. (2009) focused on GHGs resulting from the transportation of wheat products for both organic and conventional wheat production. The impact category considered was global warming potential and N_2O and CO_2 emissions were determined for analysis in terms of CO_2-e. In Germany the environmental impact of different fertiliser products was assessed using an LCA approach. The aim of the project was to convince associates in the fertiliser supply chain that by selecting alternative fertiliser products, mitigation of GHG was possible. The climate change impact category was selected on the basis that N_2O emissions from fertiliser contribute to climate change. The output GHGs, CH_4, CO_2 and N_2O, were all converted to CO_2-e (Hasler et al., 2015). Thomassen et al. (2008) compared the impact of conventional and organic milk production systems and also set out to identify hotspots in both systems in the Netherlands. The selected impact categories included land use, energy use, acidification, eutrophication and climate change. A full cradle to farm-gate analysis was completed.

Table 2.6 summarises the LCAs reviewed in this section in terms of the functional unit, the aim and the outcome. It should be noted, however, that this is not an extensive list of LCAs considered for the research. Other LCAs consulted are discussed in the relevant sections.

Table 2.6. Summary of contemporary agriculture LCAs reviewed

Agriculture LCA literature	Functional unit	Goal and system boundary	Results
Biswas et al. (2008)	One tonne of wheat transported to port for interstate or international trading.	The goal was to estimate the total GHG emitted during the production of rain-fed wheat from a farm in south-western Australia by using LCA. The system boundary expands from paddock to port.	The pre-farm stage emitted the highest concentration of GHGs followed by the on-farm and then the pre-farm stage. Fertiliser production is the hotspot.
Biswas et al. (2010)	One kg of wheat, sheep meat and wool produced from sub-clover, wheat and mixed pasture plots.	The goal was to compare the life cycle global warming performance of wheat, sheep meat and wool produced in three adjacent plots: mixed pasture, wheat and sub-clover. The system boundary was established from cradle to farm gate.	CH_4 followed by N_2O and then CO_2 were found to be the major GHG emissions from mixed pasture and sub-clover plots. N_2O was the major GHG, emitted from the wheat plot. The sub-clover plots produced more emissions than the mixed pasture system.
Grant & Beer (2008)	400 g packet of corn chips delivered to the retailer.	The goal was to quantify the GHGs from the manufacture of one packet of corn chips. The system boundary included the pre-farm, on-farm and post-farm stages.	The post-farm emissions associated with production, packaging and transport accounted for most of the GHGs. However the hotspot was GHG emissions from nitrogen fertiliser application to irrigated crops, followed by electricity use and then the oil used for frying purposes.
Hasler, Bröring, Omta, & Olfs (2015)	300 kg complex fertiliser applied to one hectare of arable land.	The goal of the study was to assess the environmental impact of different fertiliser product types. The system boundary expanded from the cradle to the field.	The production of fertilisers caused high values in the impact categories climate change, fossil fuel depletion and acidification. Resource depletion dominated in the production and transportation category and for the impact category eutrophication, the application of fertiliser was the most important factor.
Meisterling, Samara, & Schweizer (2009)	The production and delivery of one kg loaf of bread using 0.67 kg of wheat flour produced conventionally or organically.	The aim of the study was to determine the primary energy use and GWP differences between conventional and organic product life cycles of wheat transportation, by focusing on the differences between the two systems. The system boundary extends from the cradle to delivery of the product over the same distance.	The GWP of one kg of organic wheat bread was about 30 kg CO_2-e less than for one kg of conventional bread. The hotspot was the use of synthetic fertilisers on the conventionally produced wheat.

Table 2.6. (cont.) Summary of contemporary agriculture LCAs reviewed

Studies	Functional unit	Aim	Results
Nemecek , Hayer, Bonnin, Carrouée, Schneider, & Vivier (2015)	Mitigation of GHGs per hectare per year for land management function and mitigation of GHGs per € contribution margin.	The goal of the study was to quantify the environmental impact of introducing peas into standard rotations in selected French regions by means of LCA and to evaluate the potential for reducing environmental impact by diversified crop rotation and improved nitrogen management. The system boundary was from cradle to storage at the farm gate.	The mitigation of environmental impacts was found to be possible per hectare per year but also per € contribution margin through reducing the application of N-fertilisers. Nitrogen management was the hotspot in the non-renewable energy demand, the global warming potential, the ozone formation potential, the acidification potential, and the eutrophication potential.
Thomassen, van Calker, Smits, Iepema, & de Boer (2008)	One kg of fat and protein corrected milk leaving the farm-gate.	The aim of this study was to assess the environmental impact of conventional and organic milk production systems. The system boundary extended from the production of the milk to the products leaving the farm gate, excluding the transportation and processing of the raw milk. The transportation associated with the production of purchased inputs. Medicines, seeds, and machinery were excluded. Due to their small impact, and buildings were also excluded.	Organic farms have better energy use efficiency than conventional farms. The acidification potential and GWP per kilogram of milk did not differ between organic and conventional farms. Organic milk showed greater land use than conventional milk. Purchased concentrates were found to be the hotspot in the selected conventional farms in off-farm and total impact for all impact categories, whereas in the selected organic farms, concentrates were found to be the hotspot in off-farm impact besides roughage.
Barton, Thamo, Engelbrecht, & Biswas (2014)	The GHG emissions from one hectare of cropped land; or the production and the transportation of one tonne of wheat to the port.	The goal of the LCA was to compare GHG emissions from a lupin-wheat rotation with those from a wheat-wheat rotation, both with and without lime. The system boundary extended from the cradle to the port focusing on climate change and ignoring activities after the port.	The GHG emissions from rain-fed wheat grown in a semi-arid environment decreased when a grain legume was included in the rotation, on both a per hectare and per tonne of wheat basis, without compromising the grain yield. The hotspot was the production, transportation and application of N-fertilisers.

Note: The term 'functional unit' is explained in section 3.3.2.1

2.6 INTEGRATION OF RS, GIS AND LCA

Overall, by consulting Section, 2.5 it can be concluded that RS, GIS and LCA are tools that can be used effectively for agricultural purposes. A multitude of literature exists for the use of each of these tools individually and some literature exists for the use of RS and GIS together. No literature documented to date has incorporated the use of all three simultaneously.

On reviewing the standing body of knowledge for the integration of LCA, RS and GIS, desktop methods were used and searches carried out using different combinations of the words ‘life cycle assessment’, ‘geographical information systems’, remote sensing’, ‘agriculture’, ‘Australia’, ‘mitigation’ and ‘integration’. The databases accessed included Sciencedirect, Scopus and Springerlink as well as Google Scholar. The searches produced results for the aspects discussed in this literature review, however only six sources pertaining to the integration of GIS and LCA were found and none for RS with LCA.

In 1998, Bengtsson, Carlson, Molander, & Steen recognised the need for developing a tool wherein GIS and LCA were integrated, as applications of GIS were limited, but site specific LCA results were available. On presenting the data model, they implied that the integration of these two tools could enhance LCA and more relevant results could be achieved due to higher site specificity. In the model the technical, environmental and social systems were related to each other and linked. The authors furthermore inferred that geographically referenced information was not likely to be used commonly in LCA in the near future as the data requirements would increase significantly. They concluded by stating that the integration of GIS and RS could “be a powerful tool to incorporate and communicate knowledge on environmental issues into various types of decision-making such as product development and purchasing”; the only requirement for the success thereof was the development of software (Bengtsson et al., 1998, p. 74).

In 2010, Geyer, Lindner, Stoms, Davis, & Wittstock (2010) stated that the implementation of a GIS-LCA integration was slow and subsequently developed a proof-of-concept approach for coupling GIS-based calculation and LCA for biodiversity assessments of land use and applied it to a case study of ethanol production from agricultural crops in California. The first part (Part 1) focused on the use of GIS-based inventory modelling to generate elementary input flows of habitat types. The focus was on habitat condition and size of the land. A GIS land use model calculated the area location of crop land required to meet a target crop yield. Thereafter a land use map was generated for each scenario, and then finally converted to a map of habitats (Geyer, Stoms, Lindner, Davis & Wittstock, 2010). In Part 2, the paper explored which of the elementary flows, found in part 1, could be used to assess the impacts that these fuel crop production scenarios may have on biodiversity. The elementary input flows of habitat size and composition were combined with characterisation models for potential biodiversity impacts that account for species richness, abundance and evenness (Geyer, Lindner, Stoms, Davis, & Wittstock, 2010).

Mutel, Pfister & Hellweg (2012) stated that although Geyer et al. (2010) had imported GIS based calculations into LCA there was no public software available which integrated complete GIS databases into LCA calculations. Mutel et al (2012) thus combined several datasets to form a life cycle inventory database of all large electricity generators in the US for 2005, to obtain plant operation information, location information and air emissions. They then modelled the impacts of the power stations in the immediate vicinity on resource consumption, eutrophication, acidification and human health in GIS (Mutel et al., 2012).

Gasol, Gabarrell, Rigola, González-Garcı, & Rieradevall (2011) developed a method to analyse the potential biomass energy crop production and potential consumers in Catalonia by integrating GIS and LCA. At the outset the authors stated that the combined use of LCA and GIS was scarce, and they later concluded that GIS and LCA could be integrated to provide enough information and results to determine an energy crop implementation strategy for reducing energy consumption and GHG emissions. The research concluded with the authors suggesting additional research, based on this study, to analyse benefits to the farmer and economic feasibility studies.

Reviewing the literature revealed that the main deficiency was the lack of a whole farm system approach wherein all variables were considered. The literature highlighted that, in order for mitigation to be successful, not only one aspect should be considered but all aspects, as by altering one variable to decrease GHG emissions, the GHG emissions from another could increase. In addition, RS, GIS and LCA were identified as effective tools for use in agriculture and for identifying areas to which mitigation or adaptation strategies could be applied. However, the literature reviewed revealed that these three tools had never been integrated for use in the agricultural sector, for mitigation purposes. This integration has been termed Integrated Spatial Technology (IST) in this current research. The research has endeavoured to carry out the following specific objectives as described in Chapter 1 for mitigating GHG emissions from grain industries.

i. To identify the study area in GIS using geographical co-ordinates and remote sensing;
ii. To calculate the carbon footprints for individual paddocks of south-western Australian farms using an LCA-approach;
iii. To identify the hotspots in each paddock for different farms utilising an LCA approach, RS and GIS through an integrated approach;
iv. To propose mitigation measures based on cleaner production strategies for each paddock and farm;
v. To present the integrated tools as a product that can be used by farmers, the industry and academic institutions alike.

2.7 CHAPTER SUMMARY

This chapter has reviewed the standing body of knowledge on various aspects of climate change and agriculture. Furthermore it has presented to the reader current methods and policies used for the management of GHG emissions in agriculture, focusing on Western Australia specifically. Finally it has introduced the concept of integrating methods to create a new tool that could enable farmers to identify areas of concern in their agricultural practices.

CHAPTER 3
RESEARCH DESIGN AND METHODOLOGY

3.1 BACKGROUND

Chapter 2 reviewed several environmental management tools including life cycle assessment (LCA), remote sensing (RS) and geographical information systems (GIS) that have been widely used, separately, to address greenhouse gas (GHG) mitigation issues (Ahammed and Nixon, 2006; Biswas, Barton Carter, 2008; Biswas et al., 2010, 2011; Feliciano Hunter, Slee & Smith, 2013; Gaudin, Janovicek, Deen & Hooker, 2015; Grant and Beer, 2008; Yousefi-Sahzabi et al., 2011). The integration of these tools has the potential to offer accurate but also time- and cost-effective means for assessing GHG mitigation strategies for the agricultural sector and therefore warrants further investigation (Kiem & Austin, 2013). The integrated spatial technology (IST) has thus been developed in this research to integrate these tools with cleaner production (CP) strategies to aid with the formulation and application of GHG mitigation options pertinent to the Western Australian grain industry (Engelbrecht et al., 2013, see Appendix A). The IST will initially focus on calculating and presenting the carbon footprint in an easily understandable manner, but could be extended to include other environmental impacts and cover other agricultural industries.

After the initial development and evaluation of the IST, as documented in the author's paper (Engelbrecht et al., 2013), the framework required testing with real data and thereafter the identification of appropriate mitigation measures using CP strategies. This chapter focuses on the methodology used to finalise these factors and is separated into sections namely 'data collection', 'data capturing, processing and integration' and on 'mitigating GHG emissions from the grain supply chain using CP strategies'. Section 3.2 reports on the data collection methods, which included desktop studies, questionnaires, sample selection, interviews, observations and fieldwork. Section 3.3, in turn, addresses data capturing, processing and integration by incorporating three recognised environmental management tools, namely RS, GIS and LCA. Section 3.4 briefly introduces various CP strategies that may be used in agriculture. Each of these has been explained separately; however, all were employed interactively in developing the IST.

Figure 3.1 presents all of the steps in the IST, including data collection and the integration of RS, LCA and GIS, for assessing GHG mitigation through cleaner production strategies (as discussed further in section 3.4) for different rainfall zones and farm management practices (FMP). The key steps involve different processes, which when integrated present to the user/farmer a visual interpretation of the carbon footprint of the paddock being investigated.

The subsequent sections discuss the IST in the following order:

- Data collection for testing the IST
- Description of tools used in the IST
- Integration of IST tools for mitigating GHG strategies

3.2 DATA COLLECTION

The research process involved consulting relevant literature and agricultural experts to source information related to agriculture. The Department of Agriculture and Food of Western Australia (DAFWA) supplied the primary or field data from a current crop sequencing project that has been operative since June 2010. Permission was obtained from DAFWA for further interaction with the farmers.

All data not supplied by DAFWA and the farmers were obtained from a variety of sources, which included desktop studies, questionnaires, sampling of DAFWA crop sequencing sites, interviews, observations and fieldwork. Data included primary and secondary as well as quantitative and qualitative information.

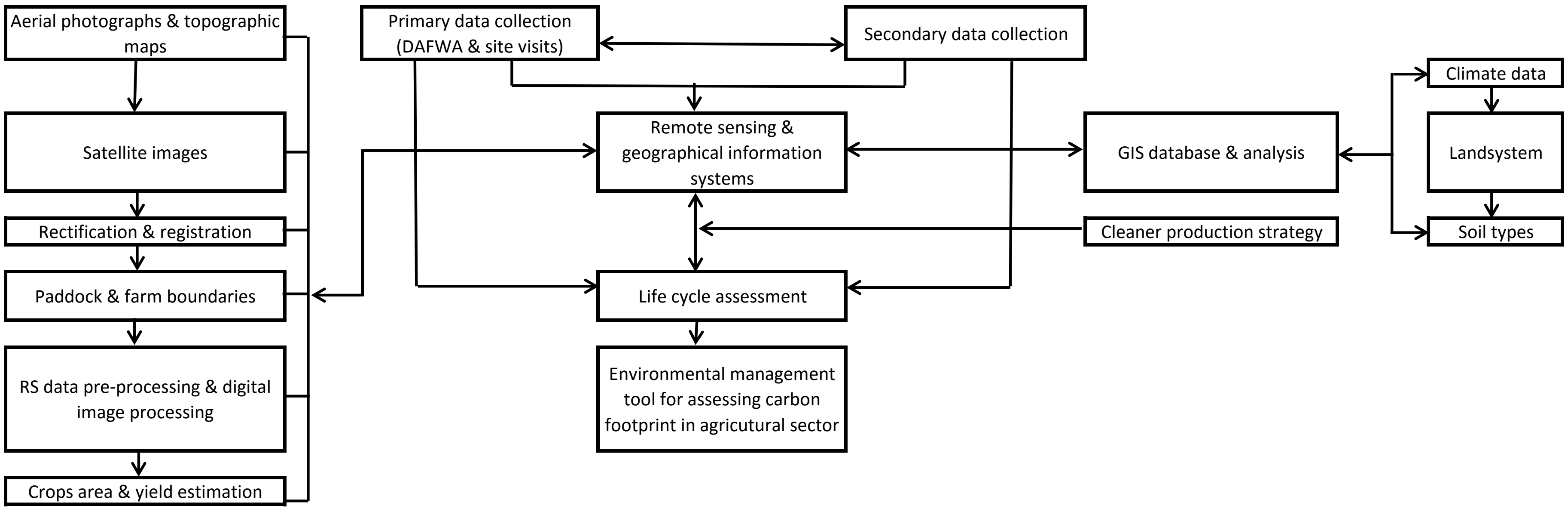

Figure 3.1. Integrated spatial technology (IST) framework (Engelbrecht et al., 2013)

3.2.1 Desktop studies

The desktop study included various forms of documentation from books, journals, archived records and the internet, and was used to obtain information on a variety of topics. This information was considered to be secondary data, although some primary data was also available. The information extracted using desktop studies for this project was considered relevant and generally not older than 10 years (Yin, 2009).

The literature review gathered information from books, journals and the internet relating to agricultural GHG emissions, the legislation pertaining to managing GHG emissions in agriculture, agriculture in Australia, and tools currently used in GHG monitoring.

Desktop studies were also used in gathering the secondary data required to complete the GHG analysis where data had not been made available by suppliers, DAFWA or the farmers. This included information required for the calculation of the life cycle inventory (LCI) and the life cycle impact assessment (LCIA).

The field information supplied by DAFWA was considered to be secondary data.

3.2.2 Questionnaires

Structured questionnaires (Appendix B) were prepared by DAFWA field staff and distributed to all participating farmers for each of the 188 paddocks to ascertain the details of management practices and production systems used for agricultural crops in the crop sequencing project. These questionnaires acquired data on critical aspects of farming and FMPs, such as paddock and farm details, land preparation methods, seed and sowing information, farm machinery use, chemical use, fertiliser use, crop rotations and resultant crop yields obtained for the adopted FMPs (Engelbrecht et al., 2013). The completed questionnaires were collected after which DAFWA made the primary data available. Data from the 24 paddocks[1] identified as being applicable to the IST were extracted from the questionnaires and an additional questionnaire (Appendix C) was developed that focused on aspects not covered by the DAFWA questionnaire and emailed to the participating farmers.

[1] A paddock is generally defined as a small, usually enclosed field near a stable or barn for pasturing or exercising animals. In Australia and New Zealand a paddock is a piece of fenced in (enclosed) land (The free dictionary, 2014; Paddock, 2014).

The data obtained from all of the above sources covered aspects such as farm machinery operation, chemical use, farm inputs, and secondary data.

3.2.2.1 Farm machinery operation

The types of farm machinery operated on the paddocks included tractors of various capacities, seeders, swathers, sprayers, spreaders and harvesters. As not all farmers used the same model of machinery it was decided that for comparative purposes, it would be advisable to standardise all machinery and use generic data (pers. comm. Riethmuller, DAFWA, Merredin, Western Australia). The generic farm machinery data comprised fuel consumption (l/hr), speed during use (km/hr), header widths (m), cost of machinery (Australian dollars (AUD)), expected life span (years (yr)) and average annual use (hours per day per year (hr/day/yr)). On request, DAFWA supplied data for the majority of the farm machinery, whilst other data such as the price of machinery was supplied by dealers. A discrepancy was noticed between the Liebe group and Western Australian No-Tillage Farmers Association (WANTFA) machinery data, however that was explained by Riethmuller (pers. comm. DAFWA, Merredin, Western Australia) and Harries (pers. comm. DAFWA, Geraldton, Western Australia) as being due to differences between soil types and soil profiles requiring unique treatments. (pers. comm. Harries, DAFWA, Geraldton, Western Australia; pers. comm. Riethmuller, DAFWA, Merredin, Western Australia). In comparison with clay soils, sandy soils generally wear down implements at a faster rate. They also allow the machinery to move through the soil at a greater speed, thus reducing fuel use. The wearing down of the tine is related to the abrasiveness of the soil particles which is higher in sandy soils (7 on the Mohs scale of hardness) compared to clays (2.5 on Mohs scale of hardness). Soils which retain more water (clays) are more ‘sticky’ slowing movement down. Hardness of soil tends to decrease as water content increases. Sandy soils are harder and retain water less efficiently (Natsis, Petropoulos & Pandazaras, 2008; Owsiak, 1999; Ta, 2007; Yu & Bhole, 1990).

The emission factor available for estimating GHG emissions from farm machinery production has a $US denominator, therefore the unit of farm machinery has been considered as $US equivalent farm machinery input for one tonne of grain production. To convert the price of the farm machinery from Australian dollars

(AUD) to United States dollars (USD), economic conversion factors were required (Barton, Thamo, Engelbrecht & Biswas, 2014; Biswas et al., 2010; Biswas & John, 2008a). These economic conversion factors together with the inflation factors from 2008 to 2011 were obtained from national reports (Index Mundi, 2012).

3.2.2.2 Chemical production and use

The chemicals used on the paddocks included fertilisers, herbicides, insecticides, pesticides, lime and adjuvants. The data required for estimating the amount and transportation of these chemicals were determined from application rates, dosage (kg/ha/yr or l/ha/yr), suppliers, country of formulation and method of transportation. The application rates, dosages and suppliers of each chemical were obtained from the farmers as primary data. The country of formulation and the methods of transporting the chemicals were obtained from the suppliers of the chemicals. Other data including the recommended dosages for Western Australia, densities and active ingredients were retrieved from the material safety data sheets (MSDS) and product labels stored on the webpages of the suppliers and the Australian Pesticides and Veterinary Medicines Authority (APVMA) (APVMA, 2014). As the GHG emissions of different brands of chemicals at varying strengths were not available in the inventory libraries, generic values were used for the GHG emissions of some of these chemicals; i.e. these chemicals were converted to the equivalent amount of a chemical performing the same function for which an emission factor was known. The emission factors for both generic and surrogate chemicals were obtained from the Australian Life Cycle Inventory (Royal Melbourne Institute of Technology (RMIT), 2007) to represent the local situation.

3.2.2.3 Transportation of farm inputs

The transportation of chemicals, fuel and machinery also contributes to agricultural GHG emissions. In this section the transportation of chemicals is the only variable considered, whereas the transportation of fuel to the farm for use in vehicles is discussed in the relevant sections. With regards to the transportation of farm machinery, since the machinery has a long term function, its transportation would need to be divided over its entire lifespan.

The distances over which the chemicals were transported from the place of formulation to the paddock are summarised in Figure 3.2. Where applicable, international distances were calculated using a maritime distance calculator accessed on the internet to determine the number of nautical miles over which the formulated chemicals were transported (Searates.com, 2013). As only urea was imported from international origins, the distances from the country of origin to Australia's closest port to ship chemicals, and then the transportation from port to the final national destination (supplier/manufacturer) were taken into consideration. National distances were determined using a land distance calculator accessed on the internet (Distance calculator, 2013). Thereafter the distances from the national manufacturers/suppliers to the paddock were calculated using the 'find direction' application on Google Earth. The point of origin in Australia was entered as a city and the point of delivery as the geographical co-ordinates of the paddock.

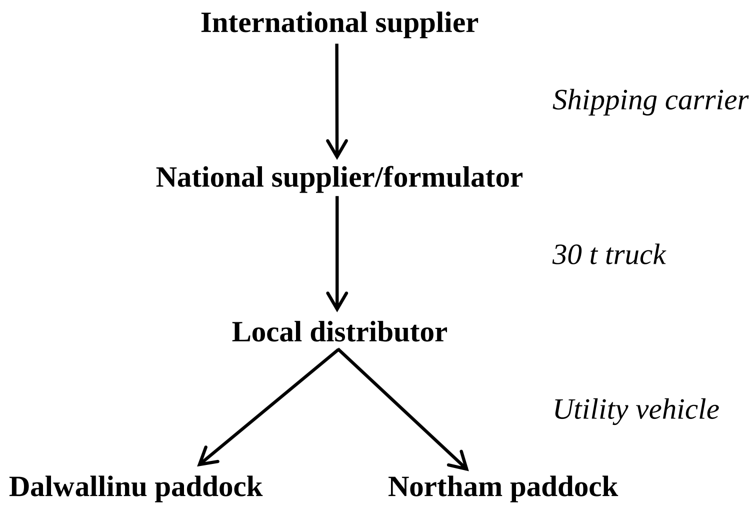

Figure 3.2. Summary of possible transportation routes and mode of transport for chemicals

The mode of transport from international manufacturers was via an international shipping carrier and national transportation was assumed to be by means of a 30 tonne truck (Barton et al., 2014). The national transportation was standardised to 30 tonnes on the advice of a Landmark (local distributor in Dalwallinu) employee who indicated that this was the most commonly used mode of national transportation for agricultural chemicals. From the local distributor the chemicals were transported to the paddocks using a one tonne utility vehicle (ute) owned by the farmers. For both international and national transportation a single leg was assumed, with the carrier transporting other goods back, for example, lime transported in and grains transported out (pers. comm., Lines, Landmark, Wongan Hills, Western Australia).

3.2.2.4 Secondary data

During the course of the project, information that could not be obtained from the field to ascertain the amount of inputs was obtained instead from secondary sources including internet websites, published articles and personal communications. These data included emission factors, data on stubble burning and decomposition, climate data, soil emission data, data on emissions generated from animal husbandry, data on chemical manufacture, use and transportation and the global warming potentials (GWP).

3.2.3 Sample selection

DAFWA's crop sequencing project was initially comprised of 144 paddocks but was later extended to 188 paddocks as represented schematically in Figure 3.3 (pers. comm., Harries, DAFWA, Geraldton, Western Australia). These paddocks are located throughout the wheatbelt area of south-western Australia. From these 188 paddocks, 44 were selected by DAFWA for inclusion in the IST as they represented a range of farming practices over various agro-ecological zones (pers. comm., Harries, DAFWA, Geraldton, Western Australia). The co-ordinates for these 44 paddocks were then plotted on two satellite images and 24 paddocks falling within or close to the boundaries of these images were extracted for the IST. As these paddocks were within the Liebe group and WANTFA grower group boundaries, the development of the IST focused on the Liebe group and WANTFA grower groups of Western Australia (Figure 3.3). Nine of the paddocks (paddocks 7, 8, 9, 13, 14, 15, 19, 20 and 21) were located close to the boundary, but not within the RS image. However, to demonstrate that the hotspot of these paddocks could still be identified without the RS image, the decision was made to include them in the analyses.

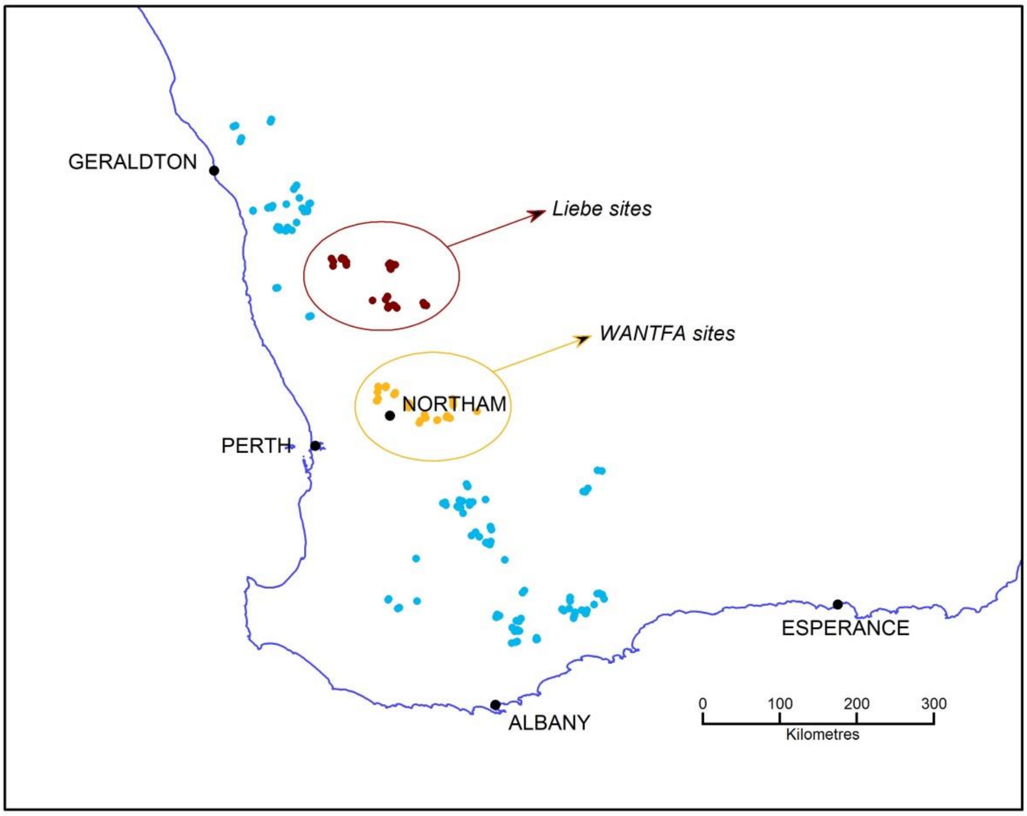

Figure 3.3. GIS image illustrating the distribution of the sites for the DAFWA crop rotation project in south-western Australia (pers. comm., Harries, DAFWA, Geraldton, Western Australia)

3.2.3.1 Liebe group

The northern agricultural group (Liebe group) was established in 1997 to address the need for local research and development to be conducted in the Buntine/Wubin area, and has now expanded to include farms in the Dalwallinu, Coorow, Perenjori and Wongan Ballidu shires (Figure 3.4). The farmers belonging to this group utilise a whole systems approach to agriculture, where each individual process in the entire farming system (e.g. farm fixed capital, operating capital, final products and all the activities and agro-technical processes which underlie these enterprises and activities (Food and Agriculture Organization (FAO), 2015) is considered to contribute (Grains Research and Development Corporation (GRDC), 2014a; Liebe group, 2014). As stated in Section 3.2.3, this area was selected as it was represented in one of the available RS images.

Figure 3.4. Representation of Liebe grower group area distribution in Western Australia (Liebe, 2014)

3.2.3.2 WANTFA

In the central wheatbelt, WANTFA was formed in 1992, and is currently the largest grower group in Western Australia. The participants of the group are not located in one specific area (pers. comm., Harries, DAFWA, Geraldton, Western Australia) but are distributed throughout south-western Australia; however, the selected sample area is found around Northam as per the method of selection described in Section 3.2.3 (Figure 3.3). The farmers in this group focus solely on conservation agriculture, which supports agricultural practices including reduced ground compaction, limited soil disturbance, permanent ground cover (stubble retention), diverse rotations and smart chemical use (WANTFA, 2014).

The farming cycle selected for inclusion in the IST project was from June 2010 to May 2011 and from June 2011 to May 2012. In this region, the crops are sown in June and harvested in November to coincide with the growing season (Pricewaterhouse Coopers (PWC), 2011). The land is fallow from December to May due to lack of rainfall, though the land may be grazed by livestock, predominantly sheep, prior to the subsequent crop being sown. Stubble burning (windrow or paddock) may occur in the following April–May. FMPs such as tillage methods, paddock preparation (spraying), crop protection (chemical spraying) and soil preparation (fertiliser and lime application) methods were also included. Although the underlying soil structure and health play an important role in the FMP employed, the soil variable was excluded here on the basis that FMP is dependent on the type of soil and cannot be directly manipulated by the farmer. Other aspects considered in the analyses were the annual, average, mean temperatures, rainfall/precipitation (P) and evapotranspiration (Et) relevant to each area. Although these cannot be manipulated, they are required to determine the ratio of Et/P which is required for allocating an emissions factor for nitrous oxide (N_2O) emissions due to leaching.

3.2.4 Interviews, observations and fieldwork

In November 2012, field visits and telephone interviews were arranged with the farmers in both the Liebe group and WANTFA areas. A DAFWA employee accompanied the researcher firstly to the farmer's office and thereafter to each of the paddocks.

During the interviews, both questionnaires were discussed with the farmers and outstanding concepts clarified. Upon the approval of the respondents, a digital voice recorder was used throughout for recording the interviews. The questionnaire was open-ended to facilitate informal discussions with any additional, undocumented questions being answered along with those already documented.

At the conclusion of the interviews, each of the farmers gave permission for the paddocks to be visited. These paddocks were located using a map of the area as well as the geographical co-ordinates, pre-registered by DAFWA, using a global positioning system (GPS). Observations recorded included the type of crop grown, whether the crop had been harvested or not, any damage that might have been caused by wind, hail or storms, and whether the expected crop yield was maintained.

3.3 DATA CAPTURING, PROCESSING AND INTEGRATION

Data capturing, processing and integration (Figure 3.1) consisted of two stages. Stage one involved the use of RS data originating from the satellite images as an input to a GIS. In the GIS, other data layers such as paddock and farm boundaries, corresponding rainfall, temperature, soil types and administrative shire boundaries were stored. Stage two involved the application of an LCA approach to calculate the carbon footprint of the paddock. The LCA approach considered cradle-to-gate studies and ignored activities after the production stage (Biswas et al., 2010). This carbon footprint was integrated with RS-based GIS so that CP strategies could be identified as mitigation measures for the quantification of environmentally benign FMPs for the selected paddocks. Each of these environmental management tools are explained separately as follows.

3.3.1 Remote sensing data

To initiate this research, the selection, acquisition and processing of high quality satellite images was required. The next section will describe the methods used to prepare the satellite images for integration into the GIS. Figure 3.5 is an outline of the process followed during the preparation of the RS images.

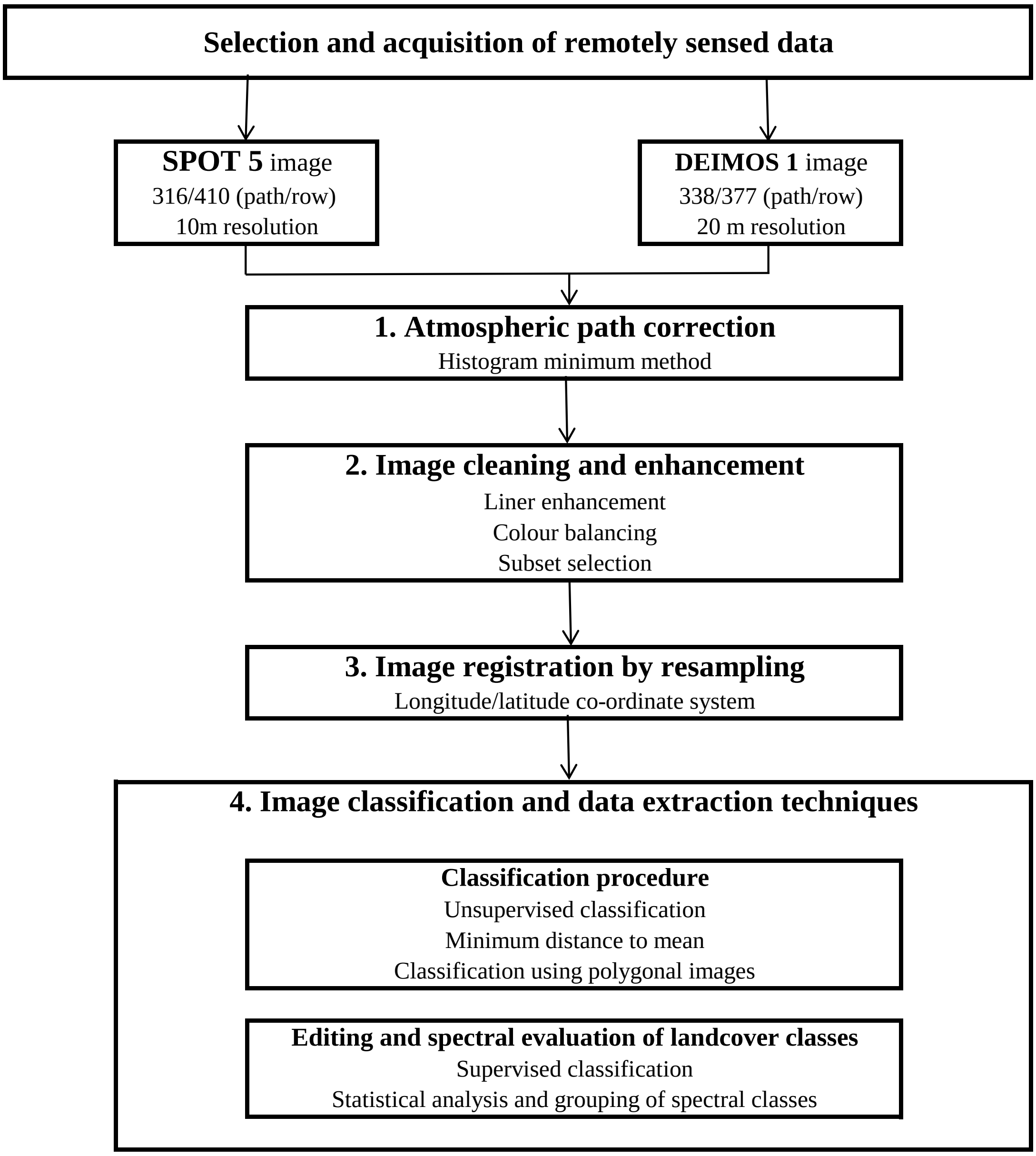

Figure 3.5. Outline of the process followed during the preparation of the satellite images

3.3.1.1 Selection and acquisition of remotely sensed data

The selection of high quality imagery is an important factor in the successful application of RS data. Among the criteria to be considered during the selection process are cloud cover, atmospheric haze and the season. The presence of clouds and haze interferes with the retrieval of surface and atmosphere information and thus should be avoided or corrected for as much as possible to ensure optimal use of a RS image (Liang et al., 2002; Jedlovec, 2009). The natural senescence of plant material during the annual growing season has a strong influence on the appearance of the vegetation, which in turn affects the normalised difference vegetation index (NDVI)[2]. It has been observed that some land cover types that can be distinguished at one time of year are extremely difficult to identify or separate at another time (Mather, 2006).

The following procedure was adopted in this study for the selection of the RS images.

1. Determination of the flight path and row of the required imagery from the RS index map of Australia.
2. Inspection of the Australian Centre for Remote Sensing (ACRES) image search program and the viewing of the coloured microfiche to determine the location of cloud cover and the general quality of the image.
3. Selection of the images taking into consideration the abovementioned criteria.

In September 2012, two satellite images (*SPOT 5* and *DEIMOS 1* images) were acquired (see Figures 3.6–3.7). The *SPOT 5* image 316/410 (path/row) was captured on 18 August 2012 (hereafter referred to as the SPOT image) providing a 10 metre resolution in the green, red, and near-infrared multispectral bands (Lillesand, Kiefer, Chipman, 2004) and 60 x 60 kilometre (3600 km^2) coverage. The *DEIMOS 1* image 338/377 (path/row) was captured on 11 June 2012 (hereafter referred to as the DEIMOS image) providing a 20 metre resolution covering 6000 km^2. It should be noted that the colour intensity differs between the two images due to differences in resolution as well as in the sensors; the red colour in the satellite imagery represents vegetation, with the intensity changes being due to variations in the infrared light reflected by each plant species, or from one plant specimen in different stages of

[2] NDVI is an index in which the near infra-red and visible reflectance of the earth surface features are related to each other. It is often used to determine ground cover or the stages of vegetation growth (Lillesand et al., 2004).

growth, which is explained further in Section 3.3.1.2. As the infrared reflectance diminishes, the red colour is removed until the image appears black, for example, with water bodies, where there is no infrared reflectance (Lillesand et al., 2004; Mather, 2006). These images were free of clouds and were subjected to the following processing prior to incorporation into the IST.

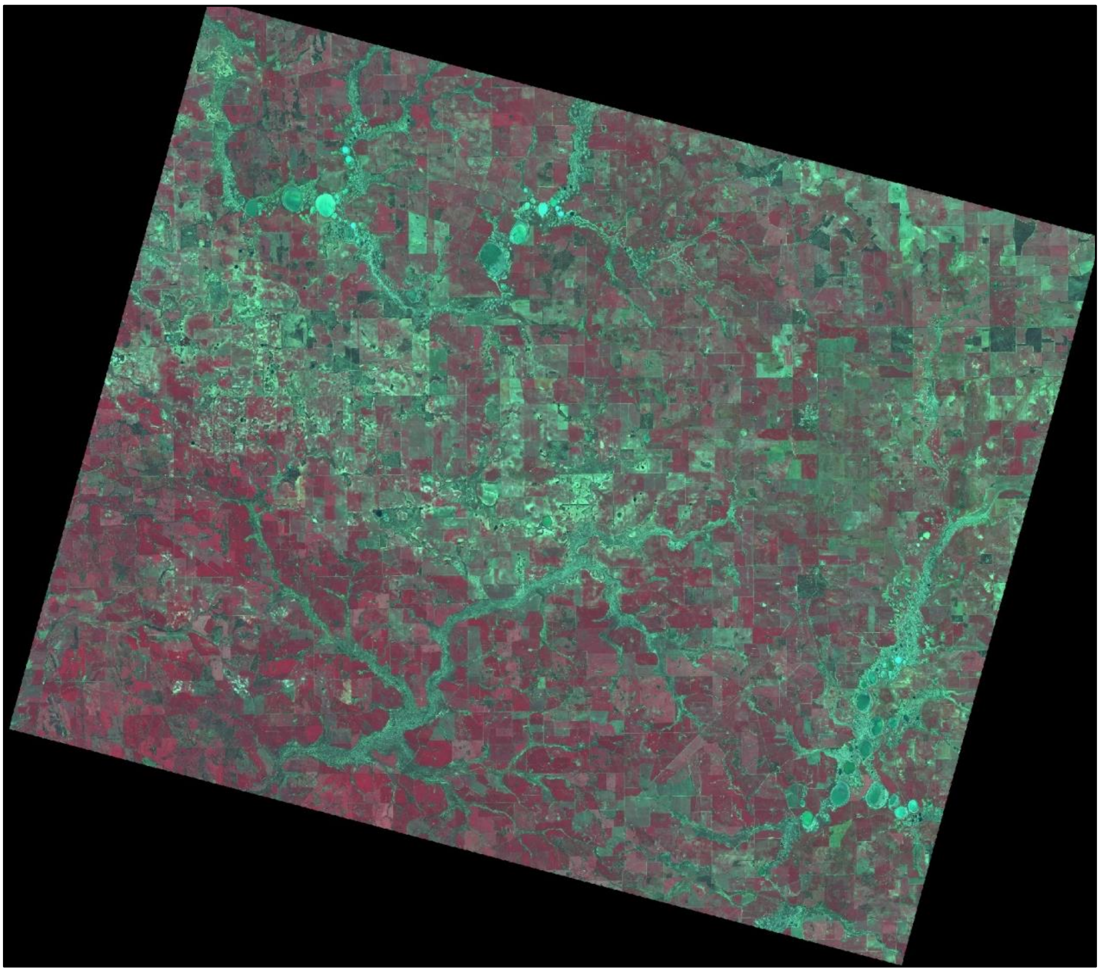

Figure 3.6. SPOT 5 satellite image for the Liebe group region

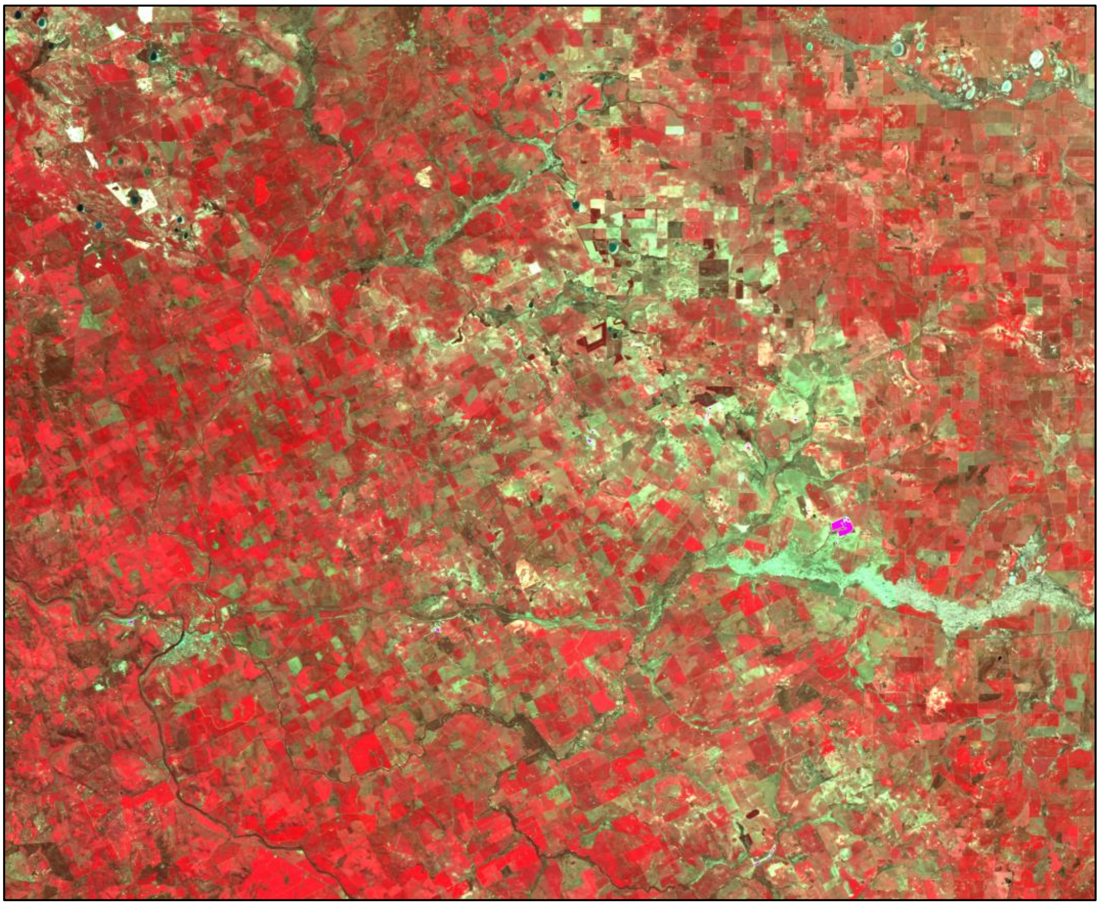

Figure 3.7. DEIMOS 1 satellite image for the WANTFA region

3.3.1.2 Image pre-processing

RS imagery are characterised by several types of radiometric and geometric errors, which need to be removed before the data can be digitally processed and/or integrated with GIS attributes. Radiometric correction removes the haze that is added to an image due to the scattering and absorption of radiation occurring in the atmosphere and sensed by the satellites (Lillesand et al., 2004). Geometric correction (also referred to as georeferencing) focuses on and corrects the errors that may occur when a RS image is projected onto a map with a specific scale and projection properties (Mather, 2006). Digital analysis usually begins with certain pre-processing techniques which correct these problems.

In this study, the data were pre-processed for atmospheric path correction (radiometric correction), stretching or colour enhancement and image rectification and registration, and thereafter classified.

- **Atmospheric path correction**

Both datasets were subjected to atmospheric path radiance correction. As outlined by Switzer, Kowalik & Lyon (1981), path radiance can be estimated as a constant term and can be removed by subtracting the estimated value from the raw data for each pixel and band. For this study, a simplified histogram minimum method (HMM) and the covariance matrix method (CMM) were evaluated (Campbell & Wynne, 2011; Chavez, 1975; Switzer et al., 1981; Taranik, 1978). It was observed that there was no significant difference between these estimates and thus the HMM method, also known as the dark object subtraction (DOS) method, was used. The DOS method is a simple, direct and universally applicable approach which corrects atmospheric path related problems (Campbell & Wynne, 2011). In the infra-red band, the dark objects selected in these images were dark water bodies, as these bodies absorb all near infra-red light. The dark water body pixels showing some reflectance (digital number[3] (DN) 6) were then subtracted from the DNs across the whole image, enabling the reduction of scattering influences (Chen, Vierling Deering, 2005; Mather, 2006). The path radiance estimates were separately applied to both RS images used.

- **Image cleaning and enhancement**

The next stage involved image cleaning and enhancement. This was achieved firstly by the spectral/spatial digitising of the unwanted area, such as water bodies, and the linear enhancement of the remaining terrestrial area. Linear enhancement focuses on increasing the range of the greyscale in the area of interest (AOI), thereby improving certain features (Lillesand, 2006). This was followed by colour balancing. As outlined by Harrison & Jupp (1990) a number of methods may be used to rescale or balance image colours. These usually involve matching the normalised histogram values of each image to obtain equivalent data ranges. In this study a simplified method was used where the histogram percentage point values of the base SPOT image and DEIMOS image were graphically compared. A regression line was fitted through the majority of points which defined a conversion scale from the base SPOT image to the corresponding values in the DEIMOS image. This technique assisted in the enhancement of the image, which enabled the identification and the labelling of the

[3] Digital numbers (DN) are positive integers that result from the quantisation of an original electric signal from the sensor to positive integer values using analog-to-digital signal conversion (Lillesand et. al, 2006)

targeted land cover types observed in the input images. The procedure was followed by the selection of a smaller subset from the larger input images, and was carried out to ensure the processing of the input images and to exclude land use/cover classes originating from those areas that are outside the scope of this project.

- **Image registration by resampling**

Image registration is an integral part of both the rectification and geometric correction process. It determines the relationship between the distorted RS imagery and its position on a horizontal plane as defined by the projection of interest to the user. It compensates for the distortions introduced by earth curvature, atmospheric refraction, relief displacement and non-linearities due to the sweep of the satellite sensor, so that the image produced has the highest practical geometric integrity (Lillesand et al., 2006). Image-based information systems, incorporating a raster grid storage scheme, require considerable data processing to make their data compatible with the chosen projection. This registration is achieved by using resampling techniques to form a common grid. These techniques relate the original image grid to a uniform grid in the selected projection (Lillesand et al., 2006).

The two most widely used map projections are the Universal Transverse Mercator (UTM) and the equidistant cylindrical projection (more commonly known as known as the latitude/longitude projection), both with advantages and disadvantages. UTM projections are frequently used but distortion of the projection away from the central meridians poses calculation problems across zones (Intergovernmental Committee on Surveying and Mapping (ICSM), 2014). Latitude/longitude projections are potentially the most accurate and the most easily transformed, but distance measurements are difficult since spherical trigonometry needs to be used (ICSM, 2014).

In this study, a latitude and longitude coordinate system was used. SPOT and DEIMOS datasets were registered to 150:000 topographic maps of the study area. This enabled the extraction of conversion equations allowing the exact determination of the map coordinate system and the corresponding line/pixel co-ordinates of the images used.

- **Image classification and data extraction techniques**

The RS image classification procedure adopted in this project is detailed below:

  - **Classification procedure**

A two tier image classification stage was followed. Stage one involved the classification of SPOT and DEIMOS images with unsupervised classification techniques using the ISODATA classification algorithm (Mather, 2004). These datasets were subjected to the minimum distance to mean classifier with optional class generation when the training sets representative of various land cover types were not exhaustive. This resulted in spectral overlap between wheat crops, barley crops, bare soil and fallow paddocks observed in the study area. In stage two, a non-conventional image classification procedure was adopted. The main objective of the non-conventional classification procedure was to produce a set of spectral classes[4] that could represent dominant land cover and agricultural crops grown in the study area and their varying stages of growth. For this purpose a large AOI representative of wheat, barley, native vegetation etc. was selected to take into account the maximum possible spectral variation within the selected cover type AOIs. Based on the information gathered from the participating farmers' data, three polygons were defined for the wheat crop, three for the barley, and two for the native vegetation, encompassing different site variabilities spread over different parts of the study area. Additional AOIs were selected to represent other land cover types prevalent in the study area. These polygons were saved as independent image files. Unsupervised classification was carried out to generate ten homogeneous classes from each of the saved polygonal images pertinent to different land cover types. The classification was iterated six times with a convergence factor of 0.95. The resultant spectral classes originating from the classification of individual polygonal images, a sum total of 110 spectral classes from the SPOT polygonal images and 85 classes from the DEIMOS images, were pooled together.

The spectral classes generated in the above stage were used as an input to the supervised classification of the whole image.

[4] The classification of the features in the image into different classes based on the energy reflected by the object in a certain wavelength (spectral signature) (NASA, 2014).

- **Editing and spectral evaluation of land cover classes**

Two separate spectral[5] signature files pertinent to the classification of SPOT and DEIMOS images were created. To reduce the large number of spectral classes to meaningful land cover classes, a three tier approach was followed. Firstly, the duplicated signatures were deleted from each of the signature files by evaluating their spectral curves and variance-covariance matrices. Classes with identical reflectance curves and variance-covariance values were also deleted. This process produced 72 and 68 spectral classes for the SPOT and DEIMOS images, respectively. Secondly, the class separability was evaluated using Euclidean distance analysis and the transformed divergence algorithm (**Equation 3.1**). The distance value ranged between 2 and 32. Classes with the lowest separable value, i.e. less than 2, were merged together. This stage resulted in 64 and 56 spectral classes for the SPOT and DEIMOS images, respectively. Finally, the classification was re-run in a supervised classification mode using the edited signature files containing 64 and 56 spectral classes.

$$\boldsymbol{D_{ij} = \frac{1}{2} tr((C_i - C_j)(C_i^{-1} - C_j^{-1})(\mu_i - \mu_j)(\mu_i - \mu_j)^T)}$$

Equation 3.1

$$\boldsymbol{TD_{ij} = 2000(1 - exp(\frac{-D_{ij}}{8}))}$$

Where, ‘i’ and ‘j’ are two spectral signature classes being compared, ‘Ci’ is the covariance matrix of class, ‘ui’ is the mean vector of class I, ‘Tr’ is the trace function and ‘T’ is the transposition function.

[5] All materials emit or absorb electromagnetic wavelengths from different portions of the spectrum unique to itself, thus enabling the analyst to differentiate between materials, this is known as the spectral signature or spectral response of that material (Lillesand et alet al., 2006)

- **Statistical analysis and grouping of spectral classes**

In order to reduce the large number of spectral classes (64 and 56) to a meaningful small number of actual land cover classes[6], the spectral separability and spatial contiguity of the classes were evaluated. In this project, contiguity of SPOT and DEIMOS datasets was established by interactive viewing of the classes on the screen. Spectral classes were only aggregated if they were spectrally similar and intermixed spatially when displayed on the screen. That is, the classes show contiguity to a point where, as an aggregated class, they form a much more spatially compact class than they would separately. Where spectrally similar classes were spatially different, those classes were kept separate. Participating farmers providing field data played a significant role in the aggregation of the spectral classes. Such editing assumes an interdependence between spatial and spectral information, and avoids aggregation based on spectral values alone.

It is important to recognise that conventional computer based classifiers do not recognise spatial patterns in the same way as the human interpreter does. The classifiers perform class assignments based only on the spectral signatures of specific pixels. They do not take into account the locations of those pixels or the spectral characteristics of surrounding pixels (Gong & Howarth, 1990).

To assign meaningful land cover labels, the classified image was geo-linked to the raw data and the database containing the participating farmer’s field data information. Each spectral class from the classified images was painted in a distinct colour and its corresponding geographic coordinates and field labels were determined. It should be noted that the aggregation of spectral classes depends on the objectives of the study. Scientists and managers with different requirements may assemble different interpretations from the same basic set of spectral classes.

[6] The classification of features in an image into different classes based on the actual covering of the land, this is mostly completed using spectral signatures (NASA, 2014)

3.3.2 Life cycle assessment approach

Once the satellite images and other data layers (i.e. paddock and farm boundaries, corresponding rainfall, temperature, soil types and administrative shire boundaries) were imported into a GIS, LCA methodology was used to incorporate the carbon footprints of grains into GIS (Figure 3.1).

The LCA approach used for this project is known as limited focus (see Section 2.5..3), as the boundary and data requirements have been limited to include only cradle-to-gate studies, ignoring activities after the production stage (Engelbrecht et al., 2013; Curran 2006). Furthermore it only focuses on calculating the carbon footprint at this stage but could be extended to include other impact categories. As shown in Figure 3.8, the following four steps were included as part of the GHG analysis following ISO 14040-44 (International Organization of Standardisation (ISO), 2006):

- Goal and scope definition (Chapter 3);
- LCI analysis (Chapter 4);
- LCIA (Chapter 5) and integration of impact assessment results into GIS (Chapter 6);
- Interpretation, which is the identification of hotspots to apply CP mitigation strategies (Chapter 7).

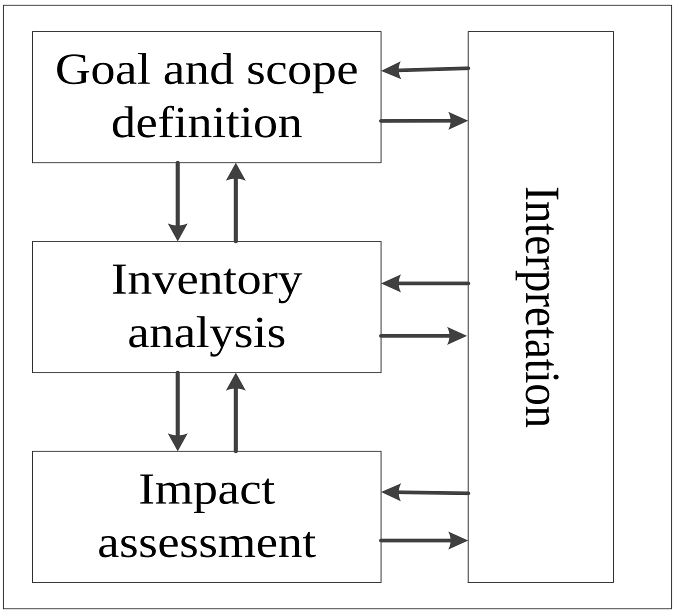

Figure 3.8. Four steps of LCA

3.3.2.1 Goal and scope definition

The goal of the LCA approach was to develop a tool that could assist with the mitigation of GHG emissions from grain production under different soil and climatic conditions. This was achieved by establishing the functional unit, selecting the system boundaries and determining the data requirements. The functional unit helps carry out a mass balance for developing a LCI and in this scenario it was considered to be the production of one tonne of grain (irrespective of the type of grain). The system boundary was established as the pre-farm and on-farm activities for each tonne of grain produced. During the pre-farm stage, farm machinery production, farm inputs and transportation were considered. In the on-farm stage, variables such as farm machinery operation, stubble burning, enteric and excreta emissions from animal husbandry, direct soil emissions (DSE) and indirect soil emissions (ISE) were quantified.

3.3.2.2 Life cycle inventory

The LCI is an initial, mandatory step required in order to carry out a carbon footprint analysis (Azapagic, 1999; Curran, 2006; Engelbrecht et al., 2013; Finnvedin et al., 2009). It is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes and other releases for the entire life cycle of a product, process or activity. All inputs (e.g. fertilisers, pesticides, machinery and outputs (e.g. crop yield emissions) for the processes which occur during the life cycle of a product are totalled in the LCI (Curran, 2006; Finnvedin et al., 2009; Roy et al., 2009; Biswas & John, 2008a). Figure 3.9 is a simplified illustration of the inputs and outputs included (within the black boundary) in this research. At the outset the LCI requires the development of a flow diagram of all processes being evaluated, the development of a data collection plan, the actual collection of the data and finally the evaluation and reporting of the results (Curran, 2006, 2013; Engelbrecht et al., 2013; Finnvedin et al., 2009).

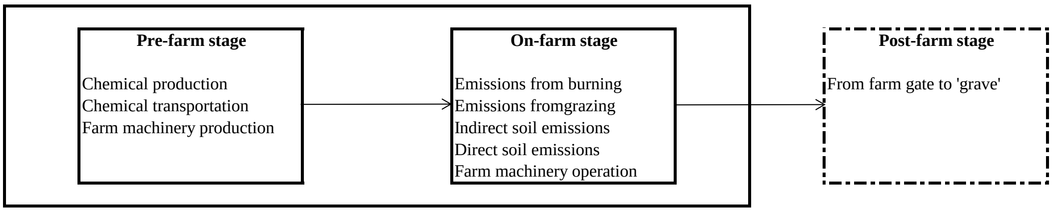

Figure 3.9. A simplified illustration of the inputs and outputs included in this research. The area enclosed in the solid lines form part of the research

As part of the LCI for this research, all data collected from each paddock and for each year (2010 and 2011) were separated into pre-farm and on-farm stages. These data were captured separately for each farm in a Microsoft Excel (hereafter referred to as Excel) workbook (eight workbooks). The workbooks were named ‘Farm A’ to ‘Farm H’, with letters being allocated to each of the farmers to ensure confidentiality. DAFWA allocated three paddocks from each of these farmers to the project and these were numbered ‘paddock 1’ to ‘paddock 24’ for the same reason. Within these workbooks, the worksheets (listed below) were used to organise the data acquired and perform the necessary calculations (as explained in the following sections) before finalising the LCI. The LCI worksheet aggregated and summarised the inputs and outputs for each paddock for both 2010 and 2011, by linkages to the relevant worksheets.

- General
- Paddock preparation (PadPrep)
- Machinery
- Chemicals
- Climatic variables
- LCI 2010 (used for calculation purposes)
- LCI 2011 (used for calculation purposes)
- LCI (an aggregation and summary of all calculated results for 2010 and 2011)

Figure 3.10 presents an illustration of the LCI worksheets created in Excel for each farm. The worksheets were arranged from right to left in the Excel workbook so that the most important worksheet (the overall carbon footprint in the LCIA section) would appear ‘on top’ upon opening the workbook.

- Introduction worksheet

The ***Introduction Worksheet*** in Figure 3.10 has been inserted for illustrative purposes only and has no function.

- General Worksheet

The ***General Worksheet*** was used as a basic summary (for the researcher) of the farm paddocks. It stored the name of the farm as well as data pertaining to the paddocks. The paddock data recorded included the names of the paddocks, geographical co-ordinates, the size of the paddocks (hectares), the dates the seed was sown, crop establishment date, type of soil, harvesting method and date, as well as stubble and stock management data. The content of the ***General Worksheet*** will not be discussed separately as all the information stored here was integrated into the other worksheets.

- Paddock preparation worksheet

The ***Paddock Preparation Worksheet*** (PadPrep) included any methods used to prepare the land for the next sowing season. These methods included weed control, control of plant residue (stubble), fertiliser application, soil tests (not within the scope of this project), soil identification (not required for this project), control of pests and the preparation of the seed beds (Department of Agriculture and Food. (2011; Farmstyle, 2014). This worksheet was used to calculate the GHG emissions resulting from stubble burning and emissions resulting from grazing livestock. In addition, the quality of the decomposing crop stubble remaining after harvest was taken into account. The decomposition rate of the stubble influences the amount of stubble available for feeding and burning, and ultimately the GHGs emitted. Other preparation methods were included as part of the machinery (swathing, spraying, spreading, claying, mouldboarding), chemicals (spraying and spreading of chemicals such as fertilisers, herbicides, insecticides and pesticides) and climatic variable (the calculation of Et/P) worksheets.

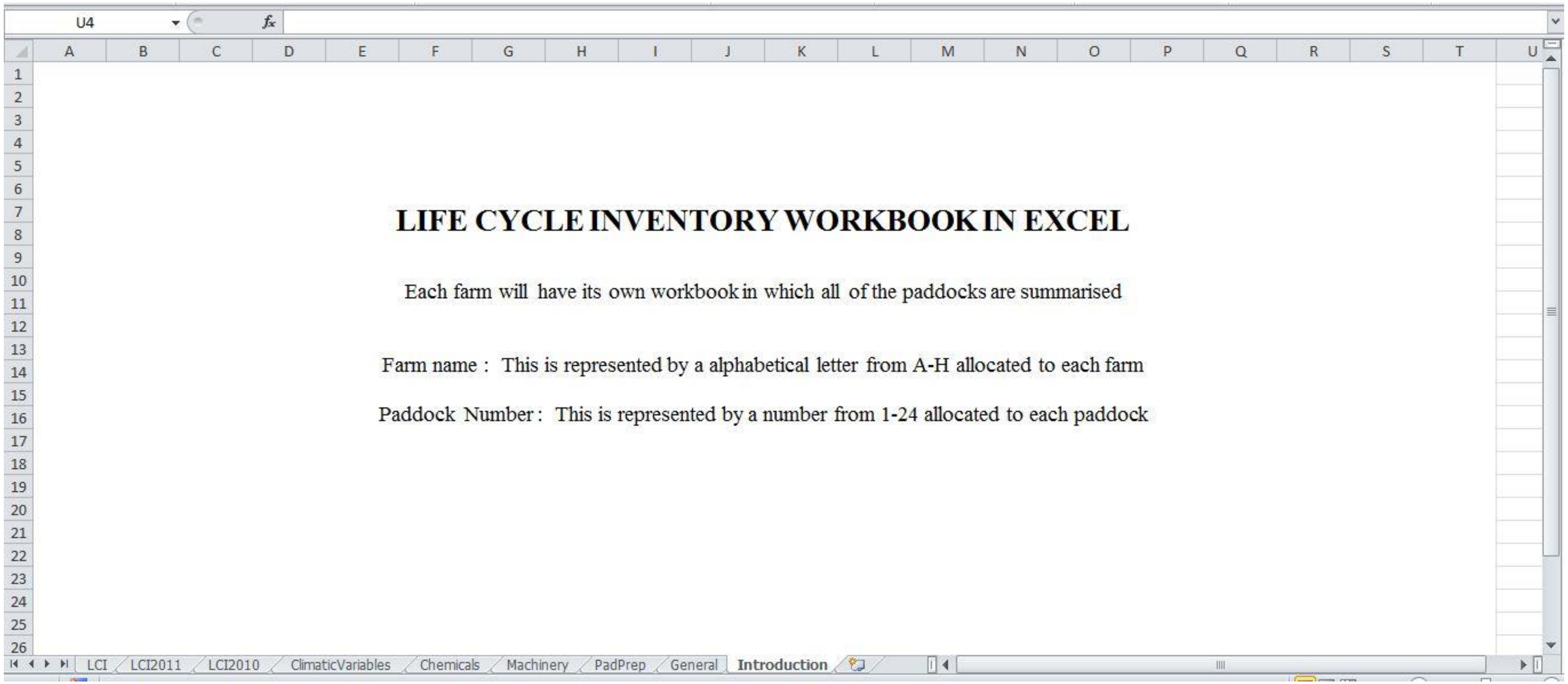

Figure 3.10. Illustration of the LCI worksheets created in Excel for each farm

Each paddock was treated as a separate entity, using only generic data where applicable. On recommendation from DAFWA, methods of ploughing the soil at varying depths, such as deep-rip, harrow and tickle, were not included as part of paddock preparation because these operations are typically performed on an *ad hoc* basis (pers. comm., Rietmuller, 2013, DAFWA, Merredin, Western Australia).

- Stubble decomposition was considered at various phases:
  - The initial phase commenced immediately after the crop was harvested and continued until sheep were grazed on the stubble.
  - The second phase commenced after the sheep had been removed from the paddock and continued until the burning of the stubble.
  - If no sheep were grazed or the paddock was not burned, stubble decomposition was considered from the end of harvesting until the start of the next planting season.

The GHG emissions resulting from stubble decomposition were not calculated as GHG emission factors could not be sourced from the literature at the time of the research. Additionally, stubble decomposition is dependent on variables such as soil and climatic conditions, crop types, activities of micro-organisms and soil fauna, quantity and quality of crop residues and the release of nitrogen (N) into the soil, which will affect the GHG emissions (Gupta, 2011). Only the first three variables (soil type, climatic conditions and crop type) were included in the scope of this project. However, a stubble decomposition rate of 30% (assumed linear) (GRDC, 2011a) was applied when calculating the mass of the stubble immediately before grazing and burning. This was necessary as the emissions resulting from stubble burning were based on efficiency factors, which are affected by the amount of stubble in the field prior to burning. Figure 3.11 illustrates an excerpt from the Excel workbook of this study showing the formulae and fixed variables used and Figure 3.12 summarises the phases in the harvesting year, showing the paddock preparation phases, including fallow or grazing, burning and land preparation.

	A	B	C	D	E	F	G	H	I	J
1	**Stubble Decomposition**			**2010**				**2011**		
2	Paddock number	Units		1	2	3		1	2	3
3	Starting mass of stubble	kg/ha								
4	Rate of stubble decomposition	%		30	30	30		30	30	30
5	Months decomposed before pasturing	months								
6	Stubble decomposed before pasturing	kg/ha								
7	Stubble remaining before pasturing	kg/ha		=D3-D6	=E3-E6	=F3-F8		=H3-H10	=I3-I11	=J3-J12
8	Stubble remaining after pasturing	kg/ha		=D32	=E32	=F32		=H32	=I32	=J32
9	Months decomposed before burning	months								
10	Stubble decomposed before burning	kg/ha		=D7*D4/100*D9/12	=E7*E4/100*E9/12	=F7*F4/100*F9/12		=H7*H4/100*H9/12	=I7*I4/100*I9/12	=J7*J4/100*J9/12
11	Stubble remaining before burning	kg/ha		=D8-D10	=E8-E10	=F8-F10		=H8-H10	=I8-I10	=J8-J10
12										
13										

Figure 3.11. Calculation of stubble decomposition (Source: Paddock preparation workbook)

Sheep were allowed to graze on the stubble either directly after harvesting, after a period of fallow, or not at all (Figure 3.12). The grazing reduced the stubble load before burning (if burned) in early autumn (April–May) or before planting in June. A feeding requirement of 1.5 kg dry matter (DM) for each sheep per day (kg per head per day, kg/hd/day) was used with a digestibility factor of 55% (Department of Climate Change, 2007). Any additional feed supplied was also factored into the feeding requirements. Since the sheep were mainly grazed for stubble management for a short period before they were transferred to another pasture and the information on life time of these sheep were unknown, it was not possible to allocate a portion of the GHG emissions to the amount of live weight gained during grazing.

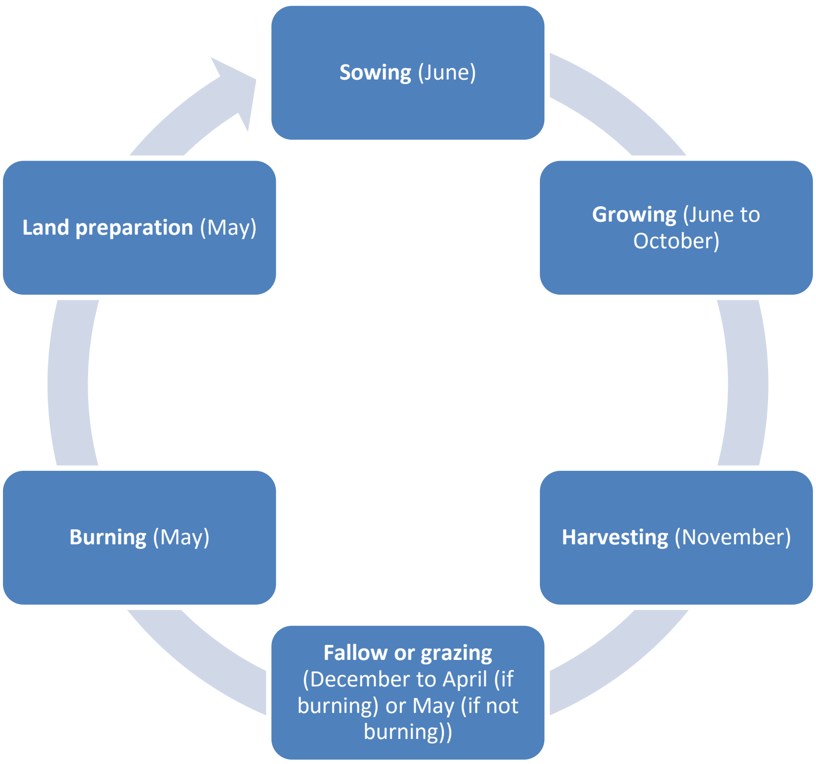

Figure 3.12. Phases in the annual agricultural cycle in the wheatbelt of south-western Australia as generated from field observations

- The CH_4 emissions generated during livestock grazing were from belching, known as enteric emissions, and from the aerobic decomposition of manure. The equations (**Equations 3.2 and 3.3**) for calculating these GHGs were obtained from Department of Climate Change (2007) and Biswas et al. (2010).

$$CH_{4manure} = \textbf{Intake x } (\mathbf{1} - \textbf{ DMD})\textbf{x}EF_{methane} \qquad \textbf{Equation 3.2}$$

$$CH_4enteric = DMI \times EF_{enteric\ methane} \qquad \textbf{Equation 3.3}$$

$$EF_{enteric\ methane} = \mathbf{0.0188 + 0.00156} \qquad \textbf{Equation 3.4}$$

Where, 'DMD' is dry matter digestibility (%), '$EF_{methane}$' is the emissions factor for methane (CH_4) = 1.4 x 10^{-5} (kg CH_4/hd/day) and 'DMI' is dry matter intake (kg/hd/day.

These emissions were then converted to emissions per hectare by dividing by the area of the paddock. Figure 3.13 shows the calculations as carried out using Excel.

	A	B	C	D	E	F	G	H	I	J
16	**Sheep Grazing**				2010				2011	
17	**Stubble Reduction calculations**	Units		1	2	3		1	2	3
18	Digestibility in summer	%		55	55	55		55	55	55
19	Sheep per paddock	ea								
20	Paddock area	ha								
21	Sheep per ha (DSE/ha)	DSE/ha		=D19/D20	=E19/E20	=F19/F20		=H19/H20	=I19/I20	=J19/J20
22	Additional feed given as lick	kg/hd/day								
23	Feed DM requirement (summertime)	kg/hd/day		1.5	1.5	1.5		1.5	1.5	1.5
24	Initial Stubble	kg/ha								
25	Number of days grazed	days								
26	Total stubble grazed	kg/ha		=D19/D20*D23*D25	=E19/E20*E23*E25	=F19/F20*F23*F25		=H19/H20*H23*H25	=I19/I20*I23*I25	=J19/J20*J23*J25
27	Stubble lost from erosion or wind									
28	Remaining stubble	kg/ha		=D24-D26	=E24-E26	=F24-F26		=H24-H26	=I24-I26	=J24-J26
29	CH_4 Emission factor for enteric emissions	kg CH_4/hd/day		0.02038	0.02038	0.02038		0.02038	0.02038	0.02038
30	GHG Emissions from enteric emissions	kg CH_4/ha		=E29*D26/D25	=F29*E26/E25	=G29*F26/F25		=H29*H26/H25	=I29*I26/I25	=J29*J26/J25
31	CH_4 Emission factor for manure emissions	kg CH_4/hd/day		1.40E-05	1.40E-05	1.40E-05		1.40E-05	1.40E-05	1.40E-05
32	CH_4 emissions from manure decomposition			=D26*(1-D18/100)*E31	=E26*(1-E18/100)*F31	=F26*(1-F18/100)*G31		=H26*(1-H18/100)*H31	=I26*(1-I18/100)*I31	=J26*(1-J18/100)*J31
33										

Figure 3.13. Calculations showing the emissions associated with grazing sheep

- Stubble burning is used in Western Australia when the stubble load is higher than required, in order to prevent the blockage of seeding equipment with plant residue or when weed and pest management via burning becomes imperative (GRDC, 2011a). If any of the paddocks were burned, burning was assumed to take place in May and was either by windrow burning or full paddock burning as stipulated by the farmer. The efficiency of burning was based on figures from the Intergovernmental Panel on Climate Change (IPCC), (2006), being 45% for windrow burning and 96% for paddock burning (IPCC, 2006). The stubble load (or fuel load) used for burning was that which was left over after fallow, decomposition and/or grazing. A combustion factor of 0.9 was applied to the stubble load being burned (IPCC, 2006). The emission factors for stubble burning, according to National Greenhouse Gas Inventory (NGGI) (2006) are 3.5 g/kg for CH_4 and 7.6 g/kg for N_2O.
- **Equation 3.5** was used to calculate GHG emissions from burning and is as follows:

$$\boldsymbol{GHG_{burn} = Area_{burn} \times Mass_{fuel} \times CF \times \frac{EF_{burn}}{1000}}$$ **Equation 3.5**

Where,'GHG_{burn}'(t) are the GHG emissions from burning, '$Area_{burn}$' is the area burned (ha), '$Mass_{fuel}$' is the fuel mass (t/ha), 'CF' is the combustion factor and 'EF_{burn}' is the emissions factor for burning (g/kg) (NGGI, 2006).

The carbon dioxide (CO_2) emissions resulting from the burning of stubble are biogenic as the CO_2 released into the atmosphere is assumed to be reabsorbed by the crop in the next growing season (IPCC, 2006). CO_2 was therefore excluded from the estimation of GHG emissions. The extract from Excel (Figure 3.14) shows the calculations used for stubble burning.

	A	B	C	D	E	F	G	H	I	J
35	**Burning**			2010				2011		
36	Paddock number			1	2	3		1	2	3
37		Unit								
38	Crop			Wheat	Wheat	Wheat		Wheat	Wheat	Wheat
39	Type of burning			windrow burn	windrow burn	paddock		none	windrow burn	none
40	Area burnt	ha								
41	Burn efficiency - paddock burn	%		45	45	45		0	45	0
42	Burn efficiency - windrow burn	%		96	96	96		96	96	96
43	Mass of fuel burnt	t/ha		=D11*D41/100	=E11*E41/100	=F11*F42/100		=H11*H41/100	=I11*I41/100	=J11*J41/100
44	Combustion factor			0.9	0.9	0.9		0.9	0.9	0.9
45	Harvest index									
46	Stubble remaining after burning	kg/ha		=D11-D43	=E11-E43	=F11-F43		=H11-H43	=I11-I43	=J11-J43
47	Emission factor CO_2	g/kg								
48	Emission factor CH_4	g/kg		3.5	3.5	3.5		3.5	3.5	3.5
49	Emission factor N_2O	g/kg		7.6	7.6	7.6		7.6	7.6	7.6
50	Equation to calculate GHG =	Area burnt (ha) x Mass of fuel (t/ha) x combustion factor x emission factor (g/kg dry matter) x 10-3								
51	CO_2	kg		=D40*D43*D44*C47/1000	=E40*E43*E44*D47/1000	=F40*F43*F44*E47/1000		=H40*H43*H44*G47/1000	=I40*I43*I44*H47/1000	=J40*J43*J44*I47/1000
52	CH_4	kg		=D43*D44*D45*C48/1000	=E43*E44*E45*$C$53/1000	=F43*F44*F45*$C$53/1000		=H43*H44*H45*$C$53/1000	=I43*I44*I45*$C$53/1000	=J43*J44*J45*$C$53/1000
53	N_2O	kg		=D43*D44*D45*C49/1000	=E43*E44*E45*$C$54/1000	=F43*F44*F45*$C$54/1000		=H43*H44*H45*$C$54/1000	=I43*I44*I45*$C$54/1000	=J43*J44*J45*$C$54/1000

Figure 3.14. Calculations of emissions from stubble burning

- Machinery worksheet

  In the ***Machinery Worksheet*** the final output (cost of the machinery per tonne grain yield in United States dollars (USD/tonne) and the fuel usage per hour per tonne grain yield (l/hr/tonne)) were quantified for claying[7], mouldboarding[8], seeding[9], swathing[10], spraying[11], top-dressing[12] (for fertilisers and lime, separately) and harvesting[13] during the on-farm stage. The data required for these calculations are listed below, and the extract from the Excel workbook (Figure 3.15) shows how the results were determined:

  - paddock size (ha),
  - number of passes,
  - machinery/implement header width (m),
  - machinery/tractor operational speed (km/hr),
  - fuel consumption (l/hr),
  - average speed for activity (km/hr),
  - cost of machinery (tractor and implement) (AUD),
  - life span of machinery (yrs) and
  - annual usage time (hr/yr).
  - The paddock size and the number of passes were obtained from project data.

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[7] Claying is the spreading of clay on light, sandy soils to help increase soil moisture, retain nutrients and overcome water repellence. Clay is applied to the topsoil by spreading and 'smudging' it to the sandy soil surface (mechanical 'top-dressing') (Pers. comm., Brockman, Albany, Western Australia, 2014; Brockman, 2015).

[8] Mouldboarding is a type of ploughing in which the soil is completely inverted. It is used to remove compaction, improve water filtration, assist in weed control, increase nitrogen mineralisation and improve nutrient access (GRDC, 2014b).

[9] Seeding refers to the scattering of seeds on land so that they may grow. Farmers use machinery that places and covers the seed in the soil. It is usually an implement that is tractor drawn (Agricultural Products India, 2014).

[10] Swathing (also known as windrowing) is the process of placing the hay or a similar crop remaining after harvesting in a long low ridge or line which has been designed to achieve the best conditions for drying or curing (The free dictionary, 2014).

[11] Spraying is the application of chemicals to the crop in the form of a solution, emulsion or suspension using a tractor drawn implement which atomises the pressurised liquid onto the crop (The free dictionary, 2014).

[12] Top-dressing is the surface application of fertilisers or lime to the soil. During top-dressing the respective implement is tractor drawn (The free dictionary, 2014).

[13] Harvesting is the gathering of the cultivated crop by cutting and then removing the edible seeds using a harvester and leaving the chaff on the ground and the stubble standing in the land (Agricultural Products India, 2014).

			2010
Yield			1.55
Details	**Units**	**Quantities**	
Width	m	6	6
No of passes			1
Fuel consumption	litres/hour	40	40
Speed	km/Hour	8	8
Cost of machinery	A$ (Year)	110000	
Life time of machinery	years	12	
Distance travelled by the contractor to bring the machinery to paddock	km	0	
Approximate usage:	weeks/yr	0.065	
	hrs/day	5.50	
	days/week	2	
Distance travelled/ha	km/ha		=100/$D5*100/1000
Total distance travelled	km		=F16*F7
Operational time (hours/ha)	hr/ha		=F16/F9
Life time of machinery (hours)	hrs		=$D$13+$D$14+$D$15
Cost of machinery per hour	AUD/hr		=$D$10/F19
Cost of machinery (AUD/hr of operation/ha)	AUD/hr		=F18*F20
Cost of machinery per tonne produced (AUD/hr of operation/ha/tonne)	AUD/hr/tonne		=F21/F2
Cost of machinery for wheat production (AUD/Ha) 1998 price	AUD/tonne		=F22/(1+$C$36)^($C$43-$C$42)
Cost of machinery for crop production (USD/Ha) 1998 price	USD/tonne		=F23*$C$39
Total fuel used per tonne of crop produced	litres/hour/tonne		=F9*F18/F2

		References
Year	Inflation rates	**Australian inflation rate (consumer prices)**
2006	2.70%	http://www.indexmundi.com/australia/inflation_rate_(consumer_prices).html
2007	3.80%	
2008	2.3%	
2009	4.4%	
2010	1.8%	
2011	2.9%	
Average	2.98%	
	USD	**Fluctuations in the value of the Australian dollar**
1998	0.6049	http://www.aph.gov.au/library/pubs/CIB/1997-98/98cib21.htm
From year	1998	
To year	2010	

Figure 3.15. Calculation of result required for machinery production and use

All other data for machinery use were supplied by DAFWA (pers. comm., Glen Riethmuller, 2013, DAFWA, Merredin, Western Australia).

For example: the following details in Table 3.1 regarding the spraying of chemicals on paddock 1 are used for the calculations that follow (**Equations 3.6–3.15**).

Table 3.1. Variables required to calculate the value of machinery and fuel usage of machinery

Details	Unit	Quantity
Paddock size	ha	159
Number of passes	ea	3
Machinery/implement header width	m	36
Machinery/tractor operational speed	km/hr	23
Fuel consumption	l/hr	30
Average speed for activity	km/hr	23
Cost of machinery (tractor and implement)	AUD	400,000
Life span of machinery	yrs	12
Weekly usage time	hrs/week	15
Usage time per year	months/yr	8

$$\boldsymbol{D_{ha}} = \frac{\mathbf{100}\boldsymbol{m}}{\boldsymbol{HW}} \times \frac{\mathbf{100}\boldsymbol{m}}{\mathbf{1000}\boldsymbol{m}}$$ **Equation 3.6**

Where, 'D_{ha}', is distance travelled per hectare (km/ha) and 'HW' is header width of implement (m).

For example: 100m/36m x 1000 = 0.277 km/ha

$$\boldsymbol{TD} = \boldsymbol{D_{ha}} \times \boldsymbol{NP}$$ **Equation 3.7**

Where, 'TD' is total distance travelled (km), 'D_{ha}', is distance travelled per hectare (km/ha) and 'NP' is the number of passes .

For example: TD = 0.277 km/ha x 3 = 0.83 km/ha

$$OT = \frac{TD}{Speed}$$ **Equation 3.8**

Where, 'OT' is operational time (hr/ha) and 'Speed' is the speed of the machinery (km/hr).

For example: OT = 0.83 km/ha / 23 km/hr = 0.36 hr/ha

$$LM = \frac{hours}{week} \times \frac{weeks}{month} \times \frac{months}{year} \times years$$ **Equation 3.9**

Where, 'LM' is the lifetime of the machinery (hours).

For example: LM = 15 hours/week x 4 weeks/month x 8 months/yr x 12 yrs = 5,760 hours

$$Cost_{hr} = \frac{Cost_{AUD}}{LM} = \frac{\$400\ 000}{5\ 760\ hours} = 69.44 \frac{AUD}{hr}$$ **Equation 3.10**

Where, '$Cost_{hr}$' is the cost of machinery per hour (AUD/hr) and '$Cost_{AUD}$' = cost of machinery in AUD.

For example: $Cost_{hr}$ = AUD 400 000 / 5,760 hours = 69.44 AUD/hr

$$Cost_{ha} = OT \times Cost_{hr}$$ **Equation 3.11**

Where, '$Cost_{ha}$' is the cost of machinery per hectare (AUD/ha).

For example: $Cost_{ha}$ = 0.036 hr/ha x 69.44 AUD/hr = 2.50 AUD/ha

$$Cost_{yield} = \frac{Cost_{ha}}{Grain\ yield}$$ **Equation 3.12**

Where, '$Cost_{yield}$' is the cost of machinery per tonne of grain yield (AUD/hr/t).

For example: $Cost_{yield}$ = 2.50 AUD/ha / 1.32 t/ha = 1.89 AUD/hr/t

$$\boldsymbol{Cost_{AUD\,1998}} = \frac{\boldsymbol{Cost_{yield}}}{(\mathbf{1} + \boldsymbol{AUD_{inf}})^{\boldsymbol{fluc}(\mathbf{2010-1998})}} \qquad \textbf{Equation 3.13}$$

Where, '$Cost_{AUD\ 1998}$' is the cost of the machinery in AUD for crop production at the 1998 price, 'AUD_{inf}' is the Australian inflation rate from 2006 to 2010 and 'fluc(2010–1998)' is the fluctuation in the value of AUD (1998–2010).

For example: $Cost_{AUD\ 1998}$ = 1.89 AUD/hr/t / (1 + 2.98%)$^{(2010\text{-}1998)}$ = 1.34 AUD/t

$$\boldsymbol{Cost_{USD\,1998}} = \boldsymbol{Cost_{AUD\,1998}} \times \boldsymbol{AUD_{inf\,1998}} \qquad \textbf{Equation 3.14}$$

Where, '$Cost_{USD\ 1998}$' is the cost of machinery in USD for crop production at the 1998 price, and 'AUD $_{inf\ 1998}$ is the Australian inflation rate in 1998.

For example: $Cost_{USD\ 1998}$ = 1.34 AUD/t x 0.6049 USD/AUD = 0.81 USD/t

$$\boldsymbol{Fuel_t} = \frac{\boldsymbol{FC} \times \boldsymbol{T}}{\boldsymbol{Y}} \qquad \textbf{Equation 3.15}$$

Where, '$Fuel_t$' is the total fuel used, 'FC' is fuel consumption (l/hr), 'T' is operational hours (hr/ha) and 'Y' is yield (t/ha).

For example: $Fuel_t$ = 30 l/hr x 0.036 hr/ha ⁄ 1.32 t/ha = 0.823 l/hr/t

Where implements were tractor drawn the machinery (tractor and implement) was considered as a unit in terms of cost, fuel usage, speed, width and operational time. The fuel consumption of a top-dresser for application of either lime or fertilisers differed as the widths (referred to as header widths) of the implements differ for each function. Specific generic data were supplied for each region (Liebe group or WANTFA) (pers. comm., Glen Riethmuller, 2013, DAFWA, Merredin, Western Australia). Regional specific data (Table 3.2) differed in terms of header widths, fuel consumption, speeds and lifetime of machinery due to variations in soil type (Section 3.3.2, farm machinery operation). Additional equations were required to complete the calculations for claying, these are specified in Appendix D.

Table 3.2. Region specific data for machinery used in the Dalwallinu and Northam regions

DALWALLINU		Seeder	Sprayer	Swather	Top-dresser/spreader		Harvester		
					Lime	Fertilisers	Wheat	Canola	Other
Equipment power	kW	300	120	120	150	150	300	300	300
Typical equipment width	m	18	36	11	10	36	11	11	11
Fuel consumption	l/hr	75	30	30	38	38	75	75	75
Fuel consumption	l/ha	5	0.4	2.4	2.8	1	5	6	5
Average work rate	ha/hr	11	70	6	24	60	8	8	8
Average speed	km/hr	10	25	7	24	24	12	12	12
Cost of tractor and implement	AUD	600,000	400,000	300,000	300,000	300,000	750,000	750,000	750,000
Lifetime of machinery/implement	yrs	12	12	12	12	12	10	10	10
NORTHAM		**Seeder**	**Sprayer**	**Swather**	**Top-dresser/spreader**		**Harvester**		
					Lime	**Fertilisers**	**Wheat**	**Canola**	**Other**
Equipment power	kW	200	100	100	120	120	200	200	200
Typical equipment width	m	14	2	9	10	24	9	9	9
Fuel consumption	l/hr	50	25	25	30	30	50	50	50
Fuel consumption	l/ha	5	0.4	2.4	2.8	1	6	7	6
Average work rate	ha/hr	9	40	4.3	14	34	5	5	5
Average speed	km/hr	9	20	6	20	20	9	9	9
Cost of tractor and implement	AUD	500,000	300,000	200,000	200,000	200,000	600,000	600,000	600,000
Lifetime of machinery/implement	yrs	15	15	15	15	12	12	12	12

- Chemicals worksheet

The ***Chemicals Worksheet*** considered the data for the chemicals (fertilisers and all other non-fertiliser chemicals) used, the supplier, relative density of the chemical, country of formulation, distance travelled from place of formulation to delivery, delivery vehicle used, ratio of international to national travel. The national portion included transportation from the chemical manufacturer or chemical distributor within Australia, via Perth, to the point of use which is either Dalwallinu for the Liebe group region or Northam for the WANTFA region, and from there to each paddock. The distances calculated from the manufacturer/distributor were fixed for each chemical by adding all of the distances transported from the origin to the local store in Dalwallinu or Northam. The distance travelled in a one tonne utility (ute) vehicle from the local store to the farm was determined using the 'find distance' application on Google Maps. In all other instances, a single journey to the destination was assumed using a 30 tonne articulated truck.

The international portion of transportation began from the closest origin port to a destination port in Australia, on a shipping tanker. Here too, a single journey was assumed. These data were required to eventually calculate the amount of chemical used per tonne of crop yield and the kilometre each tonne of chemical was transported (i.e. tonne x kilometres travelled = tkm). The emission factors for the transportation are available in the form of tkm values (e.g. 1,000 kg CO_2-e/tkm).

- Climatic variables worksheet

In the ***Climatic Variables*** worksheet, calculations were completed to determine whether there was any leaching of N_2O from the soil. At the outset, the climatic conditions, as captured by the Bureau of Meteorology (BOM) weather station closest to the paddocks were summarised. These conditions included the average temperature, Et minimums and maximums and the monthly precipitation averages. The average annual precipitation values for each paddock were calculated for both 2010 and 2011 cycles using the average monthly precipitation data recorded on this site. In calculating the N_2O emissions from leaching, the ratio of mean annual Et to annual precipitation (P) was determined for each paddock. The IPCC predicts that leaching will only occur when Et/P is outside the limits of 0.8 and 1.0 and an emission factor of 0.03 is then allocated. If the calculated value is within these limits, no leaching occurs and the emission factor is then zero (NGGI, 2006). The values for Et and P were obtained by superimposing the paddock locations on the Et and P map (as shapefiles) respectively in GIS. These Et and P maps were obtained from the BOM website (BOM, 2013).

- LCI 2010 and LCI 2011 worksheets

The next two worksheets were named ***LCI2010 and LCI2011.*** These two worksheets were used to complete the calculations required for the data to be summarised in the inventory list thereafter (LCI worksheet). They were separated into LCI 2010 (LCI2010) and LCI 2011 (LCI2011) due to the large amount of data and calculations in each of these inventories. In these worksheets, for each of the paddocks for that specific year (2010 or 2011), the following calculations were completed:

- the annual dosage of chemicals per tonne crop yield (kg/t/yr)
- the tkm (tonne x kilometre) for each chemical transported
- the soil emissions associated with fertiliser applications and liming
- the GHG emissions from stubble burning
- the CH_4 emissions from grazing
- the emissions from stubble decomposition.

The quantity of the chemical used (kg), the crop yield (t) and the density (kg/l) of the chemical (when in liquid form) were required to calculate the usage of the chemical per tonne yield and subsequent transportation to the farm using the formulae (**Equation 3.16**):

$$\boldsymbol{Chem_{use} = \frac{Chem_{rate}}{Crop_{yield}} \times Chem_{d}} \qquad \textbf{Equation 3.16}$$

Where, '$Chem_{use}$' is the use of chemical per tonne crop yield (kg/yr/t), '$Chem_{rate}$' is the application rate of the chemical (l/ha/yr), '$Crop_{yield}$' is the crop yield (t/ha) and '$Chem_d$' is the density of the chemical (kg/l).

For example: If 1.4 litres per hectare per year of glyphosate, density 1.17 kg/l, was used on a paddock that had a yield of 1.32 t/ha wheat, and the glyphosate was transported a total of 253.4 km from origin to the paddock, then:

Glyphosate usage (kg/yr/t) = (1.4 l/ha/yr ⁄ 1.32 t/ha) x 1.17 kg/l = 1.24 kg/yr/t

$$\boldsymbol{Chem_t = Chem_{use} \times Chem_{distance}} \qquad \textbf{Equation 3.17}$$

Where, ‘$Chem_t$’ is the distance each tonne of chemical is transported (tkm/yr/t), and ‘$Chem_{distance}$’ is the distance from the manufacturer/formulator to the final destination.

For example: As specified above, the glyphosate was transported 253.4 km from its origin to final destination.

$Chem_t$ = 1.24 kg/yr/t x 253.4 km = 314.2 tkm/yr/t

Each chemical was allocated to a class as a fertiliser, fungicide and insecticide, herbicide, adjuvant or lime according to the agricultural purpose.

The emissions resulting from the soil included CO_2 and non-CO_2 gases. The non-CO_2 gases were further classified as either direct or ISE. ISE comprise N_2O from leaching and runoff (N_2O leaching) and N_2O from ammonia volatilisation (N_2O volatilisation) (Department of Agriculture and Food, 2013). The terms indirect and DSE refer to the conversion of nitrogen oxides (NO_x) and NH_3 to N_2O as proposed by the IPCC methodology.

ISE are comprised of N from manure and fertilisers that have volatilised to NO_x and NH_3 soon after application to soil. During the leaching process the N is no longer available for soil uptake and usually increases the N concentration in ground and surface waters. The deposition of N compounds on soil and surface waters is known as the ‘runoff’ fraction of ISE. Furthermore the surface waters and the nitrogen deposits on soil and surface waters may contain the ammonium ion (NH_4^+) which is readily converted to nitrate. The NH_4^+ is readily taken up by the crops, and the residue is converted to nitrate. Nitrifying and denitrifying bacteria in the soil are responsible for the processes which occur during normal agricultural processes. DSE collectively refer to the soil emissions from the application of animal manure and N-fertilisers, and manure production in the field (IPCC, 2006; Nevison, n.d.; Van Der Hoek, Van Schijndel, & Kuikman, 2007).

Equation 3.18 is used to calculate the N_2O ISE, resulting from the nitrification or denitrification of N from leaching and runoff, after fertiliser application and **Equation 3.19** calculates the NO_x or NH_3 that volatilises and is converted, by calculation, to N_2O. The emissions factor of 0.008% and the ratio 44/28 to convert N to N_2O-N was obtained from IPCC (2006).

$$\boldsymbol{N_2O_{leaching}} = \sum_{f=1}^{F}(\boldsymbol{N_f} \times \boldsymbol{D_f} \times \boldsymbol{EF_{leaching}} \div \boldsymbol{Crop_{yield}}) \qquad \textbf{Equation 3.18}$$

$$\boldsymbol{N_2O_{volatilisation}} = \sum_{f=1}^{F}(\boldsymbol{N_f} \times \boldsymbol{D_f} \times \mathbf{0.008}\% \div \boldsymbol{Crop_{yield}}) \qquad \textbf{Equation 3.19}$$

Where, '$N_2O_{leaching}$' is the fraction N in the fertiliser that has leached and is converted to N_2O of NO_X, '$N_2O_{volatilisation}$' is the fraction of N from the fertilisers that volatilised as NH_3 and is converted to N_2O, 'N_f' is the percentage of N in fertiliser 'f', 'D_f' is the dose (kg/ha/yr) of fertiliser 'f', '$EF_{leaching}$' (kg N_2O-N/kg N) is the emissions factor for the paddock and '$Crop_{yield}$' is the crop yield (t/ha). 'f' = 1, 2, 3,……… for different types of fertiliser.

For example if 65kg/ha/yr of Agstar Extra (14.1% N) and 60 kg/ha/yr of urea (46% N) were applied to a paddock with a final grain yield of 2.85 t/ha, then:

$N_2O_{leaching}$ = [(% N of fertiliser 1 x actual dosage of chemical 1 x emissions factor / crop yield t/ha) + (% N of fertiliser 2 x actual dosage of chemical 2 x emissions factor) / crop yield t/ha] = [(14.1% x 65 kg/ha/yr x 0.03 kg N_2O-N/kg N / 2.85 t/ha) + (46% x 60 kg/ha/yr x 0.03 / 2.85 t/ha) = 3.87×10^{-1}kg N_2O/yr/t and,

$N_2O_{volatilisation}$ = (% N x actual dosage of the fertiliser 1 x 0.008 % x 44/28 / crop yield (t/ha) + (% N of fertiliser 2 x actual dosage of the fertiliser 2 x 0.008 % x 44/28 / crop yield (t/ha)) = (14.1% x 65 kg/ha/yr x 0.008% x 44/28 / 2.85 t/ha) + (46% x 60 kg/ha/yr x 0.008% x 44/28 / 2.85 t/ha) = 1.62×10^{-3} kg N_2O/yr/t.

DSE include the emissions of CO_2, N_2O and CH_4 resulting from urea hydrolysis (CO_2 urea hydrolysis), application of lime (CO_2 liming), fertiliser application (fertiliser containing N) and CH_4 emissions from soil (CH_4 from soil). For direct N_2O emissions an emission factor of 0.1%, the Western Australian average for non-irrigated regions (all paddocks were non-irrigated), was used. The emission factor for Western Australian irrigated lands is 0.3% (NGGI, 2006). This emission factor for direct N_2O emissions varies across regions and should ideally be determined for that area. In the areas of Western Australia where the rainfall is low, soils have been found to be more porous, thus reducing the denitrification process which results in low emissions of N_2O from the application of fertiliser containing N (N-fertiliser) (NGGI, 2006). Additionally, the use of N-fertilisers in Western Australia has historically been low, but is now increasing (Ryan, 2010). The emission factor for direct N_2O emissions tends to increase with fertiliser application due to the higher soil nitrate concentration arising from the additional N-fertiliser increasing the N content (NGGI, 2006).

The following variables were used as an example to present the calculations for the DSE by applying **Equation 3.20** (NGGI, 2006). A paddock yielding 2.85 t/ha of grain used the following chemicals: 65 kg/ha/yr Agstar Extra fertiliser (14.1% N), 40 kg/ha/yr urea (46% N) as fertiliser and 100 kg/ha/yr lime.

$$\boldsymbol{N_2O_{direct}} = \sum_{\boldsymbol{f=1}}^{\boldsymbol{F}} [(\boldsymbol{N_f} \times \boldsymbol{D_f} \times \boldsymbol{Ef_{lands}})] \div \boldsymbol{Crop_{yield}} \qquad \textbf{Equation 3.20}$$

Where, 'N_2O_{direct}' (kg N_2O/yr/t) are the emissions resulting from the application of fertilisers, $Crop_{yield}$ is the crop yield (t/ha), 'N_f' is the percentage of N in fertiliser 'f', 'D_f' is the dose (kg/ha/yr) of fertiliser 'f' and 'EF_{lands}' is the EF for irrigated or non-irrigated lands.

For example: N_2O_{direct} = (% N of fertiliser 1 x actual dosage of fertiliser 1 x emissions factor / crop yield) + (% N of fertiliser 2 x actual dosage of fertiliser 2 x emissions factor / crop yield) = (14.1% Agstar Extra x 65 kg/ha/yr x 0.1% for non-irrigated lands) + (46% for urea x 40 kg/ha/yr x 0.1% for non-irrigated lands) = 2.76 x 10^{-2} kg/ha/yr / crop yield (2.85 t/ha) = 9.67 x 10-3 kg N_2O/yr/t

The equation **(Equation 3.21**) for the calculation of CO_2 emissions from urea hydrolysis and from the application of lime was obtained from IPCC (2006).

$$\boldsymbol{CO_{2}}_{\boldsymbol{Urea}} = \frac{(\boldsymbol{EF_{UH}} \times \boldsymbol{D_U})}{\boldsymbol{Crop_{yield}}} \qquad \textbf{Equation 3.21}$$

Where, 'CO_{2Urea}' are the CO_2 emissions from urea hydrolysis (kg CO_2/yr/t), 'EF_{UH}' is the emissions factor (0.2 or 20%) for the hydrolysis of urea, '$Crop_{yield}$' is the actual crop yield (t/ha) and 'D_U' is the application rate of urea (kg/ha/yr).

For example: CO_{2Urea} = 0.2 x 40 kg/ha/yr /2.85 t/ha) = 2.81 kg CO_2/yr/t.

To calculate the CO_2 emissions from the application of lime, **Equation 3.22** was used (IPCC, 2006).

$$\boldsymbol{CO_{2_{lime}} = (EF_{lime} \times \frac{44}{12}) \div Crop_{yield}} \qquad \textbf{Equation 3.22}$$

Where, 'CO_{2lime}' are the emissions from lime (kg CO_2/yr/t), 'EF_{lime}' is the emissions factor for lime (0.12 or 12%) and 44/12 is used for the conversion of C to CO_2.

For example: CO_{2lime}= (65 kg/ha/yr x 0.12 x 44/12) / 2.85 t/ha = 10.04 kg CO_2/yr/t.

Calcium carbonate ($CaCO_3$, referred to as lime) is generally applied to Western Australian agricultural soil at the rate of one t/ha every 10 years (Department of Agriculture and Food, 2013) and this was assumed to be the case when no application rate was supplied by the farmer. The CO_2 emissions resulting from the dissolution of the 100 kg per year per paddock were then allocated to that paddock.

Soil CH_4 emissions and/or uptake were not included in the analysis, as CH_4 emissions/uptake are expected to be low (17 g CH_4-C ha^{-1}) from fertilised, rain-fed agricultural soils. This is expected as the moisture limitations inhibit the functioning of the methanotrophic community in the soil, which in turn affects the CH_4 fluxes in the soil (Barton, Murphy & Butterbach-Bahl, 2013; IPCC, 2006).

- LCI Worksheet

Once inventories for inputs and outputs for 2010 and 2011 were developed, the final worksheet namely the ***Inventory List*** (LCI 2010–11) worksheet was compiled. In this worksheet all the calculated values for the paddocks of the farmer, for both planting cycles (2010 and 2011), were summarised for ease of use under the following category headings:

- Chemical production and use
- Soil emissions
- Grazing emissions
- Stubble burn emissions
- Farm machinery and
- Transport of chemicals.

All GHG emissions summarised here were linked to each appropriate database worksheet of the inventory which also enabled automatic updating, and where necessary, each emission category was expanded (classification process) to include more extensive details as documented in the following text and illustrated in Figure 3.16.

- Chemical production and use

  This section classified the chemicals into fertilisers, fungicides and insecticides, adjuvants, herbicides and lime. For each of these classes the individual chemicals used were listed (e.g. for fertilisers Dap Extra, urea and Agstar Extra) and the quantity used stated in kg/yr/t. All calculated values were obtained from the LCI 2010 and LCI 2011 worksheets.

- Soil emissions

  Soil emissions were classified as either DSE or ISE and the values were imported from the inventory 2010 and inventory 2011 worksheets.

- Grazing emissions

  In this category the CH_4 emissions from enteric CH_4 and the CH_4 emissions from manure were quantified as kg/t/ha. These emissions were calculated in the Inventory 2010 and 2011 worksheets.

- Stubble burn emissions

  This category included the GHG emissions resulting from windrow or full paddock burning, that were extracted from the LCI 2010 and LCI 2011 worksheet as kg/t/ha.

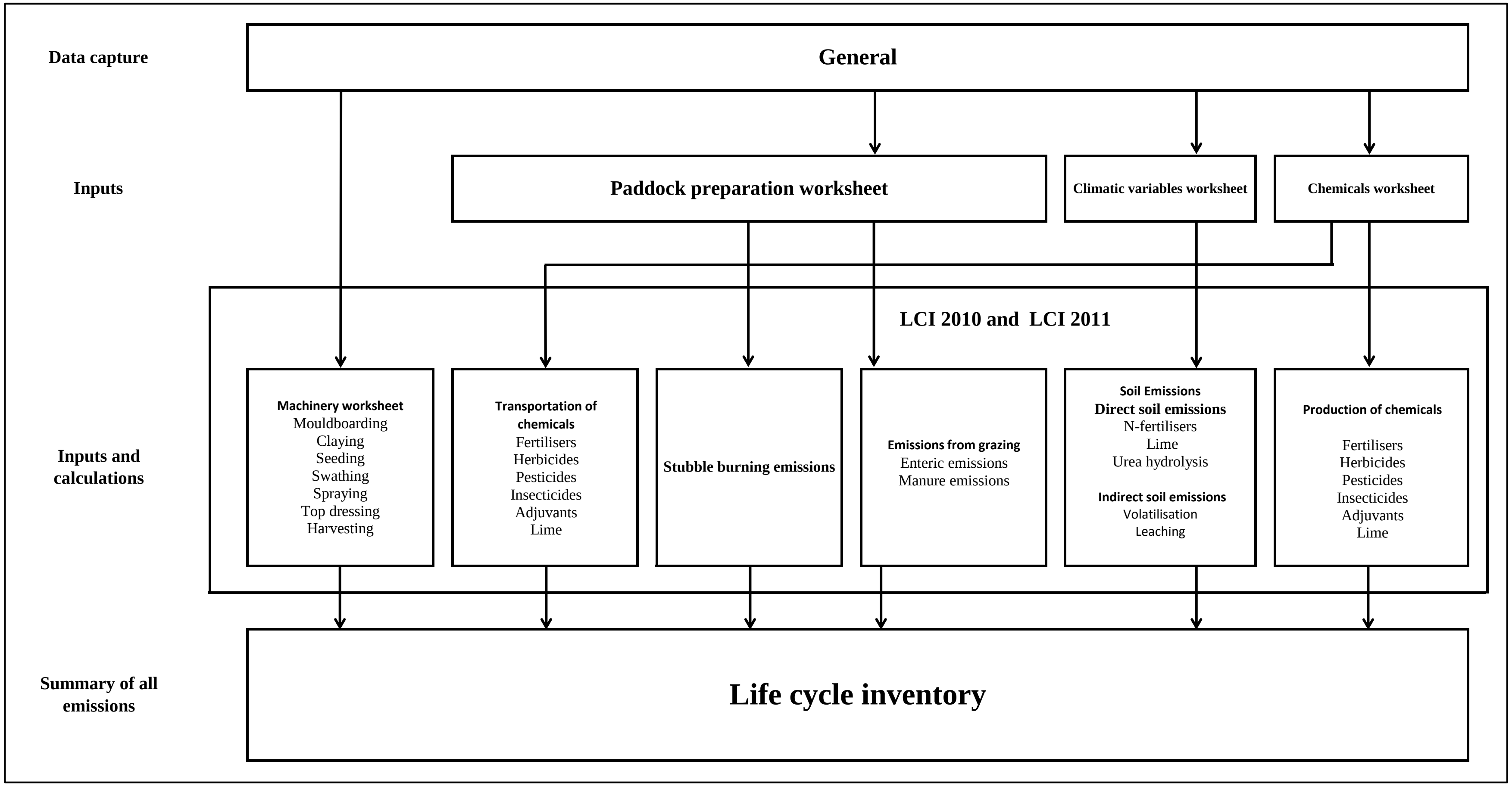


Figure 3.16. Illustration of the linkages between the Excel databases to calculate the LCI

- Farm machinery

  This section of the inventory list was linked to the machinery database worksheet and listed the machinery used. The cost of the machinery (USD/tonne) and the machinery fuel use (l/hr/tonne) were calculated in the farm machinery worksheet and extracted from this worksheet for use in other worksheets.

- Transport of chemicals

  Each of the chemicals were first identified and listed as a fertiliser, fungicide and insecticide, adjuvant, herbicide or lime, and then the tkm/t was extracted from the Inventory 2010 and Inventory 2011 worksheets.

To finalise all calculations in the LCI, the input and output data were divided by yield of the crop, as the functional unit of this GHG analysis is one tonne of grain production. After finalising the LCI the calculated values were used to initiate the LCIA.

3.3.2.3 Life cycle impact assessment

All calculations were completed in the same LCI workbook by adding worksheets specifically for the LCIA. This section initially lists all the workbooks, then discusses the data and calculations in each workbook and finally an example is used to demonstrate the process. Figure 3.17 illustrates the LCIA worksheets (listed below), in Excel, for each farm.

- EF_Chem (emission factors for chemicals)
- ConvCalcs (conversion calculations)
- ConvFactors (conversion factors)
- ChemConv10_11 (chemical conversions 2010 and 2011)
- CalcEquiv10 (calculated equivalents 2010)
- CalcEquiv11 (calculated equivalents 2011)
- CF (carbon footprint)

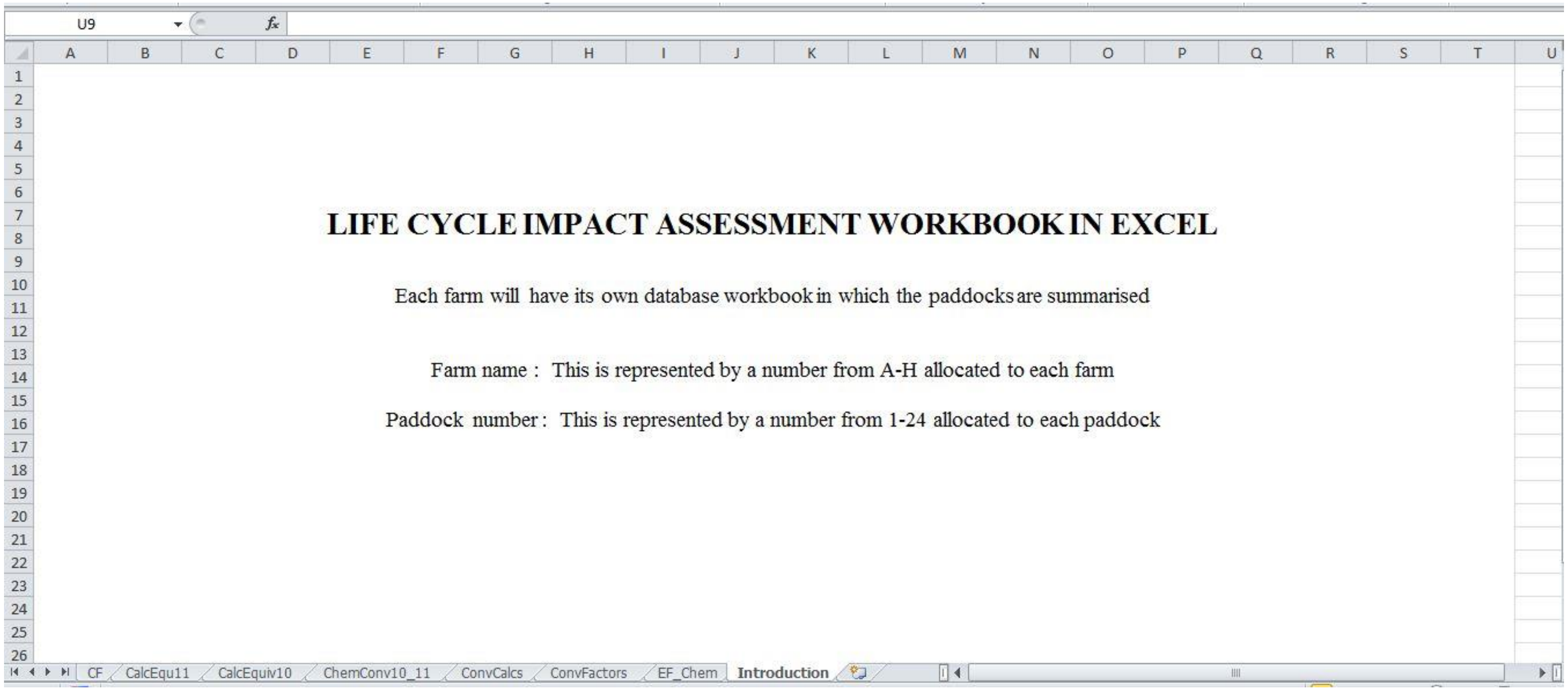


Figure 3.17. Example of LCIA workbook for each farm created in Excel

The calculations applicable to the LCIA phase were broadly divided into two groups: 1) those required for converting chemicals for which the Australian emission factors were not known to chemicals with known Australian emission factors, 2) the calculation of the total gases produced in each input/output/process and the conversion of these gases to kilogram CO_2 equivalents (kg CO_2-e), using the following equation (**Equation 3.23**) (Forster et al., 2007).

$$\mathbf{CO_2\text{-e}} = (\boldsymbol{GWP_{CO_2}} \text{ x } \mathbf{CO_2e}) + (\boldsymbol{GWP_{N_2O}} \times \mathbf{NO_2e}) + (\boldsymbol{GWP_{CH_4}} \times \mathbf{CH_4}\boldsymbol{e}) \quad \textbf{Equation 3.23}$$

Where, 'GWP_{CO2}' is 1, 'GWP_{N2O}' is 298, 'GWP_{CH4}' is 25 for a 100 year time horizon, CO_2-e is carbon dioxide equivalents, N_2O-e is nitrous oxide equivalents and CH_4-e is methane equivalents. The GWP of non-CO_2 gas was considered for a 100 year time horizon as this is commonly used (Biswas et al., 2011; Barton et al., 2014, Solomon et al., 2007).

- Conversion of chemicals worksheets

To calculate the emissions resulting from the production and use of chemicals, which included insecticides, pesticides, fertilisers, fungicides, adjuvants, lime and herbicides, the unit process emission factor database or library for Australian Agriculture (RMIT, 2007) was used. Currently the emissions factors for all different brands of chemicals used in Australia have not been determined or documented in this database, and thus surrogate values were required. An alternative emission factor was sourced for each of these chemicals and on this basis all chemicals were converted to one generic chemical, per chemical category, for which an emission factor was sourced (pers. comm., Hashem, DAFWA, Northam, Western Australia). The LCIA worksheets applicable to this section include the conversion of chemicals to an equivalent chemical (EF_Chem), conversion factor (ConvFactors), conversions calculations (ConvCalcs) and chemical conversions (ChemConv10_11) worksheets.

The following steps and the flowchart (Figure 3.18) outline the process and thereafter an example is used to demonstrate the calculations.

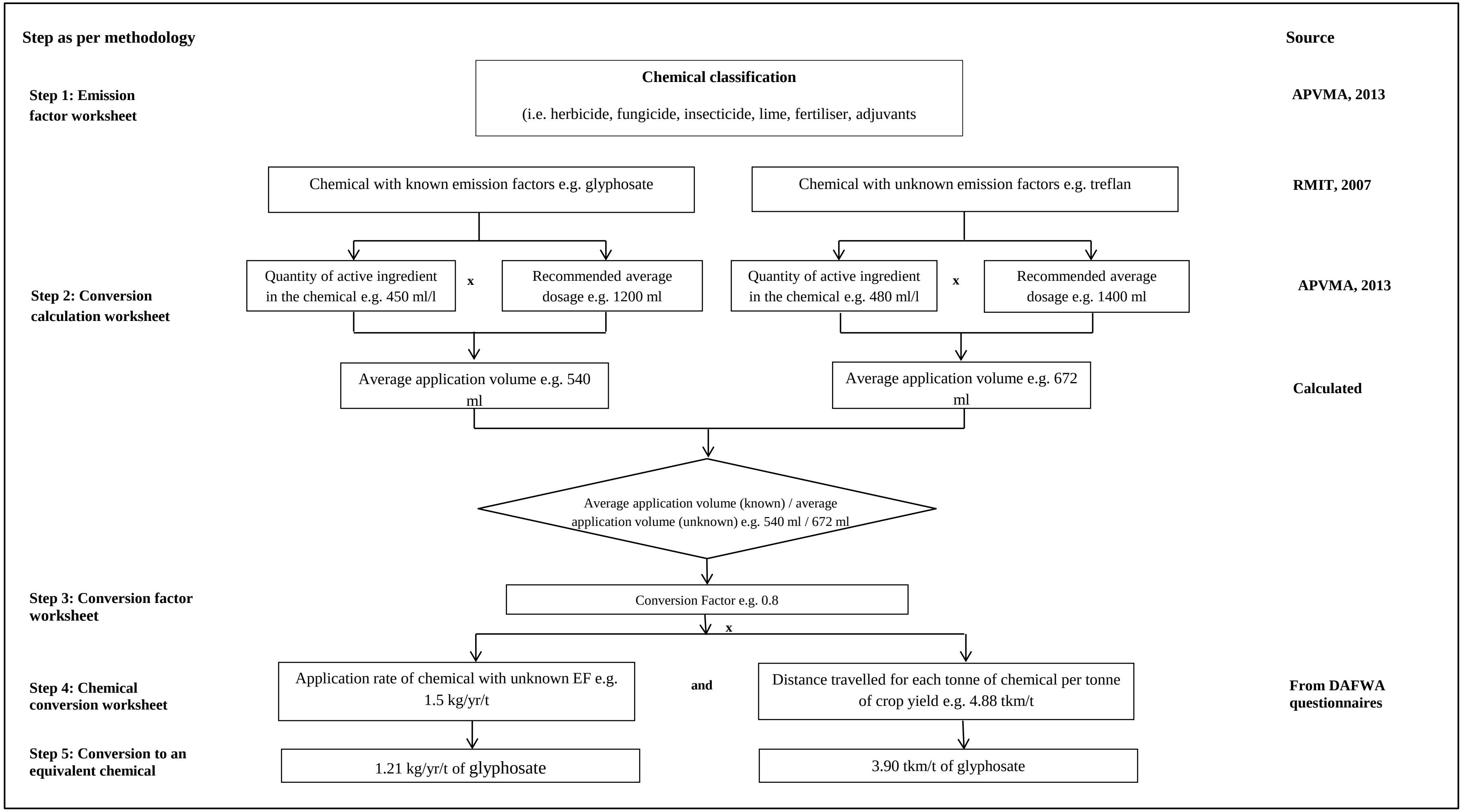


Figure 3.18. Steps showing the conversion of the chemical used to an equivalent chemical

Step 1) The '***EFChem' worksheet*** (emission factor for chemicals worksheet) lists all of the chemicals used for all paddocks for the agricultural period 2010–11. The chemicals were classified as herbicide, fertiliser, fungicide, insecticide, adjuvant or lime using the MSDS from the APVMA website (APVMA, 2013). One chemical, termed generic chemical here, was identified for each classification and thereafter the existing Australian emission factors were extracted from the unit process emission database of Australian Agriculture (RMIT, 2007) library. Table 3.3 illustrates the chemical classes, the generic equivalents and the applicable emission factors. The full list of the classified chemicals can be found in Appendix E.

Table 3.3 Chemical category, generic equivalent and GHG emission factors (RMIT, 2007)

Chemical category	Generic equivalent	CO_2 emission factor	N_2O emission factor	CH_4 emission factor
Adjuvant	Ammonium sulphate	3.91×10^{-1}	4.54×10^{-6}	4.66×10^{-7}
Herbicide	Glyphosate	8.68	8.61×10^{-5}	9.96×10^{-3}
Fungicide	Bifenthrin	1.37×10^{-2}	1.27×10^{-6}	1.99×10^{-7}
Insecticide	Bifenthrin	1.37×10^{-2}	1.27×10^{-6}	1.99×10^{-7}
Lime	Lime	1.69×10^{-2}	0	0
Fertiliser	Urea	8.42×10^{-1}	0	0

Step 2) The '***ConvCalc' worksheet*** (chemical conversion calculations worksheet) lists each chemical under a classification heading (e.g. fertiliser, adjuvant, herbicide, pesticide, insecticide and lime). The active ingredient/s and the amount present in the chemical were found on the MSDS and labels of the chemicals (summary in Appendix E). Furthermore the optimal dosage ranges for Western Australia were extracted from either the label or MSDS, and using the minimum and maximum recommended dosages a mean range was calculated for each chemical. Thereafter a 'chemical equivalent value' was determined using the formula, mean range x recommended dosage. These calculations were completed for the generic equivalent (ammonium sulphate, glyphosate, bifenthrin, lime and urea) for each category. It should be noted that the LCA considers not only the emissions from the production of active ingredients, but also the emissions from inactive ingredients which are

combined with the active ingredients to form inputs for the production of one tonne of grain.

Step 3) After calculating a conversion factor for all chemicals from all categories, all chemicals used were listed alphabetically with the applicable conversion factors in the '***ConvFactor***' (conversion factor) ***worksheet*** and linked to the '***ConvCalc***' (conversion calculation) ***worksheet*** for automatic updating.

Step 4) The '***ChemConv10_11' worksheet*** (chemical conversion 2010 and 2011) classifies and lists the chemicals for each paddock and each year. A link was established with the 'LCI' (inventory list) worksheet to import the calculated quantity of the chemical used per year per tonne of crop yield (kg/yr/t). Using this quantity the original chemical was converted to a generic chemical by applying the conversion factor as calculated in the '***ConvFactor'*** (conversion factor) ***worksheet*** (chemical usage x conversion factor). The same process was repeated for the transportation of each chemical using the value for the distance travelled for each tonne of chemical per tonne of crop yield (tkm/t) (tkm/t x conversion factor).

An example as illustrated in Figure 3.18 is shown below:

For the herbicide treflan (trifluralin) there were no emission factors, however the emission factors for the herbicide glyphosate 450 (8.68 for CO_2, 8.61 x 10^{-5} for N_2O and 9.96 x 10^{-3} for CH_4) were documented and sourced from the Australian databases (emissions factor worksheet).

Using the quantity of the active ingredient, glyphosate (450 ml/l) and the average dosage of 1200 ml (based on a dosage range of 800–1600 ml) as recommended for Western Australia, an equivalent application volume for glyphosate was calculated as 540 ml (450 ml/l x 1.2 l). Thereafter the same process was followed for the chemical Treflan (active ingredient trifluralin). The quantity of active ingredient in Treflan is 480 ml/l with a recommended average dosage of 1400 ml (dosage range of 800–2000 ml for Western Australia). The application volume calculated was 672 ml (480 ml/l x 1.4 l) (conversion calculations worksheet).

In this step the conversion factor was calculated using the formula application rate of glyphosate / application rate of Treflan = 0.80 (540 ml / 672 ml, or equivalent chemical / chemical to be converted) (Conversion calculations worksheet). All conversion factors were summarised alphabetically in a worksheet named '***Conversion Factors'***.

Finally the chemical (Treflan) was converted to the equivalent amount of glyphosate by multiplying the conversion factor with the actual application rate (e.g. 1.50 kg/yr/tonne x 0.8) or the distance the chemicals were transported (e.g. 4.88 tkm/tonne x 0.8) (conversion calculations worksheet).

- Worksheets for converting input-output data to GHG emissions

Following the conversion of the chemicals to a generic equivalent, all data was prepared for the calculation of the GHGs. Three worksheets were generated within the Excel workbook for these calculations, namely ***'CalcEquiv10'*** (calculated equivalents 2010), ***'CalcEquiv11'*** (calculated equivalents 2011), and ***'CF'*** (carbon footprint).

The following steps outline the process followed based on the flow diagram in Figure 3.19, and are thereafter discussed in more detail.

Step 1: The inventory list compiled in the LCI and the '***Conversion10_11***' (conversion 2010 and 2011) worksheet served as the starting point for the calculations.

Step 2: Two worksheets named '***Calculated equivalents 2010***' and '***Calculated equivalents 2011***' were generated for the calculation of the CO_2-e for each input and output.

Step 3: For each entity listed under the classifications (i.e. chemicals, soil emissions, stubble burn emissions, grazing emissions, farm machinery and transportation), emission factors were sourced for CO_2, N_2O and CH_4.

Step 4: Each input/output was multiplied by the respective emission factors to calculate the quantity of the GHG generated.

Step 5: The quantity of GHG was converted to its equivalent amount of CO_2-e by multiplying with the respective GWP (1, 298 and 25 for CO_2, N_2O and CH_4, respectively) (IPCC, 2007a).

Step 6: The CO_2-e were summed to determine the overall carbon footprint for the input/output.

Step 7: Where relevant the CO_2-e were summed to find an overall total for each classification.

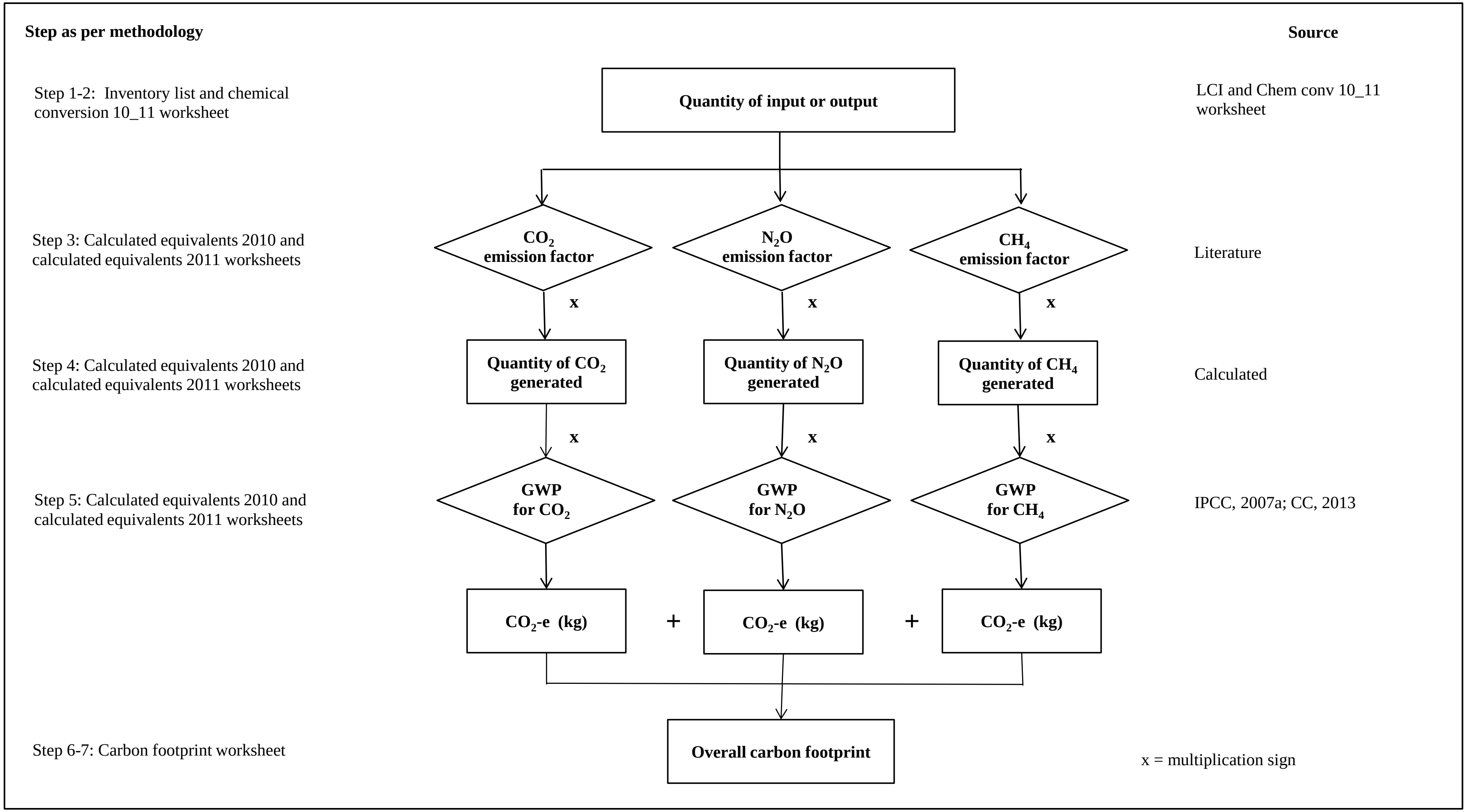


Figure 3.19. Flowchart showing the steps to calculate the GHGs from data originating in the LCI

In the '***CalcEquiv10'*** (calculated equivalents 2010) and ***'CalcEquiv11'*** (calculated equivalents 2011) worksheets, all classifications and categories were included for the final calculations to be performed, separately for each year. The 'quantity of GHG emissions released per tonne of crop yield' values were imported from the chemical conversion 2010 and 2011 (***ChemConv10_11***) worksheet for chemical production and use and chemical transportation, and from the inventory list worksheet (LCI) for soil emissions, stubble burning, grazing emissions and farm machinery emissions (Steps 1, 2 and 3 in Figure 3.19). In step 4 the amount of inputs were multiplied by GHG emission factor for estimating the CO_2, N_2O and CH_4 emissions associated with the production and use of these inputs. For example: quantity of GHG emissions released from the production and use of a chemical per tonne of crop yield (kg/yr/t) x emission factor of CO_2, or N_2O or CH_4 per kg of chemical = calculated CO_2 or N_2O or CH_4 emissions (kg/yr/t).

These emission factors for each GHG were sourced from the Unit Process Life Cycle Inventory for Australian Agriculture (RMIT, 2007) in Simapro 7.33. The individually calculated GHG emissions were then converted to equivalent CO_2 (CO_2-e) values by multiplying with the GWP (**Equation 3.24**) (1, 298 and 25 for CO_2, N_2O and CH_4, respectively) (IPCC, 2006), and then summed to determine the final CO_2-e (Steps 5, 6 and 7) (**Equation 3.24**).

$$\boldsymbol{CO_2echem = (D_{chem} \times CO_2EF_{chem} \times GWP_{CO2}) + (D_{chem} \times N_2OEF_{chem} \times GWP_{N2O}) + (D_{chem} \times CH_4EF_{chem} \times GWP_{CH4})} \qquad \textbf{Equation 3.24}$$

Where 'CO_2echem' is the carbon dioxide equivalent (kg CO_2-e/yr/t) for chemical dosage, 'D_{chem}' is the dosage of the chemical (kg/yr/t), 'EF_{chem}'is the emissions factor of CO_2, N_2O or CH_4 (kg/yr/t) by which it is preceded and 'GWP' is the GWP of CO_2 = 1, N_2O = 298 and CH_4=1.

For example: If 2 kg of glyphosate was used per tonne of yield in 2010 the CO_2-e emitted would be:

CO_2-e = (2 kg/yr/t x 8.68 kg/yr/t x 1) + 2 kg/yr/t x 8.61 kg/yr/t x 10^{-5} kg/yr/t x 298) + 2 kg/yr/t x 9.96 x 10^{-3} kg/yr/t x 25) = 17.91 kg CO_2-e/yr/t.

Soil emissions as stipulated previously (Section 3.3.2.2) included the direct and indirect emissions of CO_2, N_2O and CH_4 from the paddock soil. The GHG emissions from soil were converted to CO_2-e. The GHG emission factors for both direct and ISE were 3.67, 1.57 and 1.33 for CO_2, N_2O and CH_4 respectively (RMIT, 2007).

The emissions resulting from the *burning of stubble, grazing and stubble decomposition* were calculated in the paddock preparation (**PadPrep**) worksheet and the emission factors were applied there. Thereafter the calculated values for stubble burn and grazing were imported into the inventory list database worksheet. Stubble decomposition values were calculated in the paddock preparation worksheet. The GHG emissions per tonne of crop yield (kg/yr/t) due to stubble burning and grazing emissions, which were summarised in the inventory list, were extracted for further manipulation in the calculated equivalents 2010 and 2011 worksheets, where the GWP was used to calculate the CO_2-e for both grazing and burning. Within each of these categories the final total was the sum of all the CO_2-e values.

The category *farm machinery* required the calculation of the CO_2-e in terms of the cost of machinery (USD/t) as well as the fuel usage. The GHG emission factors used for these calculations are tabulated below (Table 3.4).

Table 3.4. GHG emission factors for the cost of machinery and fuel use of machinery (RMIT, 2007)

	Emission factor for CO_2	**Emission factor for N_2O**	**Emission factor for CH_4**
Cost of machinery (1998 price) USD/t	8.47×10^{-1}	2.89×10^{-5}	2.74×10^{-3}
Fuel use l/hr/t	2.50	1.09×10^{-4}	1.90×10^{-3}

The final set of calculations required for calculating CO_2-e, were for the *transportation of chemicals*. In transporting chemicals, where relevant, both national and international portions of travel were considered and the GHG emission factors for each portion applied (Table 3.5). For example, the fertiliser 'urea', was imported from Asia to Kwinana in Western Australia and from there to 'Farmer A' in the Liebe group area. The total distance from Asia to Kwinana was 10,056 km and the distances from Dalwallinu and finally to the farm was 235 km and 18.4 km, respectively. Hence, the international portion of travel was 10 056 km to the national portion of 252.4 or a ratio of 97.5 : 2.5

Table 3.5. National and international GHG emission factors for transportation of chemicals (Barton et al., 2014)

	Emission factor for CO_2	Emission factor for N_2O	Emission factor for CH_4
International portion	3.40×10^{-3}	2.00×10^{-5}	0.00
National portion	1.00×10^{-1}	1.64×10^{-6}	6.70×10^{-5}

The final worksheet, ***Carbon footprint***, aggregated and summarised all the calculated CO_2-e as either a pre-farm or on-farm emission. These categories were in some instances separated into classes and sub-classes as listed below:

- Pre-farm emissions
  - Chemical production emissions
    - Fertilisers
    - Fungicides and pesticides
    - Herbicides
    - Adjuvants
    - Lime
  - Farm machinery production emissions
  - Transportation of fertilisers emissions
  - Transportation of chemicals emissions
- On-farm emissions
  - Farm machinery operation
  - Stubble burning emissions
  - Grazing emissions
    - Enteric emissions
    - Excreta emissions
  - Direct soil emissions
    - CO_2 urea hydrolysis
    - CO_2 liming
    - N_2O from fertiliser
  - CH_4 from soil

- Indirect soil emissions
    - N_2O from leaching
    - N_2O from volatilisation

Using these categories, the sub-total for pre-farm and on-farm emissions for kg CO_2-e were obtained giving the carbon footprint for each paddock for the year for both the pre-farm and on-farm stages. Finally the total kg CO_2-e and the overall carbon footprints were obtained by summing the pre-farm and on-farm emissions for each paddock for each year. The breakdown of CO_2-e GHG emissions in terms of inputs and outputs, listed above, helped identify the hotspots requiring appropriate GHG mitigation strategies.

3.3.2.4 Interpretation

The interpretation phase of the GHG analysis will be concluded in Chapter 5 using only the LCIA results. In this chapter the hotspots, or in other words the inputs/outputs causing the significant portion of the total GHG emissions, will be identified. The 'hotspots' are described by utilising the LCI data in Chapter 4. Further interpretation and applicability of the IST will be finalised in Chapter 6, by incorporating the results of the LCIA with the results obtained during the integration of the LCIA with RS and GIS, obtained during the integration of the tools. In essence, the IST (Chapter 6) will be the interpretation phase of the LCIA results in terms of image representation. The LCIA results from Chapter 5 and the images generated in Chapter 6 form a whole and are not separable when using the IST, however, they are separated into two chapters to enable the reader to understand the different components of the IST and how they are linked to each other. The interpretation of the results will be finalised in Chapter 7 when mitigation measures using CP methods are recommended.

3.3.3 Geographical information systems

Data integration included RS applications, the calculation of CPs using an LCA approach and the generation of maps and images in GIS.

After the LCA was completed, the data were considered to be ready for the development of the envisaged images in a GIS software package. The software used was ArcMap 10.2 (part of ArcGIS 10.2, and hereafter referred to as ArcMap) (ArcGIS, 2013). The following steps were followed to present the GHG emissions for grain production in order to enable farmers to adopt GHG mitigation strategies for a particular geographical location in Western Australia.

Step 1: Uploading RS images and importing a map of Australia.

Step 2: Identification and demarcation of the paddocks.

Step 3: Identification of fixed variables – soil types, temperature, Et, precipitation.

Step 4: Importing/uploading tables of region-specific GHG emissions for grain production from Excel spread sheet as discussed in the previous section.

Step 5: Creation of output images.

3.3.3.1 Mapping the study area

As the project study area had previously been identified as south-western Australia, an outline map for Australia clearly showing Western Australia was obtained from the GIS Department of the Commonwealth Scientifc and Industrial Research Organisation (CSIRO). This map had previously been saved as a shapefile and could thus be imported into the ArcMap software application for immediate use. The map was georeferenced as the Australia and New Zealand, Geocentric Datum of Australia (GDA), 1994. Thereafter, the two tables (one for the Liebe group and the other for WANTFA as specified in Sections 3.3.3.4) containing the farmer identification, paddock and co-ordinate data in Excel files, were imported to GIS. By importing these data the locations of the 144 allocated paddocks appeared on the map of Western Australia as small points (enclosed by the red circle in Figure 3.20).

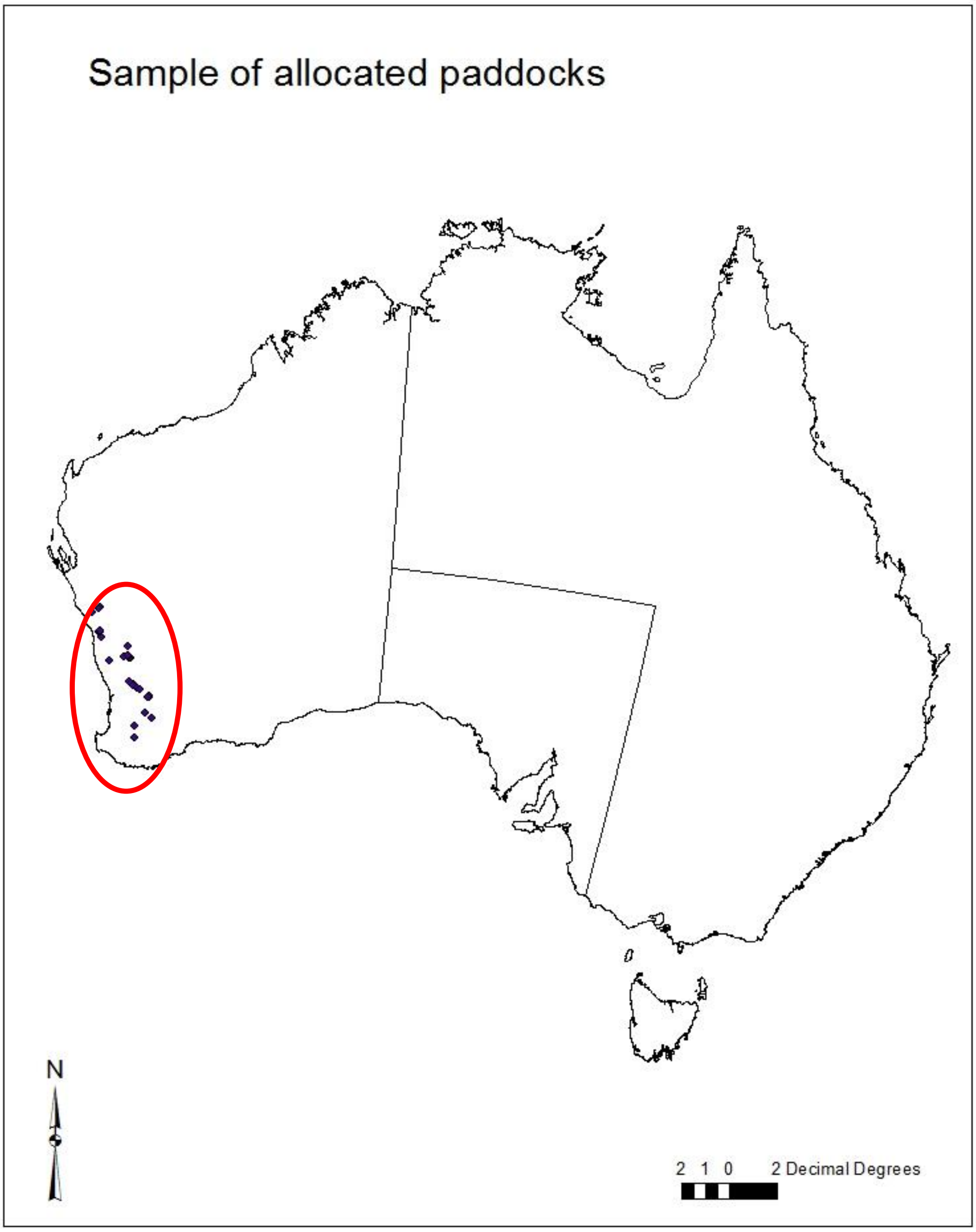


Figure 3.20. Map of Western Australia showing the location of the sampled paddocks

Following the generation of this map, the previously pre-processed satellite images were both imported into the same ArcMap file. The image created showed that all of the allocated paddocks did not fall within the boundaries of these satellite images. Figure 3.21 shows an enlarged representation of the map created. The paddocks are evident as dark markers scattered throughout the map of Western Australia and the satellite images are the coloured rectangles in the map.

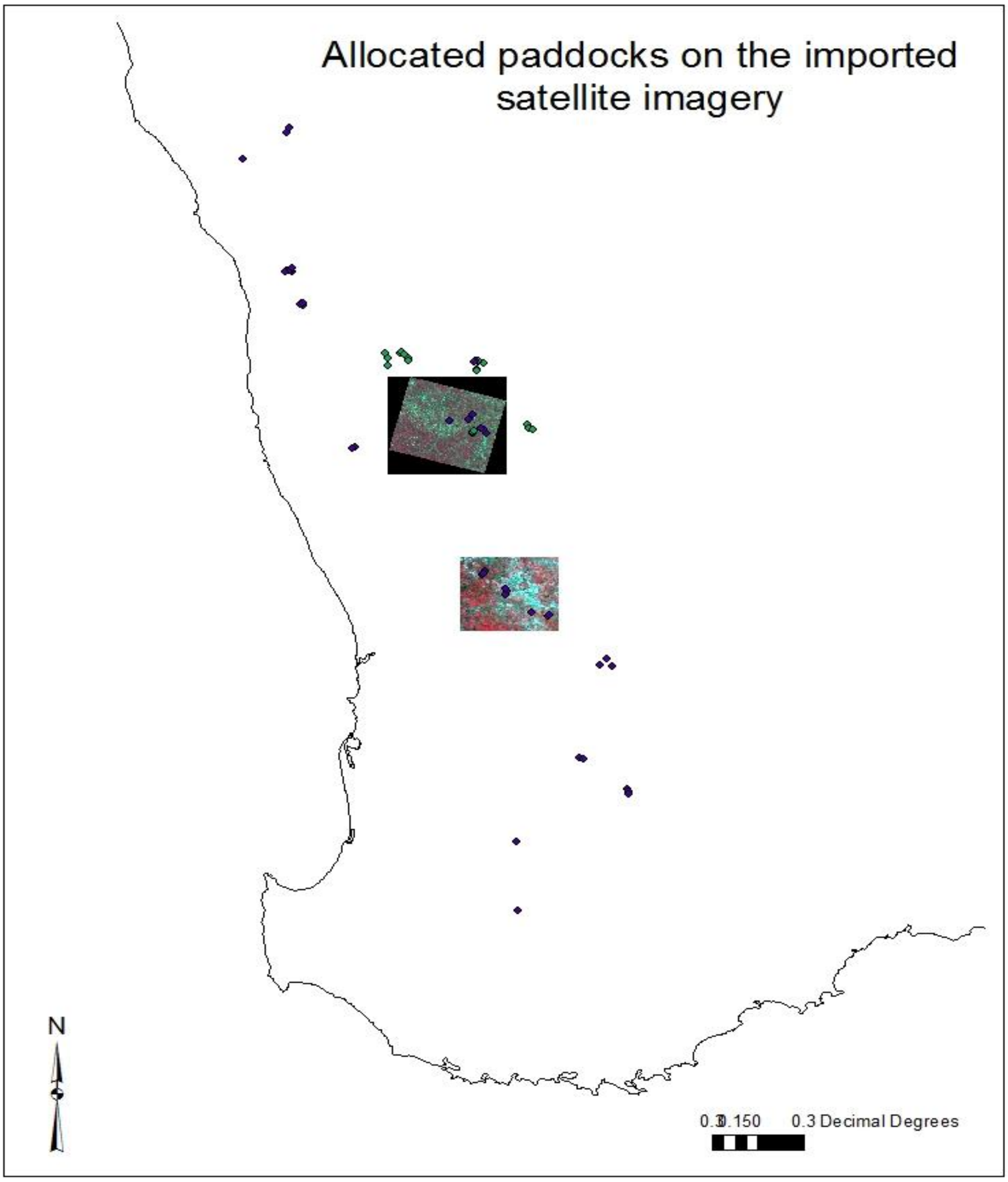


Figure 3.21. Map of Western Australia with the satellite imagery superimposed, showing the location of the sampled paddocks

In Figure 3.22 and Figure 3.23 the study area was enlarged even more to eliminate the area surrounding the satellite images and show only the co-ordinates falling within, or in close proximity to, the satellite image boundaries. The point markers were changed to yellow and the symbol size increased to enable easier identification. The labelling option (in ArcMap) was then selected to enable each paddock to be numbered according to the pre-allocated numbers (Section 3.2.2). Two new tables were created in Excel with the data for only those paddocks falling within the satellite image boundaries. These paddocks were then used for further applications and integration.

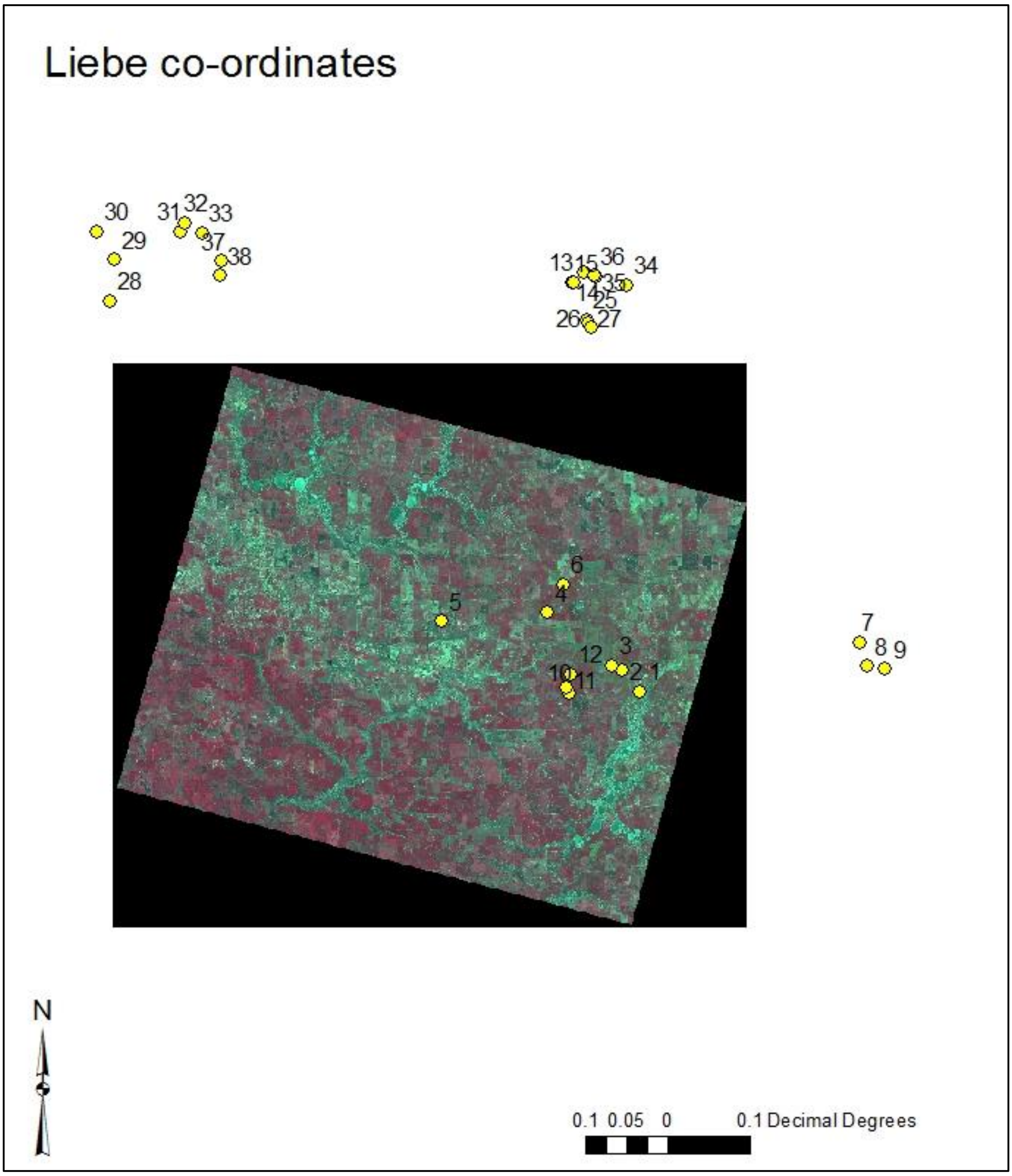


Figure 3.22. Liebe group paddock co-ordinates on the enlarged SPOT satellite image

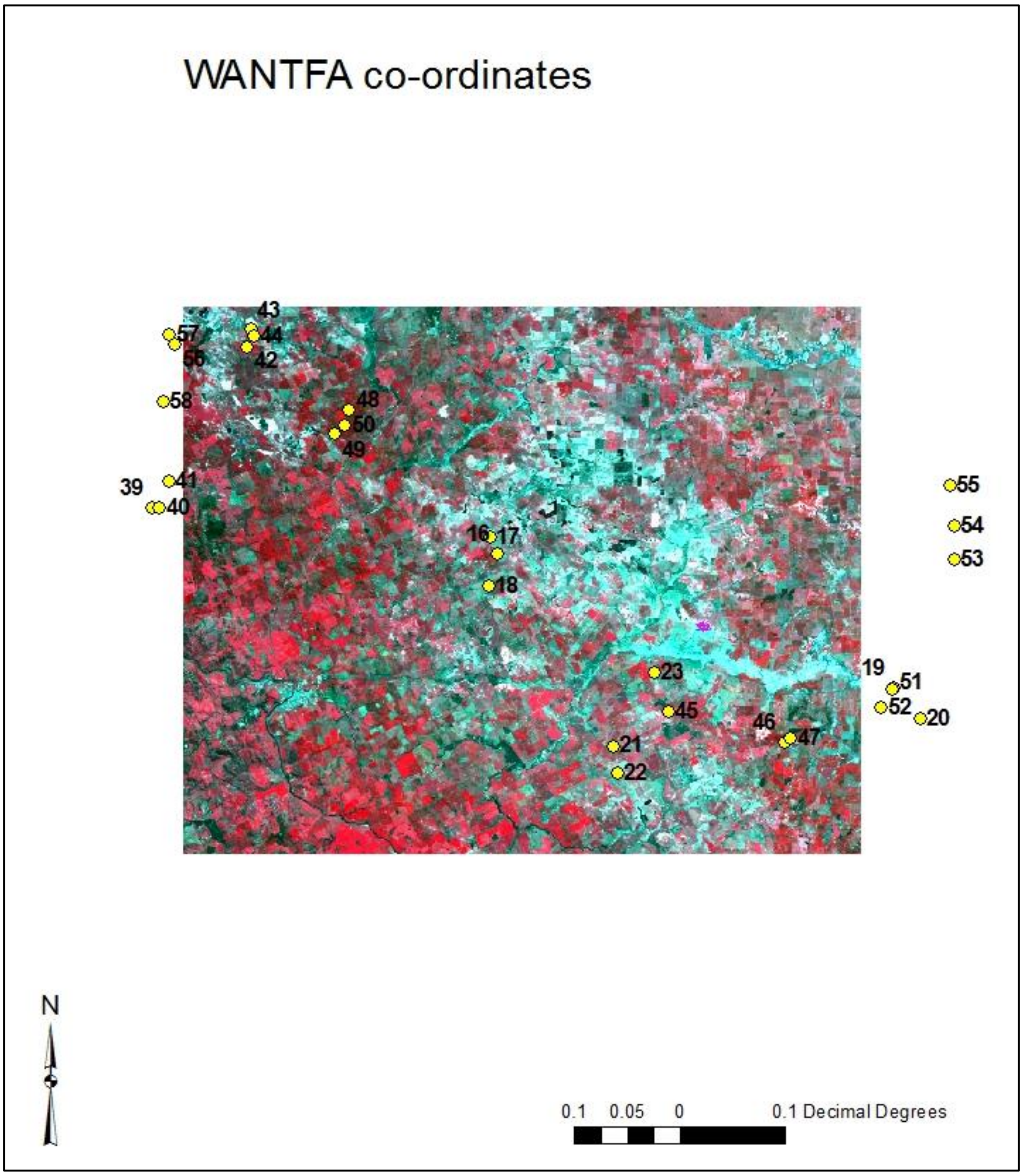


Figure 3.23. WANTFA paddock co-ordinates on the enlarged Deimos satellite image

3.3.3.2 Demarcating the paddocks

The demarcation of the paddock boundaries was initiated by enlarging Figure 3.22 and Figure 3.23 until the natural boundaries for each of the paddocks was identifiable. Using the editing and polygon construction tools in ArcMap, the visible boundary area in the satellite image was enclosed with a polygon. The colour of the polygon was changed for easier detection and saved firstly as a shapefile and then as an individual layer. The process was repeated individually for each paddock, generating 24 layers and 24 shapefiles for 24 paddocks. Figure 3.24 is an illustration of three of the 24 paddocks that have been enlarged and demarcated.

Figure 3.24. Enlarged satellite image showing the demarcated area of three paddocks

Figure 3.25 and Figure 3.26 represent the Liebe group and WANTFA areas after the polygon area had been demarcated. Each of these figures was saved as a layer file in ArcMap.

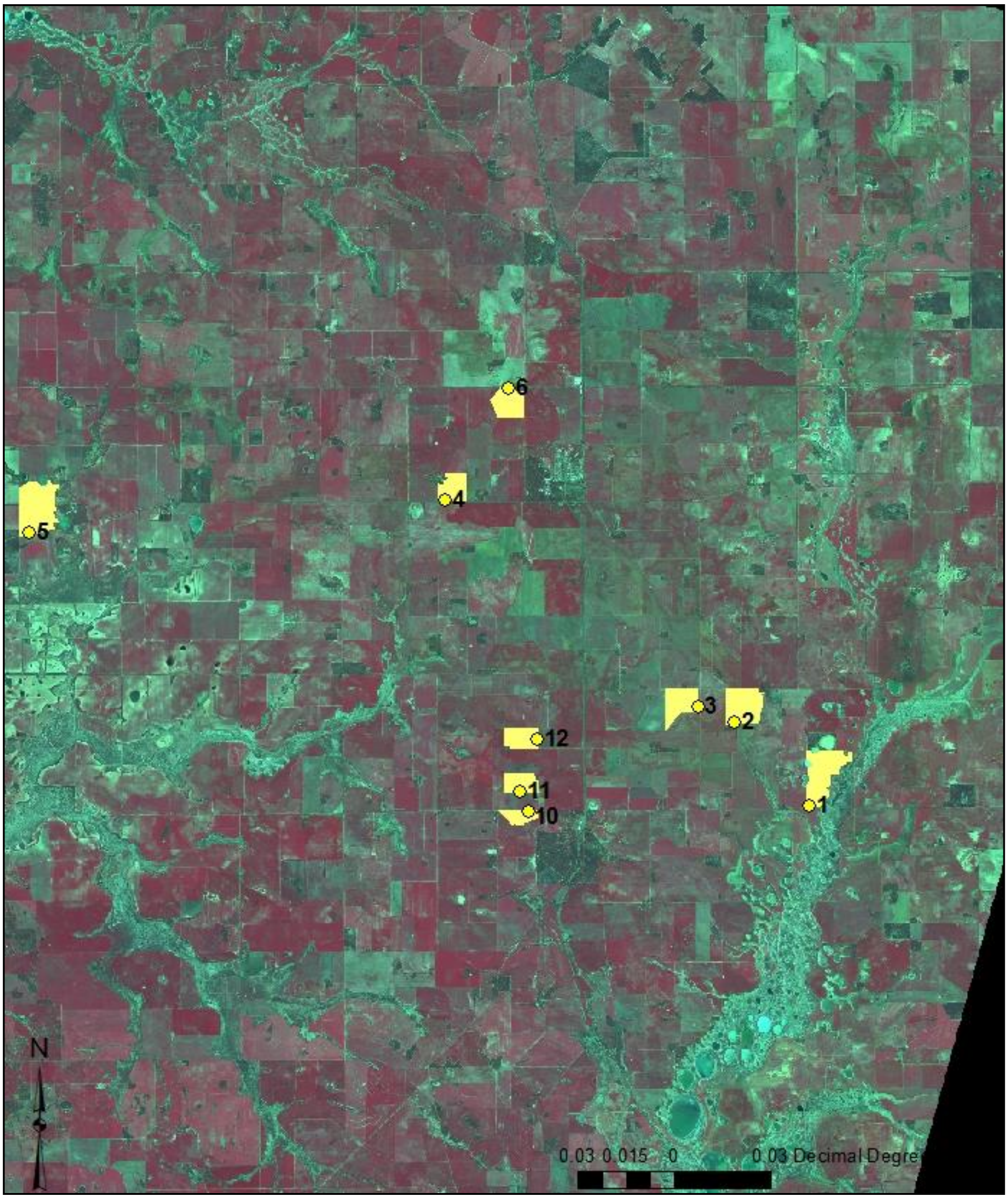


Figure 3.25. The demarcated paddocks from the Liebe group region

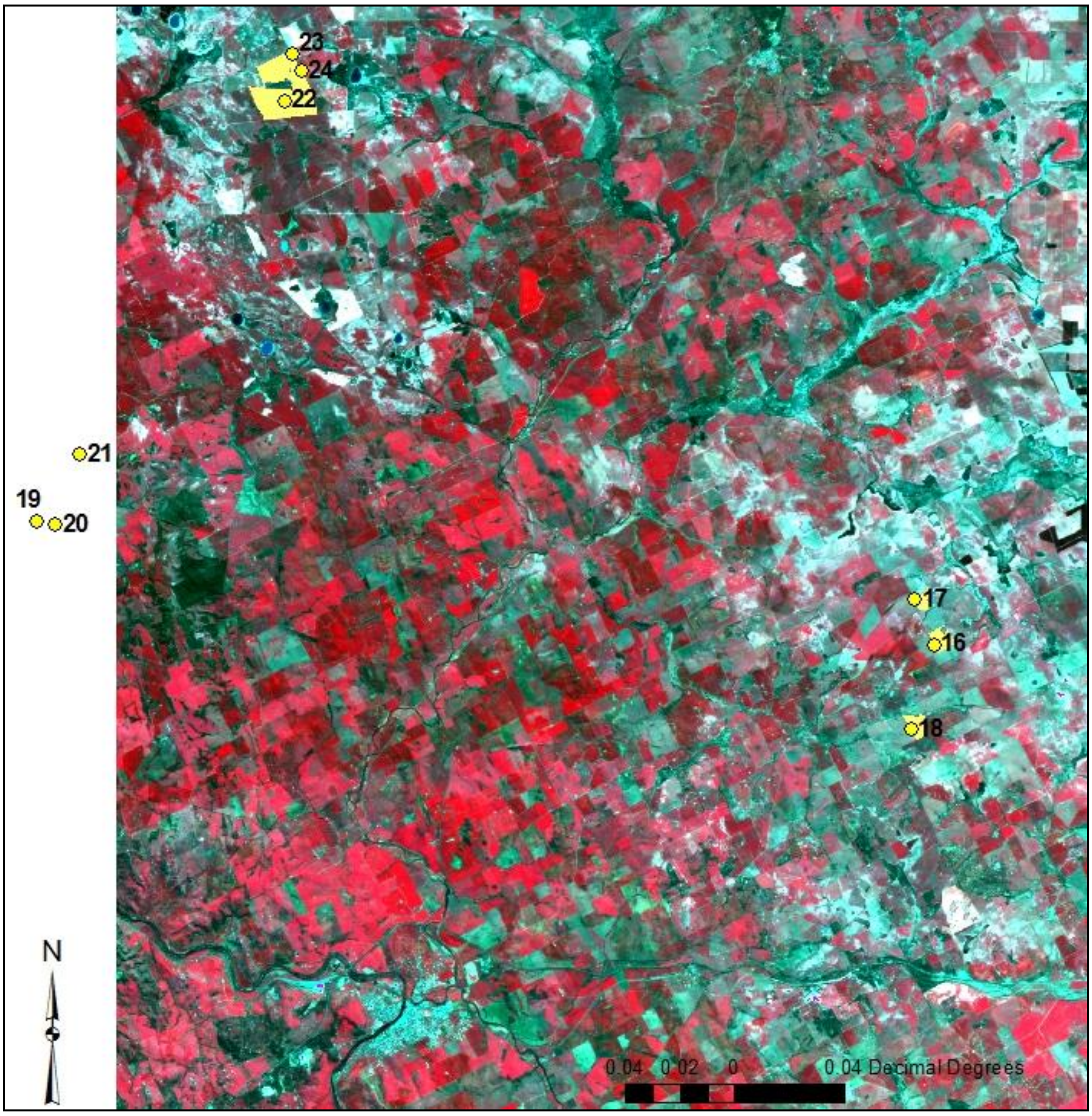


Figure 3.26. The demarcated paddocks from the WANTFA region

3.3.3.3 Importing fixed variables

As the IST focuses on the influence of soil types, temperature, precipitation and Et on FMPs, shapefiles[14] were required for these climatic variables. The metadata for the soil types were obtained from the GIS department of CSIRO and shapefiles for other variables were downloaded from the BOM website (BOM, 2013). All of these files were stored on a computer before uploading onto ArcMap.

After uploading the abovementioned shapefiles, the individual shapefiles containing the Liebe group and WANTFA co-ordinates to be used were converted to layers and superimposed on each of these shapefiles. This resulted in the maps shown in Figures 3.27–3.30 (labelled ‘a’). For clearer identification of the location of the paddock markers within the contour lines, the individual maps were enlarged (Figures 3.27–3.30, ‘b’). The positioning of the marker and the contour lines were then compared with the maps generated by BOM (Figures 3.27–3.30, marked ‘c’) to determine the values for the average annual precipitation, temperatures and Et. All of these variables were considered when performing the LCA-type analysis (Section 3.4.2).

[14] A shapefile stores non-topological geometry and attribute information for the spatial features in a data set. The geometry for a feature is stored as a shape comprising a set of vector coordinates. Shapefiles handle single features that overlap or that are non-contiguous. Shapefiles can support point, line, and area features (ESRI, 1998; ArcGIS, 2014).

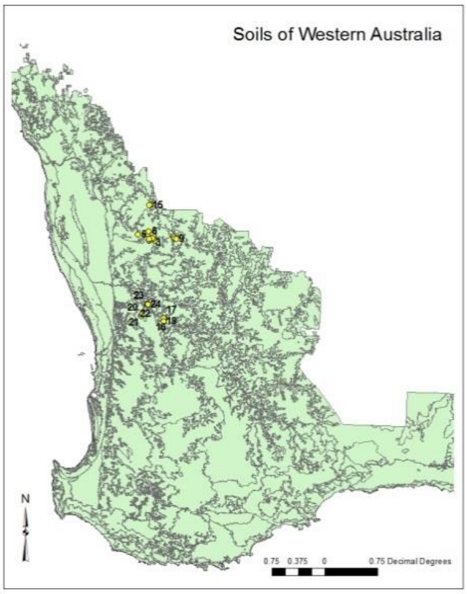


Figure 3.27 a). Map showing the soils of Western Australia and the paddock locations

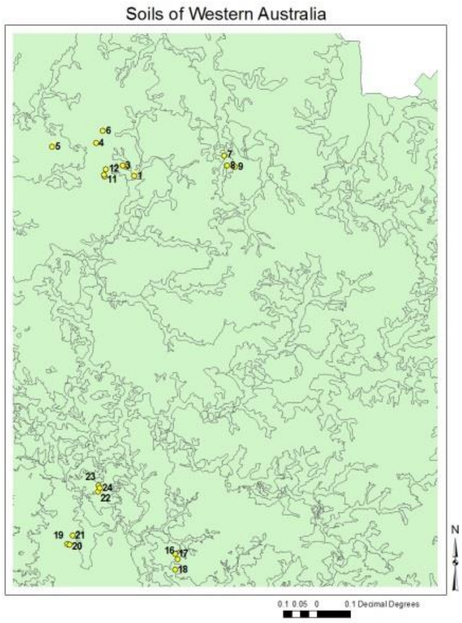


Figure 3.27b). Enlarged area of the map showing the soils of Western Australia and the paddock locations

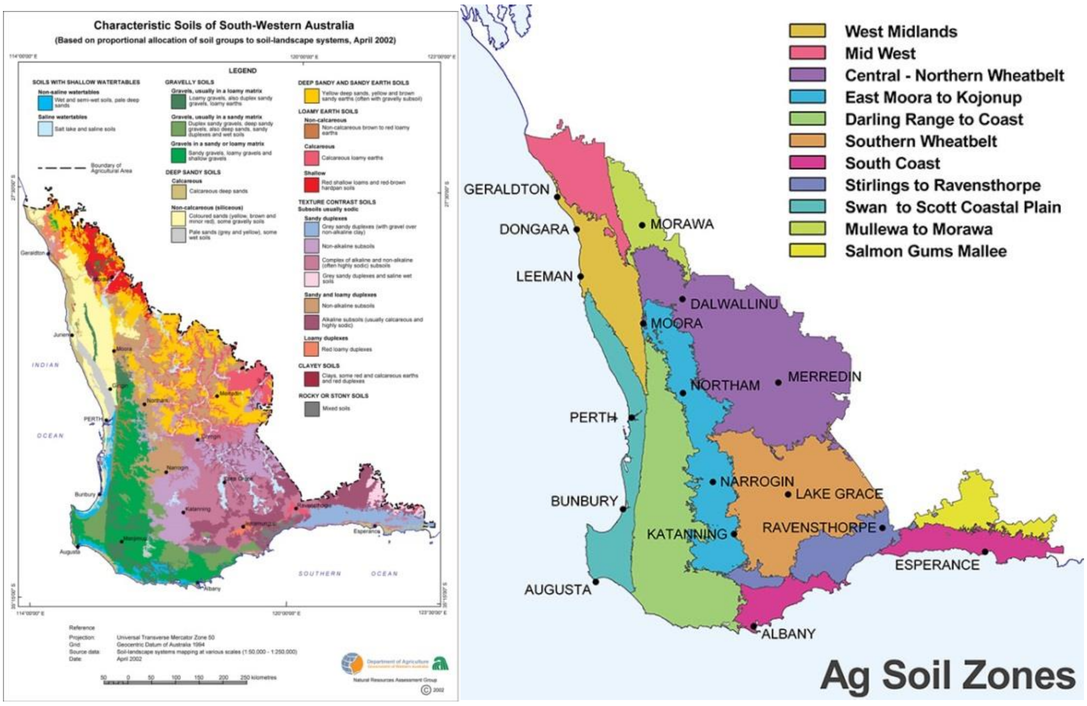


Figure 3.27 c). Simplified maps showing the soil types for south-western Australia (Department of Agriculture, 2002)

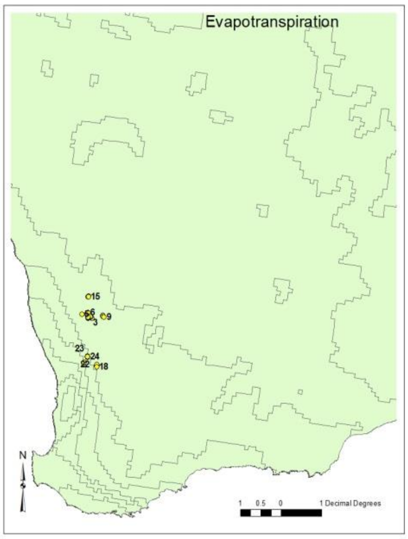


Figure 3.28 a). Map showing the average annual evapotranspiration contour lines of Western Australia and the paddock locations

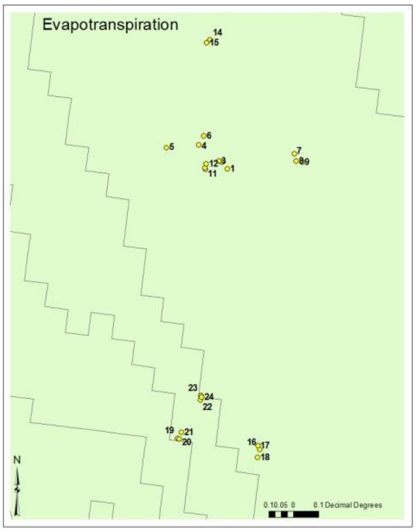


Figure 3.28 b). Enlarged area of the map showing the average annual evapotranspiration contour lines of Western Australia and the paddock locations

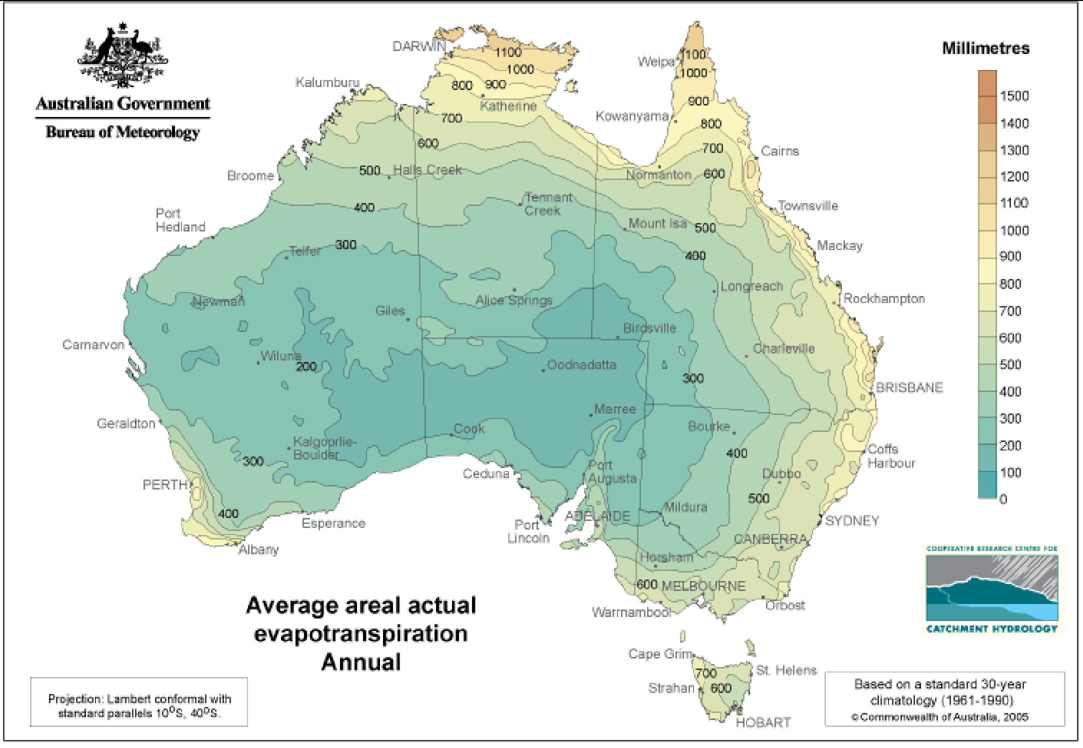


Figure 3.28 c). The average annual evapotranspiration for Australia, showing contour lines (BOM, 2013)

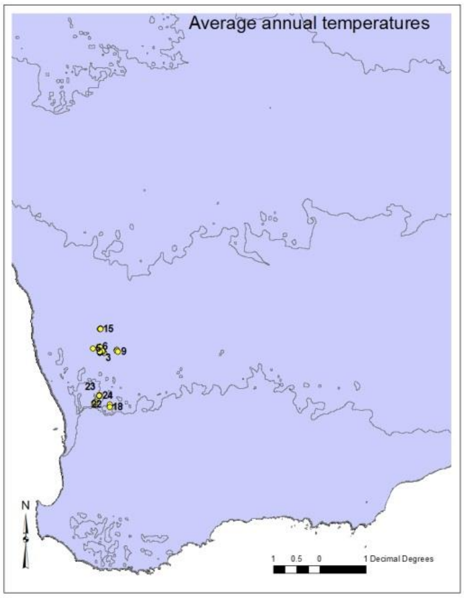
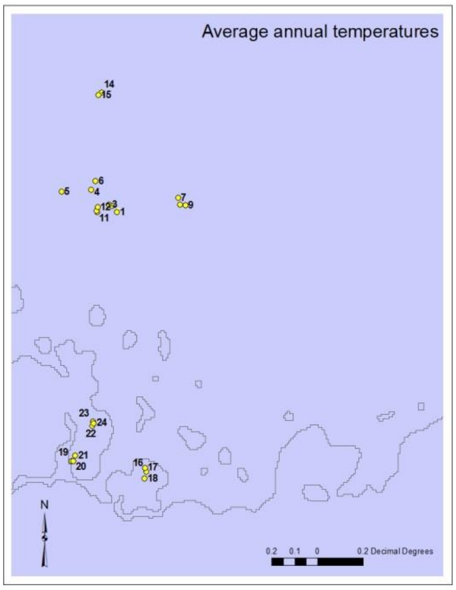
	

Figure 3.29 a). Map showing the average annual temperature contour lines of Western Australia and the paddock locations	**Figure 3.29 b). Enlarged area of the map showing the average annual temperature contour lines of Western Australia and the paddock locations**

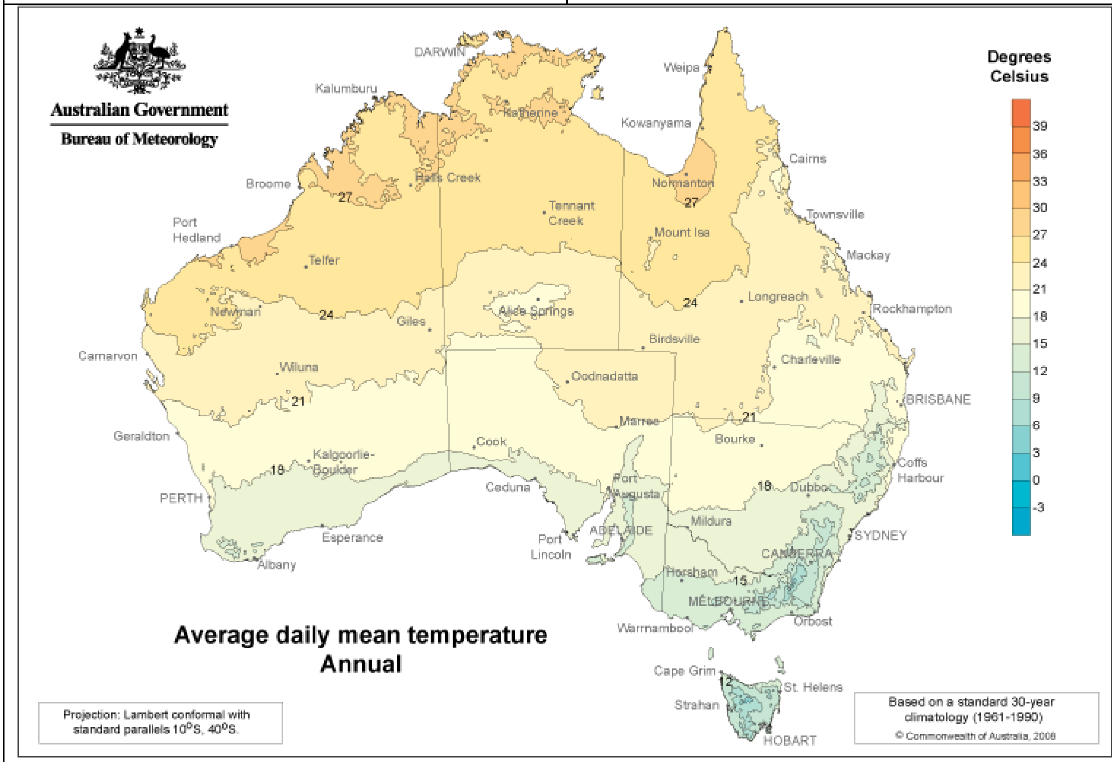
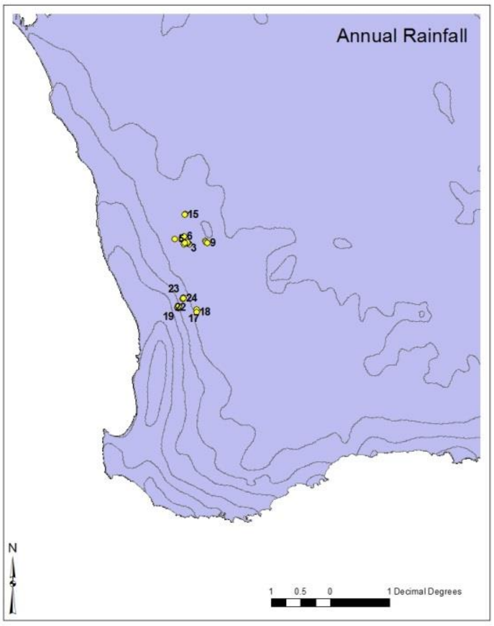


Figure 3.29 c). The average annual temperature for Australia, showing contour lines (BOM, 2013)



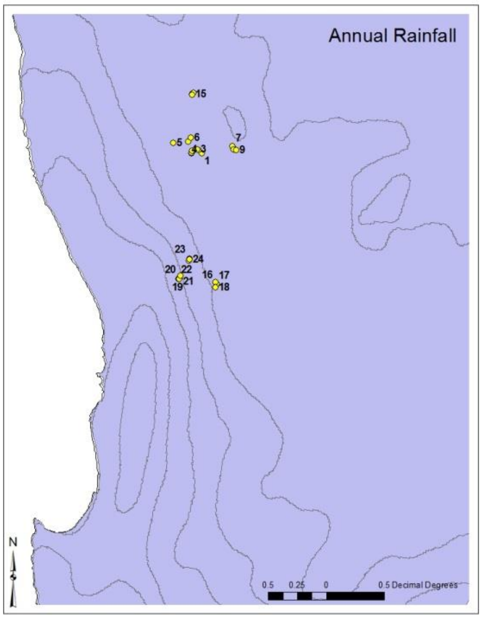


Figure 3.30 a). Map showing the soils of Western Australia and the average annual rainfall contour lines of Western Australia and the paddock locations

Figure 3.30 b). Enlarged area of the map showing the average annual rainfall contour lines of Western Australia and the paddock locations

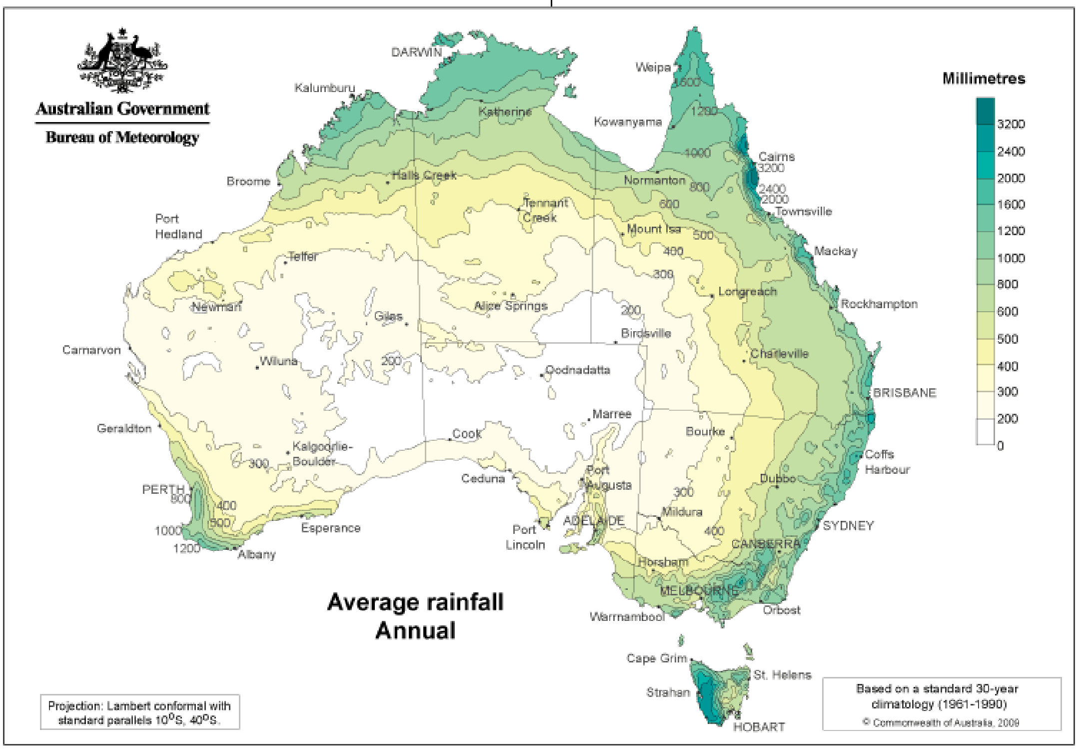


Figure 3.30 c). The average annual rainfall for Australia, showing contour lines (BOM, 2013)

3.3.3.4 Importing and uploading region specific tables

To initiate the final output maps, all the tables generated during the LCA phase were uploaded onto ArcMap software and georeferenced. Following is a list of the tables generated, with a short description thereof:

- Paddock files – the information on each of the paddocks was saved separately in tables as paddock 1–paddock 24. These tables contained values of co-ordinates, paddock number and GHG emissions from grain production for the specific paddock.
- Farm files – each of these files was saved individually as Farm A–Farm H. Each ‘farm file’ consisted of the paddocks relevant to that specific farm, for example, the file for Farm A consisted of all data for paddocks 1, 2 and 3. This paddock data incorporated into the ‘farm files’ was the same data used in the ‘paddock files’.
- All values file – this table aggregated all of the aforementioned data into one table for all farms and all paddocks.

Once these tables had been uploaded onto ArcMap software, they were converted to shapefiles and layers. In order to enable the creation of output in which different variables were specified separately or where the variables were used for comparative studies, joins were required. When tables are joined in ArcMap, a common field is identified from each table and these are linked together to create one table in the ArcMap software. These joins do not alter the original table that has been imported, and the joins can also be deleted at any stage (ArcGIS, 2014). The joins created were based on the paddock number and the geographical co-ordinates of each paddock.

3.3.3.5 Creating final output

The next step was the creation of the graphs which would be included as part of the output map, and are explained by means of a following example (Figures 3.31–3.35). All graphs included in the example were created in ArcMap and the 'snipping tool' on the computer was used to create the image files which are used for illustrative purposes in the following steps.

Step 1: In ArcMap the 'create graph wizard' is used to create a graph. In the top box the type of graph is selected e.g. vertical bar and the layer or table is specified. Firstly the layer for paddock 24 was selected and a vertical bar graph as the graph type (Figure 3.31). To add an additional series the selection box at the bottom of the 'vertical bar' tab, namely 'add', is selected. The vertical bar tab is double clicked and used to name the series. To name the x-axis paddock in the figure, the 'X Field (optional)' drop-down box is used.

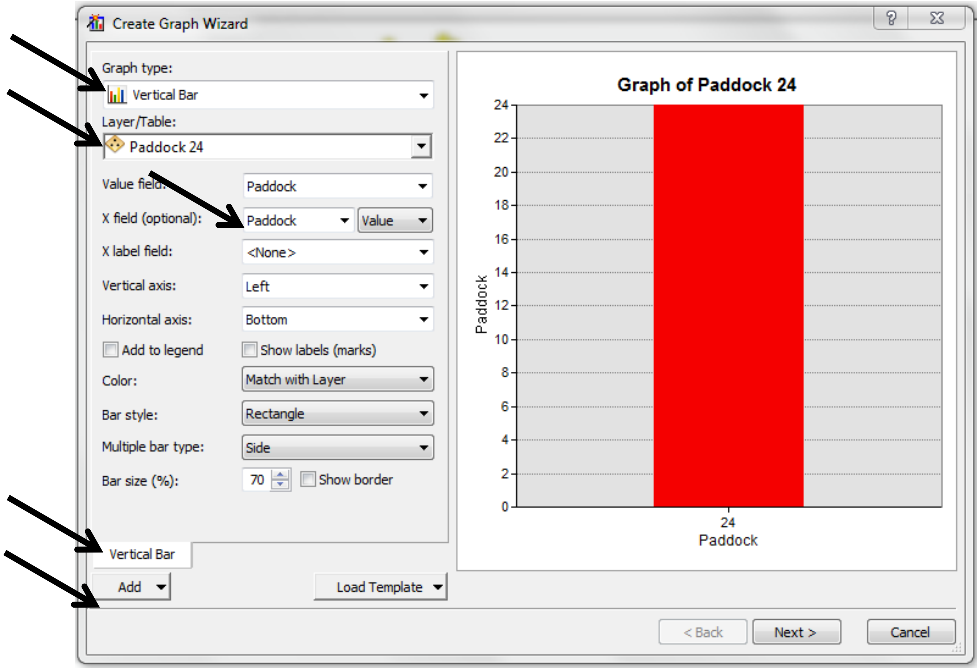


Figure 3.31. Creating a graph in ArcMap

In Figure 3.32 it can be seen that the additional series has been added (paddock 23) and the variable to be displayed is selected in the value field (e.g. Total CO_2-e/t). Furthermore the values (772 and 288) are displayed above the turquoise and red bars by selecting 'show labels (marks)'.

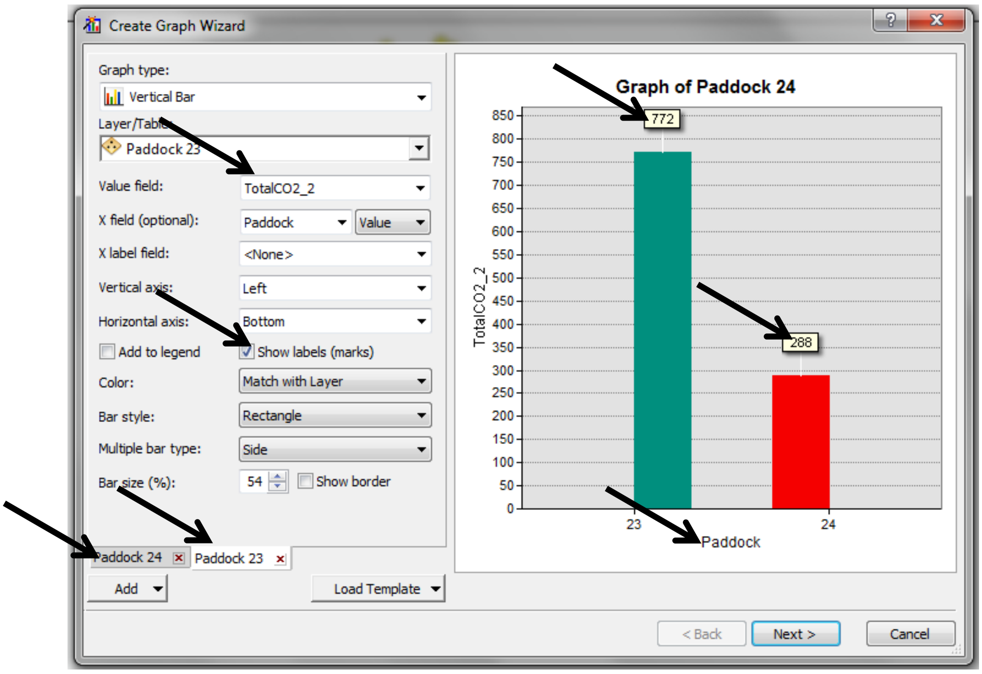


Figure 3.32. Adding an additional series in ArcMap

After clicking on the next button (Figure 3.32) in ArcMap, a page opens in which the appearance of the graph can be altered. Figure 3.33 shows how the title for the graph was added as well as the name for the x-axis.

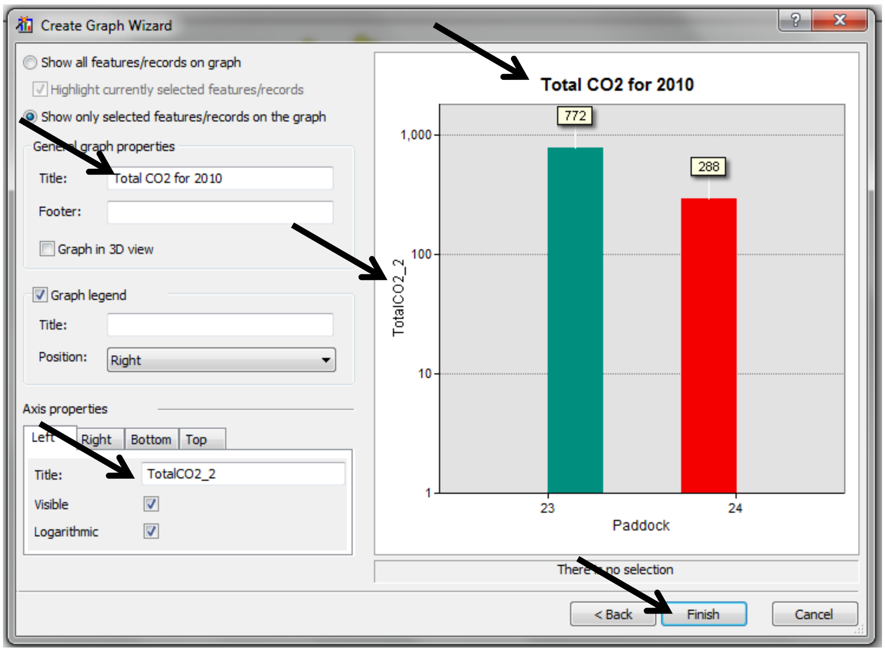


Figure 3.33. Altering the appearance of a GIS graph

The final graph (Figure 3.34) is displayed in ArcMap after ‘Finish’ is selected. This graph is then saved in ArcMap and exported to a folder on a computer.

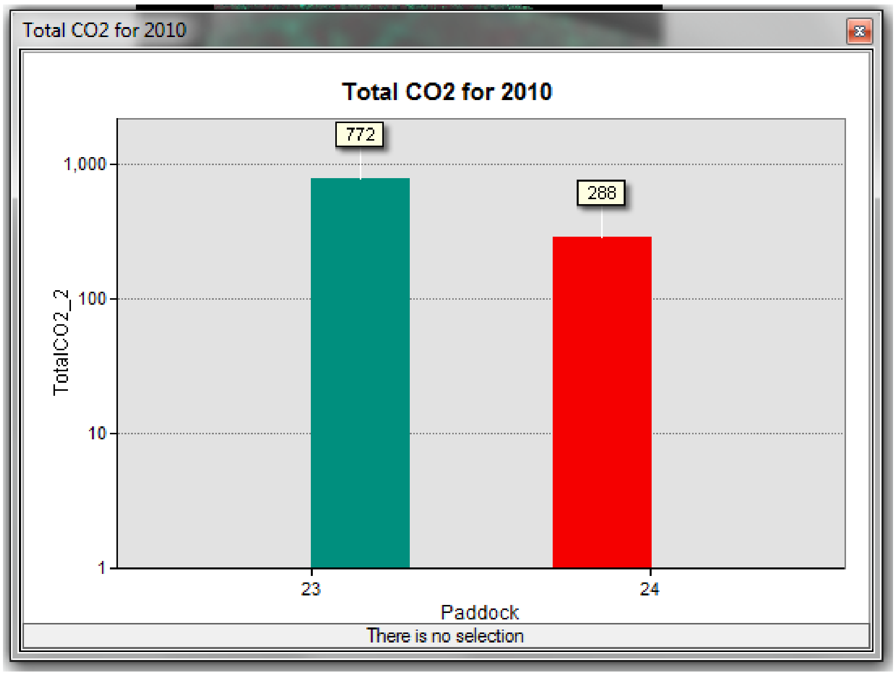


Figure 3.34. Example of graphs that can be created in ArcMap

After all of the graphs had been generated, only the creation of the final output remained. This commenced with all the required images and graphs being uploaded from the folder on the computer into the ArcGIS software. The images were then arranged to generate a figure similar to the one displayed in Figure 3.35. In this output image, the shapes of the paddocks are displayed, bar and pie graphs showing the total amount of CO_2-e/t emitted from three paddocks in 2010 and 2011, and pie and bar graphs comparing the CO_2-e/t emissions from grain production in 2010 with those in 2011 for the same paddock. This, however, is only an example of the different images that could have been generated. All other ‘graphable’ variables could have been included on this output image. Examples of these will be displayed in the results chapters (Chapters 5 and 6).

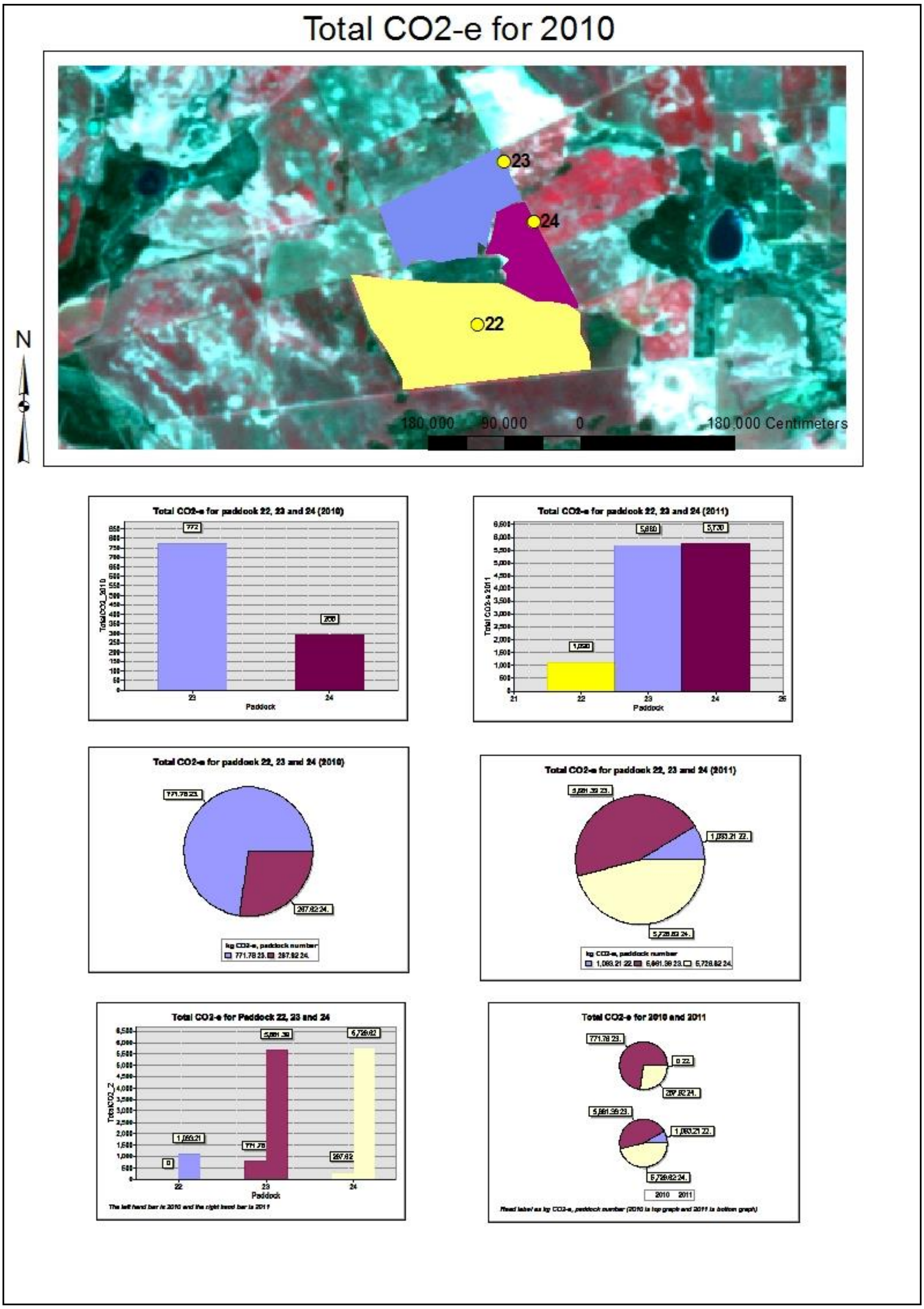


Figure 3.35. An example of the ArcMap output

3.4 MITIGATING GHG EMISSIONS FROM THE GRAIN SUPPLY CHAIN USING CLEANER PRODUCTION STRATEGIES

The previous sections discussed how RS, LCA and GIS were integrated to present location-wise GHG emissions from grain production. The next step identifies the environmental hotspots in the grain supply chain to apply appropriate CP techniques in order to improve environmental performance. CP initiatives involve the continuous application of an integrated preventative strategy to processes, products and services to increase efficiency and reduce negative human impacts on the environment (van Berkel, 2007; Biswas et al., 2011). Biswas et al. (2011) and van Berkel (2007) furthermore highlight some of the prevention practices that may reduce undesirable impacts:

- Good housekeeping is used to improve operation, maintenance and management procedures; for example the rotation of wheat with legumes.
- Input substitution is the use of environmentally preferred and 'fit-for-purpose' process inputs; for example, by introducing earthworms the use of chemicals for grain production can be reduced.
- Technology modification improves the production facility; for example, zero tillage reduces fuel use and subsequently GHG emissions.
- Product modification is used to change product features to reduce its life cycle environmental impacts; for example, the on-site processing of grains into canola oil.
- Re-use and recycling by on site recovery and re-use of materials, energy and water; for example, the re-use of highly treated and disinfected waste-water for irrigation.

In this research, appropriate CP mitigation strategies were identified and suggested for each paddock and farm for application to the grain supply chain (Chapter 7), as follows:

Step 1: The hotspot for each paddock was identified by consulting the GIS images showing the pre-farm and on-farm stages for both years. This was reported as the **farming stage hotspot**. For example, if the bar graph showed higher emissions for the pre-farm stage of 2011 (and the included table), it was considered to be the farming stage hotspot for that paddock.

Step 2: Using the GIS generated image for the stage hotspot, as identified in Step 1, the category emitting the most emissions was visually identified as the highest bar in the bar graph. This was termed the **category hotspot**. For example, if the stage hotspot was the pre-farm stage of 2011, an image was generated in GIS focussing on the categories within this farming stage. By comparing the graph (and the included table) the tallest bar was selected from amongst fertiliser production and use, chemical production and use, fertiliser transportation, chemical transportation and machinery production.

Step 3: Within some categories there were subdivisions. For example, for the production and use of chemicals the sub-categories were the production and use of herbicides, fungicides and pesticides, adjuvants and lime. If a category had sub-divisions, further GIS images were generated to ascertain which of the sub-divisions generated the most GHGs. For example, within the category production and use of chemicals the production and use of herbicides may have been identified as the hotspot. This was then considered the hotspot on the paddock. If there was no subdivision then the final hotspot was the category hotspot.

Step 4: After identifying the hotspot the CP methods were consulted to ascertain which would apply to mitigating the GHG emissions from that hotspot. For example, if the hotspot was identified as the production and use of herbicides, the applicable CP methods could include good housekeeping (e.g. reduce spillages), input modification (e.g. use of an alternative herbicide that generates less GHGs) or technology modification (e.g. find a manufacturer using greener methods of formulation) methods.

Step 5: Finally the mitigation strategy was tested by substituting theoretical values into the LCIA worksheet and thereby calculating a ‘new’ theoretical carbon footprint for the category. The theoretical GHG emission values were then compared to the actual GHG emission values to ascertain whether the mitigation strategy was viable or not. However, it must be remembered in testing CP mitigation strategies that they were entirely theoretical and not based on any scientific basis, such as soil testing, chemical resistance or economic factors.

3.5 CHAPTER SUMMARY

This chapter focused on the methodology that was used to create the IST. It commenced by explaining the data collection and from there showed how RS, GIS and LCA were integrated to generate output images for the GHG emissions of grain production. It concluded by introducing CP practices that may be implemented into the grain supply chain to aid with the reduction of GHGs.

The following chapters (Chapters 4, 5, 6) will present and discuss the results for each of the RS, LCA and GIS phases individually by utilising the field data from 24 paddocks in south-western Australia.

CHAPTER 4

GOAL AND SCOPE DEFINITION AND THE LIFE CYCLE INVENTORY

The International Organization for Standardization (ISO) divides the life cycle assessment (LCA) process into goal and scope definition (ISO 14040), life cycle inventory (LCI) (ISO 14041), life cycle impact assessment (LCIA) (ISO 14042) and interpretation (ISO 14043). The requirements and guidelines for conducting an LCA are specified in ISO 14044 (Curran, 2006; Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2013; ISO, 2006; Rebitzer et al., 2004). This chapter will present the goal and scope as well as the LCI results obtained for the LCA.

Where relevant, references have been made to previous chapters or excerpts were extracted and used. Additionally terms will be expanded upon according to the ISO requirements. The methodology for the LCI is documented in Chapter 3, section 3.3.2.2.

Although this study is a limited scope LCA (Finkbeiner, et al. 2011) it will use the same terminology and steps as a full LCA (Barton et al., 2014; Biswas, Engelbrecht, & Rosano, 2013a; Biswas, Thomson, & Islam, 2013b; Engelbrecht et al., 2013).

4.1. GOAL DEFINITION AND SCOPE FOR LIFE CYCLE ASSESSMENT

To initiate an SLCA the goal and scope of the study required definition. In defining these, a foundation was laid whereby all comparisons could be made objectively, the objectives of the study were set, the application for the study was determined and the future use for the functional unit was established (Curran, 2006, 2013; Landu, 2006; Goedkoop et al., 2013).

As each of the remote sensing (RS), geographical information systems (GIS) and LCA sections of the research have different purposes, only those applicable to the SLCA phase will be included in this chapter. It should however be understood that although each of these three tools have different goals, aims and scopes, they cannot be separated from the overall aim of the project (as stated in Chapter 1), but should be seen as interacting with each other to bring about a final product.

4.1.1 Goal of the study

According to the ISO 14040–44 standards, the primary goal of an LCA is to identify the best product, process or service with the least detrimental effect on human health and the environment. Furthermore it should identify the intended audience, the type of review to be conducted and the reasoning behind the study (Curran, 2006, 2013; Goedkoop et al., 2013; ISO, 2006; Rebitzer et al., 2004).

The goal of the current LCA is:

> *To estimate greenhouse gas (GHG) emissions of grain production and identify GHG emissions opportunities that may assist with the development of an environmental management plan to minimise GHG emissions in grain industries. This approach integrates RS, GIS and LCA (integrated spatial technology (IST) utilising the data of case studies in south-western Australia.*

The specific objectives of the streamlined life cycle assessment (LCA) are:

- The identification and documentation of the inventory in the pre-farm and on-farm phases of the project.
- The calculation of the carbon footprint for the various categories, e.g. GHG emissions originating from farm machinery operation identified in the project.
- The calculation of the overall carbon footprint for each paddock[1] for each year. This includes obtaining the sum of the GHG emissions from each of the categories in both farming stages (pre-farm and on-farm) and then adding them together.
- The identification of 'hotspots' in the agricultural production lines for each paddock, specifically focusing on pre-farm, on-farm and total emissions for proposing mitigation measures.
- The preparation of the LCA for inclusion into the GIS and RS applications.

[1] Universally a paddock is defined as a small, usually enclosed field near a stable or barn for pasturing or exercising animals. In Australia and New Zealand a paddock is a piece of fenced in (enclosed) land (The Free dictionary, 2014; Dictionary.com, 2014).

The intended audience includes suppliers and distributors of farm inputs (e.g. fertilisers), farmers, government departments with an interest in grain industries and GHG abatement and control, and research organisations.

In order to reach suppliers and distributors of farm inputs, both the national and international markets can be explored to identify alternative best practice methods of manufacture and transportation to reduce GHG emissions in chemical and energy production. Farm managers may be enabled to make more informed choices with regards to farm management practices that could impact positively on the emission of GHGs in their businesses. Policymakers in government departments may be able to use the LCA portion of the tool to identify areas where GHG emission levels are of concern and thereby assist farm managers to identify reduction methods and allocate funds for appropriate mitigation strategies. Finally, researchers may use this entire study, not only the LCA portion, to focus on additional research into the development of GHG mitigation tools, or further investigate the potential of this SCLA approach for other agricultural commodities.

4.1.2 Scope of the study

The scope of this LCA included the pre-farm and on-farm stages of an annual grain cycle in a dryland broadacre[2] cropping system in Western Australia. The crop growing season for these paddocks is typically a seven month growing period, although the LCA takes into account a 12 month period. The pre-farm stage commenced with the preparation of the paddocks in autumn (of any year) for seeding and concluded after the crops were harvested (November–December) and then took into account stubble management in preparation for the following season. Hence, the study period was set from June to the following May to best take into account the agronomic cycle of a grain crop. The post-farm stage which commenced with the transportation of the crops to storage facilities and all other subsequent processes were not included as part of the study. Only the carbon footprint, which consisted of the carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions to air

2 Broadacre is a term used, mainly in Australia, to describe farms or industries engaged in the production of grains, oilseeds and other crops (especially wheat, barley, peas, sorghum, maize, hemp, safflower, and sunflower), or the grazing of livestock for meat or wool on a large scale (i.e., using extensive parcels of land) (Organisation for Economic Co-operation and Development (OECD), 2001).

(collectively referred to as the GHG emissions), were quantified in this study. All non-GHG emissions to air, land and water were not considered.

Additionally, as part of the scope of any LCA the functional unit is defined, the boundaries of the study stated and assumptions and limitations identified (Curran, 2006; Goedkoop et al., 2013; ISO, 2006).

4.1.2.1 Defining the functional unit

The functional unit describes the function of the product or process that is being studied and provides a frame of reference to which the inputs and outputs can be related. It also helps carry out a mass balance for developing a life cycle inventory (Curran, 2006; Dantes, 2014; Goedkoop et al, 2013; ISO, 2007). As stated in Chapter 3, the functional unit for this research was the production of one tonne of grain.

4.1.2.2 Defining the system boundaries

It is crucial to define the system boundaries in a study in which there are many processes. Doing this assists in refining the study by including only the unit processes which are of interest (Curran, 2006; Dantes, 2014; Goedkoop et al., 2013; ISO, 2007). The system boundary in this study was defined by the planting of one tonne of grain, starting in June 2010 and June 2011 and ending in May 2011 and May 2012, and included both pre-farm and on-farm stages. The season starting in 2010–2011is referred to as the 2010 season and the season 2011–2012 is referred to as the 2011 season.

The first boundary established was that of quantifying only the CO_2, N_2O and CH_4 GHG emissions to air, these being the most important GHGs produced by agriculture (United States Environmental Protection Agency (EPA), 2014). Secondly, the post-farm subsystem was excluded in the analysis as the farmer was determined to have no influence over the GHG emissions after crop harvest. Thirdly, the study was limited to south-western Australian grain growers for 2010 and 2011, in order to take into account project data provided by the Department of Agriculture and Food of Western Australia (DAFWA). Additionally, information on the production of chemicals and machinery was sourced from databases (with Australian data) (Royal

Melbourne Institute of Technology (RMIT), 2007) which quantified the raw material extraction and energy requirement for those unit processes. The transportation of the chemicals was included using Australian life cycle data from Simapro 7.33 (RMIT, 2007). Finally, human resources were not included in the study.

Figure 4.1 illustrates the system boundary for the growing cycle for one tonne of grain. The shaded boxes were included as part of this LCA.

4.1.2.3 Assumptions and limitations

The following assumptions were made during the research:

- Allocation issues were avoided as only the pre-farm and on-farm stages were included. In very few cases, residue may have market value which is much lower than that of grains, and so economic allocation has not been considered. Incorporation of an economic allocation to allocate GHG to residue and grains could thus slightly lower the overall GHG emissions of the entire system.
- Where lime was not applied in either 2010 or 2011, the application of 100 kg of lime per year, as per recommended industry standard, was assumed on the basis that one tonne of lime was applied every 10 years to paddocks in Western Australia (Barton et al., 2014; Gazey & Ryan, 2014; Lee, 2014). However, research shows that the requirement for more lime to be applied is increasing and is also dependent on the soil acidity (Gazey & Ryan, 2014b; Lee, 2014).
- All international and interstate chemicals were first transported to Kwinana (the main cargo handling port of Western Australia in the region of study (Department of Transport, 2014)) before being transported to the town closest to the paddocks investigated (i.e. Dalwallinu or Northam).
- The destination of the chemicals was to the farm rather than applied to individual paddocks.

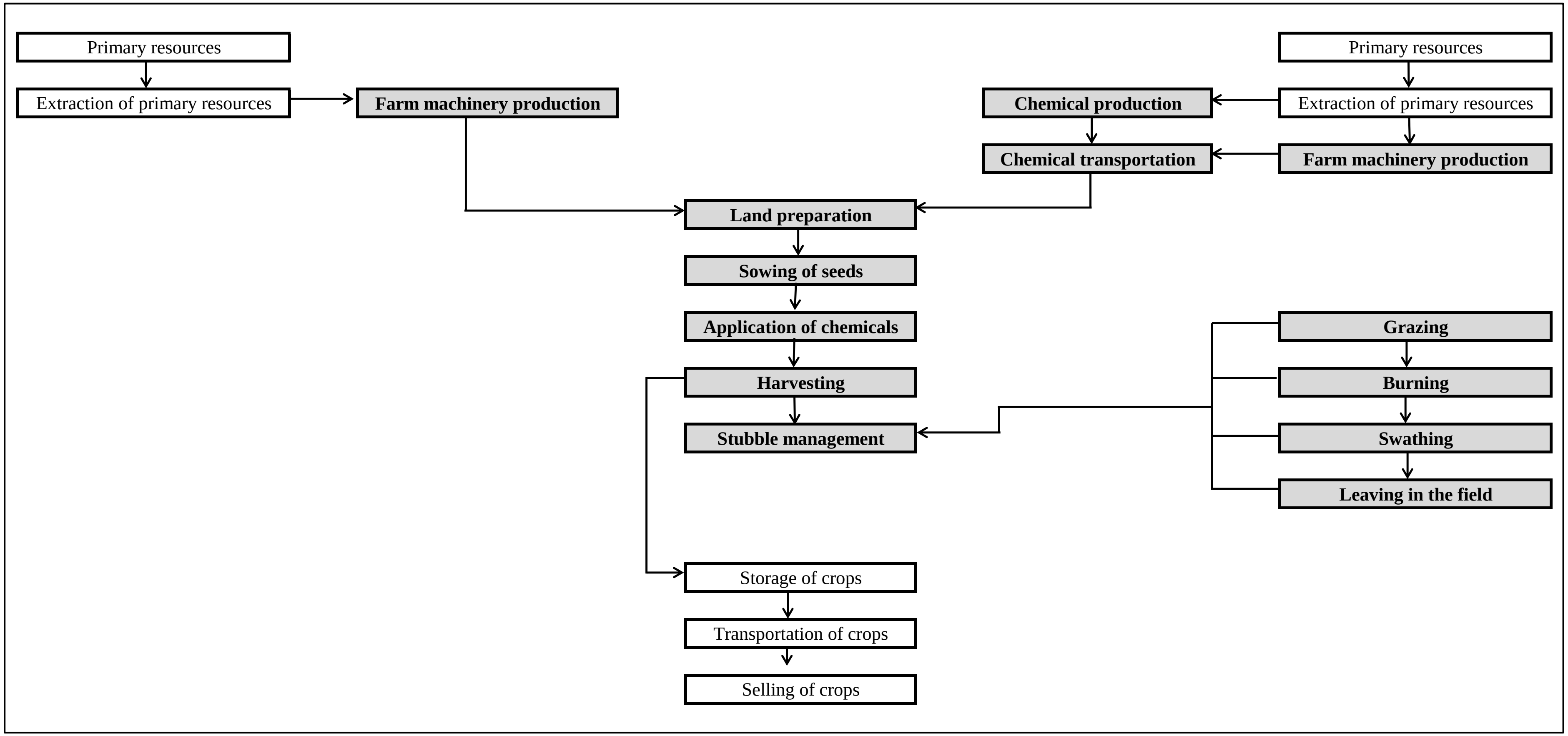


Figure 4.1. The system boundary for the growing cycle for one tonne of grain [The unshaded boxes were excluded as part of this LCA]

- Products imported from international origins were allocated nationally and internationally ratio-wise in terms of distance and was used for all calculations involving travel distances. For example the fertiliser urea was imported from Asia to Kwinana, trucked to Dalwallinu and then to the local farm. The total distance from Asia to Kwinana was 10,056 km, the international travel, plus 247.9 km of national travel to the farm. Ratio-wise this equates to 97.6 : 2.4 (international : national).
- The crop yield was based on the data provided to DAFWA by the farmer after harvesting. If no crop yield data was provided by the farmer, a yield was calculated by DAFWA by harvesting a small area of crop by hand. Cuts were taken of mature plants (4 x 1 m rows) by cutting the crop at ground level. The total above ground biomass of the cut was weighed, the grain was threshed out of the plant and then the grain was weighed. Thereafter, estimates of the grain yield were made by converting the threshed grain weight to kg/ha based on the sample area (pers. comm, Harries, DAFWA, Geraldton, Western Australia).
- Where no stubble yield was supplied by DAFWA, the paddock questionnaire was scrutinised to determine whether burning or grazing practices were employed in that growing cycle. The paddock was excluded from the study if neither of these practices were used as stubble yield was required to calculate the GHG emissions from burning and/or grazing. However, if neither burning nor grazing took place on the paddock, the stubble yield was not required for any calculations and thus the paddock was included in the analyses.
- Where the paddocks were used as pasture and no grain was planted, results were excluded from the research.
- All sheep that were grazed on the paddocks were classified as two year olds, being a common class of livestock in the region. Lambs accounted for 32.3% of the sheep population in 2009, hoggets (1–2 year olds) for 17.1% and the adults (older than 2 years) for 50.7% (Curtis, 2009; National Inventory Report (NIR), 2012)?

The following limitations were experienced during the research:

- Since the sheep were mainly grazed for stubble management, for a short period, before they were transferred to another pasture and the information on lifetime of these sheep were unknown, it was not possible to allocate a portion of inputs and outputs to the amount of live weight gained during grazing.
- Time series satellite imagery could have made the identification of different growth phases or grains possible.
- Additional data from farmers with paddocks falling within the satellite imagery boundaries may have enabled the extension of the analyses for even more accurate results.
- As the crop yield estimate by hand cutting was only completed once, the results could be inaccurate. For a more accurate result the hand cutting procedure should be completed more than once at different locations, due to crop yield variabilities in a paddock.

4.2 LIFE CYCLE INVENTORY

This section discusses the development and documentation of the life cycle inventory. It was initiated by the evaluation of all relevant processes after which flow diagrams were developed. Finally, a data collection plan was established prior to the collection, evaluation and reporting of the results.

4.2.1 Process flows

As part of the life cycle inventory (LCI), the entire project system, broadly illustrated in Figure 4.1, was described as explained in section 4.1.2.2. However, within the overarching system two smaller subsystems were also recognised, namely the pre-farm and on-farm stages of agriculture. As discussed in Chapter 3, the LCI of one tonne of grain included the inputs and processes of the pre-farm and on-farm stages of the grain life cycle. Flowcharts were generated for each of the pre-farm (Figure 4.2) and on-farm subsystems demonstrating the process flow (Figure 4.3). Coloured lines in these figures were used for grouping purposes to illustrate the flow and for ease of identification. The following section will discuss the inclusions and exclusions for each of these stages.

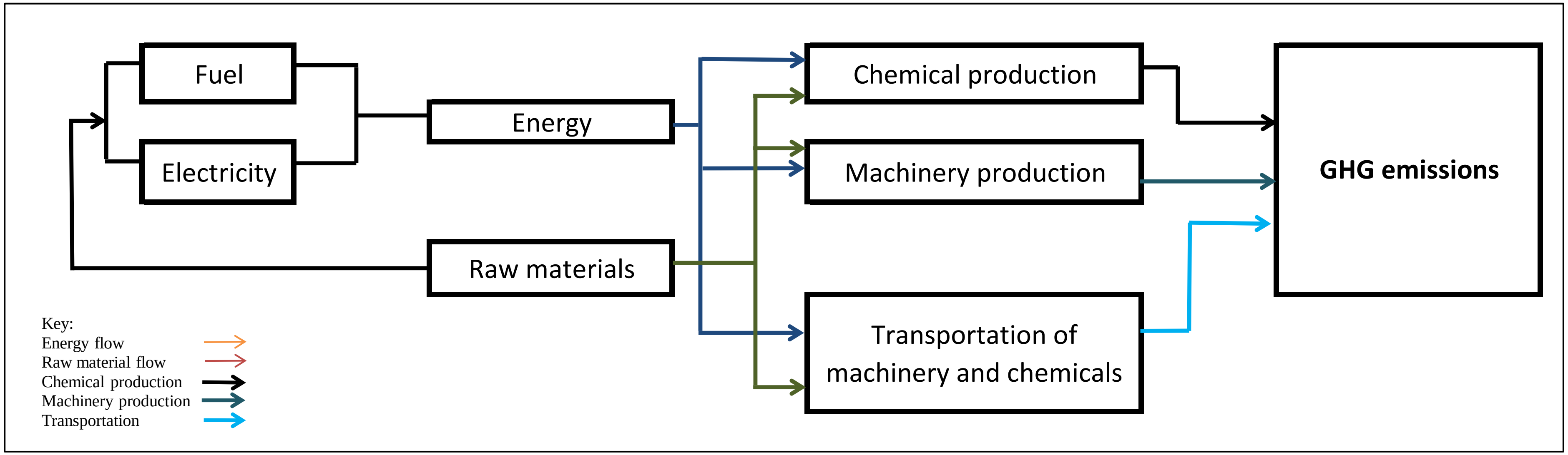


Figure 4.2. Pre-farm subsystem showing the system boundaries

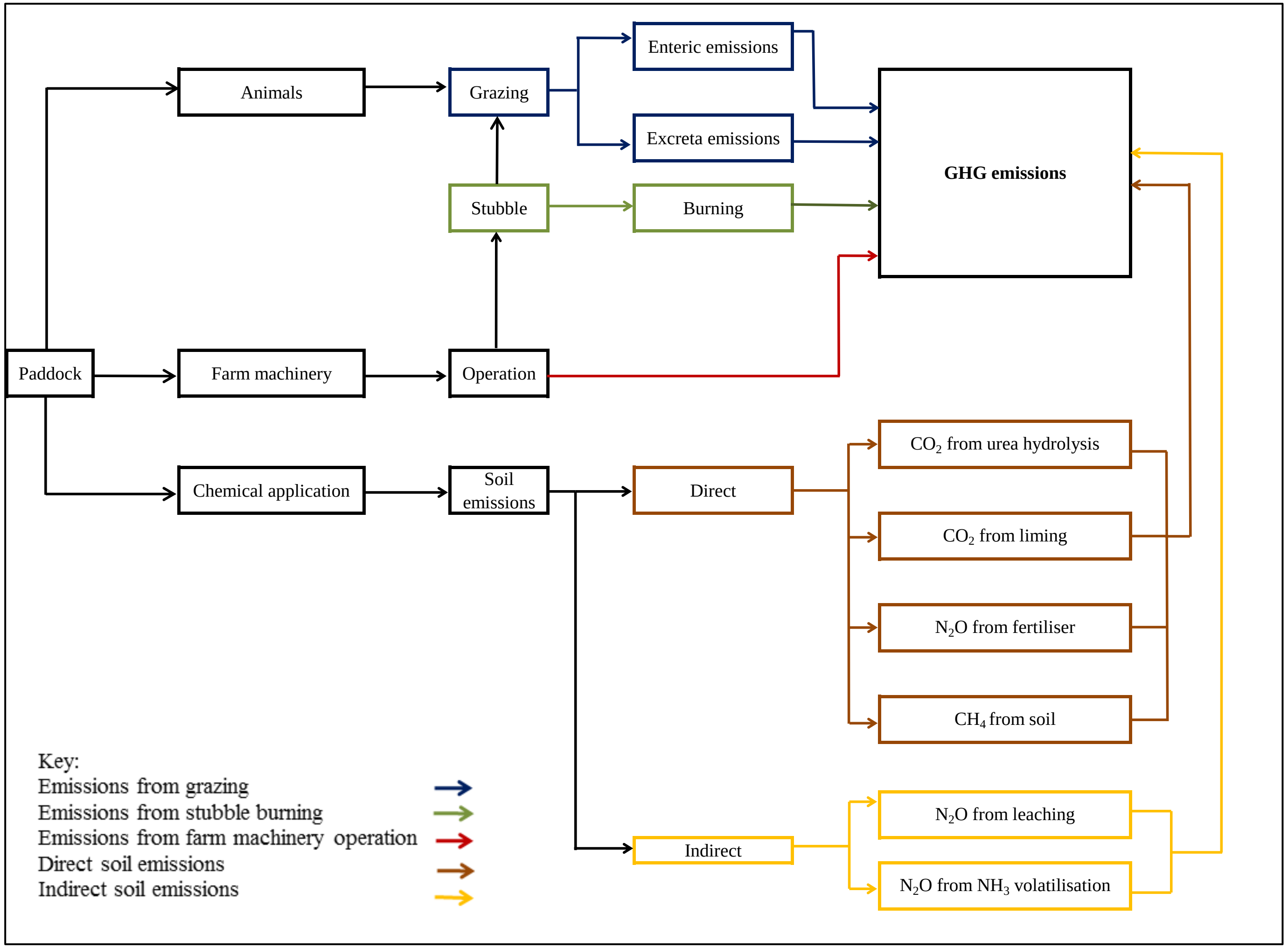


Figure 4.3. On-farm subsystem showing the system boundaries

4.2.1.1 Pre-farm stage input/output inclusions and exclusions

In the pre-farm stage (Figure 4.2), the chemical production and use (including fertilisers), machinery production and the transportation of chemicals (including fertilisers) were the categories considered. Each category was analysed to identify which inputs and outputs were to be included in this research.

The production of machinery and chemicals required raw materials and energy as input in the production process. The generation of energy, in turn, required fuel and/or electricity, and also required raw materials for the production of the electricity. During the production of the chemicals, GHG emissions were released into the environment. The use of the machinery and chemicals in turn also released emissions into the environment.

The transportation of chemicals required the combustion of diesel in the internal combustion engine of heavy vehicle engines this energy in turn was responsible for the generation of GHG emissions due to the burning of fossil fuels.

The inputs considered were the energy and raw materials required for the production of these products. Additionally, raw materials, fuel and electricity were required for the generation of the energy used in the production process. The outputs included the emissions of CO_2, N_2O and CH_4 into the air, water or soil, whether directly or indirectly.

It should be noted that the LCI considers not only the active ingredients, but also the inactive ingredients which are combined with the active ingredients to form inputs for the production of grains.

4.2.1.2 On-farm stage input/output inclusions and exclusions

In the on-farm stage, the categories taken into consideration included animal grazing, stubble burning, the operation of farm machinery, direct soil emissions (DSE) and indirect soil emissions (ISE). Each of these categories generated CO_2, N_2O and CH_4 emissions which were collectively converted to CO_2-e.

The sheep (in this study) grazed on the stubble that remained on the fields after harvesting. The emissions quantified and converted to GHGs included enteric CH_4 and CH_4 from excreta (although considered negligible (NIR, 2012)). Also as mentioned earlier, the estimation of live-weight gained during the short period of time was beyond the scope of the research.

Stubble remained on the fields after harvesting the paddock. This stubble was either reduced by grazing animals as explained above, by windrow or full paddock burning, or by natural decomposition which took place from the time of harvesting until the next planting season. The burning of stubble generated CO_2, N_2O and CH_4. However CO_2 was not included in the formulation of the LCI as it is considered biogenic (Intergovernmental Panel on Climate Change (IPCC), 2006).

The operation of farm machinery required the input of fuel. As outputs, CO_2, N_2O and CH_4 were generated and released to the air, and all three of these GHGs were considered in the LCI.

Soil emissions are responsible for direct and indirect emissions. These soil emissions are primarily generated through the application of agro-chemicals that are, in turn, influenced by factors such as varying climate. In the DSE category the GHG considered were CO_2 from urea hydrolysis, CO_2 from liming, and N_2O from fertiliser. As the CH_4 emissions from soil are low (Barton et al., 2014; Biswas et al., 2008) they were excluded from the analysis. The ISE category quantised N_2O emissions resulting from the nitrification and denitrification stages of the N cycle. The N_2O emissions included the volatilisation of nitrogen (N) as ammonia (NH_3) and the leaching and runoff from land, from N from synthetic and organic fertiliser additions (IPCC, 2006).

The production of capital equipment, including road, infrastructure and articulated trucks, are not included in the system boundary of the LCA analysis due to its long-term span (Biswas, 2009).

4.2.2 Data identification and collection

After identifying the flow of the entire system, the data required and the methods of collecting and organising the data were ascertained. These methods of collection are explained in full in Chapter 3 and the results obtained are documented in this section.

4.2.2.1 Classification and categorisation

Initially the data was allocated to either the pre-farm or on-farm stage of farming for each agricultural year, thereafter the identified inputs and processes were classified and finally categorised. Categorisation was based on the type of process, for example, production, transportation, application or emissions, as specified in the categorisation column in Table 4.1. Classification identified individual processes within each category such as enteric emissions and excreta emissions which both occur within the grazing emissions class. These are listed in the classification column in Table 4.1. Furthermore, within the chemical production and use category the classes were further subdivided (sub-classes) to include all of the chemicals used in this research (Appendix E, Table E.1-E.4), e.g. for fertilisers, urea and Flexi-N, amongst others. The production and transportation of non-fertiliser chemicals (from here on referred to as chemicals) and the production and transportation of fertilisers were kept separate as fertiliser has been found in many research projects to be the main GHG emitter. Furthermore, nitrogenous fertilisers (N-fertilisers) also contribute to ISE and DSE (Biswas et al., 2008; Brock, Muir, & Simmons, 2014; Wang & Dalal, 2015).

Table 4.1. Categorisation and classification within the annual pre-farm and on-farm farming stages

Farming stage	Categorisation	Classification
Pre-farm	Chemical production and use	Adjuvants
		Fertilisers
		Fungicides and pesticides
		Herbicides
		Lime
	Farm machinery production	
	Transportation of fertilisers	International transportation
		National transportation
	Transportation of chemicals	International transportation
		National transportation
On-farm	Farm machinery operation	
	Stubble emissions	
	Grazing emissions	Enteric emissions [Section 3.3..2.2]
		Manure excreta [dung and urine] emissions
	Direct soil emissions	CO_2 from urea hydrolysis
		CO_2 from lime
		N_2O from fertiliser
	Indirect soil emissions	N_2O from leaching
		N_2O from NH_3 volatilisation

4.2.2.2 General information

The initial paddock details obtained from DAFWA included the grower group, the name of the farm, the paddock name, the Australian soil classification (ASC) name and common names of the soil types, the soil pH and the geographical coordinates of each of the paddocks (Table 4.2). As documented previously, the names of the farms and paddocks were replaced with alphabetical letters and numbers, respectively. Additional data acquired using questionnaires are presented hereafter.

Although the soil type was not used in the final analyses, details have been documented with regard to soil factors which affect the yield of grains, such as the type of soil, soil health, the hardness of the soil, and the water holding capacity (Bell et al., 2007; Bennett et al., 2010; Natsis et al., 2008). Furthermore, soil pH, soil types and soil health affect farm management practices, which include crop selection and tillage methods (Bell et al., 2007; Bennett et al., 2010; Natsis et al., 2008).

Table 4.2. Paddock details for each paddock included in the study

Grower group	Farm	Paddock	Coordinates (decimal degrees south)	Coordinates (decimal degrees east)	Soil type (common name)	Australian soil classification (ASC)*	Soil pH
Liebe Group	A	1	-30.38408	116.75134	red sandy earth	Red Kandosol	6.6
		2	-30.35705	116.72456	calcareous loamy earth	Calcic Calcarosol	6.7
		3	-30.35220	116.71121	calcareous loamy earth	Variable	.8
	B	4	-30.28617	116.62030	yellow/brown shallow loamy duplex	Yellow Chromosol	5.7
		5	-30.29622	116.47002	yellow deep sand	Orthic Tenosol	5.9
		6	-30.25070	116.64339	calcareous loamy earth	Calcic Calcarosol	8.3
	C	7	-30.32339	117.06142	red loamy earth	Red Kandosol	6.8
		8	-30.35304	117.07137	yellow/brown deep sandy duplex	Yellow Sodosol	5.3
		9	-30.35679	117.09812	yellow deep sand	Orthic Tenosol	
	D	10	-30.3855	116.6499	grey shallow sandy duplex	Grey Sodosol	4.7
		11	-30.3791	116.64702	brown sandy earth	Brown Kandosol	4.8
		12	-30.3626	116.65337	red loamy earth	Red Kandosol	7.1
	E	13	-29.87485	116.65735	brown sandy earth	Brown Kandosol	6.2
		14	-29.86282	116.67301	red shallow loamy duplex	Red Chromosol	6.6
		15	-29.87555	116.65772	yellow/brown deep loamy duplex	Yellow Chromosol	6.0
WANTFA	F	16	-31.51618	116.89998	yellow sandy earth	Yellow Kandosol	6.1
		17	-31.49948	116.89180	yellow deep sand	Orthic Tenosol	6.
		18	-31.54728	116.89005	ironstone gravelly soils supergroup	Variable	6.1
	G	19	-31.46997	116.51488	brown loamy earth	Brown Kandosol	5.5
		20	-31.47113	116.52287	grey shallow loamy duplex	Grey Chromosol	5.7
		21	-31.4453	116.53362	yellow deep sand	Orthic Tenosol	6.3
	H	22	-31.31512	116.62202	yellow/brown deep sandy duplex	Yellow Sodosol	6.7
		23	-31.29783	116.6254	yellow sandy earth	Yellow Kandosol	6.5
		24	-31.30427	116.62905	brown sandy earth	Brown Kandosol	6.2

* Australian Soil Classification (ASC) (Isbell, 1996)

4.2.2.3 Farm level life cycle inventory

The overarching purpose of the LCI is the presentation of the results as inventory lists. These results are used to identify and inform about the inputs and outputs/emissions for the entire system being analysed. As detailed in the methodology chapter (section 3.4.2.2), an LCI was generated for each paddock by establishing linkages with the relevant databases (worksheets) in Excel. The paddocks from each farm were grouped together separately. In this section the inputs and outputs will be summarised in one table according to the classification. The classifications (paddock preparation, machinery emissions, chemical emissions, climatic variables) are discussed in the order in which they were generated. An additional statistical table has been added for each classification in which the minimum input/output value, maximum input/output value, mean and standard deviations (SD) are specified. The SD is focused on the calculated mean of the values and refers to the reliability and dispersion around the mean. If the SD value is low it means that the values are not excessively spread out and are thus more reliable, and vice versa for a larger SD value. It must be remembered, however, that these SD values are relative to the range of the values and should be analysed in the context of the values reported.

As there is a large number of inventory lists they have been included in Appendix F and the statistical tables only serve as a summary.

- Paddock preparation

The paddock preparation database presented data for stubble decomposition, stubble reduction through the grazing of sheep and stubble burning. The input data were required for the calculation of emissions arising from stubble reduction mechanisms. As specified in section 3.3.2.2, no GHG emissions were calculated for stubble decomposition.

The inputs required are tabulated below (Table 4.3). The third column specifies the origin of the data.

Table 4.3. Inputs required to calculate the load of stubble present

Variable	Unit	Source of data
Starting mass of stubble	kg/ha	Primary data from DAFWA
Rate of stubble decomposition	%	Secondary data from literature
Months decomposed before pasturing	months	Calculated
Stubble decomposed before pasturing	kg/ha	Calculated
Stubble remaining before pasturing	kg/ha	Calculated
Stubble remaining after pasturing	kg/ha	Calculated
Months decomposed before burning	months	Calculated
Stubble decomposed before burning	kg/ha	Calculated
Stubble remaining before burning	kg/ha	Calculated

Table 4.4 communicates the statistical values calculated for the stubble load present at the various stages of stubble decomposition. The complete inventory list has been included in Appendix F (Table F.1). The starting mass of the stubble was initially determined after harvesting, in both years. The mass of the initial stubble depended on factors such as the stubble height after harvesting and the stubble density remaining after harvesting. Additional factors such as the grain type and the machinery used also contributed to the stubble density after harvesting (Grains Research and Development Corporation (GRDC), 2011a), however, the analyses of these are not within the scope of this research.

Table 4.4. Statistical analyses of stubble reduction

Statistical details		Starting mass of stubble	Stubble mass before pasturing	Stubble mass after pasturing	Stubble mass before burning	Stubble mass after burning	Total stubble decomposed
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
2010	Minimum	554	554	528	475	34	63
	Maximum	2659	2659	2659	2327	2327	365
	Mean	1410	1391	1348	1184	917	185
	Median	1297	1297	1297	1135	757	168
	Standard deviation	634	626	643	563	695	92
2011	Minimum	1623	1582	1448	1303	1287	185
	Maximum	10599	10599	10599	9274	5101	1325
	Mean	4460	4352	4198	3737	3476	558
	Median	4210	4033	3892	3443	3443	537
	Standard deviation	1877	1868	1872	1634	1139	270

Table 4.4 shows greater initial stubble retention for 2011 (end of season in May 2012) (minimum, maximum and mean values) than for 2010 (end of season in May 2011). The amount of stubble retained is dependent on the yield of the crop, and a higher crop yield means a higher stubble mass in the field (pers. comm, Harries, DAFWA, Geraldton, Western Australia) (Table 4.5). The reduction in the mean values for the stubble mass after pasturing shows that more farmers elected to graze their paddocks in 2011 than in 2010. Alternatively, this could show that the same number of farmers increased the number of stock on the paddocks in 2011. Stubble reduction due to animal husbandry was calculated at 3.1% in 2010 versus 3.5% in 2011 (**Equation 4.1**). The small difference in the means for stubble burning (270 kg/ha for 2010 and 261 kg/ha in 2011) indicates that the load of stubble burned did not differ much from 2010 to 2011 overall, however based on the total reduction value, 22.6% stubble was reduced by burning in 2010 and 6.9% in 2011 (**Equation 4.2**). The total stubble decomposed in 2010 totalled 13.1% and 12.5% in 2011 (**Equation 4.3**). The SD of stubble decomposition in 2011 was very high (49.7% of the mean in 2010 and 48.4% of the mean in 2011) which was mainly due to the wide range of stubble management practices, including stubble burning, grazing and decomposition during the fallow land period. The stubble reduction after animal husbandry ($Stubble_{AH}$, %) has thus been calculated as:

$$\boldsymbol{Stubble_{AH} = \frac{Stubble_{MBP} - Stubble_{MAP}}{Stubble_{MH}} \times 100\%}$$ **Equation 4.1**

Where, '$Stubble_{MBP}$' is the mean stubble mass before pasturing (kg/ha), '$Stubble_{MAP}$' is the mean stubble mass after pasturing (kg/ha) and '$Stubble_{MH}$' is the mean stubble mass after harvesting x 100% (kg/ha).

In the case of the stubble reduction after burning ($Stubble_{AB}$, %):

$$\boldsymbol{Stubble_{AB} = \frac{Stubble_{MBB} - Stubble_{MAB}}{Stubble_{MS}} \times 100\%}$$ **Equation 4.2**

Where, '$Stubble_{MBB}$' is the mean stubble mass before burning (kg/ha), '$Stubble_{MAB}$' is the mean stubble mass after burning (kg/ha) and '$Stubble_{MS}$' is the starting mass of the stubble x 100% (kg/ha).

The stubble decomposed ($Stubble_{decom}$, kg/ha) is expressed as follows:

$$\% \, \boldsymbol{Stubble_{decom}} = \frac{\boldsymbol{Stubble_{TDecom}}}{\boldsymbol{Stubble_i}} \times \mathbf{100}\% \qquad \textbf{Equation 4.3}$$

Where, ‘$Stubble_{TDecom}$’ is the total stubble decomposed (kg/ha) and ‘$Stubble_i$’ is the starting mass of the stubble (kg/ha).

Table 4.5. Statistical summary of the crop, crop yield and rainfall per paddock

Paddock number	2010			2011		
	Crop	Yield (t)	Rainfall	Crop	Yield (t)	Rainfall
1	Wheat	1.3	201.0	Wheat	2.9	271.2
2	Wheat	1.2	201.0	Wheat	2.0	271.2
3	Wheat	1.4	201.0	Wheat	2.2	271.2
4	Wheat	2.1	332.2	Barley	2.8	443.3
5	Wheat	1.9	226.7	Lupin	2.4	436.6
6	Wheat	2.4	276.2	Wheat	2.6	419.2
7	Wheat	1.6	231.4	Wheat	2.2	361
8	Wheat	0.9	247.2	Pasture	3.5	364.4
9	Wheat	1.1	247.2	Lupin	0.8	364.4
11	Wheat	1.8	179.2	Barley	3.1	271.2
12	Wheat	2.0	179.2	Wheat	3.0	271.2
13	Wheat	1.2	412.7	Wheat	3.4	149.6
14	Wheat	1.3	412.7	Wheat	3.4	149.6
15	Wheat	1.1	412.7	Oats	1.8	149.6
16	Wheat	2.1	233.8	Pasture	5.5	393.2
19	Wheat	1.6	281.4	Wheat	3.8	431.3
20	Wheat	1.9	281.4	Wheat	4.0	431.3
21	Wheat	2.2	281.4	Wheat	2.6	431.3
23	Wheat	1.9	269.4	Wheat	3.1	449
24	Wheat	1.5	269.4	Wheat	3.1	449
Min		0.9	179.2		0.8	149.6
Max		2.4	412.7		5.5	449.0
Mean		1.6	268.9		2.9	338.9

Some of the farmers allowed sheep to graze on the paddocks to reduce stubble during the fallow land period in both 2010 and 2011. However, sheep grazing also increases GHG emissions through enteric emissions (flatulence, belching) and breathing as well as from the decomposition of excreta (manure and urine). The inputs required for the quantification of these GHG emissions are summarised in Table 4.6. Appendix F (Table F.2) presents the data calculated for 2010 and 2011 for the enteric and manure decomposition emissions, where applicable, for each of the 24 paddocks.

Table 4.6. Inputs required for the calculation of GHG emissions from the grazing of sheep

Variable	Unit	Source
Digestibility in summer	%	Secondary data from literature
Sheep per paddock	ha	Primary data from DAFWA
Paddock area	DSE*/ha	Primary data from DAFWA
Sheep per ha (DSE/ha)	kg/head/day	Primary data from DAFWA
Additional feed given as lick	kg/head/day	Primary data from DAFWA
Feed DM requirement (summertime)	kg/ha	Secondary data from literature
Initial stubble	days	Primary data from DAFWA
Number of days grazed	kg/ha	Primary data from DAFWA
Total stubble grazed		Calculated
Remaining stubble	kg/ha	Calculated
CH_4 emission factor for enteric emissions	kg CH_4/ha	Secondary data from literature
Amount of CH_4 from enteric emissions	kg CH_4/head/day	Calculated
CH_4 emission factor for manure emissions**	kg CH_4/ha	Secondary data from NIR (2012) literature
CH_4 from manure decomposition	kg CH_4/head/day	Calculated

* Dry stock equivalent (DSE) is the method used to standardise an animal unit and is the amount of feed required by a two year old (Meat and Livestock Australia (MLA), 2015)
** Dung and urine

Table 4.7 shows basic statistical analyses of the data presented in Appendix F (Table F.3). The table shows the total amount of stubble grazed and the mass of the remaining stubble on each paddock in terms of minimums, maximums, mean, median and SD.

Table 4.7. Statistical analysis for stubble burning

Statistical details		Initial stubble load	Total stubble grazed	Remaining stubble	GHG emissions from enteric emissions	GHG emissions from manure decomposition
		kg/ha	kg/ha	kg/ha	kg/CH_4/hd/day	kg/CH_4/hd/day
2010	Minimum	607	80	528	1.08E+00	1.08E-03
	Maximum	2416	208	2245	2.83E+00	1.39E-03
	Mean	1131	141	990	1.91E+00	1.24E-03
	Median	967	135	769	1.84E+00	1.25E-03
	Standard deviation	665	55	646	7.41E-01	1.38E-04
2011	Minimum	1291	123	914	1.21E-01	8.46E-04
	Maximum	6198	1128	5070	1.53E+01	7.11E-03
	Mean	3334	349	2985	2.54E+00	2.54E-03
	Median	3645	257	3388	1.37E+00	2.20E-03
	Standard deviation	1537	286	1417	4.42E+00	1.6734E-03

Note: crop and yield were obtained from DAFWA and rainfall from the Bureau of Meteorology (BOM)

The difference in the range of stubble load between 2010 and 2011 may be due to seasonal differences in the crop yield and type (Table 4.5) from one year to another and the amount of the stubble that remains in the fields after harvesting, made available for grazing. The mean of the total stubble grazed in 2010 was 12.5% compared to 10.5% in 2011 (**Equation 4.4**). The reduction in stubble grazing could be attributed to less livestock grazed in the paddock in 2011. Equation 4.4 was used to calculate the % of the stubble grazed, based on mean values.

$$\%\, \boldsymbol{Stubble_{MSG}} = \frac{\boldsymbol{Stubble_{MTG}}}{\boldsymbol{Stubble_{Mi}}} \times \mathbf{100}\% \qquad \textbf{Equation 4.4}$$

Where '$Stubble_{MSG}$' is the mean of the total stubble grazed (%), '$Stubble_{MTG}$' is the mean total stubble grazed (kg/ha) and '$Stubble_{Mi}$' is the mean initial stubble load (kg/ha).

The mean for the enteric emissions for 2010 is lower than for 2011, showing that the different types of crop stubble possibly influence the animals' GHG emissions in this study (Table 4.5). In 2010 all paddocks (20) were planted to wheat, in 2011 65% (13) were planted to wheat, 5% (1) used as pasture, 10% (2) planted to lupin and barley, and 5% (1) to oats and canola. These percentages show that the use of wheat as stubble feed could possibly produce lower GHG emissions than the stubble from other grains. When considering the means by which emissions arise from manure decomposition, it can be concluded that the stubble from the grains (which differed) in 2011 generated more emissions than those of 2010. This may be because of the fact that this research has assumed the livestock to be two year olds for emissions calculations, however younger or older livestock may be part of the stocking rate which in turn would influence the amount of manure deposition and thus the GHG emissions from the manure (Chapter 2, section 2.3.4.1)(NIR, 2012).

The final part in managing the stubble load is windrow or full paddock burning to prepare the land for planting in the coming season and for weed control (Chapter 2, section 2.5.5.5. Stubble burning is not practiced by all farmers (GRDC, 2011a). Table 4.8 tabulates the input data required for the calculation of the emissions from stubble burning. The calculated GHG emissions resulting from the burning of stubble, where applicable, have been provided in detail in Appendix F (Table F.3). Table 4.9 specifies the type of burn, the mass of the fuel burned and the mass of the stubble remaining after burning.

Table 4.8. Input data required to calculate the emissions arising from the burning of stubble

Variable	Unit	Source
Type of burning	Windrow or paddock	Primary data from DAFWA
Area burnt	ha	Primary data from DAFWA
Burn efficiency for windrow burning	%	Secondary data from literature
Burn efficiency for paddock burning	%	Secondary data from literature
Mass of fuel burnt	t/ha	Calculated
Combustion factor		Secondary data from literature
Stubble remaining after burning	kg/ha	Calculated
Emission factor CO_2	g/kg	Secondary data from literature
Emission factor CH_4	g/kg	Secondary data from literature
Emission factor N_2O	g/kg	Secondary data from literature
CO_2 emissions	kg	Calculated
CH_4 emissions	kg	Calculated
N_2O emissions	kg	Calculated

Table 4.9. Stubble burning per paddock

Paddock number	2010			2011		
	Type of burn	Mass of fuel burned (kg/ha)	Remaining stubble load (k/ha)	Type of burn	Mass of fuel burned (kg/ha)	Remaining stubble load (kg/ha)
1	windrow burn	480.77	587.6	none		3541.0
2	windrow burn	478.01	584.2	windrow burn	1052.9	1286.8
3	windrow burn	218.14	266.6	none		2385.2
11	paddock burn	820.51	34.2	none		1789.3
12	windrow burn	255.81	312.7	none		3119.5
18	none			windrow burn	4173.2	5100.6
19	paddock burn	1236.48	51.5	none		4474.0
20	paddock burn	1848.84	77.0	none		4651.2

Statistical data for the burning of stubble are presented in Table 4.10. On consulting the mean values, it can be seen that the mass of the stubble burned on the paddocks in 2010 and 2011 differed considerably. In 2010 a total mass of 73.6% (**Equation 4.5**) of stubble was burned, when burned in windrows in four paddocks and fully burned in three paddocks. In 2011 the mass of the fuel burned reduced the stubble load to 45% when burned in windrows in two paddocks. Furthermore, the mean values for the CH_4 emissions and N_2O emissions from burning show that more emissions were generated in 2010 than in 2011, which is mainly due to the full paddock burning.

$$\%\boldsymbol{Stubble_{MB}} = \frac{\boldsymbol{Stubble_{MB}}}{\boldsymbol{Stubble_{Mi}}} \times \mathbf{100}\% \qquad \textbf{Equation 4.5}$$

Where, ‘$Stubble_{MB}$’ is the stubble mass burned (kg/ha) and $Stubble_{Mi}$ is the initial stubble mass (kg/ha).

Table 4.10. Statistical data for the burning of stubble

Statistical details		Initial stubble load	Mass of fuel burned	Remaining stubble	CH_4 emissions from burning	N_2O emissions from burning
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
2010	**Minimum**	485	218	34	3.37E-04	7.31E-04
	Maximum	1926	1849	588	3.49E-01	7.59E-01
	Mean	1036	763	273	1.10E-01	2.39E-01
	Median	1062	481	267	5.80E-02	1.26E-01
	Standard deviation	485	595	239	1.34E-01	2.91E-01
2011	**Minimum**	2340	1053	1287	1.23E-03	2.66E-03
	Maximum	9274	4173	5101	5.52E-03	1.20E-02
	Mean	5807	2613	3194	3.37E-03	7.33E-03
	Median	5807	2613	3194	3.37E-03	7.33E-03
	Standard deviation	4903	2206	2697	3.04E-03	6.59E-03

- Machinery emission databases

The machinery inputs that mainly include production and operation costs have been captured for this database. Table 4.11 tabulates all the input requirements specifying the unit as well as the source from which the data was obtained. The machinery operations in this research include seeding, spraying of chemicals, fertiliser and lime top-dressing, harvesting, claying and mouldboarding. The use of machinery is specific to the farm management practices and crops grown on a farm. For example, swathing (Chapter 3, footnote 10) is an additional farm machinery operation required for canola (pers. comm, Harries, DAFWA, Geraldton, Western Australia). Region-specific data for each of the machinery was supplied by DAFWA and is summarised in Chapter 3 (Table 3.1, section 3.4.2.2). The data in Table 3.1 were used for all calculations. The calculated emissions resulting from machinery production and use of fuel have been summarised in Appendix F (Table F.4-F.5), for each paddock and each application for both 2010 and 2011.

Table 4.11. Input data required to calculate the emissions arising from the production and use of farm machinery

Variable	Unit	Source
Width of header	m	Secondary data from DAFWA
Number of passes over the paddock	each	Primary data from DAFWA
Fuel consumption	litres/hour	Secondary data from DAFWA
Speed	km/hour	Secondary data from DAFWA
Cost of machinery	AUD/yr)	Secondary data from DAFWA
Lifetime of machinery	yrs	Secondary data from DAFWA
Approximate usage:	weeks/yr	Secondary data from DAFWA
Approximate usage:	hrs/day	Secondary data from DAFWA
Approximate usage:	days/week	Secondary data from DAFWA
Distance travelled/ha	km/ha	Calculated
Total distance travelled	km	Calculated
Operational time	hrs/ha	Calculated
Lifetime of machinery	hrs	Calculated
Cost of machinery	AUD/hr	Calculated
Cost of machinery (AUD/hr of operation/ha)	AUD/hr	Calculated
Cost of machinery per tonne produced (AUD/hr of operation/ha/tonne)	AUD/hr/tonne	Calculated
Cost of machinery for wheat production (AUD/ha) 1998 price	AUD/tonne	Calculated
Cost of machinery for crop production (USD/ha) 1998 price	USD/tonne	Calculated
Total fuel used per tonne of crop produced	litres/hr/tonne	Calculated

Table 4.12 summarises machinery inputs for minimum, maximum, mean, median and SD values for the production of the farm machinery. Mouldboarding and claying were not included in this table as these practices were conducted only on one paddock, producing only one set of data each, thus not allowing for statistical analysis.

Table 4.12. Statistical summary of the machinery production costs

Statistical details		Seeding	Swathing	Spraying	Top-dressing fertiliser	Top-dressing lime	Harvesting
		USD/ha/t	USD/ha/t	USD/ha/t	USD/ha/t	USD/ha/t	USD/ha/t
2010	Count	20		18	7	18	20
	Minimum	1.48		0.17	1.24	0.01	6.22
	Maximum	3.98		0.92	4.21	17.69	16.64
	Mean	2.48		0.49	2.56	3.06	10.13
	Median	2.25		0.48	2.72	0.53	9.64
	Standard deviation	0.79		0.24	1.16	5.75	2.82
2011	Count	20	3	20	17	20	20
	Minimum	0.85	1.81	0.09	0.97	0.01	3.54
	Maximum	4.47	3.43	2.67	7.97	6.41	18.72
	Mean	1.54	2.35	0.47	2.45	1.18	6.39
	Median	1.27	1.81	0.30	1.76	0.40	5.29
	Standard deviation	0.81	0.93	0.58	1.82	1.81	3.46

Note: No swathing was carried out on these paddocks in 2010

In both 2010 and 2011, 20 out of 24 paddocks were seeded. The mean cost per grain yield for seeding of 2.48 USD/ha/t in 2010 was higher than 1.54 USD/ha/t in 2011, possibly due to increased average grain yields (44.8% higher) in 2011 related to the increased rainfall (20.7% higher) in the region (Table 4.5). As the grain yield (denominator) increases, the USD (numerator) are distributed over a larger yield. The SD around the mean for 2010 (0.79 USD/ha/t) is slightly lower than the SD of 0.81 USD/ha/t in 2011. Swathing was carried out on three paddocks in 2011 with a mean cost of machinery of 2.35 USD/ha/t. The mean value of the cost of machinery, for spraying, was 0.49 USD/ha/t in 2010 and 0.475 USD/ha/t in 2011, due to the higher grain yield (Table 4.5). As the grain yield increases, the overall cost of machinery use is expected to decrease. In 2010, 18 paddocks were sprayed and 20 were sprayed in 2011. However, some of these paddocks may have been sprayed more than once if the weed or pest burden was high. For additional applications the crop is usually sprayed in spring when it is ripe enough to mature (pers. comm., Harries, DAFWA, Geraldton, Western Australia) (Appendix F, Table F.4). The SD of 0.24 USD/ha/t around the mean of 0.49 USD/ha/t, in 2010, shows that the cost of machinery was more closely distributed to the mean, than the value of 0.58 USD/ha/t in 2011. This may be as a result of the number of times the sprayer was used in 2010 (18 x) vs 2011 (20 x) (Appendix F, Table F.4). If more values are obtained for a variable there is a greater likelihood that the dispersion around the mean will be more spread out than if there were less values. The top-dresser applied fertiliser to the paddocks seven times in 2010 versus 17 times in 2011. The means for these years are 2.56 USD/ha/t in 2010 versus 2.45 USD/ha/t in 2011, showing that the cost of machinery production per tonne of wheat in 2011 was slightly less than in 2010, possibly due to the increased use of the machinery. As machinery use increases, the cost of the machinery (numerator) is more diffuse due to the cost being spread over a larger area (denominator). The SD of 1.82 USD/ha/t in 2011 was higher than the SD of 1.16 USD/ha/t in 2010. More values (17) were available in 2010 than in 2010 (7), thus the allocation of these values for 2011 may be further from the mean than those of 2010. The mean value of lime application in 2010 was 3.06 USD/ha/t versus 1.18 USD/ha/t in 2011. This difference in the means was mainly due to the increased average crop yield 2011 vs 2010 (Table 4.12). The SD of 5.75 USD/ha/t for lime in 2010 is higher than the SD of 1.81 USD/ha/t in 2011. The mean value of the cost of machinery per tonne of grain yield for harvesting in 2010 was 10.3 USD/ha/t (SD = 2.82 USD/ha/t) while in 2011 the mean was 6.39 USD/ha/t (SD = 3.46 USD/ha/t). Twenty paddocks were harvested in 2010 and 2011. The lower mean in 2011 shows that the machinery used exhibited a lower cost for the farmer in 2011, although less paddocks were harvested. In addition the higher yield (denominator) for most paddocks in 2011 may have reduced the cost of the machinery through diluting the cost of the machinery (numerator).

Table 4.13 summarises the minimum, maximum, mean, median and SD values of machinery inputs for the fuel use (machinery operation) of the farm machinery. As only one data set was available, thus not allowing for accurate statistical analysis, mouldboarding and claying were not included in this table.

Table 4.13. Statistical summary of the machinery operation in terms of fuel use

Statistical details		Seeding	Swathing	Spraying	Top-dressing fertiliser	Top-dressing lime	Harvesting
		l/hr/t	l/hr/t	l/hr/t	l/hr/t	l/hr/t	l/hr/t
2010	Count	20		18	7	18	20
	Minimum	1.73		0.19	0.18	0.03	2.36
	Maximum	4.63		0.82	0.91	2.60	6.31
	Mean	2.78		0.48	0.48	0.46	3.84
	Median	2.62		0.45	0.40	0.08	3.66
	Standard deviation	0.79		0.21	0.30	0.84	1.07
2011	Count	20	3	20	17	20	20
	Minimum	0.99	2.45	0.10	0.14	0.01	1.34
	Maximum	5.21	4.64	1.81	1.73	0.94	7.10
	Mean	1.74	3.18	0.41	0.46	0.20	2.42
	Median	1.47	2.45	0.31	0.31	0.06	2.01
	Standard deviation	0.94	1.27	0.39	0.43	0.27	1.31

Note: No swathing was carried out on these paddocks in 2010

In 2010 and 2011, all 20 paddocks were seeded, with a mean fuel consumption of 2.78 l/hr/t and 1.74 l/hr/t, respectively. The SD of 0.79 l/hr/t in 2010 was lower than that of 0.94 l/hr/t in 2011. As the area seeded and the machinery used remained the same for both years, it would appear that the crop yield for these paddocks altered the values. A higher crop yield in 2011 resulted in a lower mean value, thus indicating that the consumption of fuel was less in 2011 than in 2010 (Table 4.5) (Appendix F, Table F.5). Swathing was carried out on the same farm in 2011 with a mean fuel consumption of 3.18 l/hr/t. No further analyses could be made for swathing from the data from this current research, as only one dataset was available. A mean of 0.48 l/hr/t (2010) versus a mean of 0.40 l/hr/t (2011) was calculated for spraying chemicals on 18 and 20 paddocks respectively, and this difference is due to the difference in grain yields in these years (Table 4.5). A SD of 0.21 l/ha/t showed less dispersion of results about the mean than 0.39 l/ha/t for 2011 (Appendix F, Table F.5). Although only seven paddocks were top-dressed with fertiliser in 2010 versus 17 in 2011, the means are in close agreement with each other, 0.48 l/hr/t in 2010 versus 0.46 l/hr/t in 2011, showing that the average fuel consumption was almost the same for top-dressing of fertilisers in both years. The higher SD of 0.43 l/hr/t in 2011 versus 0.30 l/hr/t in 2010 shows more dispersed results about the mean. This higher level of dispersion is expected as the sample count is more in 2011.

The mean of the amount of lime applied for the top-dressing in 2010 was 0.42 l/hr/t and 0.20 l/hr/t for 2011. The sample sizes were 18 and 20, respectively. As the sample size does not differ much or the area of application, it can be stated that this difference is due to the increased average crop yield for 2011 (Table 4.5). The SD is 0.84 l/ha/t for 2010 and 0.27 l/ha/t in 2011. When calculating the machinery fuel consumption for harvesting, a mean value of 3.84 l/hr/t in 2010 and 2.42 l/hr/t in 2011 was determined, which correlates with the increased grain yield in 2011 (Table 4.5). The SD was lower in 2010 (1.07 l/hr/t) than in 2011 (1.31 L/ha/t). This may also be as a result of the higher grain yield in 2011.

- Chemical emissions database

The use of chemicals for agricultural applications generates emissions due to the production, transportation and application thereof. In this project the emissions were quantified in terms of the production of chemicals used per tonne of crop yield (kg/yr/t) and the emissions generated during the transportation of the chemical (tkm/yr/t). The chemical databases provided the total distance the chemicals were transported, from manufacture or formulation, to the paddock as discussed in Chapter 3 (section 3.3.2.2). The list of classified chemicals specifying the name of the chemical, the producer/formulator, the country of origin, the density, the distances travelled and capacities of the transporting vehicle, as well as the national or international allocation, are included in Appendix F (Tables F.6-F.11) and explained using an example. The production and transportation of fertilisers is included in these discussions as the methods used are the same.

Tables 4.14–4.18 are statistical summaries of the chemicals used by the farmers over both seasons and specifies the chemical class used.

Table 4.14. Statistical analyses of fertilisers used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
Fertilisers	Ag Flow Extra							2	17.5	18.4	18.0	18.0	0.7
	Agras	2	55.0	55.6	55.3	55.3	0.4	2	32.3	33.3	32.8	32.8	0.8
	Agstar Extra							3	22.8	32.3	28.3	29.7	4.9
	Agstar Trace	1	48.8	48.8	48.8	48.8							
	Agyield Extra	1	27.0	27.0	27.0	27.0	0.0	1	25.2	25.2	25.2	25.2	
	Cereal							4	12.9	68.8	31.0	21.3	25.4
	Copper							2	13.9	23.0	18.4	18.4	6.4
	DAP	3	46.2	54.5	50.7	51.3	4.2	2	19.1	19.1	19.1	19.1	0.0
	DAPSZC	3	15.6	27.8	22.0	22.7	6.1						
	Dap Extra	3	28.2	34.6	31.0	30.3	3.3						
	K Till Extra	2	43.7	46.9	45.3	45.3	2.3	1	38.3	38.3	38.3	38.3	
	Macro pro plus	2	50.0	51.5	50.8	50.8	1.1	1	38.5	38.5	38.5	38.5	
	Macro Pro Etra												
	MAP	1	42.9	42.9	42.9	42.9	0.0	2	33.4	42.9	38.1	38.1	6.7
	MAPSZC	3	15.6	27.8	22.0	22.7	6.1						
	MaxAmFLO	1	93.2	93.2	93.2	93.2	0.0	1	50.0	50.0	50.0	50.0	
	MaxAamRite							1	22.7	22.7	22.7	22.7	
	MOP	1	18.2	18.2	18.2	18.2	0.0	3	18.8	25.5	23.3	25.5	3.9
	Sodium molybdate							1	0.0	0.0	0.0	0.0	
	UAN	3	30.0	51.0	40.4	40.2	10.5	11	5.5	51.9	23.9	21.1	12.1
	Urea	6	15.6	63.1	33.9	25.3	21.0	10	0.2	38.5	17.0	15.6	13.2
	Zinc/Manganese							1	0.7	0.7	0.7	0.7	

Table 4.15. Statistical analyses of fungicides and insecticides used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/year/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
Fungicides and insecticides	Alpha Cypermethrin							7	0.0258	0.1163	0.0525	0.0450	0.0305
	Alpha Duo	3	0.04	0.05	0.04	0.05	0.01						
	Dimethoate							1	0.0000	0.0000	0.0000	0.0000	
	Dividend	1	1.49	1.49	1.49	1.49	0.00	2	0.0604	0.0756	0.0680	0.0680	0.0108
	Folicur							2	0.0589	0.0767	0.0678	0.0678	0.0126
	Le-Mat	2	0.07	0.61	0.34	0.34	0.38	1	0.0407	0.0407	0.0407	0.0407	
	Lorsban	1	0.08	0.08	0.08	0.08	0.00	4	0.0374	0.1034	0.0766	0.0827	0.0279
	Premis	1	0.01	0.01	0.01	0.01	0.00						
	Prosaro 420							1	0.0540	0.0540	0.0540	0.0540	
	Raxil	1	0.01	0.01	0.01	0.01	0.00						
	Tilt							1	0.1106	0.1106	0.1106	0.1106	
	Vincit	1	0.04	0.04	0.04	0.04	0.00	2	0.0233	0.0245	0.0239	0.0239	0.0009

Table 4.16. Statistical analyses of herbicides used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
Herbicides	Ally	1	3.030	3.030	3.030	3.030	0.000						
	Amine 625							1	0.425	0.425	0.425	0.425	
	Amine 720	1	0.300	0.300	0.300	0.300	0.000						
	Atlantis	1	0.155	0.155	0.155	0.155	0.000						
	Atraxine 500							1	1.729	1.729	1.729	1.729	
	Avadex	1	0.750	0.750	0.750	0.750	0.000	2	0.769	1.288	1.029	1.029	0.367
	Bifenthrin							1	46.500	46.500	46.500	46.500	
	Brodal							1	0.147	0.147	0.147	0.147	
	Bromicide							1	0.125	0.125	0.125	0.125	
	Crusader							2	0.001	0.108	0.054	0.054	0.076
	Diuron	2	0.023	0.218	0.121	0.121	0.138	4	0.096	1.026	0.438	0.315	0.443
	Eclipse	1	0.002	0.002	0.002	0.002							
	Ester 600	1	0.455	0.455	0.455	0.455		1	0.247	0.247	0.247	0.247	
	Ester 680	2	0.180	2.362	1.271	1.271	1.543	1	0.320	0.320	0.320	0.320	
	Ester 800	2	0.152	0.237	0.195	0.195	0.061						
	Garlon	1	0.398	0.398	0.398	0.398		2	0.034	0.077	0.055	0.055	0.030
	Gladiator	2	0.583	0.938	0.760	0.760	0.251						
	Gramoxone							3	0.009	0.446	0.201	0.149	0.223
	Jaguar	1	0.556	0.556	0.556	0.556		3	0.035	0.833	0.352	0.186	0.424
	Lexone							3	0.053	0.377	0.185	0.125	0.170
	Logran	15	0.001	1.558	0.322	0.025	0.527	10	0.004	5.821	0.682	0.132	1.807
	Lorsban	1	0.480	0.480	0.480	0.480		10	0.004	5.821	0.752	0.173	1.792

Table 4.16 (continued). Statistical analyses of herbicides used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
Herbicides	MCPA LVE	3	0.017	0.232	0.156	0.218	0.120	7	0.0003	0.7663	0.309	0.137	0.352
	MONZA	2	0.018	0.019	0.019	0.019	0.001						
	Precept	3	0.001	1.157	0.505	0.358	0.592						
	Roundup	15	0.002	2.305	0.817	0.792	0.501	16	0.100	0.871	0.409	0.367	0.187
	Select							3	0.169	0.339	0.268	0.297	0.089
	Simazine 500							1	1.581	1.581	1.581	1.581	
	Sprayseed	1	0.194	0.194	0.194	0.194		2	0.042	1.463	0.752	0.752	1.005
	Tigrex	2	0.362	0.425	0.394	0.394	0.045	5	0.007	0.502	0.216	0.165	0.186
	Topik	1	0.560	0.560	0.560	0.560							
	Treflan	14	0.001	1.515	0.711	0.625	0.600	14	0.003	0.858	0.311	0.270	0.242
	Triasulfuron	1	0.019	0.019	0.019	0.019							
	Trifluralin	3	0.041	1.091	0.638	0.781	0.539						
	TRIFLURX	1	0.634	0.634	0.634	0.634		1	0.712	0.712	0.712	0.712	
	Velocity	2	0.243	0.260	0.252	0.252	0.013						
	Verdict							1	0.575	0.575	0.575	0.575	

Table 4.17. Statistical analyses of adjuvants used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
Adjuvants	Ammonium Sulphate							1	0.199	0.199	0.199	0.199	
	Hasten	2	0.21	0.45	0.33	0.33	0.17	7	0.013	0.493	0.176	0.194	0.172
	LI 700							2	0.000	0.006	0.003	0.003	0.004
	Uptake							1	0.084	0.084	0.084	0.084	
	Wetter BS 1000							8	0.002	0.096	0.023	0.005	0.037

Table 4.18. Statistical analyses of lime used in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t	count	minimum kg/yr/t	maximum kg/yr/t	mean kg/yr/t	median kg/yr/t	standard deviation kg/yr/t
	Lime	20	41.5	136.4	80.8	75.5	27.8	20	28.6	187.5	49.7	38.0	34.9

The large variation in range shows that the individual chemical applications were specific for each paddock as well as for each chemical used. Application rates of chemicals varied due to the type of crops planted, the incidence of the pest targeted, crop resistances to the chemicals, recommended dosages and general soil health. The number of applications (count) was determined by factors such as resistance to the chemicals and concentrations of applications. Furthermore, the choice of the chemicals varied across paddocks possibly as a result of the personal preferences of the farmers, economic factors, soil types and soil health.

When comparing the mean values over both seasons it was taken into account that these averages were based on the actual application rates of the actual chemical (not converted to a generic chemical) and are not recommended dosages. No specific deductions should be made from these dosages other than communicating a value. The SDs have been calculated where the sample size is larger than one and communicates the distribution of the dosages about the mean. A lower SD will indicate that the dispersion about the mean is smaller and thus the results may be assumed to be more reliable. This could likely be a result of more accurate applications of the chemicals on the paddocks.

The transportation route was separated into four different journeys, of which the route could include all four or only one depending on the origin of the product (Figure 4.4). The distance from Kwinana (the industrial area of Perth) to Dalwallinu was established as 235 km and from Kwinana to Northam as 107 km (Figure 3.2).

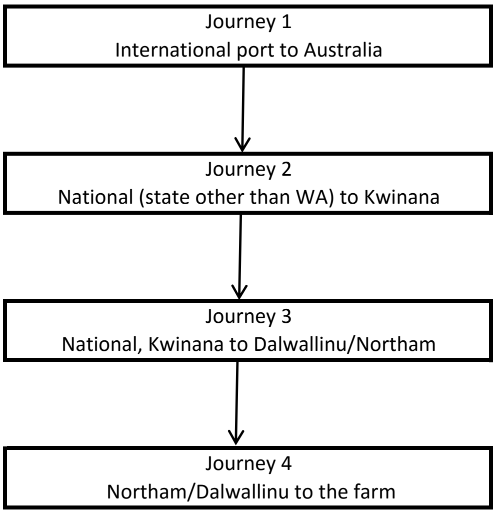


Figure 4.4. Simplified representation of the four journeys applicable to chemical transportation

Table 4.19 specifies the distances from either Dalwallinu or Northam to each farm. Figure 3.3 shows the locations of the paddocks relative to each other and relative to Perth.

Table 4.19 Distances from local town of delivery to the farm

Farm	Paddocks	Distance from local area to the farm (km)	Grower group
A	1, 2, 3	18.4	Liebe Group
B	4, 5, 6	10.4	Liebe Group
C	7, 8, 9	48	Liebe Group
D	10, 11, 12	12.9	Liebe Group
E	13, 14, 15	65	Liebe Group
F	16, 17, 18	32	WANTFA
G	19, 20, 21	37.9	WANTFA
H	22, 23, 24	51.8	WANTFA

The following tables (Tables 4.20–4.24) are statistical summaries of the distances the chemicals used by the farmer were transported (km), from origin to delivery, and the quantity of the chemicals (t) applied. The count specifies how many times each chemical was used in that year.

The criteria specified in these tables, namely minimum, maximum, median, mean, and SD, are analysed using the same basis as for the production and use of chemicals as specified in the foregoing text.

Table 4.20. Statistical analyses of fertilisers transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum	maximum	mean	median	standard deviation	count	minimum	maximum	mean	median	standard deviation
			tkm/t	tkm/t	tkm/t	tkm/t	tkm/t		tkm/t	tkm/t	tkm/t	tkm/t	tkm/t
Fertilisers	**AgFlow Extra**							2	2.54	2.67	2.60	2.60	0.09
	Agras	2	13.63	13.77	13.70	13.70	0.10	2	8.00	8.26	8.13	8.13	0.19
	Agstar Extra							3	5.78	8.19	7.16	7.52	1.25
	Agstar Trace	1	7.07	7.07	7.07	7.07	0.00						
	Agyield EXtra	1	6.62	6.62	6.62	6.62	0.00	1	0.06	0.06	0.06	0.06	
	Cereal							4	3.65	19.53	7.72	3.85	7.87
	Copper							2	0.05	0.10	0.08	0.08	0.04
	Dap	3	198.83	234.98	218.25	220.92	18.22	2	82.36	82.36	82.36	82.36	0.00
	DAP SZC	3	67.05	119.19	94.59	97.52	26.20						
	Dap Extra	3	7.14	8.76	7.86	7.68	0.83						
	Gypsum												
	K Till Extra	2	10.72	11.50	11.11	11.11	0.55	1	9.39	9.39	9.39	9.39	
	Macropro plus	2	7.25	7.47	7.36	7.36	0.16						
	Macropro Extra							1	5.57	5.57	5.57	5.57	
	MAP	1	5.96	5.96	5.96	5.96		2	5.96	144.00	74.98	74.98	97.61
	MAP SZC	3	67.05	119.19	94.59	97.52	26.20						
	MaxAmFLO	1	12.95	12.95	12.95	12.95		1	6.95	6.95	6.95	6.95	
	MaxAmRite							1	6.43	6.43	6.43	6.43	
	MOP	1	5.15	5.15	5.15	5.15		3	1.33	5.31	2.66	1.33	2.29
	Sodium molybdate							1	0.004	0.004	0.004	0.004	
	UAN	3	4.35	7.39	5.86	5.83	1.52	11	1.67	84.00	12.38	5.45	23.89
	Urea	6	161.6	650.11	349.2	261.1	215.6	10	4.8	394.2	210.4	201.0	117.0
	Zinc/Manganese							1	0.10	0.10	0.10	0.10	

Table 4.21. Statistical analyses of fungicides and insecticides transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum	maximum	mean	median	standard deviation	count	minimum	maximum	mean	median	standard deviation
			tkm/t	tkm/t	tkm/t	tkm/t	tkm/t		tkm/t	tkm/t	tkm/t	tkm/t	tkm/t
Fungicides and insecticides	Alpha Cypermethrin							7	0.003	0.035	0.011	0.007	0.011
	Alphasip Duo	3	0.010	0.013	0.012	0.012	0.001						
	DIMETHOATE												
	Dividend	1	17.439	17.439	17.439	17.439		2	0.713	0.885	0.799	0.799	0.122
	Folicur							2	0.274	0.356	0.315	0.315	0.058
	Le-Mat	2	1.034	8.895	4.965	4.965	5.559	1	0.593	0.593	0.593	0.593	
	Lorsban	1	0.011	0.011	0.011	0.011		4	0.010	0.014	0.012	0.011	0.002
	Premis	1	0.045	0.045	0.045	0.045							
	Prosaro 420							1	0.250	0.250	0.250	0.250	
	Raxil	1	0.041	0.041	0.041	0.041							
	Tilt							1	0.418	0.418	0.418	0.418	
	Vincit	1	0.009	0.009	0.009	0.009		2	0.004	0.004	0.004	0.004	0.000

Table 4.22. Statistical analyses of herbicides transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum tkm/t	maximum tkm/t	mean tkm/t	median tkm/t	standard deviation tkm/t	count	minimum tkm/t	maximum tkm/t	mean tkm/t	median tkm/t	standard deviation tkm/t
Herbicides	Ally	1	44.10	44.10	44.10	44.10							
	Amine 625							1	1.368	1.368	1.368	1.368	
	Amine 720	1	1.669	1.669	1.669	1.669							
	Atlantis	1	2.954	2.954	2.954	2.954							
	Atraxine							1	0.240	0.240	0.240	0.240	
	Avadex	1	0.199	0.199	0.199	0.199		2	0.103	0.141	0.122	0.122	0.027
	Bifenthrin							1	174.61	174.61	174.61	174.61	
	Brodal							1	0.687	0.687	0.687	0.687	
	Bromicide							1	0.031	0.031	0.031	0.031	
	Crusader							2	2.254	2.765	2.509	2.509	0.362
	Diuron	2	0.009	0.054	0.032	0.032	0.032	4	0.019	0.036	0.028	0.029	0.007
	Eclipse	1	0.030	0.030	0.030	0.030							
	Ester 600	1	1.467	1.467	1.467	1.467		1	0.078	0.078	0.078	0.078	
	Ester 680	2	0.733	2.362	1.547	1.547	1.152						
	Ester 800	2	0.037	0.058	0.048	0.048	0.015						
	Garlon							2	0.077	0.109	0.093	0.093	0.022
	Gladiator	3	0.098	0.230	0.157	0.143	0.067						
	Gramaxone							4	0.030	0.113	0.068	0.066	0.040
	Jaguar	1	0.104	0.104	0.104	0.104		3	0.072	0.113	0.093	0.094	0.021
	Lexone							3	0.773	1.823	1.256	1.173	0.530
	Logran	15	0.000	0.738	0.107	0.069	0.182	9	0.016	20.702	2.438	0.061	6.851
	Lorsban	1	0.013	0.013	0.013	0.013							

Table 4.22 (cont.). Statistical analyses of herbicides transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum	maximum	mean	median	standard deviation	count	minimum	maximum	mean	median	standard deviation
			tkm/t	tkm/t	tkm/t	tkm/t	tkm/t		tkm/t	tkm/t	tkm/t	tkm/t	tkm/t
Herbicides	**MCPA LVE**	3	0.047	0.073	0.063	0.069	0.014	7	0.000	0.087	0.041	0.034	0.033
	Monza	2	0.065	0.068	0.067	0.067	0.002	1	0.364	0.364	0.364	0.364	
	Precept	3	1.624	2.179	1.881	1.842	0.279						
	Roundup	15	0.000	0.584	0.216	0.215	0.134	16	0.009	0.214	0.103	0.100	0.060
	Select							3	0.041	0.084	0.058	0.047	0.023
	Simazine 500							1	23.06	23.06	23.06	23.06	
	Sprayseed	1	0.048	0.048	0.048	0.048		4	0.010	0.414	0.126	0.040	0.193
	Tigrex	2	0.109	0.128	0.118	0.118	0.013	5	0.002	0.077	0.033	0.024	0.028
	Topik	1	2.105	2.105	2.105	2.105		2	0.091	0.112	0.102	0.102	0.014
	Treflan	14	0.003	4.981	2.266	2.116	1.939	14	0.002	5.374	1.686	1.589	1.354
	Triasulfuron	1	0.042	0.042	0.042	0.042							
	Trifluralin	3	0.010	21.901	7.368	0.192	12.587						
	Triflurx	1	0.156	0.156	0.156	0.156		1	0.175	0.175	0.175	0.175	
	Velocity	2	1.126	1.208	1.167	1.167	0.058						
	Verdict							1	1.872	1.872	1.872	1.872	

Table 4.23. Statistical analyses of adjuvants transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum	maximum	mean	median	standard deviation	count	minimum	maximum	mean	median	standard deviation
			tkm/t	tkm/t	tkm/t	tkm/t	tkm/t		tkm/t	tkm/t	tkm/t	tkm/t	tkm/t
Adjuvants	Ammonium Sulphate	2	0.05	0.11	0.08	0.08	0.04	8	0.004	0.15	0.05	0.03	0.06
	BS 1000							8	0.03	1.39	0.34	0.07	0.53
	Hasten							1	0.75	0.75	0.75	0.75	
	LI 700							2	0.000	0.002	0.001	0.001	0.001
	Uptake							1	0.31	0.31	0.31	0.31	

Table 4.24. Statistical analyses of lime transported in 2010 and 2011

Chemical Classification	Chemical Type	2010						2011					
		count	minimum	maximum	mean	median	standard deviation	count	minimum	maximum	mean	median	standard deviation
			tkm/t	tkm/t	tkm/t	tkm/t	tkm/t		tkm/t	tkm/t	tkm/t	tkm/t	tkm/t
	Lime	20	11.30	52.91	27.76	26.93	11.94	20	8.86	58.13	17.59	13.38	11.91

The variation in the quantity and the kilometres travelled will influence the range of the calculated chemical payload. The count of each chemical was determined by factors such as how many applications of the chemical were used in that specific year. The differences in the types of chemicals used varied as a result of the personal preferences of the farmers, economic factors, soil types and soil health.

When comparing the mean values of 2010 with 2011 it was taken into account that these averages were based on the actual application rates of the actual chemical (not converted to a generic chemical) and not on the recommended dosages, as well as the actual distance travelled from point of manufacture/formulation to the delivery of the chemical on the farm. As the dosages per farm, paddock and year differ the means are not expected to correlate in all instances, as the variables (t and km) will differ. No specific deductions should be made from these tkm values other than just communicating a value. The SDs have been calculated where the sample size is larger than one and conveys the distribution of the tkm about the mean.

- Climatic variables

The input data required to calculate the emission factors to determine whether leaching will take place in a specific soil profile are the annual rainfall and the minimum and maximum evapotranspiration (Et) rates. These input data are used to calculate Et/P (P = precipitation (mm)), which in turn determines the emissions factor and subsequently whether or not leaching takes place at that paddock (Chapter 3, section 3.3.2.2). All the calculated values are tabulated in Appendix F (Table F.12) and are summarised in Table 4.25. The annual average rainfall (P) for each paddock was calculated using the monthly rainfall figures obtained from the BOM website, based on the cropping cycle for a 12 month period starting from the month of June (Appendix F, Table F.13-F.14). The Et values were also obtained from the BOM website (Table 4.25) (BOM, 2014c). The emissions factor was allocated as 0 if Et/P was between 0.8 and 1.0 as no leaching took place, and as 0.03 when Et/P was not within 0.8–1.0, as leaching took place.

Table 4.25. Summary of climatic variables

2010	Average rainfall (2010) mm	Et min mm	Et max mm	Average ET/P	Emission factor	Leaching/not leaching	Average rainfall (2011)	Et min mm	Et max mm	Average ET/P	Emission factor	Leaching/not leaching
1	201.0	300	400	1.7	0.03	leaching	271.2	300	400	1.3	0.03	leaching
2	201.0	300	400	1.7	0.03	leaching	271.2	300	400	1.3	0.03	leaching
3	201.0	300	400	1.7	0.03	leaching	271.2	300	400	1.3	0.03	leaching
4	332.2	300	400	1.1	0.00	no leaching	443.3	300	400	0.8	0.00	no leaching
5	226.7	300	400	1.5	0.03	leaching	436.6	300	400	0.8	0.00	no leaching
6	276.2	300	400	1.3	0.03	leaching	419.2	300	400	0.8	0.00	no leaching
7	231.4	300	400	1.5	0.03	leaching	361.0	300	400	1.0	0.03	leaching
8	247.2	300	400	1.4	0.03	leaching	364.4	300	400	1.0	0.00	no leaching
9	247.2	300	400	1.4	0.03	leaching	364.4	300	400	1.0	0.00	no leaching
10												
11	179.2	300	400	2.0	0.03	leaching	271.2	300	400	1.3	0.03	leaching
12	179.2	300	400	2.0	0.03	leaching	271.2	300	400	1.3	0.03	leaching
13	412.7	300	400	0.8	0.00	no leaching	149.6	300	400	2.3	0.03	leaching
14	412.7	300	400	0.8	0.00	no leaching	149.6	300	400	2.3	0.03	leaching
15	412.7	300	400	0.8	0.00	no leaching	149.6	300	400	2.3	0.03	leaching
16												
17												
18	233.8	300	400	1.5	0.03	leaching	393.2	300	400	0.9	0.00	no leaching
19	281.4	500	600	2.0	0.03	leaching	431.3	500	600	1.3	0.03	leaching
20	281.4	500	600	2.0	0.03	leaching	431.3	500	600	1.3	0.03	leaching
21	281.4	500	600	2.0	0.03	leaching	431.3	500	600	1.3	0.03	leaching
22												
23	269.4	400	500	1.7	0.03	leaching	449.0	400	500	1.0	0.00	no leaching
24	269.4	400	500	1.7	0.03	leaching	449.0	400	500	1.0	0.00	no leaching

- Life cycle inventories

The aforementioned databases were combined to develop an LCI for each of the two years for each of the 24 paddocks, under the eight farms included in this current research as elaborated on in Chapter 3 (section 3.3.2.2). There were no new input requirements for the unit processes or the entire system, as all the inputs for these databases were calculated and links were established for importing the values into the LCI databases to conduct the LCIA analysis in Chapter 5.

- Inventory list

The inventory lists for this project, wherein the results for each farm consist of a number of paddocks, for each classification (as separate tables) have been summarised in one Appendix F, (Table F.15-F.54).

4.3. CHAPTER SUMMARY

The aim of this chapter was to present the goal and scope as well as the LCI of this research, as they are prerequisites to calculating carbon footprints. The first section revisited the goal and scope of the LCA by defining the functional unit, setting system boundaries and specifying the assumptions and limitations. The next section expanded on the LCI by illustrating the process flows, explaining the data collection phase and finally generating the LCI lists.

The next chapter (Chapter 5) will commence by discussing the conversion of chemicals summarised in the LCIs to appropriate equivalents, and then convert them to impacts by multiplying with the emission factors known as LCIA. The chapter will then present and interpret the results obtained for the LCIA. LCI will assist in the interpretation of LCIA as to which inputs or outputs cause the predominant impact. The inputs and outputs in the LCIs, as discussed in this chapter will be multiplied by the corresponding emission factors to calculate the carbon footprint of grain products in Western Australia in the next chapter. Furthermore, the LCIA analysis in Chapter 5 will enable the identification of 'hotspots' for determining mitigation strategies. Thereafter, Chapter 6 will expand more on the LCIA by presenting the results obtained when integrating the LCA with the GIS portion of the project.

CHAPTER 5

INTERPRETATION OF LIFE CYCLE IMPACT ASSESSMENT RESULTS

The development of the life cycle inventory (LCI) including inputs and outputs, multiplied by the corresponding emission factors, is used to carry out the life cycle impact assessment (LCIA), which is then interpreted to determine the causes of any significant impact. This chapter will make use of the LCIs that have been compiled in the previous chapter to initiate the LCIA to determine the carbon footprint of grain production and to identify ‘hotspots’. The results will be further analysed and interpreted in this chapter before being integrated into the geographical information systems (GIS) and remote sensing (RS) applications in the next chapter.

5.1 LIFE CYCLE IMPACT ASSESSMENT

As part of a life cycle assessment, LCIA is the phase that is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. The obligatory elements of the LCIA are classification and characterisation and there are optional elements that may be included in the assessment, such as normalisation, ranking, grouping and weighting (Goedkoop et al., 2013; ISO, 2006).

During classification, the LCI results are assigned to impact on categories such as global warming and are thereafter characterised when the LCI impacts are modelled within the impact categories. Normalisation is used to express the impacts in ways they may be compared with each other, usually by dividing or multiplying by a reference value to make the impact category dimensionless. Grouping is used to sort or rank the indicators, weighting emphasises the most important potential impacts, and finally all of the results of the LCIA are analysed and reported (Azapagic, 1999; Curran, 2006; Finnvedin et al., 2009; Margni & Curran, 2012).

This section will first present the results obtained during the conversion of all farm chemicals identified in the project to a generic or reference chemical and will thereafter focus on the elements (classification, characterisation, normalisation) of the LCIA used. The interpretation of the LCIA results are expanded on, and confirmed using the IST in Chapter 6.

5.2 CONVERSION OF CHEMICALS

The conversion of field data to standard generic chemicals is not specifically a function of the LCIA but is included here as it is necessary to complete this particular LCIA.

Chapter 3 (section 3.3.2.3) detailed the steps followed, and summarised here, for the conversion of the chemicals to generic equivalents.

1) the allocation of each chemical to a class (Table 4.14-4.18) to enable the identification of the emission factor that would later be applied to that class and the chemicals therein.
2) The calculation of the average recommended application rate of each chemical (generic and actual) (Appendix E, Table E.2-E4).
3) The calculation of a conversion factor for each chemical based on the volumes calculated in step 3 (Appendix G, Table G.1).
4) The actual conversion of the chemical to a generic equivalent chemical (section 3.3.2.3).
5) Finally the calculation for the application rates and the distances transported from place of manufacture/formulation to final delivery location.

5.3 ELEMENTS OF LIFE CYCLE IMPACT ASSESSMENT

The impact category considered in this study was the global warming impact category. The details of the impact category are specified and discussed in the literature review (Chapter 2).

Following the documentation of the LCI, all gases were converted to carbon dioxide equivalents per tonne of grain (CO_2-e/t) during normalisation (Appendix G, Tables G.2– G.41) to represent the total amount of CO_2-e/t emissions per tonne of grain harvested as discussed in Chapter 3 (section 3.3.2.3), for comparative purposes. Thereafter these results were aggregated and presented as the carbon footprint (Appendix H.1–H.8). The results in these carbon footprint tables were used for modelling purposes (the characterisation element of the LCIA, as presented in Chapter 6). All results were calculated and then presented separately for 20 paddocks within eight farms.

The next section presents the paddock logistics and the different management methods applicable to this study. Additionally the pre-farm and on-farm GHG emissions were reported on, analysed and interpreted using literature, LCI inputs and outputs in Chapter 4 for each farm and paddock. The integration of the LCIA with GIS and RS is discussed in Chapter 6.

5.4 FARMS AND PADDOCKS

The farms in Western Australia have been further divided into smaller management units, locally known as paddocks. The boundaries of these paddocks are typically defined by fences, water, pathways or other means. Within farms, the farm management practices (FMP) may vary between paddocks. Three paddocks have been selected for experimental purposes from each of the eight farms included in DAFWA's farming system research project. All farms are located within a dry temperate zone and predominantly broadacre cropping systems. The majority of rain falls during the growing season from June to November (Price Waterhouse Cooper (PWC), 2011). The following text presents the details of the FMP for the selected farms including their paddocks.

5.4.1 Farm A, paddocks 1, 2 and 3

The average annual rainfall for paddocks 1, 2 and 3 on Farm A is 300–400 mm with an average annual temperature of 18–21 °C (Bureau of Meteorology (BOM), 2014c). The mean measured rainfall was 201.0 mm in 2010 and 271.2 mm in 2011, and lower than the long term average (Appendix F, Table F.12–F.14). The soil types are red Kandosol (red sandy earth), Calcic Calcarosol (calcareous loamy earth) and variable soils (ironstone gravelly soils supergroup), respectively (Table 4.2, section 4.2.2.2). Table 5.1 summarises the practices used on these three paddocks. In 2010 wheat was planted in June and harvested in November, and the stubble burned in windrows[1] in the following May. In 2011, wheat was planted in June and harvested in November and then the stubble of all three paddocks was grazed by sheep. Only

[1] Windrow burning is the burning of plant slash that has been piled into long continuous rows (Define, 2015)

paddock 2 was windrow burned. The wheat yield in 2011 was higher than 2010 for all three paddocks. In both years, for all paddocks, fertiliser was applied with the seed during sowing. Paddock 1 and 3 received an additional two fertiliser applications in 2011.

Table 5.1. Farming practices for Farm A

2010			2011		
Paddock 1	**Paddock 2**	**Paddock 3**	**Paddock 1**	**Paddock 2**	**Paddock 3**
159 ha	97 ha	114 ha	159 ha	97 ha	114 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat
Grain yield: 1.32 t/ha	Grain yield: 1.21 t/ha	Grain yield: 1.38 t/ha	Grain yield: 2.85 t/ha	Grain yield: 2.01 t/ha	Grain yield: 2.19 t/ha
No grazing	No grazing	No grazing	Grazing of 900 head of sheep for 60 days	Grazing of 430 head of sheep for 31 days	Grazing of 450 head of sheep for 59 days
Windrow burn	Windrow burn	Windrow burn	No burn	Windrow burn	No burn

The GHG emissions are expected to vary between the three paddocks due to the different FMP in terms of one tonne of grain production from pre- and on-farm stages; presented in Tables 5.2 and 5.3, which resulted from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm A’ in Tables G2-G7 in Appendix G.

Table 5.2. Pre-farm CO_2-e/t emissions resulting from paddocks 1, 2, 3

Farm A			Pre-farm CO_2-e/t emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	1	kg CO_2-e/t	9.58E+01	6.24E+01	2.75E+01	9.31E+01	1.92E+02	4.70E+02
	2	kg CO_2-e/t	3.04E+01	7.65E+01	3.08E+01	4.07E+01	2.35E+02	4.14E+02
	3	kg CO_2-e/t	3.18E+01	6.71E+01	2.55E+01	5.70E+01	2.06E+02	3.88E+02
Totals			1.58E+02	2.06E+02	8.37E+01	1.91E+02	6.34E+02	1.27E+03
2011	1	kg CO_2-e/t	1.34E+02	1.35E+02	1.14E+01	1.40E+02	2.26E+03	2.68E+03
	2	kg CO_2-e/t	3.80E+01	8.88E+01	1.48E+01	8.13E+01	1.39E-02	2.23E+02
	3	kg CO_2-e/t	7.44E+01	1.68E+02	1.58E+01	2.57E+02	3.67E+03	4.19E+03
Totals			2.46E+02	3.92E+02	4.20E+01	4.78E+02	5.93E+03	7.09E+03

Table 5.3. On-farm CO_2-e/t emissions resulting from paddocks 1, 2 and 3

Farm A			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing*	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	1	kg CO_2-e/t	2.70E+01	2.93E-01	0.00E+00	3.58E+01	7.47E+01	1.38E+02	6.08E+02
	2	kg CO_2-e/t	2.85E+01	3.18E-01	0.00E+00	2.49E+01	9.39E+00	6.31E+01	4.77E+02
	3	kg CO_2-e/t	2.49E+01	1.64E-01	0.00E+00	2.28E+01	8.04E+01	1.28E+02	5.16E+02
Totals			8.03E+01	7.75E-01	0.00E+00	8.35E+01	1.64E+02	3.29E+02	1.60E+03
2011	1	kg CO_2-e/t	1.22E+01	0.00E+00	1.55E+00	3.44E+01	2.62E+02	3.10E+02	2.88E+03
	2	kg CO_2-e/t	1.60E+01	4.10E-01	1.20E+00	2.40E+01	6.42E+01	1.06E+02	3.29E+02
	3	kg CO_2-e/t	1.60E+01	0.00E+00	1.08E+00	7.18E+01	3.36E+02	4.25E+02	4.61E+03
Totals			4.42E+01	4.10E-01	3.82E+00	1.30E+02	6.62E+02	8.41E+02	7.82E+03

Key: Red shading indicates the highest GHG emissions for each paddock.

*The main purpose of grazing was for stubble management during the fallow land period. Since the animals were grazed for a short period of time and then were moved to another pasture, and the lifetime of these animals and the amount of stubble fed was beyond the scope of this research, it was not possible to allocate a portion of GHG emissions to the amount of live weight gained during grazing.

5.4.1.1 Observations of GHG emissions from paddocks 1, 2 and 3

The following observations can be made for the **pre-farm** stage (Table 5.2):

- Paddocks 1 and 3 had higher GHG emissions in 2011 than in 2010, paddock 2 had lower GHG emissions in 2011.
- In 2010 paddock 1 had the highest GHGs and paddock 3 the lowest.
- In 2011 paddock 3 had the highest GHGs and paddock 2 the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 1 – transportation of fertilisers (2010 and 2011);
    - paddock 2 – transportation of fertilisers (2010), fertiliser production (2011);
    - paddock 3 – transportation of fertilisers (2010 and 2011).

The following observations can be made for the **on-farm** stage (Table 5.3):

- An increase in GHG emissions can be seen from 2010 to 2011 for all paddocks;
- In 2010 the paddock with the highest GHG emissions was paddock 1 and paddock 2 had the lowest emissions;
- In 2011 paddock 3 had the highest GHG emissions and paddock 2 had the lowest;
- The hotspots for each of the paddocks for each year is as follows:
    - paddock 1 – indirect soil emissions (2010 and 2011);
    - paddock 2 – farm machinery operation (2010), indirect soil emissions (2011);
    - paddock 3 – indirect soil emissions (2010 and 2011).

5.4.1.2 Interpretation of GHG emissions from paddock 1

The hotspots for the pre-farm stage of paddock 1 in 2010 and 2011 (Table 5.2) were emissions from the transportation of fertilisers and increased from 1.92 x 10^2 kg CO_2-e/t in 2010 to 2.26 x 10^3 kg CO_2-e/t in 2011. In 2010 there was only one application of fertiliser (along with the seed) using one fertiliser (DAP Extra). By contrast, in 2011 there were three applications of fertiliser (Table 5.4). In the first application, Agstar Extra and urea were applied with the seed, in the second application Copper and Flexi-N were applied together and in the third only Flexi-N was applied. As there were four different types of fertilisers applied in 2011 versus the one type of fertiliser applied in 2010, it can be deduced that the transportation of these fertilisers would generate more GHG emissions as collectively the distance covered to transport three fertilisers (assuming individual trips for each fertiliser) would generate more GHGs than when only one was transported (Table 5.4). In addition urea was sourced internationally, thus causing the generation of more GHG emissions through freighting. The production of a greater amount of fertiliser in 2011 thus increased the GHG emissions compared to those GHG emissions from fertiliser production in 2010. Although the GHG emissions (numerator) associated with the increased use of chemicals and transportation increased in 2011, the increase in productivity (denominator) associated with increased fertiliser application actually reduced the GHG emissions when emissions are considered on a per tonne basis.

Table 5.4. Carbon footprint from fertiliser transportation on paddock 1

Fertiliser transportation	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
Agstar Extra		9.80E-03
Copper		4.59E-01
DAP Extra	1.92E+02	
Flexi-N		2.02E-02
Urea		2.26E+03
Total	**1.92E+02**	**2.26E+03**

Overall, the total pre-farm stage emissions for paddock 1 increased from 4.70 x 10^2 kg CO_2-e/t in 2010 to 2.68 x 10^3 kg CO_2-e/t in 2011, mainly due to the increase in GHG emissions from the production of fertilisers by 7.30 x 10^1 kg CO_2-e/t, the transportation of fertilisers by 4.66 x 10^1 kg CO_2-e/t and chemical production by 3.79 x 10^1 kg CO_2-e/t. Farm machinery production decreased slightly in the second year.

Table 5.3 shows that the hotspot during the on-farm stage of paddock 1 in 2010 and 2011 was the indirect soil emissions (ISE) category, with emissions of 7.47 x 10^1 kg CO_2-e/t and 2.62 x 10^2 kg CO_2-e/t respectively, an increase of 1.87 x 10^2 kg CO_2-e/t due to an increase in the application rate of nitrogenous fertilisers (N-fertilisers). The increased application rate of N-fertilisers not only increases the direct GHG emissions but also causes indirect emissions from leaching when annual rainfall is high. In 2010, the application rate of DAP Extra was 40 kg/ha and the nitrogen (N) content of this fertiliser was 17.5% (Table 5.5). In 2011, Agstar Extra (65 kg/ha, 14.1% N), Copper (0.4 kg/ha, 13.9% N), Flexi-N (60 kg/ha, 32% N) and urea (40 kg/ha, 46% N) were applied. The annual rainfall for paddock 1 increased from 201 mm in 2010 to 271.2 mm in 2011, thereby increasing the leaching of N-fertiliser, resulting in increased ISE. The total (on-farm) emissions for paddock 1 increased from 1.38 x 10^2 kg CO_2-e/t in 2010 to 3.10 x 10^2 kg CO_2-e/t in 2011 due to the increase in ISE (1.87 x 10^2 kg CO_2-e/t) as explained above, followed by an increase of 1.55 kg CO_2-e/t from grazing. The emissions from grazing livestock were higher in 2011 as no animals were grazed in 2010. By contrast, the emissions due to farm machinery operation decreased with 1.48 x 10^1 kg CO_2-e/t, and direct soil emissions (DSE) showed a reduction of 1.38 kg CO_2-e/t and the emissions from stubble burning was reduced by 2.93 x 10^{-1} kg CO_2-e/t.

Table 5.5. Percentage nitrogen in the N-fertilisers used in this research (sourced from the material safety data sheet (MSDS) of the fertilisers)

Fertiliser	% N	Fertiliser	% N	Fertiliser	% N
AgFlow Extra	12.7	DAP SZC	17.5	MAP SZC	11.1
AgNP	11	DAP Extra	17.5	MaxAmFlo	22
Agras	16.1	Flexi –N (also known as UAN)	32	MaxAmRite	12.8
Agstar Extra	14.1	K-till Extra	10	NPS Range-Cereal	12.5
Agstar Trace	14.2	Macropro Extra	9.7	UAN (also known as Flexi- N)	32
Agyield Extra	17.2	Macropro Plus	10	Urea	46
Copper (Stratosol)	13.9	MAP	11.2		

It should be noted that the percentage N (Table 5.5) in the N-fertilisers is required to calculate the application of the fertiliser to the soil and the loss of N is related to the percentage N in the fertiliser (National Greenhouse Gas Inventory (NGGI), 2006).

The difference between the sum of the pre-farm and on-farm stages of this paddock showed an overall increase in emissions from 2010 to 2011 (i.e. 2.99 x 10^3 kg CO_2-e – 6.08 x 10^2 kg CO_2-e/t = 2.38 x 10^3 kg CO_2-e/t) (Table 5.3).

5.4.1.3 Interpretation of GHG emissions paddock 2

In the pre-farm stage for paddock 2, for 2010, the transportation of fertilisers presented itself as the hotspot (2.35 x 10^2 kg CO_2-e/t) (Table 5.2). The GHG emissions from the transportation of fertilisers in 2011 were lower than in 2010; mainly due to the increase in yield in 2011 compared to 2010. Since the rate of increase in productivity (denominator) is higher than the rate of increase in GHG emissions (numerator) associated with the increased amount of fertiliser, the carbon footprint 2011, for grain production is lower than in 2010. Increased productivity associated with the application of a higher amount of carbon intensive chemicals can offset GHG emissions. In 2010 the application rate for fertilisers was 45 kg/ha/yr and transportation was 8.78 tkm, though when normalised by the grain yield (1.21 t/ha) it was reduced to 35 kg/t/yr and 1.21 tkm/t. By contrast the application rate for fertilisers in 2011 was higher at 65 kg/ha/yr, but decreased to 32 kg/t/yr when normalised against the grain yield of 2.01 t/ha and transportation of fertilisers increased from 8.19 tkm to 2.01 tkm/t. Furthermore when applying the respective fertiliser conversion factors (2.63 for DAP Extra and 3.26 for Agstar Extra) to urea the calculated GHG emissions were as presented in Table 5.6.

Table 5.6. Carbon footprint for fertiliser transportation for paddock 2

Fertiliser transportation	2010 kg CO_2-e/t	2011 kg CO_2-e/t
DAP Extra	2.35E+02	
Agstar Extra		1.39E-02
Total	**2.35E+02**	**1.39E-02**

The hotspot for the pre-farm stage in 2011 was the production of fertilisers with a calculated value of 8.88 x 10^1 kg CO_2-e/t vs 7.65 x 10^1 kg CO_2-e/t in 2010 The GHG emissions originated solely from the application of DAP Extra in 2010 and Agstar Extra in 2011 (Table 5.7). The normalised application rate for DAP in 2010 was 34.6 kg/yr/t and for Agstar Extra in 2011 it was 32.3 kg/yr/t, thus a decrease in GHG emissions were expected. The increase in GHG emissions is, however, explained by the higher conversion factor of 3.3 for Agstar Extra vs 2.6 for DAP (Appendix G, Table G.1), which submitted a higher GHG emission through calculation

Table 5.7. Fertiliser production carbon footprint for paddock 2

Fertiliser production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
DAP Extra	7.65E+01	
Agstar Extra		8.81E+01
Total	**7.65E+01**	**8.81E-01**

The emissions from farm machinery operation presented as the hotspot in the on-farm stage in 2010 (2.85×10^1 kg CO_2-e/t). As the farm machinery had only been used for common farming practices such as seeding, spraying of chemicals, the top-dressing of lime and harvesting it can be assumed that the other output emissions in this farming stage, totalling 6.31×10^1 kg CO_2-e/t, were well managed and produced lower GHG emissions than the farming machinery operation. In 2011, the emissions from farm machinery operation were lower than in 2010 (1.60×10^1 kg CO_2-e/t), possibly due to the grain yield (denominator) increasing and thus reducing the overall GHG emissions. In 2011 ISE was the output category with the highest GHG emissions (6.42×10^1 kg CO_2-e/t), due to quantised nitrous oxide (N_2O) emissions from N leaching. An emissions factor of 0.03 N_2O-N was applied to N-fertilisers as Et/P = 1.3. The fertiliser DAP Extra (14.1% N) was applied to this paddock in 2011, thereby contributing to GHG emissions through leaching.

As previously stated in section 3.3.2.2, the Intergovernmental Panel on Climate Change (IPCC) predicts that no leaching will occur when Et/P is between 0.8 and 1.0 and an emission factor of zero is then allocated. If the calculated value is outside these limits, leaching occurs and the emission factor is then 0.03 (NGGI, 2006).

The total GHG emissions decreased from 4.77 x 10^2 kg CO_2-e/t in 2010 to 3.29 x 10^2 kg CO_2-e/t in 2011, mainly due to the decrease in the emissions from the transportation of fertilisers (2.35 x 10^2 kg CO_2-e/t, decreased almost 100% (99.99%)), and farm machinery production (1.60 x 10^1 kg CO_2-e/t, decreased by 51.9%) (Table 5.2 and Table 5.3).

5.4.1.4 Interpretation of GHG emissions from paddock 3

The transportation of fertilisers to this paddock during the pre-farm stage was the hotspot for both years (i.e. 2.06 x 10^2 kg CO_2-e/t in 2010 and 3.67 x 10^3 kg CO_2-e/t in 2011) (Table 5.2). All fertilisers for both 2010 and 2011 were sourced locally except for urea, which originated from Asia (Table 5.8). As a result, the emissions from the transportation of urea alone accounted for 99.99% of the fertiliser transportation emissions in 2011.

Table 5.8. Carbon footprint from the transportation of fertilisers for paddock 3

Fertiliser transportation	**2010**	**2011**
	kg CO_2-e/t	**kg CO_2-e/t**
Agstar Extra		1.28E-02
Copper		8.96E-01
DAP Extra	2.06E+02	
Flexi-N		2.41E-01
Urea		3.67E+03
Total	**2.06E+02**	**3.67E+03**

The on-farm stage for paddock 3 was *s*imilar to paddock 1, as ISE presented as the hotspot for paddock 3 during the on-farm stage in 2010 and 2011, with a total of 8.04 x 10^1 kg CO_2-e/t and 3.36 x 10^2 kg CO_2-e/t being emitted respectively (Table 5.3). This is because of the increase in N leaching (quantised as N_2O) into the soil due to the increased use of N-fertilisers in 2011 (71.0 kg/year/t in 2011 vs 30.33 kg/year/t in 2010). In addition an emissions factor of 0.03 N_2O-N was allocated to both paddocks as Et/P was 1.7 and 1.3 (section 5.4.1.3) for 2010 and 2011, respectively, thus increasing the calculated GHG emissions through N leaching (quantised as N_2O).

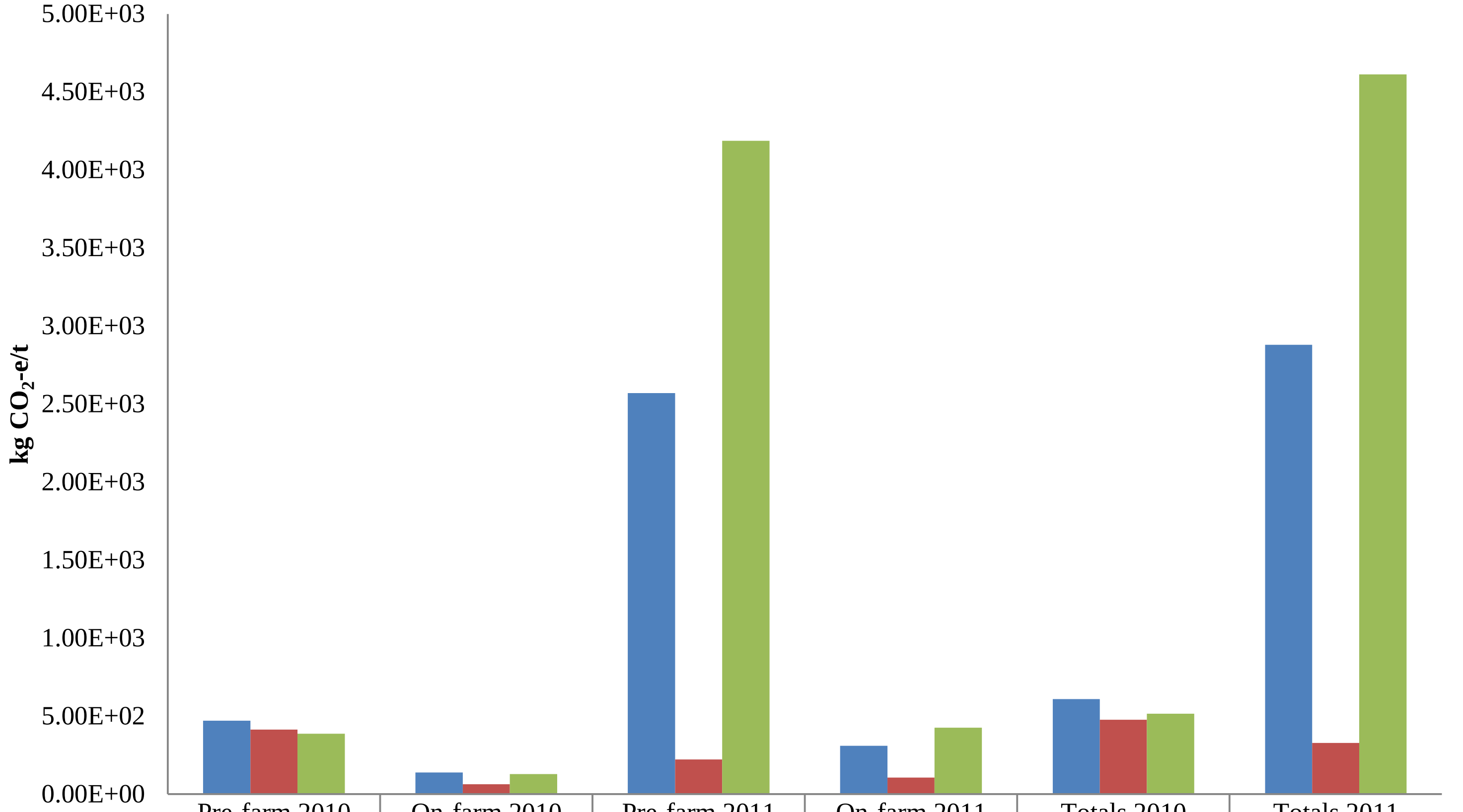
The total emissions for 2011 (4.61 x 10^3 kg CO_2-e/t) were higher than those for 2010 (5.16 x 10^2 kg CO_2-e/t), due to an increase in both the pre-farm and on-farm emissions (Table 5.2 and Table 5.3). In the pre-farm stage the GHG emissions from the transportation of fertilisers showed the highest increase followed by the transportation of chemicals, fertiliser production and then chemical production (3.47×10^3 kg CO_2-e/t, 2.00×10^2 kg CO_2-e/t, 1.01×10^2 kg CO_2-e/t and 4.26×10^1 kg CO_2-e/t). In contrast the emissions from farm machinery production decreased by an amount of 9.67 kg CO_2-e/t. The emissions from the transportation of fertilisers were dependent on the use of imported urea as explained previously. In the on-farm stage an increase in GHG emissions of 2.56×10^2 kg CO_2-e/t, 4.91×10^1 kg CO_2-e/t and 1.08 kg CO_2-e/t was calculated for ISE, DSE and emissions from grazing, respectively. The emissions from the burning of stubble and farm machinery production were reduced by 1.64×10^{-1} kg CO_2-e/t and 8.95 kg CO_2-e/t, respectively.

5.4.1.5 Summary for Farm A

Over the two years, Farm A generated a total of 9.42×10^3 kg CO_2-e/t emitted from the three paddocks, ranging from 3.29×10^2 kg CO_2-e/t to 4.61×10^3 kg CO_2-e/t for the six measurements quantified (5.05 kg CO_2-e/ha – 8.86×10^1 kg CO_2-e/ha), with a standard deviation (SD) of 1.48×10^2 kg CO_2-e/t (3.51×10^1 kg CO_2-e/ha). Although the functional unit is the production of GHG emissions per one tonne of grain, in some situations the GHG emissions were converted to represent a per hectare functional unit. This was so that comparisons could be made with other reviewed research that used a per hectare functional unit. Figure 5.1 presents the breakdown of GHG emissions in terms of the three paddocks of Farm A. It appears that the GHG emissions from paddock 3 in 2011 contributed to 47% of this farm's total GHG emissions, increasing by 42% from 2010. Paddock 2 showed an increase in emissions from 5% to 6% and the emissions from paddock 1 increased from 6% to 30%. When comparing the three paddocks it can be seen that wheat was planted in both years in these paddocks (Table 5.1) and the grain yield increased from 2010 to 2011. In addition the paddocks were grazed for a period by sheep in 2011, but not in 2010, and paddock 1 and paddock 3 were not burned in 2011. From these observations the conclusion can be drawn that paddock 3 showed an increase in GHG emissions primarily due to the use of urea which was from international sources. The GHG emissions in paddock 2 increased by 2% as ISE and chemical production GHG emissions increased from 2010 to 2011. The increase in emissions for paddock 1 can mostly be attributed to the transportation of fertilisers in 2011.

The overall hotspot category for this farm was the transportation of fertilisers in 2011 for paddock 3 (3.67 x 10^3 kg CO_2-e/t), and according to Figure 5.1 the paddock generating the highest emissions was paddock 3 in 2011, and the hotspot between the stages was the pre-farm stage of 2011 on paddock 3.

The GHG emissions, although slightly higher for paddocks 1 and 3 in 2010 (2.27 x 10^3 kg CO_2-e/t for paddock 1 and 4.10 x 10^3 kg CO_2-e/t for paddock 3 and lower by 1.48 x 10^2 kg CO_2-e/t for paddock 2, all three paddocks compared favourably with other studies conducted on arable crops, with/without burning practices and with/without livestock grazing. White & van Rees (2011) quantified GHG emissions in New South Wales, Australia in the range 3.16 t CO_2-e/ha – 4.71 t CO_2-e/ha, Franks & Hadingham (2012) conducted a study on arable crops in England and reported a range of GHG emissions from 2.60 t CO_2-e/ha – 4.71 t CO_2-e/ha, and Brock et al. (2014) reported GHG emissions ranging from 1.39 x 10^2 kg CO_2-e/t – 2.19 x 10^2 kg CO_2-e/t on various studies conducted in New South Wales, Australia.



	Pre-farm 2010	On-farm 2010	Pre-farm 2011	On-farm 2011	Totals 2010	Totals 2011
1	4.70E+02	1.38E+02	2.57E+03	3.10E+02	6.08E+02	2.88E+03
2	4.14E+02	6.31E+01	2.23E+02	1.06E+02	4.77E+02	3.29E+02
3	3.88E+02	1.28E+02	4.19E+03	4.25E+02	5.16E+02	4.61E+03

Figure 5.1. Summary of GHG emissions per paddock for Farm A

5.4.2 Farm B, paddocks 4, 5 and 6

Paddocks 4, 5 and 6, cultivated on Farm B, are located in an average annual rainfall zone of 300–400 mm and average annual temperature zone of 18–21 °C (BOM, 2014c). The mean measured rainfall was 332.2, 226.7 mm and 276 mm respectively in 2010 and 443.3 mm, 436.6 mm and 419.2 mm respectively in 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The soil types are yellow Chromosol (yellow/brown shallow loamy duplex), Orthic Tenosol (yellow deep sand) and Calcic Calcarosol (calcareous loamy earth) for paddocks 4, 5 and 6 respectively (Table 4.2). In 2010 wheat was planted in and harvested from all three paddocks and in 2011 barley, lupin and wheat were planted in and harvested from paddocks 4, 5 and 6 respectively. No animals were grazed and the stubble was not burned in any of these paddocks (Table 5.9). Fertiliser was applied with the seed whilst sowing for all paddocks for both years, while in 2010 paddocks 4 and 5 received an additional fertiliser application and in 2011 paddock 4 received one more fertiliser application than the other two paddocks.

Table 5.9. Farming practices for Farm B

2010			2011		
Paddock 4	**Paddock 5**	**Paddock 6**	**Paddock 4**	**Paddock 5**	**Paddock 6**
90 ha	220 ha	104 ha	90 ha	220 ha	104 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested barley	Planted and harvested lupin	Planted and harvested wheat
Grain yield: 2.06 t/ha	Grain yield: 1.92 t/ha	Grain yield: 2.41 t/ha	Grain yield: 2.81 t/ha	Grain yield: 2.35 t/ha	Grain yield: 2.58 t/ha
No grazing	No grazing	No grazing	No grazing	No grazing	No grazing
No burning	No burning	No burning	No burning	No burning	No burning

Tables 5.10 and 5.11 give an overall impression of the emissions from the different categories associated with the pre-farm and on-farm stages for this farm. Tables G.8−G11 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm B’, resulting from the different FMP on each of these paddocks.

Table 5.10. Pre-farm CO_2-e/t emissions resulting from paddocks 4, 5 and 6

Farm B			Pre-farm CO_2-e/t emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	4	kg CO_2-e/t	4.80E+01	2.22E+02	1.09E+01	1.87E+00	1.26E+01	**2.96E+02**
	5	kg CO_2-e/t	2.95E+01	2.30E+02	1.12E+01	4.02E-01	1.22E+01	**2.83E+02**
	6	kg CO_2-e/t	1.22E+01	7.47E+01	8.93E+00	1.93E-02	3.79E+00	**9.96E+01**
Totals			**8.97E+01**	**5.27E+02**	**3.10E+01**	**2.29E+00**	**2.86E+01**	**6.78E+02**
2011	4	kg CO_2-e/t	1.33E+01	-	7.66E+00	1.03E+00	-	**2.20E+01**
	5	kg CO_2-e/t	1.37E+01	1.80E+02	9.54E+00	1.37E+00	8.97E+00	**2.14E+02**
	6	kg CO_2-e/t	3.50E+03	7.31E+01	8.35E+00	2.55E+00	7.15E-02	**3.58E+03**
Totals			**3.53E+03**	**2.54E+02**	**2.55E+01**	**4.95E+00**	**9.05E+00**	**3.82E+03**

Table 5.11. On-farm CO_2-e/t emissions resulting from paddocks 4, 5 and 6

Farm B			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	4	kg CO_2-e/t	1.52E+01	-	-	8.33E+01	1.25E+00	**9.97E+01**	**3.95E+02**
	5	kg CO_2-e/t	1.49E+01	-	-	7.95E+01	1.16E+00	**9.56E+01**	**3.79E+02**
	6	kg CO_2-e/t	1.19E+01	-	-	3.62E+01	4.60E-01	**4.85E+01**	**1.48E+02**
Totals			**4.20E+01**	**-**	**-**	**1.99E+02**	**2.87E+00**	**2.44E+02**	**9.22E+02**
2011	4	kg CO_2-e/t	1.02E+01	-	-	1.57E+01	-	**2.59E+01**	**4.78E+01**
	5	kg CO_2-e/t	1.33E+01	-	-	5.68E+01	8.03E-01	**7.09E+01**	**2.85E+02**
	6	kg CO_2-e/t	1.11E+01	-	-	3.75E+01	4.97E-01	**4.91E+01**	**3.63E+03**
Totals			**3.46E+01**	**-**	**-**	**1.10E+02**	**1.30E+00**	**1.46E+02**	**3.96E+03**

Key: Red shading indicates the highest GHG emissions for each paddock.

5.4.2.1 Observation of GHG emissions from paddocks 4, 5 and 6

The following can be observed from Table 5.10 for the **pre-farm** stage:

- Lower GHG emissions for paddocks 4 and 5 in 2011 than in 2010, and higher GHG emissions for paddock 6 in 2011.
- In 2010 paddock 4 had the highest GHGs and paddock 6 the lowest.
- In 2011 paddock 6 had the highest GHGs and paddock 4 the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 4 – the production of fertiliser (2010), the production of chemicals (2011);
    - paddock 5 – the production of fertilisers (2010 and 2011);
    - paddock 5 – the production of fertiliser (2010), the production of chemicals (2011).

The following observations can be made for the **on-farm** stage (Table 5.11):

- A decrease in GHG emissions can be seen from 2010 to 2011 for paddocks 4 and 5 and an increase for paddock 6.
- In 2010 the paddock with the highest GHG emissions was paddock 4 and paddock 6 had the lowest emissions.
- In 2011 paddock 5 had the highest GHG emissions and paddock 4 had the lowest.
- The hotspots for each of the paddocks for each year is as follows:
    - paddock 4 – direct soil emissions (2010 and 2011);
    - paddock 5 – direct soil emissions (2010 and 2011);
    - paddock 6 – direct soil emissions (2010 and 2011).

5.4.2.2 Interpretation of GHG emissions from paddock 4

Fertiliser production yielded the highest GHG emissions (2.22 x 10^2 kg CO_2-e/t) in 2010 during the pre-farm stage for paddock 4, and the production of chemicals resulted in the highest emissions (1.33 x 10^1 kg CO_2-e/t) in 2011 (Table 5.10). The fertilisers used in 2010 were urea, which was imported from Asia, and K-till Extra, which was formulated locally in Kwinana. No fertiliser was used on this paddock in 2011, thus there was a reduction in GHG emissions from fertilisers of 2.22 x 10^2 kg

CO_2-e/t. The application rate of chemicals in 2011 was 100.96 kg/ha/yr and when normalised against the crop yield of 2.81 t/ha it was 35.93 kg/yr/t. Within this category (Table 5.12) the production of herbicides, namely Bromicide and Select, emitted the most GHGs. In 2010 the application rate of chemicals was 106.96 kg/ha/yr and normalised as 51.92 kg/yr/t. After converting to equivalent chemicals and applying the corresponding emissions factors, the production of chemicals generated 4.80 x 10^1 kg CO_2-e/t in 2010 and 1.33 x 10^1 kg CO_2-e/t in 2011.

Table 5.12. Carbon footprint from the production of chemicals

Chemical production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
Alphasip Duo	3.53E-04	
Ammonium Sulphate	1.75E-01	
Bromicide		1.92E+00
Ester 800	8.70E-01	
Gladiator	5.22E+00	
Glyphosate	3.06E+00	
Lemat	1.86E-03	
Lime	8.20E-01	6.01E-01
Premis	2.70E+01	
Select		1.05E+01
Sprayseed		9.06E-02
Tigrex		1.99E-01
TriflurX	4.56E+00	
Velocity	6.32E+00	
Total	**4.80E+01**	**1.33E+01**

The direct soil emissions (DSE) were found to be the hotspots during the on-farm stage for both 2010 (8.33x10^1 kg CO_2-e/t) and 2011 (1.57 x 10^1 kg CO_2-e/t) (Table 5.11). The DSE from CO_2-urea hydrolysis were the highest (56%) followed by CO_2-liming (26%) and N_2O-fertiliser (19%) in 2010. After the DSE the emissions resulting from the operation of farm machinery (1.52 x 10^1 kg CO_2-e/t) yielded the next highest GHG emissions followed by ISE (1.25 kg CO_2-e/t). In 2011 in the DSE category, the GHG emissions from CO_2-liming contributed 100% of the emissions as no fertilisers had been applied to this paddock in 2011.

The total GHG emissions for 2011 (4.78 x 10^1 kg CO_2-e/t) were lower than those for 2010 (3.95 x 10^2 kg CO_2-e/t) (Table 5.10-5.11). This is due to the reduction in DSE, farm machinery operation and ISE from 2010 to 2011. No emissions resulted from either stubble burning or grazing of sheep. The reduction of farm machinery operation emissions were partially due to the increase in crop yield and partially as a result of less fuel consumed during chemical spraying in 2011. In 2010 machinery passed over the paddock five times to apply chemicals and in 2011 it passed over the paddock twice, thereby increasing the amount of fuel consumed (relative to the grain yield as the denominator) from 2010 to 2011.

5.4.2.3 Interpretation of GHG emissions from paddock 5

Fertiliser production was the hotspot in the pre-farm stage in both 2010 and 2011 with 2.3 x 10^2 kg CO_2-e/t and 1.80 x 10^2 kg CO_2-e/t being emitted respectively (Table 5.10) for this paddock. In both years, urea and K-till Extra were the fertilisers of choice. The application rate for K-till Extra was 90 kg/ha/yr for both 2010 and 2011. The application rate for urea was 110 kg/ha/yr in 2010 and 90 kg/ha/yr in 2011. Both the increased yield (2.35 t/ha) (denominator) and the emissions associated with reduced fertiliser application (90 kg/ha/yr) (numerator) in 2011 contributed to the reduction of 4.94 x 10^1 kg CO_2-e/t. There was a reduction in pre-farm emissions from 2010 to 2011 by an amount of 6.92 x 10^1 kg CO_2-e/t, mainly due to reduced GHG emissions from the input categories fertiliser production (4.94 x 10^1 kg CO_2-e/t) and chemical production (1.58 x 10^1 kg CO_2-e/t).

The DSE from paddock 5 was the hotspot for the on-farm stage for both 2010 and 2011 with emissions of 7.95 x 10^1 kg CO_2-e/t and 5.68 x 10^1 kg CO_2-e/t, respectively (Table 5.11). There was a reduction in DSE of 2.27 x 10^1 kg CO_2-e/t from 2010 to 2011. Within this category, the CO_2 emissions from urea hydrolysis were the highest followed by CO_2 emissions from liming and finally direct N_2O from fertilisers for both years. The CO_2 emissions from urea hydrolysis were influenced by the normalised dosage of urea, which was lower in 2011 (38.27 kg/yr/t) compared to 51.29 kg/yr/t in 2010. The normalised dosage of fertilisers for 2010 was 272.91 kg/yr/t of which K-till extra contributed the most. In 2011 K-till extra also contributed the most to the fertiliser dosage which was 214.28 kg/yr/t when normalised. Similarly, the N_2O emissions resulting from the use of fertilisers were less in 2011 due to the reduction in the dosages as well as the increased crop yield. Overall the GHG emissions for the on-farm stage were less in 2011 than in 2010.

The total GHG emissions for 2010 (3.79×10^2 kg CO_2-e/t) were higher than the total GHG emissions for 2011 (2.85×10^2 kg CO_2-e/t) (Table 5.10 and Table 5.11). The results indicate that the on-farm emissions for both years were lower than the pre-farm emissions (2.83×10^1 kg CO_2-e/t vs 9.56×10^1 kg CO_2-e/t for 2010 and 2.14×10^2 kg CO_2-e/t vs 7.09×10^1 kg CO_2-e/t for 2011). All categories in both the pre-farm and on-farm stages showed a decrease in GHG emissions from 2010 to 2011, except for the transportation of chemicals category which showed an increase in GHG emissions from 2010 to 2011. The overall hotspot for paddock 5 was the fertiliser production input category in the pre-farm stage of 2010.

5.4.2.4 Interpretation of GHG emissions from paddock 6

The hotspot for 2010 for this paddock in the pre-farm stage was fertiliser production emitting 7.47×10^1 kg CO_2-e/t, and for 2011 it was the production of chemicals emitting 3.50×10^3 kg CO_2-e/t (Table 5.10). In 2011 fertiliser production showed a decrease in the GHGs emitted (7.31×10^1 kg CO_2-e/t), as the overall application rate was higher in 2011 (105 kg/yr/t compared to 115 kg/yr/t) than in 2010 and the crop yield was higher in 2011 (2.41 t/ha) than in 2010 (2.57 t/ha). Urea and Agyield Extra were the only fertilisers applied in this paddock in both years.

The GHG emissions from the production of chemicals in 2011 (3.50×10^3 kg CO_2-e/t) were higher than the GHG emissions from the production of chemicals in 2010 (1.22×10^1 kg CO_2-e/t) (Table 5.10 and Table 5.11). In 2011 Logran had the highest GHG emissions (3.49×10^3 kg CO_2-e/t), followed by Treflan (4.36 kg CO_2-e/t) (Table 5.13). Neither of these herbicides was applied in 2010.

Table 5.13. Carbon footprint of the production of chemicals for paddock 6

Chemical production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
Alpha Cypermethrin		3.97E-04
Ammonium Sulphate	8.13E-02	
Aphasip Duo	3.02E-04	
Ester 800	5.56E-01	
Garlon	1.01E+01	
Lemat		1.24E-04
LI 700		1.36E-07
Lime	7.01E-01	6.56E-01
Logran		3.49E+03
Roundup		2.68E+00
Sprayseed	4.23E-01	
Treflan		4.36E+00
Trifluralin	2.99E-01	
Total	**1.22E+01**	**3.50E+03**

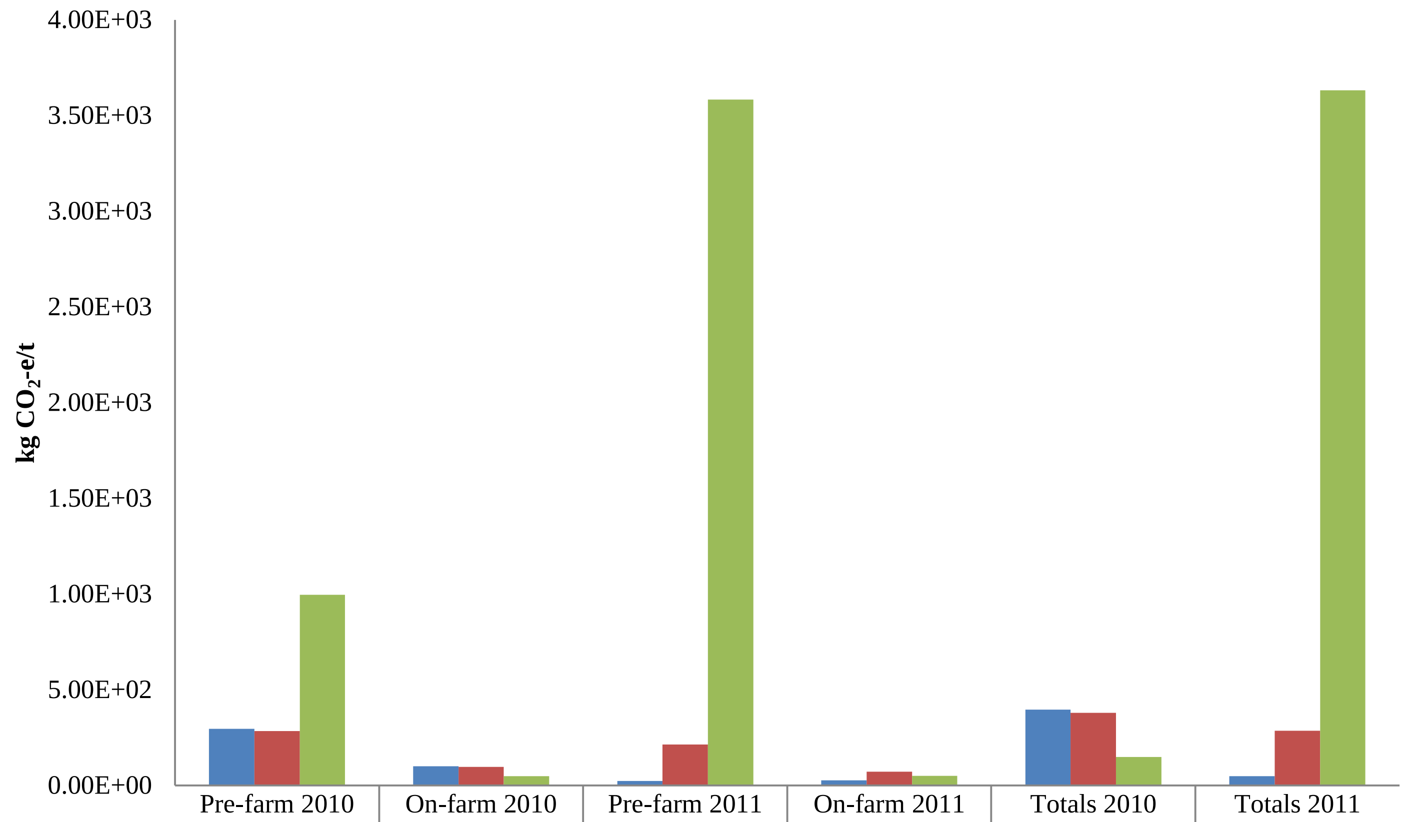
For the on-farm stage the category with the highest GHG emissions was DSE in both years (Table 5.11). In 2010, 3.62 x 10^1kg CO_2-e/t were emitted and in 2011, 3.75 x 10^1 kg CO_2-e/t were emitted. Furthermore, in this category for both years, the CO_2 emissions from liming were the highest (1.83 x 10^1 kg CO_2-e/t for 2010, 1.71 x 10^1 kg CO_2-e/t for 2011), followed by CO_2 emissions from urea hydrolysis (1.22 x 10^1 kg CO_2-e/t for 2010, 1.42 x 10^1 kg CO_2-e/t for 2011) and then direct N_2O emissions from the application of N-fertilisers (5.75 kg CO_2-e/t for 2010, 6.21 kg CO_2e/t for 2011). Thus there is an increase in GHG emissions in the DSE category from 2010 to 2011 which is because of the increase of normalised application rate of urea (16.6 kg/yr/t in 2010 and 19.4 kg/yr/t in 2011) and N-fertilisers (urea and Agyield Extra) (105 kg/yr/t in 2010 and 115 kg/yr/t in 2011).

The total emissions over all categories showed an increase from 2010 (1.48 x 10^2 kg CO_2-e/t) to 2011 (3.63 x 10^3 kg CO_2-e/t) which is mainly due to an increase of 3.48 x 10^3 kg CO_2-e/t in the pre-farm stage (Table 5.10 and Table 5.11). The production of chemicals and the transportation of chemicals both showed increases, but the transportation of fertilisers, fertiliser production, and the production of farm machinery showed a slight decrease in GHGs emitted from 2010 to 2011, possibly due to the slightly higher grain yield (denominator) in 2011 (2.41 t/ha for 2010 and 2.58 t/ha for 2011), which allows for a greater distribution of the GHGs (numerator).

The overall hotspot for paddock 6 was the chemical production (more specifically herbicides) input category in the pre-farm stage of 2011.

5.4.2.5 Summary for Farm B

A total of 4.89 x 10^3 kg CO_2-e/t was emitted by Farm B for the years 2010 and 2011, ranging from 4.78 x 10^1 kg CO_2-e/t to 3.63 x 10^3 kg CO_2-e/t (1.49 kg CO_2-e/ha – 9.01 x 10^1 kg CO_2-e/ha). In 2011 paddock 6 contributed 74% of the total emissions for the farm over both years, followed by paddock 4 in 2010 and paddock 5 in 2010, which both contributed 8% to this total (Figure 5.2). This figure shows that there was a reduction in GHG emissions from paddock 4 from 8% in 2010 to 1% in 2011, paddock 5 showed a reduction in GHG emissions from 8% to 6% from 2010 to 2011. Paddock 6 showed an increase in GHG emissions from 3% in 2010 to 74% in 2011. Table 5.9 shows that there was a slight increase in grain yield for all three paddocks from 2010 to 2011 with no stubble burning or grazing on any of the paddocks. In 2011 paddock 4 was planted to and harvested barley, paddock 5 lupin and paddock 6 wheat. Tables 5.10 and 5.11 identifies the stage with the highest GHG emissions as the pre-farm stage of 2011 and the paddock generating the most emissions was paddock 6 in 2011. Within the pre-farm stage of 2011 chemical production is the overall hotspot, with herbicides emitting the highest volume of GHGs (3.52 x 10^3 kg CO_2-e/t). More specifically Logran caused 96% of GHG emissions in 2011 on paddock 6 and of Farm B, 71% of the GHG emissions.



	Pre-farm 2010	On-farm 2010	Pre-farm 2011	On-farm 2011	Totals 2010	Totals 2011
4	2.96E+02	9.97E+01	2.20E+01	2.59E+01	3.95E+02	4.78E+01
5	2.83E+02	9.56E+01	2.14E+02	7.09E+01	3.79E+02	2.85E+02
6	9.96E+02	4.85E+01	3.58E+03	4.91E+01	1.48E+02	3.63E+03

Figure 5.2. Summary of GHG emissions per paddock for Farm B

When comparing the scenarios as presented to other studies from Australia for the same farming systems (i.e. no stubble burning and no grazing), such as Barton et al. (2014); Biswas et al. (2008); Biswas et al. (2011) and Brock et al. (2014), it was observed that the production and transportation of fertilisers contributed to a large portion of the GHG emissions in these studies. Biswas et al. (2008) quantified the GHG emissions for the production of one tonne of wheat from cradle to gate. On recalculating only the emissions for the pre-farm and on-farm stages (269.37 kg CO_2-e/t) it was found that fertilisers (production and transportation) contributed to 79% of the pre-farm emissions and 40% of the total emissions, and the production of herbicides 26% and 10% respectively. After recalculating to include only the pre-farm and on-farm stages, the production of fertilisers followed by the production of herbicides in the pre-farm stages appeared to be the hotspots in a study by Biswas et al. (2011). Fertilisers contributed to 61% of the pre-farm stage emissions and 32% of the total emissions, and herbicides contributed 33% and 17% respectively. In studies by Barton et al. (2014), where GHG emissions were quantified in a semi-arid climate, and by Brock et al. (2012) in various cropping systems, it was consistently found that the production of fertilisers followed by the production of herbicides were the hotspot where only pre-farm and on-farm stages were considered. On Farm B, from this research, GHG emissions from the production of fertilisers ranged between 50 and 56% for the paddocks in which it was the hotspot (paddock 4, 5 and 6 for 2010 and paddock 5 in 2011). The production of herbicides (primarily Logran) for paddock 6 in 2011 was the hotspot contributing to 96% of the overall emissions for that paddock.

5.4.3 Farm C, paddocks 7, 8 and 9

The average annual rainfall zone on paddocks 7, 8 and 9, cultivated on Farm C, is 300–400 mm (BOM, 2014c). The annual average temperatures vary between 18 and 21 °C (BOM, 2014c). The actual rainfall for paddocks 7, 8 and 9 in 2010 was 231.4 mm, 247.2 mm and 247.2 mm and for 2011, 361.0 mm, 364.4 mm and 364.4 mm respectively (Appendix F, Table F.12-F14). The soil types include red Kandosol (red loamy earth), yellow Sodosol (yellow/brown deep sandy duplex) and Orthic Tenosol (yellow deep sand) (Table 4.2). All three paddocks were planted to wheat in 2010, and then oats, wheat and lupin were planted in 2011 in the three paddocks, respectively. The stubble load was not burned in 2010 or 2011 in any of the paddocks. Sheep did not graze the stubble on paddock 8 and 9 in 2010, however, sheep grazed on paddock 7 in 2010 and on all the paddocks in 2011 (Table 5.14). Fertiliser was applied to all paddocks on Farm C in both years whilst sowing the seed, with an exception that paddock 7 received one more fertiliser application in 2011.

Table 5.14. Farming practices for Farm D

2010			2011		
Paddock 7	**Paddock 8**	**Paddock 9**	**Paddock 7**	**Paddock 8**	**Paddock 9**
105 ha	75 ha	137 ha	105 ha	75 ha	137 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested oats	Planted and harvested wheat	Planted and harvested lupin
Grain yield: 1.6 t/ha	Grain yield: 0.9 t/ha	Grain yield: 1.1 t/ha	Grain yield: 2.2 t/ha	Grain yield: 3.5 t/ha	Grain yield: 0.8 t/ha
Grazing of 400 head of sheep for 30 days	No grazing	No grazing	Grazing of 450 head of sheep for 40 days	Grazing of 400 head of sheep for 32 days	Grazing of 400 head of sheep for 23 days
No burning	No burning	No burning	No burning	No burning	No burning

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 7, 8 and 9 are summarised in Tables 5.15 and 5.16. Tables G.12−G16 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm C’, resulting from the different FMP on each of these paddocks.

Table 5.15. Pre-farm CO_2-e/t emissions resulting from paddocks 7, 8 and 9

Farm C			Pre-farm CO_2-e/t emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	7	kg CO_2-e/t	1.03E+01	1.03E+02	1.17E+01	2.25E+00	4.86E+01	**1.76E+02**
	8	kg CO_2-e/t	3.04E+01	1.83E+02	1.97E+01	4.49E+00	8.64E+01	**3.24E+02**
	9	kg CO_2-e/t	3.24E+01	1.60E+02	1.66E+01	5.04E+00	7.10E+01	**2.85E+02**
Totals			**7.32E+01**	**4.45E+02**	**4.80E+01**	**1.18E+01**	**2.06E+02**	**7.84E+02**
2011	7	kg CO_2-e/t	1.52E+01	9.65E+01	1.00E+01	1.64E+00	4.38E+00	**1.28E+02**
	8	kg CO_2-e/t	5.90E+00	3.98E+01	5.51E+00	9.16E-01	1.37E+00	**5.35E+01**
	9	kg CO_2-e/t	1.31E+02	2.24E+02	2.41E+01	7.06E+00	7.71E+00	**3.94E+02**
Totals			**1.52E+02**	**3.60E+02**	**3.97E+01**	**9.61E+00**	**1.35E+01**	**5.75E+02**

Table 5.16. On-farm CO_2-e/t emissions resulting from paddocks 7, 8 and 9

Farm C			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	7	kg CO_2-e/t	1.76E+01	-	3.64E+01	4.44E+01	1.65E+02	**2.63E+02**	**4.39E+02**
	8	kg CO_2-e/t	2.93E+01	-	-	7.90E+01	2.93E+02	**4.01E+02**	**7.25E+02**
	9	kg CO_2-e/t	2.48E+01	-	-	8.46E+01	2.55E+02	**3.64E+02**	**6.49E+02**
Totals			**7.16E+01**	-	**3.64E+01**	**2.08E+02**	**7.12E+02**	**1.03E+03**	**1.81E+03**
2011	7	kg CO_2-e/t	1.38E+01	-	3.97E+01	3.44E+01	1.82E+02	**2.70E+02**	**3.98E+02**
	8	kg CO_2-e/t	8.36E+00	-	1.10E+02	1.33E+01	6.02E-02	**1.31E+02**	**1.85E+02**
	9	kg CO_2-e/t	3.66E+01	-	4.28E+01	8.65E+01	3.22E-01	**1.66E+02**	**5.60E+02**
Totals		**kg CO_2-e/t**	**5.87E+01**	-	**1.92E+02**	**1.34E+02**	**1.83E+02**	**5.68E+02**	**1.14E+03**

Key: Red shading indicates highest GHG emissions for each paddock.

5.4.3.1 Observation of GHG emissions from paddocks 7, 8 and 9

The following can be observed for the **pre-farm** stage Table 5.15:

- Lower GHG emissions for paddocks 7 and 8 in 2011 than in 2010, paddock 9 showed an increase in emissions from 2010 to 2011.
- In 2010 paddock 8 had the highest GHGs and paddock 7 the lowest.
- In 2011 paddock 9 had the highest GHGs and paddock 8 the lowest.
- The hotspots for each of the paddocks for each year is as follows:
    - paddock 7 – the production of fertilisers (2010 and 2011);
    - paddock 8 – the production of fertilisers (2010 and 2011);
    - paddock 9 – the production of fertilisers (2010 and 2011).

The following observations can be made for the **on-farm** stage (Table 5.16):

- A decrease in GHG emissions can be seen from 2010 to 2011 for paddocks 8 and 9, paddock 7 showed an increase in GHG emissions from 2010 to 2011.
- In 2010 paddock 8 had the highest GHG emissions and paddock 7 had the lowest emissions.
- In 2011 paddock 7 had the highest GHG emissions and paddock 8 had the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 7 – indirect soil emissions (2010 and 2011);
    - paddock 8 – indirect soil emissions (2010), emissions from grazing (2011);
    - Paddock 9 – indirect soil emissions (2010), direct soil emissions (2011).

5.4.3.2 Interpretation of GHG emissions from paddock 7

The hotspot during the pre-farm stage for both 2010 and 2011 for paddock 7 was the production of fertiliser (Table 5.16). Normalised against the grain yield the application rates were 46.87 kg/yr/t and 49.09 kg/yr/t for 2010 and 2011 respectively. The GHG emissions from this paddock in this category decreased from 1.03 x 10^2 kg CO_2-e/t to 9.65 x 10^1 kg CO_2-e/t over the two years, possibly due to the increase in grain yield from 0.9 t/ha to 3.5 t/ha, which decreased the GHG emissions due to normalisation. In 2010 the fertilisers generating the highest GHG emissions were MAP SZC (5.5 x 10^1 kg CO_2-e/t), then DAP SZC (3.46 x 10^1 kg CO_2-e/t) followed by urea (1.32 x 10^1 kg CO_2-e/t). In 2011 MaxamRite (6.88 x 10^1 kg CO_2-e/t) emitted the highest GHG emissions, then Flexi N (1.82 x 10^1 kg CO_2-e/t) and finally urea (9.57 kg CO_2-e/t) during the production process (Table 5.17).

Table 5.17. Carbon footprint from fertiliser production on paddock 7

Fertiliser production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
DAP SZC	3.46E+01	
MAP SZC	5.50E+01	
Urea	1.32E+01	9.57E+00
Flexi-N		1.82E+01
MaxamRite		6.88E+01
Total	**1.03E+02**	**9.65E+01**

During the on-farm stage of production for both years, ISE were the highest GHG emitter, generating 1.65 x 10^2 kg CO_2-e/t in 2010 and 1.82 x 10^2 kg CO_2-e/t in 2011 (Table 5.16) with an increase of 1.76 x10^1 kg CO_2-e/t over the two years. Further analyses of the ISE category showed that the N_2O emissions derived from the leaching of N increased the ISE by an amount of 1.64 x 10^2 kg CO_2-e/t and 1.82 x 10^2 kg CO_2-e/t for 2010 and 2011 respectively, and the N_2O emissions derived from the volatilisation of N as ammonia (NH_3) by 4.38 x 10^{-1} kg CO_2-e/t and 4.85 x 10^{-1} kg CO_2-e/t respectively. This increase in GHG emissions is consistent with the increased application rates of N-fertilisers from 2010 to 2011. An emissions factor of 0.03 N_2O-N was allocated (Et/P = 1.5) which indicates leaching of N-fertilisers into the soil, as explained in section 5.4.1.3.

The total GHG emissions decreased from 4.39 x 10^2 kg CO_2-e/t in 2010 to 3.98 x 10^2 kg CO_2-e/t in 2011 (Table 5.15–5.16). The pre-farm stage showed a decrease of 4.79 x 10^1 kg CO_2-e/t in emissions over this period and the on-farm stage an increase of 7.16 kg CO_2-e/t. The transportation of fertiliser showed a decrease and chemical production showed an increase in GHG emissions in the pre-farm stage. In the on-farm stage ISE showed the greatest increase in GHG emissions followed by emissions from grazing. Farm machinery operation and DSE both emitted reduced GHGs from 2010 to 2011. The overall hotspot for paddock 7 was ISE (the quantised N_2O emissions from N leaching) in the on-farm stage of 2011.

5.4.3.3 Interpretation of GHG emissions from paddock 8

During the pre-farm stage for 2010 and 2011 the hotspot was the production of fertilisers (1.03 x 10^2 kg CO_2-e/t for 2010 and 3.98 x 10^1 kg CO_2-e/t for 2011) (Table 5.15). The emissions from the production of fertilisers was lower in 2011 (5.90 kg CO_2-e/t) than in 2010 (Table 5.15 and Table 5.18).

Only one fertiliser was used in 2011 'NPS range-Cereal' and three fertilisers, namely DAP SZC, MAP SZC and urea were used in 2010 (Table 5.19). The normalised application rate of the fertilisers was 86.36 kg/yr/t in 2010 and 87.50 kg/yr/t in 2010, emitting 1.83 x 10^2 kg CO_2-e/t and 3.98 x 10^1 kg CO_2-e/t respectively. The production of MAP SZC emitted the highest level of GHGs in 2010, followed by DAP SZC and then urea (Table 5.18). Overall the GHG emissions in the pre-farm stage decreased over all categories by a total of 2.70 x 10^2 kg CO_2.

Table 5.18. Carbon footprint for fertiliser production on paddock 8

Fertiliser production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
DAP SZC	6.15E+01	
MAP SZC	9.78E+01	
Urea	2.34E+01	
NPS range-Cereal		3.98E+01
Total	**1.83E+02**	**3.98E+01**

The ISE (2.93 x 10^2 kg CO_2-e/t) and the emissions from grazing (1.10 x 10^2 kg CO_2-e/t) were found to be the hotspots during the on-farm stage in 2010 and in 2011, respectively. Within the ISE category, the calculated N_2O emissions from N leaching were the highest at 2.92 x 10^2 kg CO_2-e/t (2010) (Table 5.16). Leaching took place on this paddock in 2010 (Et/P = 1.4) and an emissions factor of 0.03 was allocated (section 5.4.1.3). The emissions from grazing increased from 2010 to 2011 as no sheep were grazed on the stubble load in 2010, whereas 400 sheep grazed for 32 days in 2011. The enteric emissions in this category were 1.09 x 10^2 kg CO_2-e/t and excreta emissions were 5.08 x 10^{-2} kg CO_2-e/t.

The total GHG emissions decreased by 5.40 x 10^2 kg CO_2-e/t from 2010 to 2011 (Table 5.15 and Table 5.16). Both pre-farm and on-farm stages experienced a reduction in the total GHG emissions from 2010 to 2011. The pre-farm GHG emissions were 3.24 x 10^2 kg CO_2-e/t and 5.35 x 10^1 kg CO_2-e/t and the on-farm emissions were 4.01 x 10^2 kg CO_2-e/t and 1.31 x 10^2 kg CO_2-e/t for 2010 and 2011 respectively. All categories in the pre-farm stage showed a decrease in GHG emissions from 2010 to 2011, with fertiliser transportation presenting a significant decrease of 98% (8.64 x 10^1 kg CO_2-e/t in 2010 and 1.37 kg CO_2-e/t in 2011). The only category in the on-farm stage that showed an increase (1.10 x 10^2 kg CO_2-e/t) in GHG emissions was the grazing category. ISE were reduced by 2.93 x 10^2 kg CO_2-e/t, which can directly be attributed to a lower application rate of N-fertilisers in 2011 compared to 2010. The overall hotspot for paddock 8 was the ISE output category in the pre-farm stage of 2010.

5.4.3.4 Interpretation of GHG emissions from paddock 9

Fertiliser production was the category with the highest GHG emissions for both 2010 (1.60×10^2 kg CO_2-e/t) and 2011 (2.24×10^2 kg CO_2-e/t) in the pre-farm stage for paddock 9 (Table 5.16). These emissions also showed an increase from 2010 to 2011 that can primarily be attributed to the lower grain yield of 0.8 t/ha in 2011 when compared to 1.1 t/ha in 2010. The fertiliser application rates were 95 kg/yr/t and 70 kg/yr/t, for 2010 and 2011 respectively and when normalised, the application rates were 86.36 kg/yr/t and 87.5 kg/yr/t respectively. The fertiliser generating the most GHGs in 2010 was MAP SZC and in 2011 NPS range-Cereal (Table 5.19).

Table 5.19. Carbon footprint from production of fertilisers for paddock 9

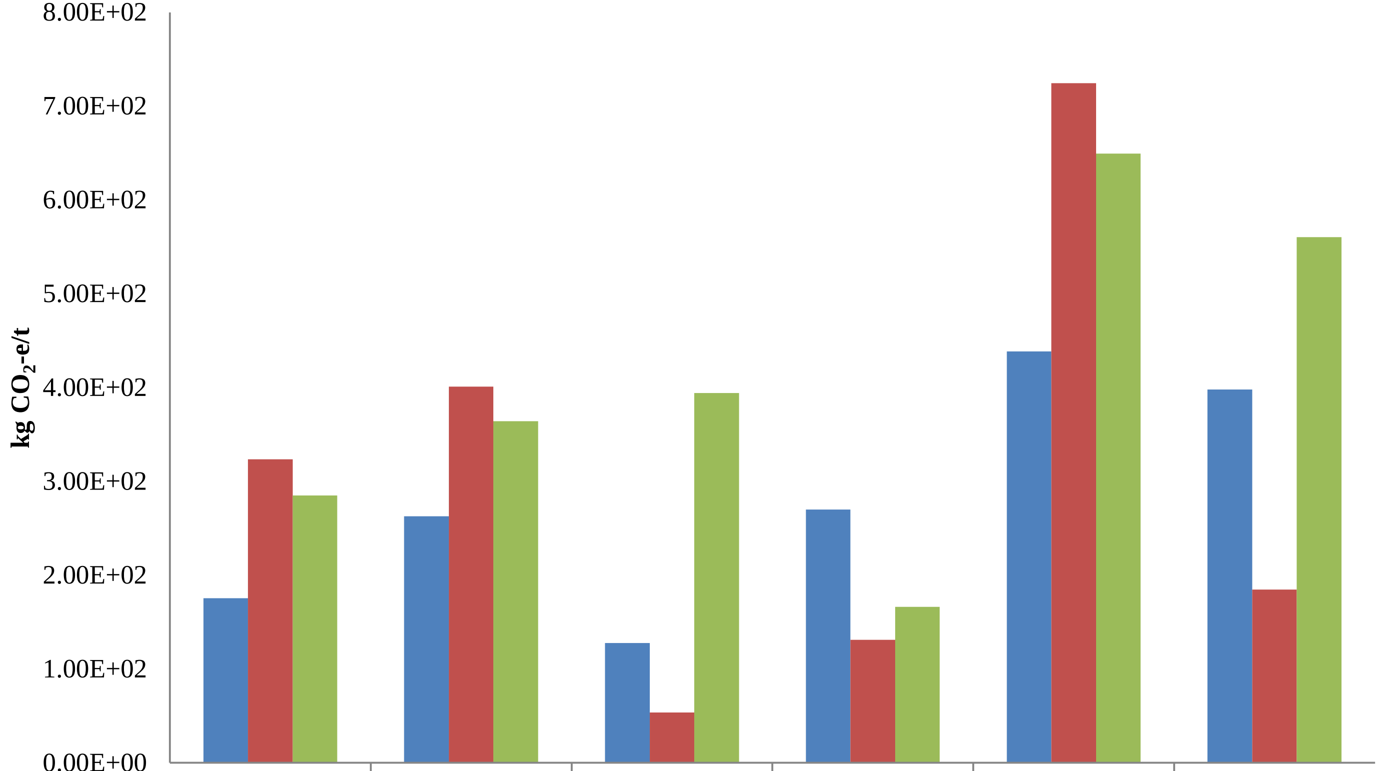
Fertiliser production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
NPS range-Cereal		2.13E+02
DAP SZC	5.03E+01	
MAP SZC	8.00E+01	
MOP	1.06E+01	1.09E+01
Urea	1.91E+01	
Total	**1.60E+02**	**2.24E+02**

In the on-farm stage, the hotspot for 2010 was ISE emitting 2.55×10^2 kg CO_2-e/t and in 2011 DSE emitted were 8.65×10^1 kg CO_2-e/t (5.16). The emissions of N_2O derived from the leaching of N for paddock 9 were the highest within the ISE category. Leaching took place in this paddock as the Et/P was 1.4, thus an emissions factor of 0.03 N_2O-N was allocated (section 5.4.1.3). The CO_2 emissions generated from lime application were the greatest emissions in the DSE category (8.25×10^1 kg CO_2-e/t), followed by the N_2O emissions generated from N- fertilisers (4.02 kg CO_2-e/t).

Overall for the years 2010 to 2011, the total GHG emissions decreased from 6.49×10^2 kg CO_2-e/t to 5.60×10^2 kg CO_2-e/t (Table 5.15 and Table 5.16). In 2010 the on-farm GHG emissions were higher than the pre-farm emissions (2.85×10^2 kg CO_2-e/t vs 3.64×10^2 kg CO_2-e/t), and in 2011 the on-farm emissions were lower than the pre-farm emissions (3.94×10^2 kg CO_2-e/t vs 1.66×10^2 kg CO_2-e/t). In the pre-farm stage all categories showed an increase in GHG emissions except the transportation of fertilisers which showed a decrease. The largest increase in GHGs in this farming stage was for chemical production (9.89 x 10^1 kg CO_2-e/t), followed by fertiliser production (6.39 x 10^1 kg CO_2-e/t), farm machinery production (7.55 kg CO_2-e/t), and then the transportation of chemicals (2.01 kg CO_2-e/t). In the on-farm stage all categories, except for emissions from stubble burning and ISE, showed an increase in GHG emissions. The increases in GHG emissions were due to the emissions from grazing (4.28 x 10^1 kg CO_2-e/t) and then farm machinery operation (1.18 x 10^1 kg CO_2-e/t), followed by DSE (1.90 kg CO_2-e/t) in decreasing order of magnitude.

5.4.3.5 Summary for Farm C

A total of 2.96 x 10^3 kg CO_2-e/t was emitted by paddocks 7, 8 and 9 on Farm C for 2010 and 2011, ranging from 1.85 x 10^2 kg CO_2-e/t – 7.25 x 10^2 kg CO_2-e/t for the individual paddocks. Of these emissions 25% were generated by paddock 8 in 2010 followed by paddock 9 with 22% in 2010 (Figure 5.3). Paddock 7 showed a decrease in GHG emissions from 15% to 13%, paddock 8 from 25% to 6% and paddock 9, 22% to 19%, from 2010 to 2011. Figure 5.3 and Tables 5.15 and 5.16 shows that the farming stage generating the most emissions is the on-farm stage of 2010 and the category hotspot is ISE in 2010 on paddock 8. Within the output category ISE the leaching of N (quantised as N_2O) generated the highest GHG emissions (Table 5.16). The ISE output category contributed 40.4% of the total emissions from paddock 8 in 2010.



	Pre-farm 2010	On-farm 2010	Pre-farm 2011	On-farm 2011	Totals 2010	Totals 2011
7	1.76E+02	2.63E+02	1.28E+02	2.70E+02	4.39E+02	3.98E+02
8	3.24E+02	4.01E+02	5.35E+01	1.31E+02	7.25E+02	1.85E+02
9	2.85E+02	3.64E+02	3.94E+02	1.66E+02	6.49E+02	5.60E+02

Figure 5.3. Summary of GHG emissions per paddock for Farm C

The results obtained for this farm are consistent with Biswas et al. (2008), Biswas et al. (2011), Brock et al. (2012) and Barton et al. (2014), wherein it was concluded that the GHG emissions generated from the production of fertilisers were the hotspot in the pre-farm and on-farm stages and then the production of herbicides. In addition, the ISE are directly related to the application of N-fertilisers and the rainfall for that growing period. White & van Rees (2011) conducted a study in Victoria, Australia wherein GHG emissions from mixed cropping/grazing systems were quantified, and found that the GHG emissions (40–160 kg CO_2-e/t, 28–45% of the total emissions) from livestock presented as the hotspot. Browne, Eckard, Behrendt, & Kingwell (2011) quantified GHG emissions from livestock in a study in south eastern Australia as ranging between 2.8 t/ha – 4.3 kg CO_2-e/ha. The GHG emissions from livestock, on paddock 8 in 2011 (i.e. the second hotspot), contributed 59% of the total GHG emissions (1.10×10^2 kg CO_2-e/t or 5.13 kg CO_2-e/ha). Livestock GHG emissions are dependent on the stocking rate on the paddock, the type of stock and the grazing time. Since the grazing period was very short (i.e. a few weeks) in the current study, the GHG contribution from grazing in the current study will not always agree with the GHG emissions from other research. Furthermore the range of results of this research (3.27 kg CO_2-e/ha – 8.70 kg CO_2-e/ha, SD = 2.20 kg CO_2-e/ha) (Table 5.14 and Table 5.15) has been compared with studies by Franks & Hadingham (2012) wherein the range is specified as 2.60 kg CO_2-e/ha – 4.71 kg CO_2-e/ha , Barton et al. (2014) with a range of 227 kg CO_2-e/t– 364 kg CO_2-e/t (Tables 5.15–5.16, 1.85×10^2 kg CO_2-e/t – 1.33×10^3 kg CO_2-e/t) for wheat growing in Western Australia, and Biswas et al. (2008) that quantified emissions from wheat in Western Australia as 269.37 kg CO_2-e/t for no animal grazing. The GHG emissions from paddock 7 in 2010 and 2011 and paddock 8 in 2011 were found to be at the higher end of the range. The higher GHG emissions for paddock 7 in 2010 and 2011 are due to the production of fertiliser and the ISE associated with fertiliser application, N content of the fertilisers (Table 5.5) and the growing season rainfall. The emissions from grazing in 2011 on paddock 8 placed the GHG emissions from this input category on the higher end of the range due to the enteric emissions of the livestock on that paddock.

5.4.4 Farm D, paddocks 10, 11 and 12

Paddocks 10, 11 and 12 were cultivated on Farm D. The average annual rainfall for all three paddocks is between 300 and 400 mm and the average annual temperature is between 18 and 21 °C based on figures from BOM (2014c). The actual rainfall for all three paddocks in 2010 was 179.2 mm and 271.2 mm in 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The soil types are grey Sodosol (grey shallow sandy duplex), brown Kandosol (brown sandy earth) and red Kandosol (red loamy earth) respectively (Table 4.2). Table 5.20 summarises the practices employed on these three paddocks for both years. In 2010 wheat was planted in all three paddocks and then sheep grazed on all paddocks after the harvest. Paddock 10 was not burned, whereas the stubble in paddock 11 was paddock burned and paddock 12 was windrow burned. In 2011 canola, barley and wheat were planted in each of the paddocks respectively, no sheep were grazed on any paddocks, and only paddock 10 was windrow burned (Table 5.20). The fertiliser was applied with seeding for all paddocks in both years, paddock 10 received an additional application in 2010 and all three paddocks received a second application of fertiliser in 2011.

Paddock 10 was not considered for further analysis as data received was incomplete.

Table 5.20. Farming practices for Farm E

2010			2011		
Paddock 10	**Paddock 11**	**Paddock 12**	**Paddock 10**	**Paddock 11**	**Paddock 12**
50 ha	80 ha	72 ha	50 ha	80 ha	72 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested canola	Planted and harvested barley	Planted and harvested wheat
Grain yield: 1.6 t/ha	Grain yield: 1.8 t/ha	Grain yield: 2.0 t/ha	Grain yield: 1.5 t/ha	Grain yield: 3.1 t/ha	Grain yield: 3.0 t/ha
Grazing of 200 head of sheep for 43 days	Grazing of 200 head of sheep for 50 days	Grazing of 200 head of sheep for 50 days	No grazing	No grazing	No grazing
No burning	Paddock burn	Windrow burn	Windrow burn	No burning	No burning

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 11 and 12 are summarised in Tables 5.21 and 5.22. Tables G.17−G22 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm D’, resulting from the different FMP on each of these paddocks.

5.4.4.1 Observation of GHG emissions from paddocks 11 and 12

When consulting Table 5.21 the following can be observed for the **pre-farm** stage:

- Lower GHG emissions for paddocks 11 and 12 in 2011 than in 2010.
- In 2010 paddock 11 had the highest GHGs and paddock 12 the lowest.
- In 2011 paddock 12 had the highest GHGs and paddock 11 the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 11 – the production of fertilisers (2010 and 2011);
    - paddock 12 – the production of fertiliser (2010 and 2011).

The following observations can be made for the **on-farm** stage (Table 5.22):

- A decrease in GHG emissions can be seen from 2010 to 2011 for paddock 11 and an increase for paddock 12.
- In 2010 the paddock with the highest GHG emissions was paddock 11 and paddock 12 had the lowest emissions.
- In 2011 paddock 12 had the highest GHG emissions and paddock 11 had the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 11 – indirect soil emissions (2010 and 2011);
    - paddock 12 – indirect soil emissions (2010 and 2011).

Table 5.21. Pre-farm CO_2-e/t emissions resulting from paddocks 11 and 12

Farm D			Pre-farm CO_2-e/t emissions					
Description	**Paddock number**	**Units**	**Chemical production**	**Fertiliser production**	**Farm machinery production**	**Transportation of chemicals**	**Transportation of fertilisers**	**Sub-total**
2010	10	kg CO_2-e/t	-	-	-	-	-	-
	11	kg CO_2-e/t	3.26E+01	1.34E+02	1.03E+01	2.25E+01	4.02E+00	**2.03E+02**
	12	kg CO_2-e/t	1.13E+01	1.32E+02	9.48E+00	2.02E+01	3.98E+00	**1.77E+02**
Totals			**4.39E+01**	**2.66E+02**	**1.98E+01**	**4.28E+01**	**8.00E+00**	**3.80E+02**
2011	10	kg CO_2-e/t	-	-	-	-	-	-
	11	kg CO_2-e/t	1.98E+01	1.03E+02	7.28E+00	1.85E+00	3.11E+00	**1.35E+02**
	12	kg CO_2-e/t	1.78E+01	1.07E+02	7.52E+00	1.55E+00	3.21E+00	**1.37E+02**
Totals			**3.76E+01**	**2.10E+02**	**1.48E+01**	**3.40E+00**	**6.32E+00**	**2.72E+02**

Table 5.22. On-farm CO_2-e/t emissions resulting from paddocks 11 and 12

Farm D			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	**Paddock number**	**Units**	**Farm machinery operation**	**Emissions from burning**	**Emissions from grazing**	**Direct soil emissions**	**Indirect soil emissions**	**Subtotal**	
2010	10	kg CO_2-e/t	-	-	-	-	-	-	-
	11	kg CO_2-e/t	1.48E+01	7.72E+01	3.54E+01	2.86E+01	1.26E+02	**2.82E+02**	**4.85E+02**
	12	kg CO_2-e/t	1.38E+01	1.95E+01	3.54E+01	2.54E+01	1.02E+02	**1.96E+02**	**3.73E+02**
Totals			**2.86E+01**	**9.67E+01**	**7.08E+01**	**5.40E+01**	**2.28E+02**	**4.78E+02**	**8.59E+02**
2011	10	kg CO_2-e/t	-	-	-	-	-	-	-
	11	kg CO_2-e/t	9.80E+00	-	-	1.98E+01	1.46E+02	**1.76E+02**	**3.11E+02**
	12	kg CO_2-e/t	1.01E+01	-	-	2.05E+01	1.75E+02	**2.05E+02**	**3.42E+02**
Totals			**1.99E+01**	**-**	**-**	**4.03E+01**	**3.21E+02**	**3.81E+02**	**6.53E+02**

Key: Red shading indicates the highest GHG emissions for each paddock.

5.4.4.2 Interpretation of GHG emissions from paddock 11

During the pre-farm stage for paddock 11 the GHG emissions from the category fertiliser production were the highest for both years (Table 5.21). However, there was a reduction in GHG emissions in this category from 2010 to 2011 by an amount of 3.03 x 10^1 kg CO_2-e/t. As there was an increase in the application of fertiliser per tonne of crop yield from 100 kg/year/t in 2010 to 166 kg/year/t in 2011, an increase in the GHG emissions from fertiliser may have been expected, however the increase in productivity (i.e. the crop yield increasing from 1.8 t/ha to 3.1 t/ha) caused an overall reduction in the use of fertiliser on a per tonne basis in 2011 and thus the reduction in the GHG emissions. In 2010 Agras was the fertiliser of choice emitting 1.34 x 10^2 kg CO_2-e/t, whereas in 2011 Agras and Flexi-N were applied, emitting 7.76 x 10^1 kg CO_2-e/t and 2.58 x 10^1 kg CO_2-e/t respectively. Thus in this category, over these two years, Agras was found to be the hotspot emitting a total of 2.11 x 10^2 kg CO_2-e/t.

The output category ISE during the on-farm stage was found to be the hotspot in 2010 and 2011 (Table 5.22), primarily the N_2O emissions derived from N leaching, was the highest for both years, 1.26 x 10^2 kg CO_2-e/t in 2010 and 1.46 x 10^2 kg CO_2-e/t in 2011, with a negligible amount of N_2O derived from the volatilisation of NH_3 (3.35 x 10^{-1} kg CO_2-e/t and 4.50 x 10^{-1} kg CO_2-e/t respectively). As Et/P was 1.95 in 2010 and 1.29 in 2011, an emission factor of 0.03 of N_2O-N applied was allocated to paddock 11 (section 5.4.1.3). The fertiliser Agras (16.1% N) was applied at a normalised rate of 56 kg/yr/t to the paddock in 2010 and 32.3 kg/yr/t of Agras (16.1% N) and 21.3 kg/yr/t of Flexi N (32%) in 2011 (Table 5.5). GHG emissions from grazing usually contribute to a significant portion of the total GHG emissions, but in the current research the sheep were grazed for a short period of time, thus the livestock emissions did not contribute significantly to the total GHG emissions.

Overall there was a decrease in the total GHG emissions from 4.85 x 10^2 kg CO_2-e/t in 2010 to 3.11 x 10^2 kg CO_2-e/t in 2011. This is mainly related to the reduction in the GHG emissions from fertiliser production as explained in the first paragraph of this section. The transportation of chemicals (2.07 x 10^1 kg CO_2-e/t), chemical production (1.28 x 10^1 kg CO_2-e/t) and farm machinery production (3.03 kg CO_2-e/t) showed a decrease in GHG emissions in order of magnitude. In the on-farm category, other than ISE, all other categories emitted less GHGs in 2011 than 2010. The GHG emissions from stubble burning were reduced by 7.72 x 10^1 kg CO_2-e/t, from 2010 to 2011 (there was no stubble burning in 2011) and thereafter the emissions from grazing (3.54 x 10^1 kg CO_2-e/t), DSE (8.82 kg CO_2-e/t) and farm machinery operation (5.01 kg CO_2-e/t).

As a result, the total on-farm GHG emissions for both years were higher than the total pre-farm emissions (Tables 5.21–5.22). Within the pre-farm stage all categories showed a reduction in the GHG emissions quantified, from 2010 to 2011. The greatest reduction in pre-farm GHG emissions was in the production of fertiliser category which was reduced by 3.03 x 10^1 kg CO_2-e/t. The overall hotspot for paddock 11 was the ISE (more specifically the calculated N_2O emissions from N leaching) output category in the on-farm stage of 2010.

5.4.4.3 Interpretation of GHG emissions from paddock 12

The production of fertiliser in paddock 12 was the hotspot in the pre-farm stage in 2010 and 2011, emitting 1.32 x 10^2 kg CO_2-e/t and 1.07 x 10^2 kg CO_2-e/t, respectively (Table 5.21). The application rate of fertiliser (Agras) in 2010 was 55 kg/yr and 165 kg/yr (Agras and Flexi-N) in 2011, normalised to 55 kg/yr/t in both cases. As the normalised application rates were the same in both years, the differences in GHG emissions were attributed to the conversion factors in converting these fertilisers to the urea equivalence (2.86 for Agras and 1.44 for Flexi-N, Appendix G, Table G.1) and application rates (normalised) for each chemical. In 2010, 55 kg/yr/t was applied to the paddock, and in 2011, 33 kg/yr/t for Agras and 22 kg/year/t for Flexi-N.

Similar to paddock 11, the ISE output category for paddock 12 presented itself as the hotspot in 2010 and 2011, generating 1.02 x 10^2 kg CO_2-e/t and 1.75 x 10^2 kg CO_2-e/t respectively (Table 5.22). Consistent with paddock 11, the derived N_2O emissions from the N leaching sub-category was the major contributor of GHGs within the ISE category, generating 1.01 x 10^2 CO_2-e/t of the total 1.02 x 10^2 kg CO_2-e/t in 2010, and 1.74 x 10^2 kg CO_2-e/t of the total 1.75 x 10^2 kg CO_2-e/t in 2011. The normalised application rate of N-fertilisers was the same in both years, however the N content differed for each year (Agras – 16.1% N for 2010 and Agras – 16.1% and Flexi-N – 32% N for 2011) (Table 5.5).

The pre-farm GHG emissions from fertiliser production, transportation of chemicals, farm machinery production and transportation of fertilisers were reduced from 2010 to 2011 by an amount of 2.55 x 10^1 kg CO_2-e/t, 1.87 x 10^1 kg CO_2-e/t, 1.96 kg CO_2-e/t and 7.67 x 10^{-1} kg CO_2-e/t respectively. GHG emissions from chemical production increased with 6.49 x 10^1 kg CO_2-e/t (Table 5.21). Overall the emissions from 2010 to 2011 decreased from 1.77 x 102 kg CO_2-e/t to 1.37 kg CO_2-e/t, mainly due to the reduction in the emissions from fertiliser production as explained in the preceding section. In the on-farm stage the only category showing an increase in GHG emissions from 2010 to 2011 was ISE (7.26 x10^1 kg CO_2-e/t). Emissions from grazing emissions, stubble burning, DSE and farm machinery operations were less in 2011 than in 2010 by an amount of 3.54 x 10^1 kg CO_2-e/t, 1.95 x 10^1 kg CO_2-e/t, 4.92 kg CO_2-e/t and 3.64 kg CO_2-e/t respectively. Overall the total GHG emissions showed a reduction from 3.73 x 10^2 kg CO_2-e in 2010 to 3.42 x 10^2 kg CO_2-e/t in 2011, mainly due to the reduction in emissions from no grazing in 2011. The hotspot for paddock 12 was the ISE output category, with calculated N_2O emissions from N leaching generating the most GHGs in the on-farm stage of 2011.

5.4.4.4 Summary for Farm D

The total GHG emissions for 2010 and 2011 on Farm D totalled 1.51 x 10^3 kg CO_2-e/t, with the bulk of the emissions (32%) being generated in paddock 11 during 2010, followed by paddock 12 (2010) generating 25% of the GHG emissions. In 2011, paddock 12 emitted 23% and paddock 11 emitted 21%, showing a reduction of 11% and 2% for paddocks 11 and 12 respectively (Figure 5.4). The farming stage emitting the highest volume of GHGs was the on-farm stage of 2010. Within the 2010 on-farm stage, ISE on paddock 11 presented as the hotspot, emitting 45% of the paddock's total emissions of 4.85 x 10^2 kg CO_2-e/t (Figure 5.4 and Tables 5.21–5.22).

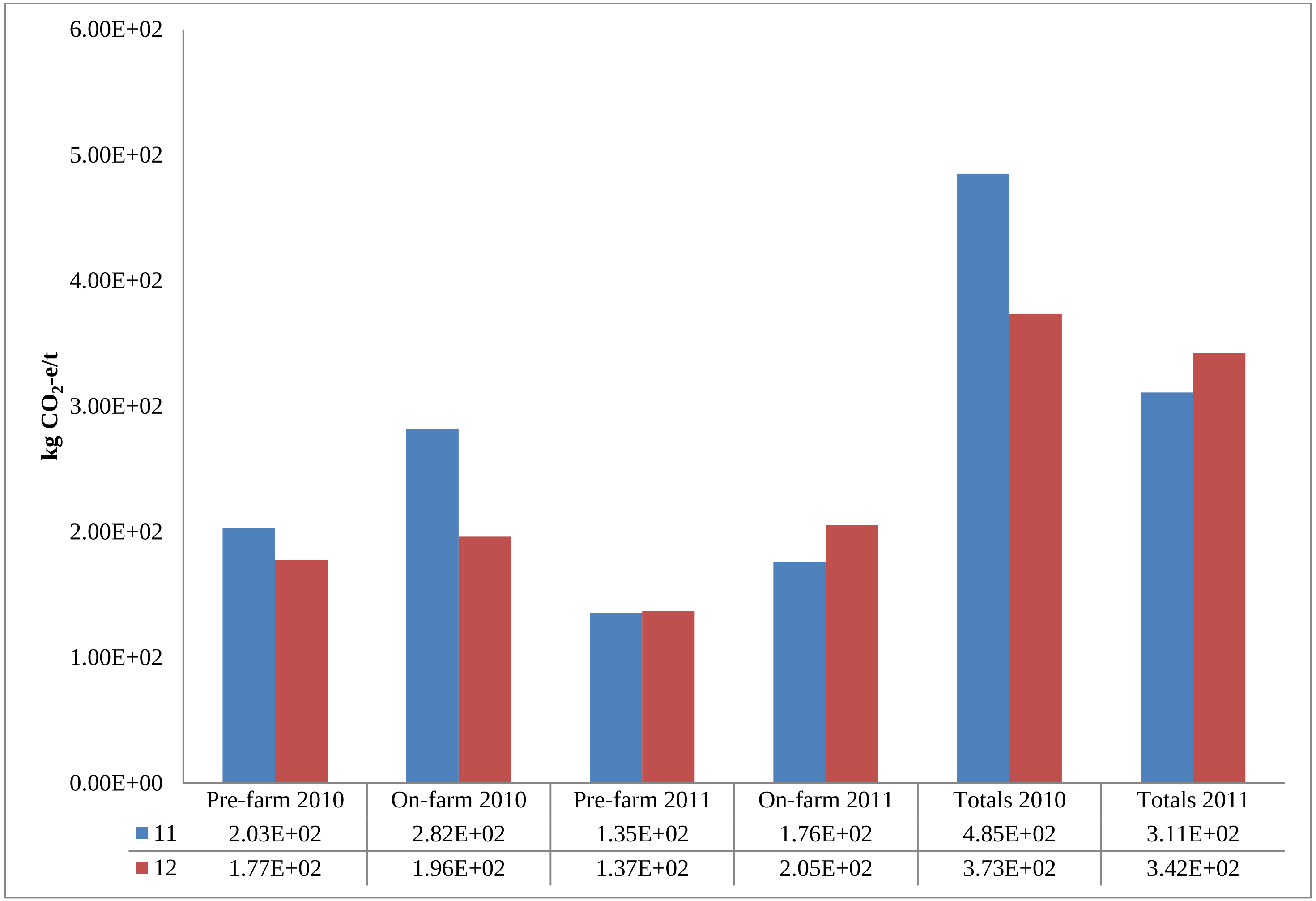


Figure 5.4. Summary of GHG emissions per paddock for Farm D

The hotspots for this farm were the production of fertilisers in the pre-farm stages and ISE in the on-farm stages. The overall hotspot for this farm was ISE in paddock 12 in 2011. The hotspots for this farm are similar to the hotspots on Farm A and Farm B, and consistent with the literature as specified in those analyses.

The range of emissions from Farm D (1.77 x 10^2 kg CO_2-e/t – 4.85 x 10^2 kg CO_2-e/t; 1.04 x 10^1 kg CO_2-e/ha – 1.42 x 10^1 kg CO_2-e/ha) are in agreement with the results reported by Biswas et al. (2008) of 2.69 x 10^2 kg CO_2-e/t for wheat emissions in Western Australia, Barton et al. (2014) of 2.27 x 10^2 kg CO_2-e/t – 3.64 10^2 kg CO_2-e/t for wheat emissions as in Western Australia, Biswas et al. (2010) of 3.90 x 10^2 kg CO_2-e/t in crops in Victoria, Australia and Brock et al. (2014) of 2.00 x 102 kg CO_2-e/t for wheat grown in New South Wales, Australia .

5.4.5 Farm E, paddocks 13, 14 and 15

Paddocks 13, 14 and 15 were cultivated on Farm E with an average annual temperature between 18 and 21 °C and an average annual rainfall between 300 and 400 mm (BOM, 2014c). The actual rainfall for these three paddocks was 412.7 mm in 2010 and 149.6 mm in 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The soil types for Farm E varied over paddocks and for paddocks 13, 14 and 15 were brown Kandosol (brown sandy earth), red Chromosol (red shallow loamy duplex) and yellow Chromosol (yellow/brown deep loamy duplex) respectively (Table 4.2). Wheat was planted to all paddocks in 2010 and 2011, except for Paddock 15 that was planted to oats. Sheep grazed on the stubble on all three paddocks over both years and the stubble was not burned at all (Table 5.23). After applying fertiliser to all paddocks with the seed, fertiliser was applied to paddock 13 twice more in 2011 and once more to paddock 14.

Table 5.23. Farming practices for Farm F

2010			2011		
Paddock 13	**Paddock 14**	**Paddock 15**	**Paddock 13**	**Paddock 14**	**Paddock 15**
136 ha	136 ha	113 ha	136 ha	136 ha	113 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested oats
Grain yield: 1.17 t/ha	Grain yield: 1.3 t/ha	Grain yield: 1.1 t/ha	Grain yield: 3.4 t/ha	Grain yield: 3.4 t/ha	Grain yield: 1.8 t/ha
Grazing of 300 head of sheep for 30 days	Grazing of 300 head of sheep for 30 days	Grazing of 200 head of sheep for 30 days	Grazing of 220 head of sheep for 59 days	Grazing of 220 head of sheep for 65 days	Grazing of 280 head of sheep for 60 days
No burning	No burning	No burning	No burning	No burning	No burning

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 13, 14 and 15 have been presented in Tables 5.24 and 5.25. Tables G.23−G27 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm E’, resulting from the different FMP on each of these paddocks.

5.4.5.1 Observation of GHG emissions from paddocks 13, 14 and 15

In Table 5.24 the following can be observed for the **pre-farm** stage:

- Lower GHG emissions for all paddocks in 2011 than in 2010.
- In 2010 paddock 15 had the highest GHGs and paddock 14 the lowest.
- In 2011 paddock 15 had the highest GHGs and paddock 13 the lowest.
- The hotspots for each of the paddocks are as follows:
  - paddock 13 – production of fertilisers (2010 and 2011);
  - paddock 14 – production of fertilisers (2010 and 2011);
  - paddock 15 – production of fertilisers (2010 and 2011).

Table 5.24. Pre-farm CO_2-e/t emissions resulting from paddocks 13, 14 and 15

Farm E			Pre-farm CO_2-e/t emissions					
Description	**Paddock number**	**Units**	**Chemical production**	**Fertiliser production**	**Farm machinery production**	**Transportation of chemicals**	**Transportation of fertilisers**	**Sub-total**
2010	13	kg CO_2-e/t	3.51E+01	1.14E+02	1.74E+01	4.15E+00	5.93E+01	**2.30E+02**
	14	kg CO_2-e/t	2.79E+01	1.02E+02	1.55E+01	3.53E+00	5.34E+01	**2.02E+02**
	15	kg CO_2-e/t	5.55E+01	1.21E+02	2.11E+01	5.78E+00	6.31E+01	**2.66E+02**
Totals			**1.19E+02**	**3.36E+02**	**5.40E+01**	**1.35E+01**	**1.76E+02**	**6.98E+02**
2011	13	kg CO_2-e/t	2.56E+01	2.92E+01	1.01E+01	1.82E+00	1.23E+01	**7.90E+01**
	14	kg CO_2-e/t	8.35E+00	5.84E+01	9.21E+00	1.51E+00	2.45E+01	**1.02E+02**
	15	kg CO_2-e/t	5.73E+00	1.18E+02	1.59E+01	2.36E+00	6.15E+01	**2.03E+02**
Totals			**3.97E+01**	**2.05E+02**	**3.52E+01**	**5.68E+00**	**9.83E+01**	**3.84E+02**

Table 5.25. On-farm CO_2-e/t emissions resulting from paddocks 13,14 and 15

Farm E			On-farm CO_2-e/t emissions						**Total CO_2-e/t emissions**
Description	**Paddock number**	**Units**	**Farm machinery operation**	**Emissions from burning**	**Emissions from grazing**	**Direct soil emissions**	**Indirect soil emissions**	**Subtotal**	
2010	13	kg CO_2-e/t	2.39E+01	0.00E+00	2.88E+01	5.12E+01	3.36E-01	**1.04E+02**	**3.34E+02**
	14	kg CO_2-e/t	2.08E+01	0.00E+00	2.60E+01	5.37E+01	3.03E-01	**1.01E+02**	**3.03E+02**
	15	kg CO_2-e/t	2.64E+01	0.00E+00	2.46E+01	5.45E+01	3.58E-01	**1.06E+02**	**3.72E+02**
Totals			**7.11E+01**	**0.00E+00**	**7.94E+01**	**1.59E+02**	**9.96E-01**	**3.11E+02**	**1.01E+03**
2011	13	kg CO_2-e/t	1.63E+01	0.00E+00	1.43E+01	2.60E+01	8.55E+01	**1.42E+02**	**2.21E+02**
	14	kg CO_2-e/t	1.54E+01	0.00E+00	1.58E+01	3.59E+01	1.71E+02	**2.38E+02**	**3.40E+02**
	15	kg CO_2-e/t	2.82E+01	0.00E+00	2.23E+01	3.24E+01	5.18E+01	**1.35E+02**	**3.38E+02**
Totals			**5.99E+01**	**0.00E+00**	**5.24E+01**	**9.43E+01**	**3.08E+02**	**5.15E+02**	**8.99E+02**

Key: Red shading indicates the highest GHG emissions for each paddock.

The following observations can be made for the **on-farm** stage (Table 5.25):

- An increase in GHG emissions can be seen from 2010 to 2011 for all three paddocks.
- In 2010 the paddock with the highest GHG emissions was paddock 15 and paddock 14 had the lowest emissions.
- In 2011 paddock 14 had the highest GHG emissions and paddock 15 had the lowest.
- The hotspots for each of the paddocks for each year is as follows:
  - paddock 13 – direct soil emissions (2010), indirect soil emissions (2011);
  - paddock 14 – direct soil emissions (2010), indirect soil emissions (2011);
  - paddock 15 – direct soil emissions direct soil emissions (2010), indirect soil emissions (2011).

5.4.5.2 Interpretation of GHG emissions from paddock 13

For the pre-farm stage for paddock 13, for years 2010 and 2011, the production of fertilisers was the hotspot with GHG emissions of 1.14 x 10^2 kg CO_2-e/t and 2.92 x 10^1 kg CO_2-e/t respectively (Table 5.24). The fertiliser DAP was applied at a rate of kg/year/t in 2010 and DAP, urea and sodium molybdate were applied at the rates of 9.56 kg/yr/t, 9.56 kg/yr/t and 9 x10^{-3} kg/yr/t, respectively in 2011. The GHG emissions from the production of DAP exceeded the emissions of the other two fertilisers used in 2011 (Table 5.26). The lower application rate of the fertilisers in 2011 is the cause of the emissions from the production of fertilisers being less in 2011 than in 2010. In addition to the lower normalised application rates of the fertilisers in 2011, the increase in crop yield for 2011 (1.17 t/ha in 2010 and 3.4 t/ha in 2011) also contributed to the lowering of the GHG emissions for 2011.

Table 5.26. Carbon footprint from the production of chemicals on paddock 13

Production of fertilisers	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
DAP	1.14E+02	2.12E+01
Urea		8.05E+00
Sodium molybdate		5.17E-04
Total	**1.14E+02**	**2.92E+01**

The DSE is the hotspot in the on-farm stage in 2010 (Table 5.25). DSE are comprised of the CO_2 emissions from hydrolysis of urea and liming and the N_2O emissions from N-fertilisers (Table 5.27). Within the DSE category the CO_2 emissions resulting from the application of lime were the highest of the GHG emissions, followed by N_2O emissions from fertiliser in 2010, thus contributing directly to the DSE as the hotspot for the on-farm stage of 2010 (Table 5.27). This does not take into consideration the increased uptake of CO_2 from the increased growth of plants due to the altered pH. Lime application has been shown to decrease the GHG emissions from the application of N-fertilisers when precipitation is present, at the same time increasing CO_2 emissions from the lime application (Barton et al., 2013; Gibbons et al., 2014; West & McBride, 2005).

Table 5.27. Carbon footprint from direct soil emissions on paddock 13

Direct soil emissions	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
CO_2 from urea hydrolysis	0.00E+00	1.40E+01
CO_2 from liming	4.70E+01	1.62E+01
N_2O from fertiliser	4.20E+00	5.68E+00
Total	**5.12E+01**	**3.59E+01**

In 2011 the hotspot of the on-farm stage was ISE on paddock 13. This in turn is related to the application of N-fertilisers and the Et/P on the paddock. Higher application rates of fertilisers and Et/P not falling within 0.8–1.0 increases the mobility of nitrogen into the soil resulting in increased GHG emissions (NGGI, 2006). In 2010 the Et/P = 0.8 for this paddock and in 2011 the Et/P = 2.3. Furthermore, N-fertilisers urea (46% N) and DAP (12.5% N) were used on this paddock thus increasing the leaching of N as NO_3^- and converted to N_2O in the soil in 2011.

The total GHG emissions for this paddock decreased from 3.34 x 10^2 kg CO_2-e/t in 2010 to 2.21 x 10^2 kg CO_2-e/t in 2011 mainly due to less GHG emissions from the production of fertilisers and the transportation of fertilisers in 2011. The reduction in GHG emissions from the production of fertilisers was 8.43 x 10^1 kg CO_2-e/t and for the transportation of fertilisers 4.71 x 10^1 kg CO_2-e/t (Table 5.24 and Table 5.25). The overall GHG emissions from the on-farm stage increased by 3.79 x 10^1 kg CO_2-e/t. The increase in GHG emissions during the on-farm stage was due to an increase in GHG emissions in the ISE category, primarily as a result of GHG emissions from N leaching (zero leaching in 2010 and 8.53 x 10^1 kg CO_2-e/t in 2011). The calculated Et/P for this paddock was 2.3 and the associated emission factor 0.03 N_2O-N for leaching in 2011, compared to Et/P = 0.8 and an emission factor of zero in 2010. A decrease in GHG emissions occurred (in decreasing order) in the categories DSE, emissions from grazing and farm machinery operation for 2010 to 2011. The overall hotspot for paddock 13 was fertiliser production in the pre-farm stage of 2010.

5.4.5.3 Interpretation of GHG emissions from paddock 14

The production of fertiliser was again found to be the category with the highest GHG emissions for the pre-farm stage in 2010 (1.02 x 10^2 kg CO_2-e/t) and 2011 (5.48 x 10^1 kg CO_2-e/t) (Table 5.24). The only fertiliser applied to this paddock in 2010 was DAP and in 2011 DAP and urea were both applied. The 2011 GHG emissions however, for the production of fertilisers, showed a decrease irrespective of the more than double application rate of these fertilisers. The decrease in GHG emissions from the production of fertilisers is thus associated with a 260% increase in grain yield in 2011 (1.3 t/ha to 3.4 t/ha), allowing the normalised application rates to be reduced. These results clearly show that the productivity associated with the use of increased inputs outweighs the additional GHG emissions from the use of increased inputs. Even though the production of fertiliser showed a decrease in GHG emissions from 2010 to 2011 it was still the hotspot in the pre-farm category for 2011.

The hotspot category during the on-farm stage for 2010 was DSE (5.37 x 10^1 kg CO_2-e/t) and in 2011 it was ISE (1.71 x 10^2 kg CO_2-e/t) (Table 5.25). Within the DSE category for 2010 the CO_2 emissions from the application of lime (4.23 x 10^1 kg CO_2-e/t) directly resulted in these elevated GHG emissions (Table 5.28). As the yield increased from 2010 to 2011, the emissions due to the application of lime on a tonne of grains basis were lower in 2011 than in 2010. The category ISE presented as the hotspot for 2011 due to the leaching of N as NO_3^- (converted to N_2O) into the soil.

Table 5.28. Carbon footprint from direct soil emissions on paddock 14

Direct soil emissions	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
CO_2 from urea hydrolysis	0.00E+00	1.40E+01
CO_2 from liming	4.23E+01	1.62E+01
N_2O from fertiliser	1.13E+01	5.68E+00
Total	**5.37E+01**	**3.59E+01**

All input categories during the pre-farm stage of this paddock showed an overall reduction in GHG emissions of 1.00 x 10^2 kg CO_2-e/t from 2010 to 2011, with the largest reduction over this time period for the production of fertilisers (4.37 x 10^1 kg CO_2-e/t) (Tables 5.24–5.25). In terms of the order of mitigation potential, the GHG emissions from the transportation of fertilisers (2.89 x 10^1 kg CO_2-e/t), chemical production (1.96 x 10^1 kg CO_2-e/t), farm machinery production (6.25 kg CO_2-e/t), and transportation of chemicals (2.03 kg CO_2-e/t) were all reduced from 2010 to 2011. As the grain yield (i.e. denominator) increased from 2010 to 2011, the GHG emissions (i.e. numerator) resulting from the larger yield reduced the overall GHGs. The on-farm stage showed an increase in GHG emissions of 1.37 x 10^2 kg CO_2-e/t from 2010 to 2011. This was primarily influenced by the increase of 1.71 x 10^2 kg CO_2-e/t in the ISE input category, which was mainly due to leaching taking place in the paddock in 2011 and not in 2010. The output category ISE from the on-farm stage of 2011 was the overall hotspot, and N from leaching (converted to N_2O) contributed to the majority of the ISE.

5.4.5.4 Interpretation of GHG emissions from paddock 15

Similar to paddock 14, the fertiliser production input category, for the pre-farm stage, was the hotspot for this paddock in 2010 (1.21×10^2 kg CO_2-e/t) and 2011 (1.18×10^2 kg CO_2-e/t). There was a slight decrease in GHG emissions from fertiliser production from 2010 to 2011 by an amount of 3.03 kg CO_2-e/t. In 2011 the only fertiliser applied on this paddock was MAP (33.42 kg/year/t) and in 2010 only DAP was applied (54.55 kg/year/t). Although the conversion factor (i.e. to convert the actual fertilisers used to equivalent amount of urea) of MAP was 4.18 and DAP 2.63, the application rate was so low in 2011 that it resulted in a slight reduction in GHG emissions.

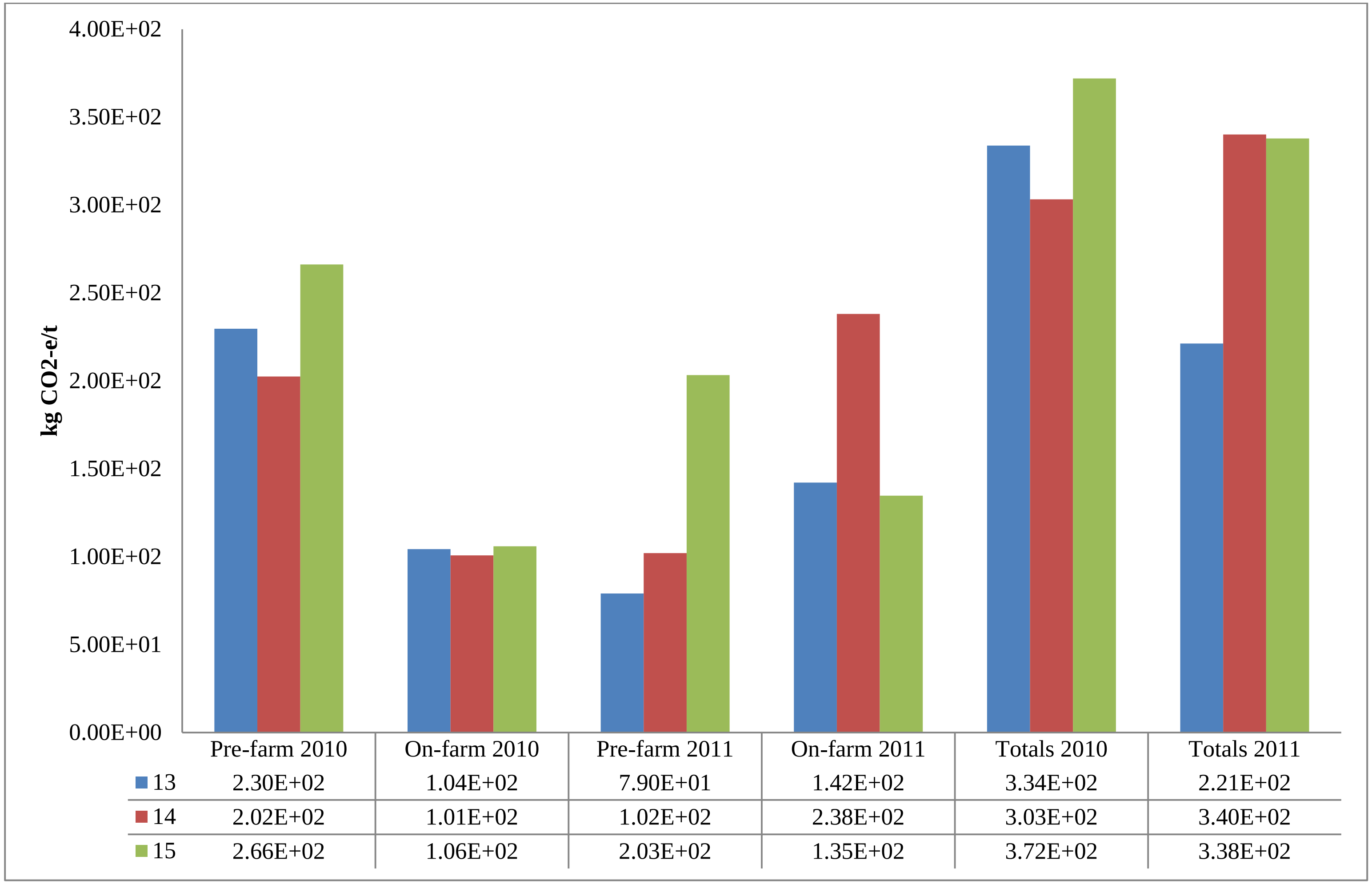
In 2010 the output category generating the highest quantity of GHGs was DSE emissions (5.45×10^1 kg CO_2-e/t), followed by emissions from farm machinery operation (2.64×10^1 kg CO_2-e/t), emissions from grazing (2.46×10^1 kg CO_2-e/t), and then ISE (3.58×10^{-1} kg CO_2-e/t). Within the DSE output category for 2010, the CO_2 emissions from liming (5.0×10^1 kg CO_2-e/t) were the most concerning followed by the N_2O emissions from fertiliser (4.47 kg CO_2-e/t). No emissions were quantified for CO_2 from urea hydrolysis as the farmer had not applied urea in 2010. The DSE were lower in 2011 (3.24×10^1 kg CO_2-e/t) than in 2010 by an amount of 2.21×10^1 kg CO_2-e/t, primarily due to a reduction in CO_2 emissions from liming that were lower by 3.06×10^1 kg CO_2-e/t in 2011. This in turn is related to the increased grain yield (denominator) lowering the emissions during normalisation. In 2011 the ISE output category contributed the highest GHG emissions (5.18×10^1 kg CO_2-e/t) followed by DSE (3.24×10^1 kg CO_2-e/t), the emissions from grazing (2.32×10^1 kg CO_2-e/t) and the emissions from farm machinery operation (1.62×10^1 kg CO_2-e/t). As the Et/P was 2.3 for 2011, leaching occurred on this paddock during this year, elevating the N emissions from leaching (converted to N_2O) and subsequently the overall GHG emissions.

When comparing the total GHG emissions across all input and output categories it is evident that the GHG emissions for this paddock decreased from 2010 (3.72×10^2 kg CO_2-e/t) to 2011 (3.38×10^2 kg CO_2-e/t) (Table 5.24 and Table 5.25). However the on-farm stage showed an increase in GHG emissions from 1.06×10^2 kg CO_2-e/t to 1.35×10^2 kg CO_2-e/t, due to the increase in ISE from 2010 to 2011. All other categories showed a decrease in GHG emissions during the on-farm stage. In contrast, the GHG emissions from all the categories in the pre-farm stage decreased from 2010 to 2011 by an amount of 6.30×10^1 kg CO_2-e/t. The GHG emissions in the input category chemical production showed the greatest reduction (4.98×10^1 kg CO_2-e/t) during this time period mainly due to a reduction of 5.79×10^1 kg CO_2-e/t in the GHG emissions from the production of herbicides. The fertiliser production input category from the pre-farm stage of 2010 presented as the overall hotspot for this paddock.

5.4.5.5 Summary for Farm E

Farm E emitted 1.88×10^3 kg CO_2-e/t over the two years with the majority of the emissions originating from paddock 15 in 2010 (19%), followed by paddock 14 in 2011 (18%) (Figure 5.5). Paddock 13 and paddock 15 showed a decrease in GHG emissions from 2010 to 2011, the emissions from paddock 13 decreased by 5.9% and paddock 15 by 1.8%, whereas paddock 14 increased from 16% to 18%. Tables 5.24 and 5.26 indicate that the farming stage generating the most emissions over this two year period was the pre-farm stage of 2010, and within that stage the input category hotspot was fertiliser production on paddock 15 for 2010, generating 1.21×10^2 kg CO_2-e/t, equating to 45% of the GHG emissions in the pre-farm stage and 32% of the GHG emissions from the paddock. Overall paddock 15 produced the highest level of GHGs in 2010 for this farm, but emitted 2% less GHGs in 2011 directly due to decreased chemical use in 2011, thus the GHGs from chemical production were reduced.

The pre-farm hotspots for this farm were fertiliser production for all three paddocks for both years and for the on-farm stage it was the DSE for 2010 and ISE for 2011. The DSE and ISE are dependent on the quantity of N-fertilisers applied, the percentage N content (Table 5.5) in the N-fertiliser and the precipitation level for that year (Biswas et al., 2008).



	Pre-farm 2010	On-farm 2010	Pre-farm 2011	On-farm 2011	Totals 2010	Totals 2011
13	2.30E+02	1.04E+02	7.90E+01	1.42E+02	3.34E+02	2.21E+02
14	2.02E+02	1.01E+02	1.02E+02	2.38E+02	3.03E+02	3.40E+02
15	2.66E+02	1.06E+02	2.03E+02	1.35E+02	3.72E+02	3.38E+02

Figure 5.5. Summary of GHG emissions per paddock for Farm E

Literature pertaining to the incidence of these categories presenting as the hotspots is the same as for the preceding paddocks. The range of values for Farm E (2.13 x 10^2 kg CO_2-e/t – 3.72 x 10^2 kg CO_2-e/t) is similar to other studies in Australia employing similar FMP, such as studies in Victoria, Australia emitting 2.69 x 10^2 kg CO_2-e/t (Biswas et al., 2010), and in south-western Australia emitting 3.90 x 10^2 kg CO_2-e/t – 3.64 10^2 kg CO_2-e/t (Barton et al., 2014) and 2.69 x 10^2 kg CO_2-e/t (Biswas et al., 2010).

5.4.6 Farm F, paddocks 16, 17 and 18

Paddocks 16, 17 and 18 were cultivated on Farm F. The average annual temperature of these paddocks varies between 15 and 18 °C and the paddocks fall within the average annual rainfall zone of 300–400 mm (BOM, 2014c). The actual rainfall for these three paddocks was 233.8 mm in 2010 and 393.2 mm in 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The dominant soil types on the paddocks are yellow Kandosol (yellow sandy earth), Orthic Tenosol (yellow deep sand) and variable (ironstone gravelly soils supergroup) soils (Table 4.2). In 2010 the paddocks were all planted to wheat, no sheep were grazed on any of the paddocks and no stubble was burned. In 2011 paddocks 16 and 17 were used as pasture for sheep with no stubble burning. Paddock 18 was planted to canola, was not grazed and the stubble was windrow burned (Table 5.29). The methods of fertiliser application were not recorded for any paddocks in 2010, thus it was assumed that fertiliser was applied with the seed. Paddocks 17 and 18 had no fertiliser applied in 2011. Paddock 18 had three fertiliser applications in 2011, one application with the seed and an additional two applications thereafter. As paddock 16 and paddock 17 did not have any grain yield they were excluded from further analyses. The grain yield is the functional unit and a requirement for the completion of this LCA.

Table 5.29. Farming practices for Farm F

2010			2011		
Paddock 16	**Paddock 17**	**Paddock 18**	**Paddock 16**	**Paddock 17**	**Paddock 18**
65 ha	44 ha	51 ha	65 ha	44 ha	51 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Pasture	Pasture	Planted and harvested canola
Grain yield: 2.05 t/ha	Grain yield: 1.89 t/ha	Grain yield: 1.33 t/ha			Grain yield: 1.4 t/ha
No grazing	No grazing	No grazing	Grazing of 360 head of sheep for 60 days	Grazing of 250 head of sheep for 60 days	No grazing
No burning	No burning	No burning	No burning	No burning	Windrow burn

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 18 are presented in Tables 5.30 and 5.31. Tables G.28−G32 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of ‘Farm F’, resulting from the different FMP on each of these paddocks.

5.4.6.1 Observation of GHG emissions from paddock 18

When consulting Table 5.30 the following can be observed for the **pre-farm** stage:

- The emissions from paddock 18 stayed the same over both years.
- The hotspot for the paddock for each year is as follows:
    - paddock 18 – the production of fertiliser (2010 and 2011).

The following observations can be made for the **on-farm** stage (Table 5.31):

- A decrease in GHG emissions can be seen from 2010 to 2011.
- The hotspot for the paddock for each year is as follows:
    - paddock 18 – indirect soil emissions (2010), direct soil emissions.

Table 5.30. Pre-farm CO_2-e/t emissions resulting from paddocks 16, 17 and 18

Farm F			Pre-farm CO_2-e/t emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	16	kg CO_2-e/t	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-
	18	kg CO_2-e/t	3.62E+01	3.15E+02	1.96E+01	3.41E+00	3.87E+00	**3.78E+02**
Totals			**3.62E+01**	**3.15E+02**	**1.96E+01**	**3.41E+00**	**3.87E+00**	**3.78E+02**
2011	16	kg CO_2-e/t	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-
	18	kg CO_2-e/t	2.96E+01	3.02E+02	1.99E+01	2.10E+01	4.44E+00	**3.77E+02**
Totals			**2.96E+01**	**3.02E+02**	**1.99E+01**	**2.10E+01**	**4.44E+00**	**3.77E+02**

Table 5.31. On-farm CO_2-e/t emissions resulting from paddocks 16, 17 and 18

Farm F			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	16	kg CO_2-e/t	-	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-	-
	18	kg CO_2-e/t	1.96E+01	-	-	4.07E+01	2.30E+02	**2.90E+02**	**6.68E+02**
Totals			**1.96E+01**	**-**	**-**	**4.07E+01**	**2.30E+02**	**2.90E+02**	**6.68E+02**
2011	16	kg CO_2-e/t	-	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-	-
	18	kg CO_2-e/t	2.41E+01	2.65E+00	-	4.66E+01	1.90E+00	**7.52E+01**	**4.52E+02**
Totals			**2.41E+01**	**2.65E+00**	**-**	**4.66E+01**	**1.90E+00**	**7.52E+01**	**4.52E+02**

Key: Red shading indicates the highest GHG emissions for each paddock

5.4.6.2 Interpretation of GHG emissions from paddock 18

For both 2010 and 2011 the production of fertiliser was the input category with the highest GHG emissions in the pre-farm stage (Table 5.30). However there was a slight decrease in these emissions from 2010 (3.15×10^2 kg CO_2-e/t) to 2011 (3.02×10^2 kg CO_2-e/t). In both years MAP and MaxAmFlo were applied and UAN was applied additionally in 2011. The application rates of the fertilisers were 181 kg/year (normalised 136.02 kg/year/t) and 203 kg/year (normalised 144.71 kg/year/t) respectively and grain yields were 1.33 t/ha and 1.4 t/ha respectively. As the same emissions factors are used for all fertilisers the increase in the grain yield in 2011 would be responsible for the slight decrease in GHG emissions from 2010 to 2011. The fertilisers generating the most GHGs in 2010 and 2011 were MaxAmFlo (1.51×10^2 kg CO_2-e/t) and MAP (1.51×10^2 kg CO_2-e/t) respectively (Table 5.32).

Table 5.32. Carbon footprint from the production of fertilisers on paddock 18

Production of fertilisers	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
MAP	1.51E+02	1.51E+02
MaxAmFlo	1.64E+02	8.80E+01
UAN		6.28E+01
Total	**3.15E+02**	**3.02E+02**

In 2010, the ISE output category during the on-farm stage was responsible for 2.30×10^2 kg CO_2-e/t of the GHG emissions, due to N leaching (quantised as N_2O) as explained in paddock 17 (Table 5.31). The GHG emissions in this output category showed a reduction of 2.28×10^2 kg CO_2-e/t from 2010 to 2011. No GHGs were emitted from leaching, however GHG emissions resulting from NH_3 volatilisation (1.90 kg CO_2-e/t) were evident as N-fertilisers had been applied to this paddock in 2011. The hotspot for this paddock in 2011 was the DSE output category. Within this output category the CO_2 emissions from liming generated 3.14×10^1 kg CO_2-e/t and N_2O emissions from N-fertilisers generated 1.51×10^1 kg CO_2-e/t. In 2011 43 kg/ha/year of MAP (11% N) fertiliser, 52 kg/ha/year MaxAmFlo (22% N) and 52 kg/ha/year Flexi-N (32% N) (Table 5.5) were applied in this paddock.

Over the two year period there was a reduction of 1.31 kg CO_2-e/t in total GHG emissions during the pre-farm stage and a reduction of 2.15×10^2 kg CO_2-e/t during the on-farm stage (Table 5.30 and Table 5.31). In the pre-farm stage the chemical production and fertiliser production input categories both showed a decrease in GHG emissions, 6.57 kg CO_2-e/t and 1.32 x 10^1 kg CO_2-e/t respectively, while all the other categories showed increases (GHG emissions from farm machinery production increased by 3.10 x 10^{-1} kg CO_2-e, transportation of chemicals by 1.76 x 10^1 kg CO_2-e/t and transportation of fertilisers by 5.67 x 10^{-1} kg CO_2-e/t). During the on-farm stage ISE decreased by an amount of 2.28 x 10^2 kg CO_2-e/t from 2010 to 2011 while all other categories increased, farm machinery operation by 4.48 kg CO_2-e/t, emissions from stubble burning by 2.65 kg CO_2-e/t and DSE by 5.85 g CO_2-e/t. The overall hotspot for paddock 18 was the production of fertiliser input category from the pre-farm stage of 2010.

5.4.6.3 Summary for Farm F

In 2010 paddock 18 contributed 60% of the total 1.12 x 10^3 kg CO_2-e/t emitted over the two years for Farm F. However, the pre-farm stage of 2010 for paddock 18 presented as the hotspot emitting 33.8% of the paddock's total emissions of 6.6 x 10^2 kg CO_2-e/t for 2010 (Figure 5.6). Within the pre-farm stage of 2010 for paddock 18, the production of fertilisers was the hotspot generating 47% of the emissions for 2010, which equated to 83% of the emissions from the pre-farm stage (Table 5.30). The use of fertilisers in this paddock is expanded on in section 5.4.6.2.

The results obtained from this farm for paddock 18 are similar to the results for the preceding paddocks. In the pre-farm stages in 2010 and in 2011, the production of fertilisers was the hotspot. Studies by Grant & Beer (2006) in New South Wales, Australia, found that emissions from the production of fertilisers in irrigated maize were the hotspot and studies of cereals in Italy by Bacenetti, Fusi, Negri, & Fiala, (2015) also concluded that fertiliser production was the largest emitter of GHGs. Furthermore all studies previously mentioned support these conclusions as well as the fact that ISE and DSE are directly influenced by the application of N-fertilisers and their N percentage content. The hotspots were ISE for the on-farm stage for 2010, and DSE in 2011.

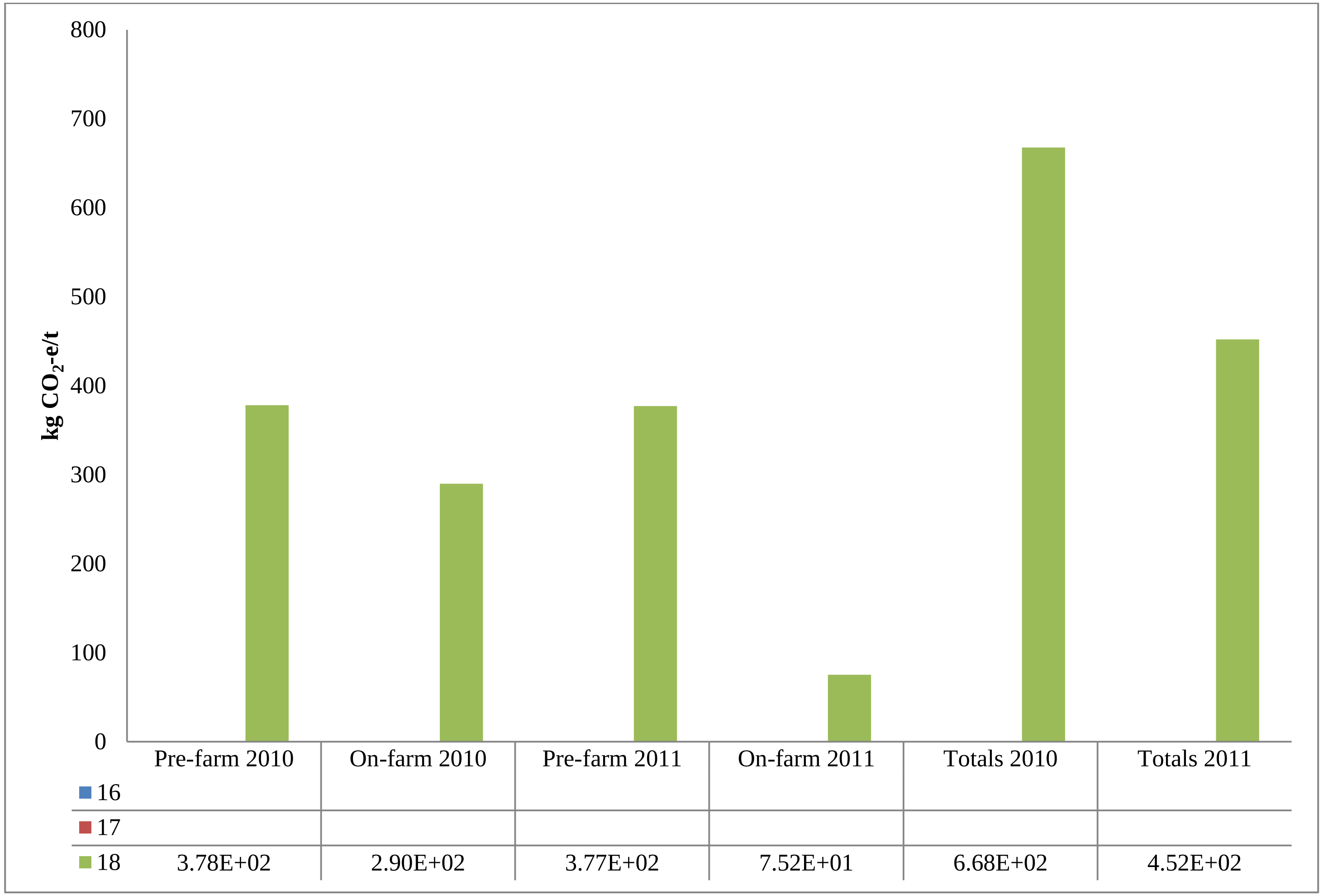


Figure 5.6. Summary of GHG emissions per paddock for Farm F

5.4.7 Farm G, paddocks 19, 20 and 21

Paddocks 19, 20 and 21 were cultivated on Farm G. These paddocks are found in a high rainfall zone with an average annual rainfall of 500–600 mm and an average annual temperature of 15–18 °C (BOM, 2014c). The actual annual rainfall for these paddocks was 281.4 mm in 2010 and 431.3 mm in 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The soil types are primarily brown Kandosol (brown loamy earth), grey Chromosol (grey shallow loamy duplex) and Orthic Tenosol (yellow deep sand). These three paddocks were planted to wheat in 2010 and 2011 and were not used for grazing sheep. The stubble was burned (paddock burn) on paddocks 19 and 20 in 2010 (Table 5.33). After applying fertiliser to all paddocks in both years during seeding, one additional application was made to paddocks 19 and 21 in 2010, two applications for paddocks 20 in 2010 and two for paddocks 19 and 20 in 2011, and paddock 21 received three fertiliser applications in 2011.

Table 5.33. Farming practices for Farm G

2010			2011		
Paddock 19	**Paddock 20**	**Paddock 21**	**Paddock 19**	**Paddock 20**	**Paddock 21**
40 ha	60 ha	47 ha	40 ha	60 ha	47 ha
Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat
Grain yield: 1.64 t/ha	Grain yield: 1.94 t/ha	Grain yield: 2.2 t/ha	Grain yield: 3.8 t/ha	Grain yield: 4.0 t/ha	Grain yield: 3.6 t/ha
No grazing	No grazing	No grazing	No grazing	No grazing	No grazing
Paddock burn	Paddock burn	No burning	No burning	No burning	No burning

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 19, 20 and 21 have been presented in Tables 5.34 and 5.35. Tables G.33−G37 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of 'Farm G', resulting from the different FMP on each of these paddocks.

Table 5.34. Pre-farm CO_2-e/t emissions resulting from paddocks 19, 20 and 21

Farm G			Pre-farm CO2-e/t emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	19	kg CO_2-e/t	2.29E+02	1.82E+02	1.54E+01	1.42E+01	1.29E+00	**4.42E+02**
	20	kg CO_2-e/t	2.48E+02	2.61E+02	1.28E+01	5.02E+00	4.60E+00	**5.31E+02**
	21	kg CO_2-e/t	1.12E+02	2.30E+02	1.13E+01	4.85E+00	4.04E+00	**3.62E+02**
	Totals		**5.89E+02**	**6.73E+02**	**3.96E+01**	**2.40E+01**	**9.93E+00**	**1.34E+03**
2011	19	kg CO_2-e/t	1.40E+02	9.19E+01	8.24E+00	3.15E+00	3.54E+00	**2.47E+02**
	20	kg CO_2-e/t	7.55E+01	8.73E+01	7.83E+00	4.58E+00	3.36E+00	**1.79E+02**
	21	kg CO_2-e/t	2.07E+01	2.03E+02	1.45E+01	3.69E+00	7.19E+00	**2.49E+02**
	Totals		**2.36E+02**	**3.82E+02**	**3.06E+01**	**1.14E+01**	**1.41E+01**	**6.74E+02**

Table 5.35. On-farm CO_2-e/t emissions resulting from paddocks 19, 20 and 21

Farm G			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	19	kg CO_2-e/t	2.09E+01	6.38E+01	-	6.29E+01	2.79E+02	**4.27E+02**	**8.69E+02**
	20	kg CO_2-e/t	1.70E+01	1.21E+02	-	5.54E+01	9.18E+02	**1.11E+03**	**1.64E+03**
	21	kg CO_2-e/t	1.50E+01	-	-	4.68E+01	2.06E+02	**2.67E+02**	**6.29E+02**
	Totals		**5.30E+01**	**1.85E+02**		**1.65E+02**	**1.40E+03**	**1.81E+03**	**3.14E+03**
2011	19	kg CO_2-e/t	9.37E+00	-	-	4.60E+01	2.24E+02	**2.80E+02**	**5.26E+02**
	20	kg CO_2-e/t	8.90E+00	-	-	4.37E+01	2.13E+02	**2.66E+02**	**4.44E+02**
	21	kg CO_2-e/t	1.52E+01	-	-	7.47E+01	3.82E+02	**4.72E+02**	**7.21E+02**
	Totals		**3.35E+01**	**-**	**-**	**1.65E+02**	**8.19E+02**	**1.02E+03**	**1.69E+03**

Key: Red shading indicates the highest GHG emissions for each paddock

5.4.7.1 Observation of GHG emissions from paddocks 19, 20 and 21

When consulting Table 5.34 the following can be observed for the **pre-farm** stage:

- Lower GHG emissions for all paddocks in 2011 than in 2010.
- In 2010 paddock 20 had the highest GHGs and paddock 21 the lowest.
- In 2011 paddock 21 had the highest GHGs and paddock 20 the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 19 – chemical production (2010 and 2011);
    - paddock 20 – fertiliser production (2010 and 2011);
    - paddock 21 – fertiliser production (2010 and 2011).

The following observations can be made for the **on-farm** stage (Table 5.35):

- An increase in GHG emissions can be seen from 2010 to 2011 for paddock 21 and a decrease in GHG emissions for paddocks 19 and 20.
- In 2010 the paddock with the highest GHG emissions was paddock 20 and paddock 21 had the lowest emissions.
- In 2011 paddock 21 had the highest GHG emissions and paddock 20 had the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 19 – indirect soil emissions (2010 and 2011);
    - paddock 20 – indirect soil emissions (2010 and 2011);
    - paddock 21 – indirect soil emissions (2010 and 2011).

5.4.7.2 Interpretation of GHG emissions from paddock 19

The hotspot for this paddock for both years in the on-farm stage was the production of chemicals. In 2010, 2.29×10^2 kg CO_2-e/t of the GHG emissions in the pre-farm stage were generated in this input category and in 2011 it was 1.40×10^2 kg CO_2-e/t (Table 5.34). The production of Logran produced the most GHGs in both years, 1.28×10^2 kg CO_2-e/t in 2010 and 1.24×10^2 kg CO_2-e/t in 2011 (Table 5.36). The GHG emissions decreased from 2010 to 2011, which could be due to the lower normalised application rate of chemicals in 2011 (125.79 kg/yr/t in 2010 vs 54.21 kg/yr/t in 2011) and the associated increase in grain yield from 1.64 t/ha in 2010 to 3.8 t/ha in

2011. The total application rates of the chemicals were 206.14 kg/yr and 206.02 kg/yr in 2010 and 2011 respectively.

Table 5.36. Carbon footprint from the production of chemicals on paddock 19

Chemical production	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
Alpha Cypermethrin		7.02E-04
Amine 720	3.17E+00	
BS 1000		8.63E-04
Crusader		8.68E+00
Gramoxone		9.90E-02
Lime	2.06E+00	8.89E-01
Logran	1.28E+02	1.24E+02
Lorsban	1.69E-04	2.99E-05
MCPA 242		3.50E+00
Precept	2.49E+01	
Raxil	2.68E-04	
Roundup	4.98E+00	1.65E+00
Sprayseed		2.34E-01
Topik	6.56E+01	
Treflan	7.08E-01	9.85E-01
Vincit		5.74E-05
Total	**2.29E+02**	**1.40E+02**

In the on-farm stage the bulk of the emissions were generated by ISE in 2010 and 2011 (Table 5.35), generating 2.79 x 10^2 kg CO_2-e/t and 2.24 x 10^2 kg CO_2-e/t respectively. The ISE decreased from 2010 to 2011 by 5.48 x 10^1 kg CO_2-e/t, due to reduction in the emissions from the leaching N (quantised as N_2O). As leaching took place in this paddock for both years, the reduction can be attributed to the increase in grain yield which is used for normalisation of the emissions. Additionally the normalised application rate of fertilisers also decreased from 89.02 kg/yr/t (actual = 146.0 kg/ha/yr) to 51.63 kg/yr/t (actual = 196.2 kg/ha/yr). The N-fertilisers applied in 2010 included 40 kg/yr/t Flexi-N (32% N) and 49 kg/yr/t Agstar Trace (14.2% N), and in 2011 Agflow Extra (18 kg/yr/t, 12.7% N), Flexi-N (12 kg/yr/t, 32% N) and urea (20 kg/yr/t, 46% N) were applied (Table 5.5). Et/P was 1.95 for 2010 and 1.3 for 2011.

The pre-farm GHG emissions generated a total of 4.42 x 10^2 kg CO_2-e/t in 2010 and 2.47 x 10^2 kg CO_2-e/t in 2011. The transportation of fertilisers was the only input category in this farming stage showing an increase, by 2.25 kg CO_2-e/t, over the two years. The input category for which the GHGs were reduced the most was the production of fertiliser category (8.99 x 10^1 kg CO_2-e/t reduction), mainly due to the lower application rates in 2011. For 2010 the on-farm emissions contributed 4.27 x 10^2 kg CO_2-e/t of the overall total GHGs from this paddock, and 2.80 x 10^2 kg CO_2-e/t in 2011 (Table 5.34 and Table 5.35). However there was a reduction in all the emissions across all categories for the on-farm stage from 2010 to 2011. The largest reduction was in the output category emissions from burning (6.38 x 10^1 kg CO_2-e/t) as the paddock was not burned in 2011, followed by ISE (5.48 x 10^1 kg CO_2-e/t), DSE (1.69 x 10^1 kg CO_2-e/t and finally farm machinery operation (1.16 x 10^1 kg CO_2-e/t). The chemical production input category from the pre-farm stage of 2010 presented as the overall hotspot for paddock 19, with herbicide production contributing the most GHGs.

5.4.7.3 Interpretation of GHG emissions from paddock 20

The hotspot for this paddock in the pre-farm stage was the production of fertiliser in both 2010 and 2011 (Table 5.34). This input category emitted 2.61 x 10^2 kg CO_2-e/t in 2010 and 8.73 x 10^1 kg CO_2-e/t in 2011. The application rates of fertilisers for 2010 was 199 kg/yr/ha (normalised as 102.58 kg/yr/ha/t) and 196.2 kg/yr/ha (normalised as 49.05 kg/yr/ha/t) for 2011. As the fertiliser application rates do not differ much between 2010 and 2011, the reduction in GHG emissions can mainly be due to more than double grain yield in 2011 (1.94 t/ha vs 4.0 t/ha).

In 2010 and 2011 ISE was the hotspot contributing 9.18 x 10^2 kg CO_2-e/t and 2.13 x 10^2 kg CO_2-e/t respectively of the total GHG emissions for the on-farm stage. For both years, N, converted to N_2O, from leaching was the largest contributor to ISE. For this output category, however, there was a reduction of GHGs from 2010 (9.18 x 10^2 kg CO_2-e/t) to 2011 (2.13 x 10^2 kg CO_2-e/t). As leaching took place in this paddock for both years, the reduction can be attributed to the increase in grain yield from 1.94 t/ha to 4.0 t/ha, which is used for normalisation of the emissions. In addition, the use of N-fertilisers, namely Flexi-N (32% N) and Macroplus (9.7% N) in 2010, and Agflow Extra (12.7% N), Flexi-N (32% N) and urea (46% N) (Table 5.5) in 2011, contributed to the leaching of N, which increased the quantised N_2O emissions.

When comparing the total GHG emissions generated in the pre-farm stage with those from the on-farm stage it is noticeable that the on-farm stage was the hotspot for both years (Table 5.34 and Table 5.35). In 2010 the on-farm stage generated 1.11 x 10^3

kg CO_2-e/t of the total GHG emissions and in 2011 2.80 x 10^2 kg CO_2-e/t. Overall the emissions from all categories in this farming stage decreased from 2010 to 2011. The highest reduction in GHG emissions was from ISE (7.05 x 10^2 kg CO_2-e/t), followed by burning (1.21 x 10^2 kg CO_2-e/t), DSE (1.17 x 10^1 kg CO_2-e/t) and farm machinery operation (8.11 kg CO_2-e/t). As all categories in the pre-farm stage had reduced emissions from 2010 to 2011 (5.31 x 10^2 kg CO_2 in 2010 and 1.79 x 10^2 kg CO_2-e/t in 2011) the increase can be attributed to the decrease in on-farm emissions and increased grain yield in 2011. The ISE output category, and more specifically the N emissions (converted to N_2O) from leaching, from the on-farm stage of 2010 presented as the overall hotspot for this paddock.

5.4.7.4 Interpretation of GHG emissions from paddock 21

Contributing 2.30 x 10^2 kg CO_2-e/t of the pre-farm GHG emissions in 2010 and 2.03 x 10^2 kg CO_2-e/t in 2011, the production of fertilisers input category was identified as the hotspot for this paddock during the farming stage (Table 5.34). In both years the fertiliser Macropro-plus generated the most GHG emissions, being 1.94 x 10^2 kg CO_2 for 2010 and 1.49 x 10^2 kg CO_2-e/t for 2011 (Table 5.37).

Table 5.37. Carbon footprint from fertiliser production on paddock 21

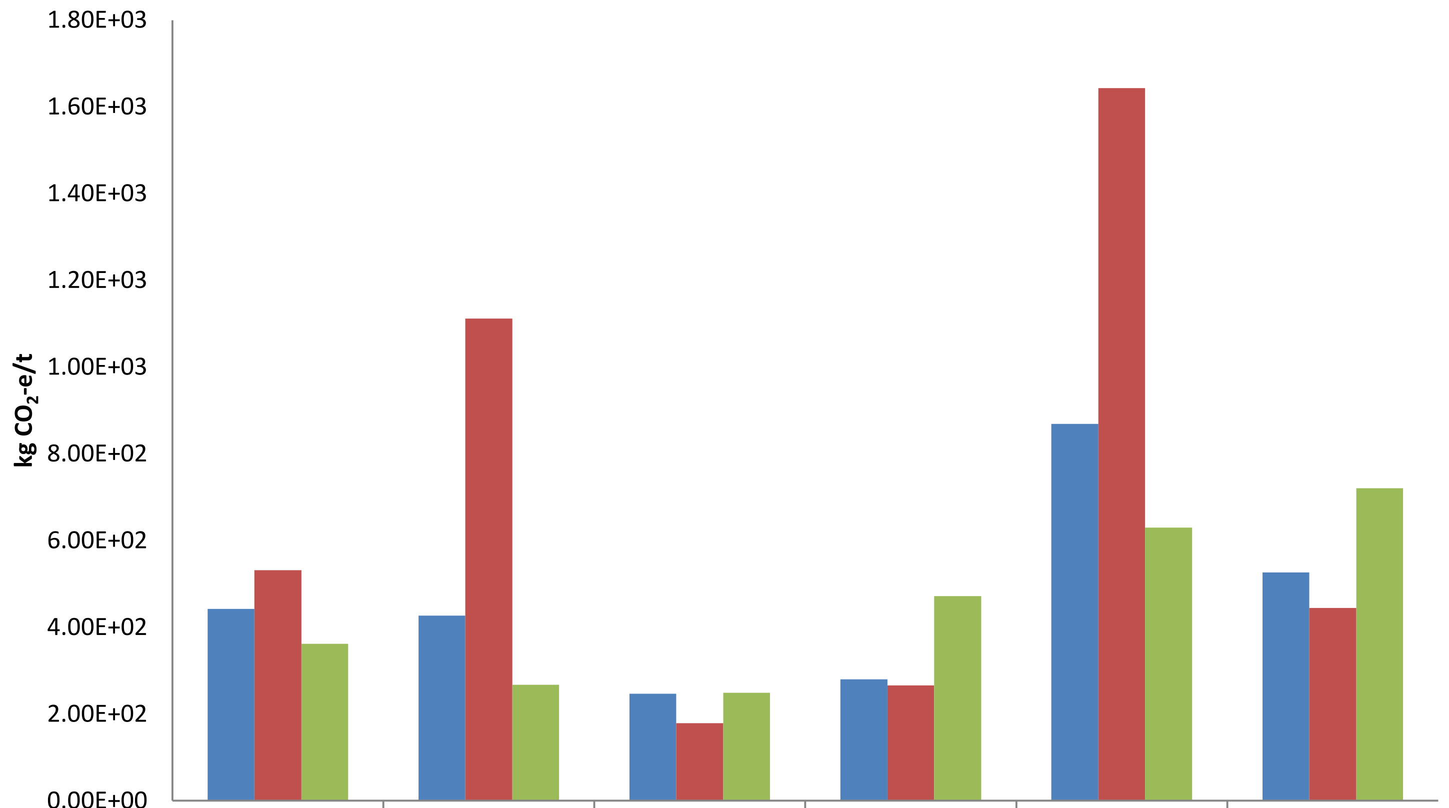
Production of fertilisers	2010	2011
	kg CO_2-e/t	kg CO_2-e/t
Flexi-N	3.63E+01	2.15E+01
MacroPro Plus	1.94E+02	1.49E+02
Urea		3.24E+01
Zinc/Manganese		6.38E-02
Total	**2.30E+02**	**2.03E+02**

The hotspot for the on-farm stage for paddock 21 was identified as ISE for both 2010 and 2011 (Table 5.35). Within this output category the emissions from the quantised N_2O emissions from N leaching were the highest in both cases – 2.05 x 10^2 kg CO_2-e/t for 2010 and 3.81 x 10^2 kg CO_2-e/t for 2011. An increase from 2.06 x 10^2 kg CO_2-e/t to 3.82 x 10^2 kg CO_2-e/t in GHG emissions in the ISE output category can be noticed, which is possibly associated with the conversion factors used in converting the fertilisers to urea. The grain yield increased from 2.2 t/ha to 2.6 t/ha over this period, which would have reduced these normalised emissions slightly.

In both 2010 and 2011 the pre-farm stage contributed 3.62 x 10^2 kg CO_2-e/t and 2.49 x 10^2 kg CO_2-e/t respectively to the overall GHG emissions. In this stage there was an overall reduction in the total GHG emissions of 1.13 x 10^2 kg CO_2-e/t from 2010 to 2011. The categories transportation of fertilisers and machinery operation increased by 3.14 kg CO_2-e/t and 3.17 kg CO_2-e/t respectively. The GHG emissions from fertiliser production, chemical production and transportation of chemicals were reduced by 2.70 x 10^1 kg CO_2-e/t, 9.11 x 10^1 kg CO_2-e/t and 1.17 kg CO_2-e/t respectively. In 2010 the on-farm stage contributed 2.67 x 10^2 kg CO_2-e/t to the total overall GHG emissions for this paddock (Table 5.34 and Table 5.35), and in 2011 the on-farm stage contributed 4.72 x 10^2 kg CO_2. All categories in the on-farm stage showed an increase in emissions from 2010 to 2011, with the greatest increase in ISE (1.76 x 10^2 kg CO_2-e/t) followed by DSE (2.79 x 10^1 kg CO_2-e/t) and then farm machinery operation (1.84 x 10^1 kg CO_2-e/t). In 2011, ISE in the on-farm stage, generated the most GHGs, thus presenting as the overall hotspot for paddock 21. The GHG emissions from the N leaching, converted to N_2O, contributed to the most GHGs in this output category.

5.4.7.5 Summary for Farm G

Paddocks 19, 20 and 21 collectively emitted 4.83 x 10^3 kg CO_2-e/t over the research period 2010–2011. In 2010, paddock 19, 20 and 21 contributed to the collective GHG total with 18%, 34% and 13% respectively. In 2011, paddock 19 emitted 11% of the collective GHG emissions, paddock 20 emitted 9% and paddock 21 emitted 15%. Furthermore, in Figure 5.7 the bar for the on-farm emissions for paddock 20 in 2010 indicates that this was the stage at which this farm generated the most GHG emissions. This on-farm stage of 2010 contributed to 68% of the GHG emissions for paddock 20. However Table 5.35 shows that the ISE and stubble burning generated the most emissions in 2010 in paddock 20. ISE generated 83% of the on-farm stage GHG emissions and 56% of the paddock GHG emissions in 2010 and the burning of stubble generated 11% of the on-farm stage GHG emissions and 7% of the paddock GHG emissions. More details on the ISE emissions are in section 5.4.7.3.



	Pre-farm 2010	On-farm 2010	Pre-farm 2011	On-farm 2011	Totals 2010	Totals 2011
19	4.42E+02	4.27E+02	2.47E+02	2.80E+02	8.69E+02	5.26E+02
20	5.31E+02	1.11E+03	1.79E+02	2.66E+02	1.64E+03	4.44E+02
21	3.62E+02	2.67E+02	2.49E+02	4.72E+02	6.29E+02	7.21E+02

Figure 5.7. Summary of GHG emissions per paddock for Farm G

The results from all paddocks on this farm are similar and consistent with the data from the other farms. On this farm, for paddock 19 for both years the hotspot in the pre-farm stage was the production of chemicals and more specifically herbicides. The hotspot for both paddocks 20 and 21 in 2010 and 2011 presented as the production of fertilisers. The on-farm stage ISE presented as the hotspot in all scenarios studied. Literature which reiterates that fertiliser use and herbicide use and their associated emissions (DSE, ISE) are of concern worldwide includes Barton et al. (2013), Bacenetti et al. (2015), Biswas et al. (2008), Biswas et al. (2011), Brock et al., (2012) and Grant & Beer, (2006);

5.4.8 Farm H, paddocks 22, 23 and 24

On Farm H paddocks 22, 23 and 24 were cultivated. The paddocks are located in the zone which receives an annual average rainfall of 400–500 mm per year and the average annual temperature is 15–18 °C (BOM, 2014c). The actual rainfall in 2010 of these three paddocks was 269.4 mm and 449.0 mm for 2011 (BOM, 2014c) (Appendix F, Table F.12-F14). The soil types are yellow Sodosol (yellow/brown deep sandy duplex), yellow Kandosol (yellow sandy earth) and brown Kandosol (brown sandy earth) respectively (Table 4.2). In 2010, wheat was planted on paddock 22, and on paddock 23 after mouldboard ploughing,[2] and paddock 24 after claying.[3] In 2011 all three paddocks were planted to wheat (Table 5.38). No sheep were grazed on any of the paddocks and the stubble was not burned. In 2011 after applying fertiliser with seeds, paddock 23 had two more applications and paddock 24 had three. As the farmer did not provide data for paddock 22 in 2010, the incomplete results from the paddock were not used for any analyses.

[2] Mouldboard ploughing is a type of ploughing in which the soil is completely inverted. It is used to remove compaction, improve water filtration, assist in weed control, increase nitrogen mineralisation and improve nutrient access (GRDC, 2014b).

[3] Claying is the spreading of clay on light, sandy soils to help increase soil moisture, retain nutrients and overcome water repellence. Clay is applied to the topsoil by spreading and ‘smudging’ it to the sandy soil surface (mechanical ‘top-dressing’) (pers. comm, Brockman, Albany, Western Australia, 2014; Brockman, 2015)

Table 5.38. Farming practices for Farm G

2010			2011		
Paddock 22	**Paddock 23**	**Paddock 24**	**Paddock 22**	**Paddock 23**	**Paddock 24**
160 ha	55 ha	120 ha	160 ha	55 ha	120 ha
Planted and harvested wheat	Mouldboard ploughing the paddock and planted and harvested wheat	Clayed the paddock and planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat	Planted and harvested wheat
Grain yield: 1.54 t/ha	Grain yield: 1.85 t/ha	Grain yield: 1.51 t/ha	Grain yield: 7.2 t/ha	Grain yield: 3.1 t/ha	Grain yield: 3.1 t/ha
No grazing	No grazing	No grazing	No grazing	No grazing	No grazing
No burning	No burning	No burning	No burning	No burning	No burning

The GHG emissions in terms of one tonne of grain production from pre- and on-farm stages for paddocks 23 and 24 are presented in Tables 5.39 and 5.40. Tables G.38−G41 (Appendix G) presents the results from the aggregation of carbon footprints of all inputs and outputs categories of 'Farm H', resulting from the different FMP on each of these paddocks.

5.4.8.1 Observation of GHG emissions from paddocks 22, 23 and 24

When consulting the tables (Table 5.39) the following can be observed for the **pre-farm** stage:

- As all results were not obtained from the farmer for paddock 22 for 2010, this paddock was not factored into the analysis.
- Total GHG emissions for paddock 23 and 24 were higher in 2011 than in 2010.
- In 2010 paddock 23 had the highest GHG emissions and paddock 24 the lowest.
- In 2011 paddock 23 had the highest GHG emissions and paddock 24 the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 23 – farm machinery production (2010), fertiliser production (2011);
    - paddock 24 – farm machinery production (2010), fertiliser production (2011).

Table 5.39. Pre-farm CO_2-e/t emissions resulting from paddocks 22, 23 and 24

Farm H			Pre-farm CO2-e emissions					
Description	Paddock number	Units	Chemical production	Fertiliser production	Farm machinery production	Transportation of chemicals	Transportation of fertilisers	Sub-total
2010	22	kg CO_2-e						
	23	kg CO_2-e	9.14E-01	-	4.44E+01	2.47E+00	-	**4.78E+01**
	24	kg CO_2-e	1.12E+00	-	1.05E+01	3.03E+00	-	**1.47E+01**
	Totals	**kg CO_2-e**	**2.03E+00**	**-**	**5.49E+01**	**5.50E+00**	**-**	**6.25E+01**
2011	22	kg CO_2-e						
	23	kg CO_2-e	2.25E+01	1.20E+02	8.49E+00	2.30E+00	2.65E+00	**1.56E+02**
	24	kg CO_2-e	2.31E+01	1.03E+02	7.31E+00	1.71E+00	2.51E+00	**1.38E+02**
	Totals	**kg CO_2-e**	**4.55E+01**	**2.24E+02**	**1.58E+01**	**4.01E+00**	**5.16E+00**	**2.94E+02**

Table 5.40. On-farm CO_2-e/t emissions resulting from paddocks 22, 23 and 24

Farm H			On-farm CO_2-e/t emissions						Total CO_2-e/t emissions
Description	Paddock number	Units	Farm machinery operation	Emissions from burning	Emissions from grazing	Direct soil emissions	Indirect soil emissions	Subtotal	
2010	22	kg CO_2-e/t							
	23	kg CO_2-e/t	1.46E+01	0.00E+00	0.00E+00	8.72E+01	0.00E+00	**1.02E+02**	**1.50E+02**
	24	kg CO_2-e/t	2.10E+02	0.00E+00	0.00E+00	1.07E+02	0.00E+00	**3.17E+02**	**3.31E+02**
	Totals	**kg CO_2-e/t**	**2.24E+02**	**0.00E+00**	**0.00E+00**	**1.94E+02**	**0.00E+00**	**4.18E+02**	**4.81E+02**
2011	22	kg CO_2-e/t							
	23	kg CO_2-e/t	9.87E+00	0.00E+00	0.00E+00	2.26E+01	6.76E-01	**3.32E+01**	**1.90E+02**
	24	kg CO_2-e/t	8.50E+00	0.00E+00	0.00E+00	2.11E+01	1.12E+00	**3.08E+01**	**1.69E+02**
	Totals	**kg CO_2-e/t**	**1.84E+01**	**0.00E+00**	**0.00E+00**	**4.38E+01**	**1.80E+00**	**6.39E+01**	**3.58E+02**

Key: Red shading indicates the highest GHG emissions for each paddock

The following observations can be made for the **on-farm** stage (Table 5.40):

- A decrease in GHG emissions can be seen from 2010 to 2011 for both paddock 23 and paddock 24.
- In 2010 the paddock with the highest GHG emissions was paddock 24 and paddock 23 had the lowest emissions.
- In 2011 paddock 23 had the highest GHG emissions and paddock 24 had the lowest.
- The hotspots for each of the paddocks for each year are as follows:
    - paddock 23 – direct soil emissions (2010 and 2011)
    - paddock 23 –farm machinery operation (2010); direct soil emissions (2011).

5.4.8.2 Interpretation of GHG emissions from paddock 23

During the pre-farm stage in 2010, farm machinery production generated 4.44 x 10^1 kg CO_2-e/t of the pre-farm GHG emissions (Table 5.39). The categories chemical production and transportation of chemicals contributed 9.14 x 10^{-1} kg CO_2-e/t and 2.47 kg CO_2-e/t to the total emissions in the pre-farm stage, respectively. No emissions were generated from fertiliser production or the transportation of fertiliser as no fertiliser was applied to this paddock in 2010. The emissions from farm machinery production dominated in the pre-farm stage in 2010 due to mouldboard ploughing increasing GHG emissions from machinery use. The emissions quantified were based on the use of an AUD value of 65 AUD/t (120 AUD/ha) for the use of mouldboard ploughing machinery, as per industry standards (Davies, 2010). The emissions from chemical production and chemical transportation categories were due to residual lime that already existed in the soil from previous applications. No other chemicals were applied. In 2011 the application of fertiliser was the hotspot contributing 1.20 x 10^2 kg CO_2-e/t to the pre-farm emissions. These emissions increased from 2010 to 2011 as there were no fertiliser applications in 2010. The fertiliser (containing N, P and K) 'NPS range-Cereal' contributed the most GHGs (6.61 x 10^1 kg CO_2-e/t) followed by UAN (3.96 x 10^1 kg CO_2-e/t) and then MOP (1.48 x 10^1 kg CO_2-e/t).

In 2010 and 2011 the DSE, mainly due to CO_2 emissions from liming (8.72 x10^1 kg CO_2-e/t and 2.26 x 10^1 kg CO_2-e/t respectively), were predominant during the on-farm stage, followed by the emissions from farm machinery operation (1.46×10^1 kg) emissions in 2010 as there were no additional chemicals, fertilisers burning or grazing employed. In 2011 additional GHG emissions were quantified in the ISE output category (6.76×10^{-1} kg CO_2-e/t) as a result of fertiliser application causing the volatilisation of ammonium (NH_4^+), quantised as N_2O from NH_3 volatilisation.

In 2010 the on-farm stage (1.02×10^2 kg CO_2-e/t) generated the most GHG emissions when compared to the pre-farm stage (4.78×10^1 kg CO_2-e/t) (Table 5.39 and Table 5.40). In 2011 the pre-farm GHG emissions (i.e. 1.56×10^2 kg CO_2-e/t) were higher than the on-farm stage (i.e. 3.32×10^1 kg CO_2-e/t) GHG emissions.

It can be noted that the GHG emissions in the pre-farm stage increased from 2010 (4.78×10^1 kg CO_2-e/t) to 2011 (1.56×10^2 kg CO_2-e/t) by 69%. The three categories contributing to the increase in GHG emissions in the pre-farm stage from 2010-2011 are chemical production, fertiliser production and transportation of fertiliser categories which increased by 96%, 100% and 100% respectively. The total GHG emissions generated during the on-farm stage were higher in 2010 (1.02×10^2 kg CO_2-e/t) than in 2011 (3.32×10^1 kg CO_2-e/t). In addition ISE increased from 2010 to 2011 by an amount of 6.76×10^{-1} kg CO_2-e/t, while DSE decreased by an amount of 6.46×10^1 kg CO_2-e/t and farm machinery operation also decreased by 4.72 kg CO_2-e/t. The ISE increased as fertilisers were applied to the paddock in 2011 which resulted in NH_4^+ volatilisation (quantised as N_2O emissions from NH_3 volatilisation), but this did not occur in 2010 as the paddock had been mouldboard ploughed and no fertiliser was applied. No leaching took place in this paddock for either year as Et/P was within 0.8–1.0. Fertiliser production in the pre-farm stage of 2011 presented as the overall hotspot for this paddock.

5.4.8.3 Interpretation of GHG emissions from paddock 24

In the pre-farm stage of paddock 24 the production of farm machinery was the hotspot emitting 9.98 kg CO_2-e/t in 2010 (Table 5.39). This input category emitted the most GHGs in 2010 due to the practice of claying, which is a machinery intensive practice. The emissions from this input category decreased to 7.31 kg CO_2-e/t, from 2010 to 2011, as the machinery used in 2011 was commonly used machinery for conventional practices including seeding, spraying, top-dressing and harvesting. In 2011 the production of fertilisers proved to be the hotspot in the pre-farm stage. As for paddock 23, the production of 'NPS range-Cereal' fertiliser emitted 5.56 x 10^1 kg CO_2-e/t and was the highest generator of GHGs followed by the production of UAN (3.36 x 10^1 kg CO_2-e/t and then MOP (1.28 x 10^1 kg CO_2-e/t). There was no fertiliser application on this paddock in 2010, thus the emissions from the production of fertilisers also showed an increase from 2010 to 2011 (1.03 x 10^2 kg CO_2-e/t in 2011).

During the on-farm stage, farm machinery operation followed by DSE proved to be the highest GHG emitters in 2010 (Table 5.40). Farm machinery was used more intensively due to claying, as further expanded on in Appendix D, and generated 2.10 x 10^2 kg CO_2-e/t. As the use of farm machinery was less intense in 2011 due to no claying being done, there was a considerable reduction (2.01 x 10^2 kg CO_2-e/t) in GHGs from one year to the next. In 2011 the hotspot for the on-farm stage occurred in the DSE output category. In this output category CO_2 emissions from liming were the major contributor (1.22 x 10^1 kg CO_2-e/t) followed by N_2O emissions originating from the application of fertilisers (8.92 kg CO_2-e/t). The emissions in this output category increased as a result of fertilisers being applied in 2011, as none were applied in 2010. Farm machinery operation was the next highest emitter contributing 8.50 kg CO_2-e/t and then ISE with 1.12 kg CO_2-e/t in the pre-farm stage for 2011.

When comparing the pre-farm stage GHG emissions for 2010 (1.41 x 10^1 kg CO_2-e/t) with the on-farm GHG emissions for 2010 (3.17 x 10^2 kg CO_2-e/t) it can be observed that the on-farm stage had the most emissions (Table 5.39 and Table 5.40). In 2011 the pre-farm stage was identified as the highest emitter (1.38 x 10^2 kg CO_2-e/t vs 3.08 x 10^1 kg CO_2-e/t). In addition, there was an increase in GHG emissions in the pre-farm stage from 2010 to 2011 by an amount of 1.24 x 10^2 kg CO_2-e/t and a decrease in the on-farm GHG emissions of 2.86 x 10^2 kg CO_2-e/t. For the pre-farm stage the categories showing a decrease in GHG emissions included farm machinery operation (2.67 kg CO_2-e/t) and transportation of chemicals (1.32 kg CO_2-e/t). In order of increasing magnitude the transportation of chemicals, chemical production and fertiliser production increased with 2.51 kg CO_2-e/t, 2.20 x 10^1 kg CO_2-e/t and 1.03 x 10^2 kg CO_2-e/t respectively. These changes can all be related to the practice of claying the paddock in the pre-farm stage. In the on-farm stage an increase in GHG emissions was evident in ISE from 2010 to 2011 of 1.12 kg CO_2-e/t, which is related to the additional use of fertilisers in 2011. A reduction in emissions occurred in the farm machinery operation output category of 2.01 x 10^2 kg CO_2-e/t and 8.57 x 10^1 kg CO_2-e/t in the DSE output category. Farm machinery was used less in 2011 than in 2010 as specified previously thus the farm machinery operation emissions and the DSE decreased due to normalisation of lime application with an increased grain yield in 2011 (1.51 t/ha versus 3.6 t/ha). Farm machinery operation in the on-farm stage of 2010 presented as the overall hotspot for paddock 24.

5.4.8.4 Summary for Farm H

Of the 8.39 x 10^2 kg CO_2-e/t emitted by the two paddocks on Farm H, paddock 23 contributed 17.8% in 2010 and 22.6% in 2011. The GHG emissions from these paddocks ranged from 1.50 x 10^2 kg CO_2-e/t – 3.31 x 10^2 kg CO_2-e/t. Paddock 24 contributed 39.5% of the GHG emissions in 2010 and 20.1% in 2011 (Figure 5.8). Both paddocks had similar FMP employed in 2010 and 2011 with similar grain yields. The farming stage presenting with the highest GHG emissions was the on-farm stage of 2010, paddock 24, emitting 63% of the total GHG emissions from the paddock. Farm machinery operation emitted 66% of the emissions generated within the on-farm stage of 2010 for paddock 24 and 63% of the total emissions from the paddock as machinery use during claying is high.

For comparison claying and mouldboard ploughing were removed from the FMP and Figure 5.9 was generated to compare the GHG emissions if these practices had not been conducted in 2010. Furthermore the grain yield for 2011 was adjusted for both paddocks. Literature by Davies (2010, 2011) shows that grain yield increases by 500–1200 kg/ha in the first year after mouldboard ploughing, thus the yield for 2011 was adjusted (to 2.75 t/ha) by subtracting the average of 750 kg/ha from the 2011 grain yield. The productivity on average increases with 20% (Biswas, 2015; GRDC, 2015) in the year after claying, thus the grain yield of 2011 for paddock 24 was adjusted down to 2.73 t/ha. It should however be remembered that this is experimental only and all variables would be affected if these practices were removed.

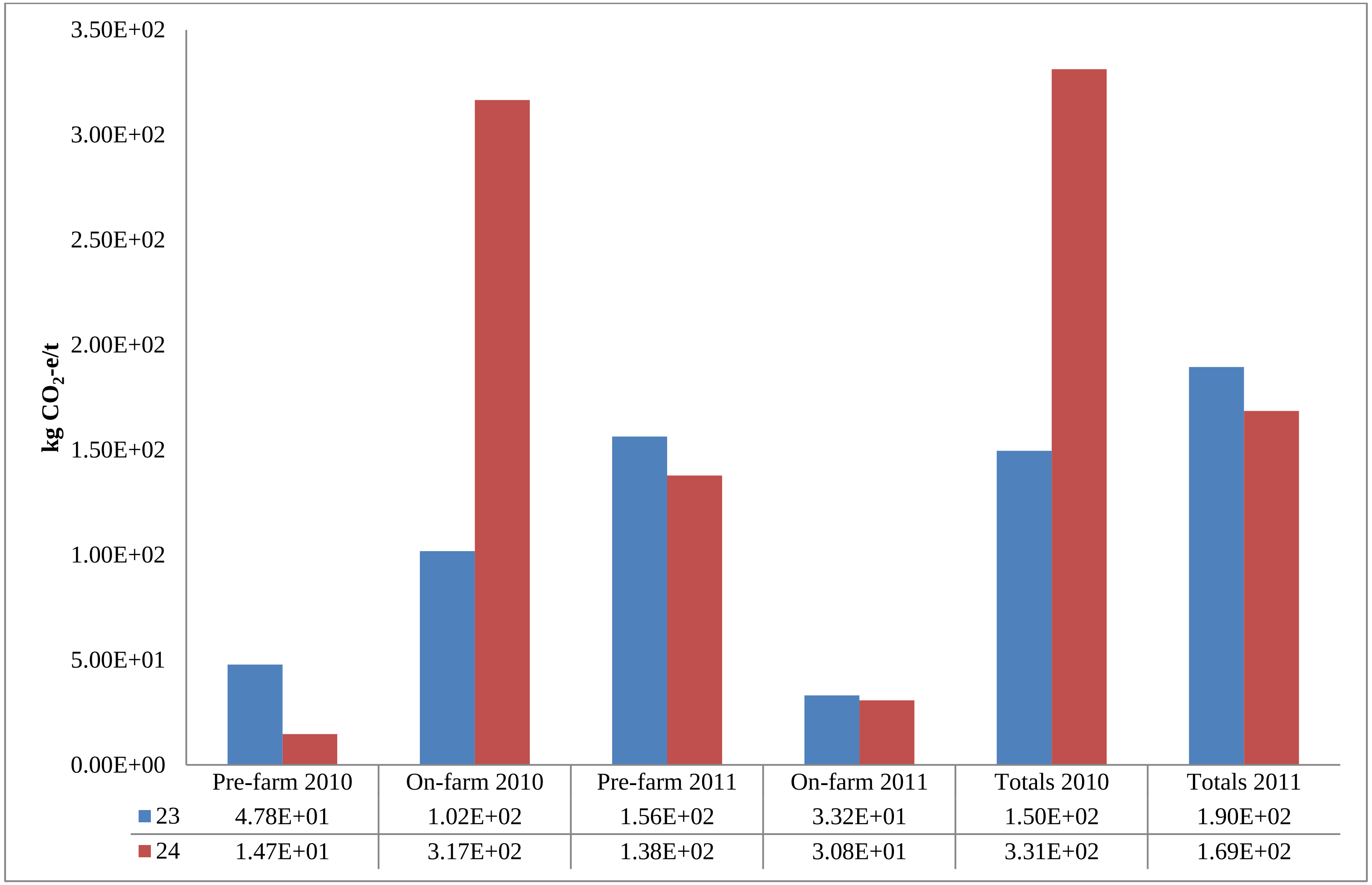


Figure 5.8. Summary of GHG emissions per paddock for Farm H

Figure 5.9 now shows that the total emissions from the two paddocks would be reduced by 16% from 9.23 x 10^2 kg CO_2-e/t to 7.77 x 10^2 kg CO_2-e/t if mouldboard ploughing and claying were not included in the calculations. The subsequent emissions ranged from 1.15 x 10^2 kg CO_2-e/t – 3.08 x 10^2 kg CO_2-e/t (0.58 kg CO_2-e/ha – 0.70 kg CO_2-e/ha). This adjusted range now compares favourably with studies in New South Wales, Australia, where the GHG emissions ranged from 1.39 x 10^2 kg CO_2-e/t – 2.19 x 10^2 kg CO_2-e/t (Brock et al., 2014). In addition the hotspot would change to DSE on-farm stage of 2010 and 2011. The DSE would then contribute to 78.6% of the on-farm stage in both years.

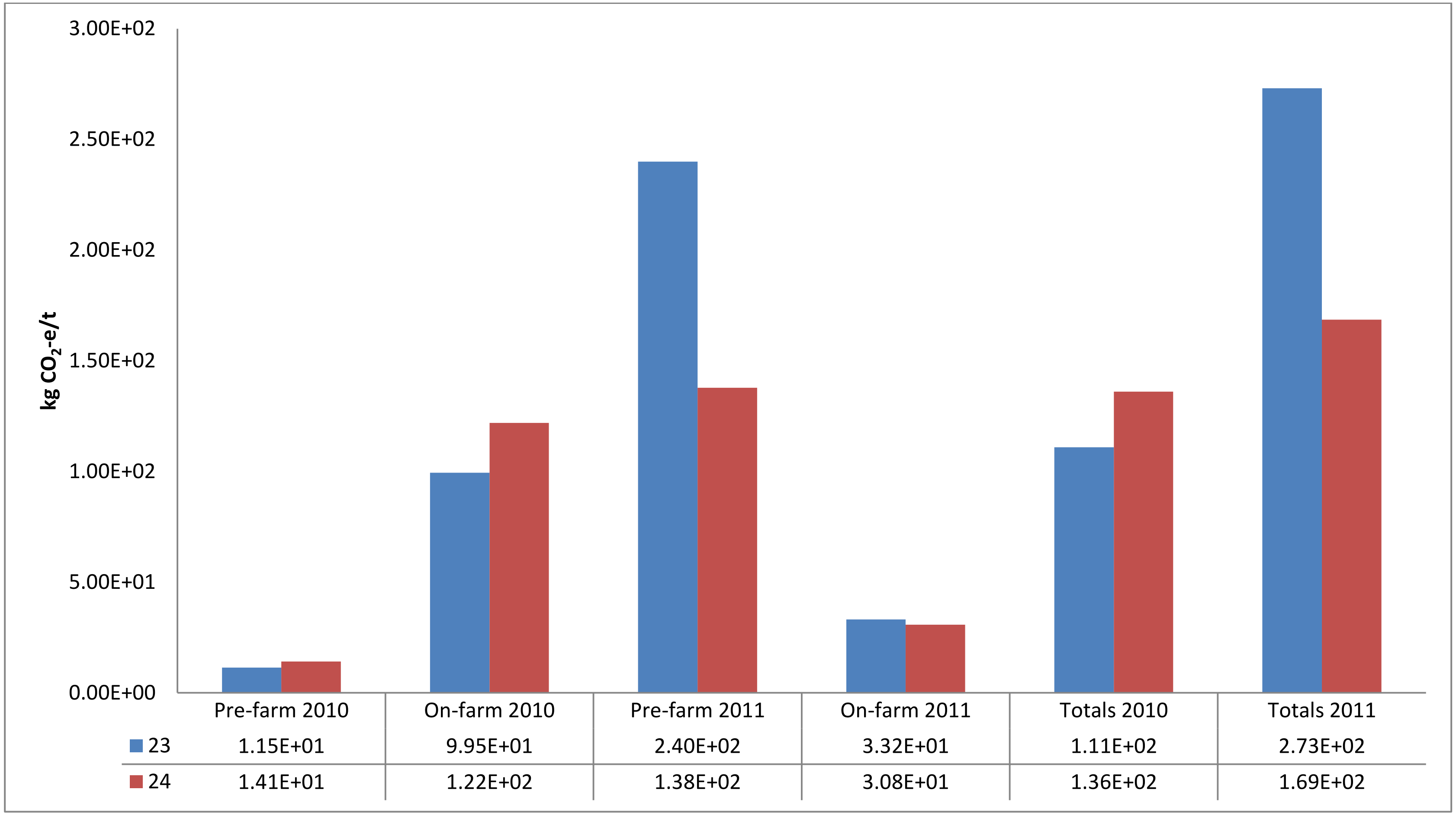


Figure 5.9. Summary of GHG emissions per paddock for Farm H, without mouldboard ploughing and claying

5.5 COMPARATIVE ANALYSIS OF EIGHT FARMS GHG EMISSIONS

Figure 5.10 presents the carbon footprint for each paddock for the entire study period, as expanded on in this chapter. In this figure it is clear that paddock 6 followed by paddock 2 and then paddock 1 were the highest GHG emitters. Paddock 23 generated the least GHGs over the research period. Paddocks 1 and 3 both had fertiliser transportation and more specifically the transportation of urea in 2011 as the hotspot. The hotspot for paddock 6 was the production of chemicals in 2011.

The GHGs per farm are illustrated in Figure 5.11. This figure clearly shows that the farm generating the most GHGs (cumulative from 2010 to 2011 for all paddocks) was Farm A, followed by Farm G. Farm F generated the second least GHGs and Farm H generated the least. This figure is consistent with the results displayed in Figure 5.10.

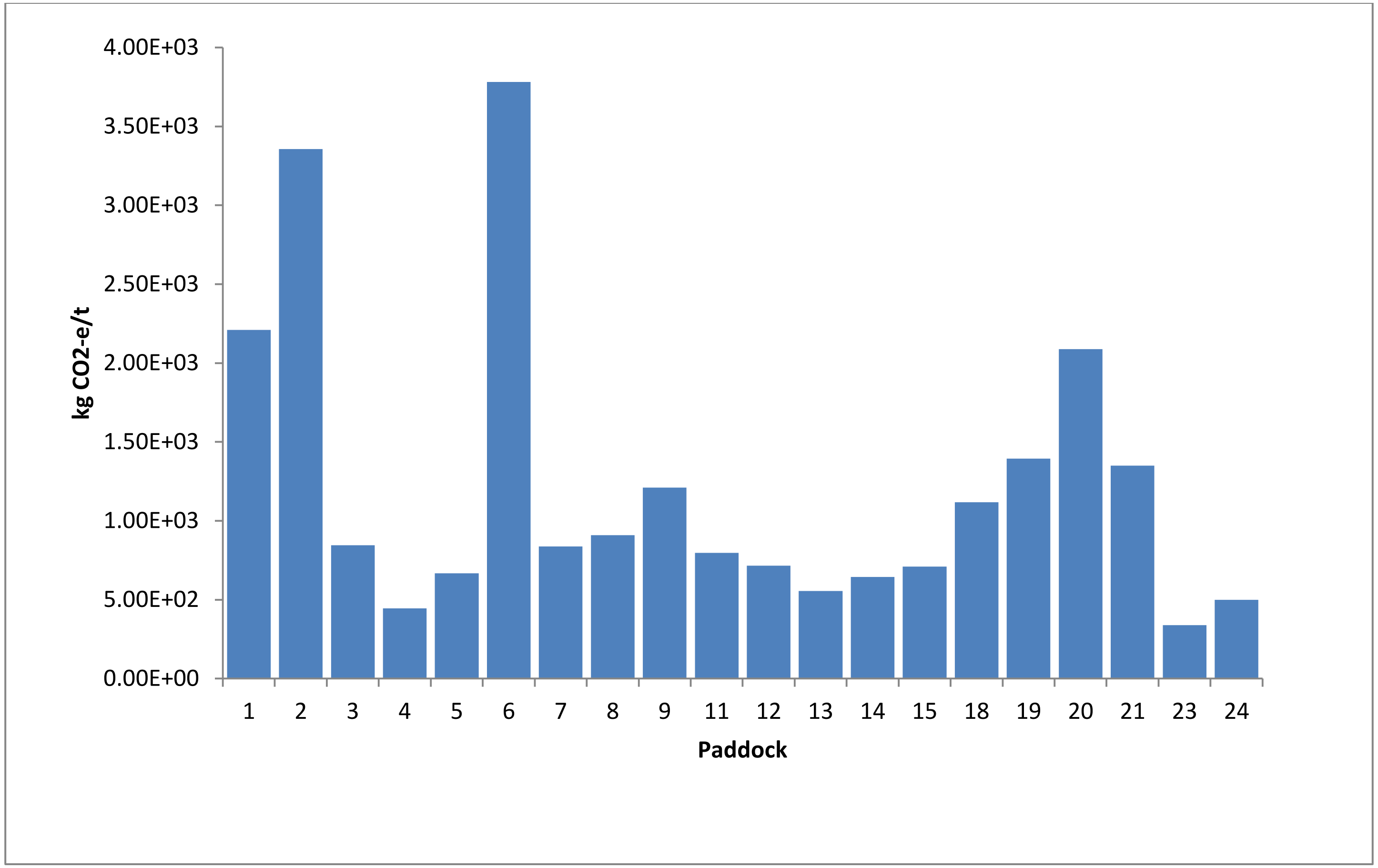


Figure 5.10. Graphical representation of the total carbon footprint for the study period, per paddock

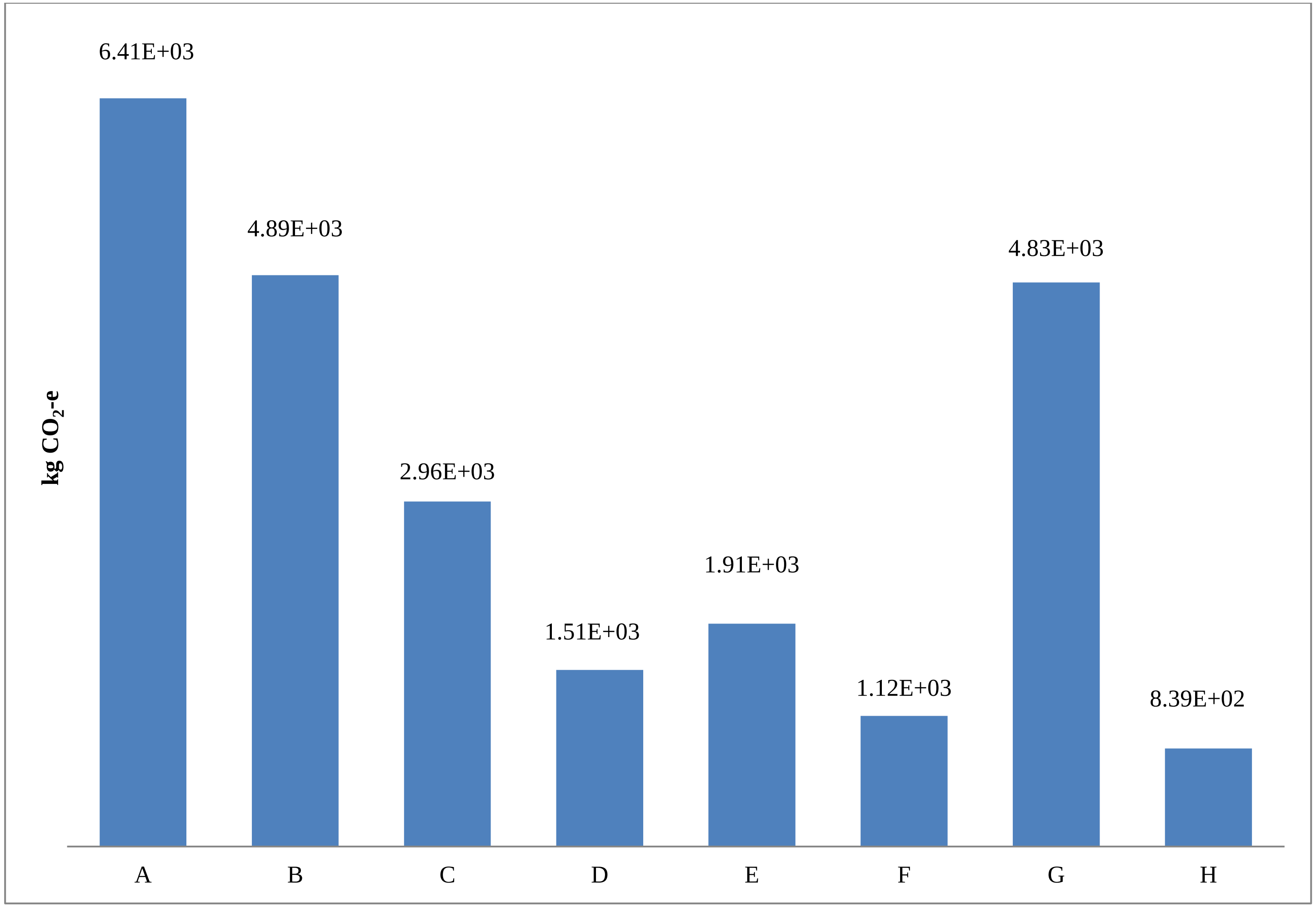


Figure 5.11. Graphical representation of the total carbon footprint for the study period, per farm

The following table (Table 5.41) is a summary of the 20 paddocks analysed in terms of crop rotation, soil type and whether or not leaching took place and has been used as a summary for these variables to highlight the hotspots (listed therein) of each of the paddocks to reach general conclusions.

From Table 5.41 the following can be summarised:

- All paddocks were planted to wheat in 2010 and 13 paddocks were planted to wheat in 2011.
- In 2011 two of the paddocks were each planted with oats, barley and lupin, and canola was planted on one paddock.
- Four of the paddocks had the soil brown Kandosol, three paddocks had Orthic Tenosol and another three red Kandosol as soil type. Calcic Calcarosol, yellow Chromosol, and variable soils were found on two paddocks each. Yellow Kandosol, red Chromosol, grey Chromosol and yellow Sodosol were each found only on one paddock.
- Leaching of N as NO_3 (quantised and reported as N_2O) occurred on 18 paddocks in 2010 and on 12 paddocks in 2011.
- The hotspots were found as follows: Fertiliser production in six paddocks, ISE in six paddocks, chemical production in three paddocks, fertiliser transportation in two paddocks, chemical transportation, direct soil emissions and farm machinery operation each in one paddock.

Table 5.41. Comparative summary of crop rotations, soil types, leaching and hotspots

Description			1	2	3	4	5	6	7	8	9	11	12	13	14	15	18	19	20	21	23	24	Sum
Crop type	2010	Wheat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	20
	2011	Wheat	✓	✓	✓			✓		✓			✓	✓	✓			✓	✓	✓	✓	✓	13
		Barley				✓						✓											2
		Lupin					✓				✓												2
		Oats							✓							✓							2
		Canola															✓						1
Soil type (ASC)	Calcic Calcarasol	Calcareous loamy earth		✓				✓															2
	Yellow Cromosol	Yellow/brown shallow loamy duplex				✓																	1
		Yellow/brown deep loamy duplex														✓							1
	Red Chromosol	Red shallow loamy duplex													✓								1
	Grey Chromosol	Grey shallow loamy duplex																	✓				1
	Red Kandosol	Red sandy earth	✓																				1
		Red loamy earth							✓				✓										2
	Brown Kandosol	Brown sandy earth										✓		✓								✓	3
		Brown loamy earth																✓					1
	Yellow Kandosol	Yellow sandy earth																			✓		1
	Yellow Sodosol	Yellow/brown deep sandy duplex								✓													1
	Orthic Tenosol	Yellow deep sand					✓				✓									✓			3
	Variable soils	Ironstone gravelly soils			✓												✓						2
Leaching	2010		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	16
	2011		✓	✓	✓				✓			✓	✓	✓	✓	✓		✓	✓	✓			12
Hotspots	Fertiliser transportation	2010		✓																			1
		2011	✓		✓																		2
	Chemical production	2010																✓					1
		2011						✓															1
	Fertiliser production	2010				✓	✓							✓		✓	✓						5
		2011									✓										✓		2
	Indirect soil emissions	2010								✓		✓							✓				3
		2011							✓				✓		✓					✓			4
	Farm machinery operation	2010																				✓	1

By focusing on the hotspot for each paddock the following similarities were found:

- For 13 of the 20 hotspots the crop rotation was wheat/wheat, then wheat/oats with 2/20 hotspots, wheat/barley with 2/20, wheat/lupin with 2/20 and wheat/canola with 1/20.
- Of the 20 paddocks, leaching occurred in 19 of them and there was no leaching in the remaining one.
- The relationships between the soil types and the hotspots are summarised in Table 5.42 and show:
    - All soils specified were classified as deficient in N, thus N-fertiliser was a FMP requirement.
    - The hotspots on the 'Kandosol' soil types were ISE, fertiliser production, chemical production and chemical transportation.
    - 'Tenosol' soil types commonly had fertiliser production and ISE as hotspots.
    - The hotspot for soil types 'Calcarasol' were fertiliser transportation and chemical production.
    - Fertiliser production and ISE were commonly the hotspots for the 'Chromosol' soil types.
    - ISE presented as the hotspot for 'Sodosols'.

Table 5.42. Relation of soil types to hotspots (adapted from Moore, 2001)

Soil types (ASC)	pH	Deficiencies	Paddocks	Hotspots
Brown Kandosols	Neutral to acidic	N and P[a]	11,13, 19, 24	ISE, fertiliser production, chemical production and farm machinery operation respectively
Orthic Tenosol	Neutral to acidic	N, P, Cu[b],Zn[c]	5, 9 and 21	Fertiliser production for the first two and ISE for paddock 21
Red Kandosol	Neutral to acidic	N, P, S[d], Cu, Zn	1,7 and 12	Chemical transportation (1) and paddocks 7 and 12 hotspot ISE
Calcic Calcarosol	Neutral to acidic	P, N, Zn	2, 6	Fertiliser transportation (2), chemical production (6)
Yellow Kandosol	Neutral to acidic	N, P, S, Cu, Zn	16,23	Fertiliser production for both
Variable soils	Neutral to acidic	P, N, K[e], S, Cu Zn, Mn[f]	3	Fertiliser transportation (3)
Yellow Chromosol	Neutral	P, N	4, 15	Fertiliser production for both
Red chromosol	Neutral	P, N,S	14	ISE
Grey Chromosol	Neutral	P,N	20	ISE
Yellow Sodosol	Neutral to acidic	N, P, K, S, Cu, Zn	8	ISE

[a]phosphorus, [b]copper, [c]zinc, [d]sulphur, [e]potassium, [f]manganese.

Table 5.43 summarises the statistical analyses of the hotspots according to the percentage contribution to the GHG emissions per paddock. In completing the statistical analyses, the year in which the hotspot occurred was ignored as the focus in this research was to identify the hotspot over the entire research period. Furthermore, chemical transportation and fertiliser transportation as well as chemical production and fertiliser production were first analysed separately as per the research analyses and thereafter a combined analysis was concluded as essentially fertiliser is a chemical.

Table 5.43. Statistical analyses of the hotspot contribution to GHG emissions

Hotspot	Year	Paddocks	Contribution to paddock GHG for the year (%)	Average contribution per hotspot (%)	Standard deviation (%)	Standard deviation (%)
Fertiliser transportation	2010	2	49.4	63.9	21.4	17.1
	2011	1	78.4			
		3	79.6	79.6	-	
Chemical production (herbicides)	2010	8	25.2	25.8	0.8	40.7
		19	26.4			
	2011	6	96.3	96.3	-	
Fertiliser production	2010	4	56.0	46.0	12.7	12.7
		5	60.5			
		13	34.0			
		15	32.4			
		18	47.2			
	2011	9	40.0	51.8	16.6	
		23	63.5			
Indirect soil emissions	2010	8	37.5	39.8	15.1	10.5
		11	26.0			
		20	55.9			
	2011	7	45.8	50.1	3.1	
		12	51.1			
		14	50.3			
		21	53.0			
Farm machinery operation	2010	24	63.4	63.4	-	-

The following observations are based on Table 5.43:

- Fertiliser transportation was the hotspot on three paddocks, contributing to an average 69.0 % of the total paddock's GHG emissions. This implies that the fertiliser was transported over a long distance (i.e. urea was imported from Asia). The SD between the three paddocks was 17.1%.

- Chemical production was the hotspot on three paddocks contributing an average of 49.3% of the GHG emissions, with a SD of 40.7%. The majority of the GHG emissions from chemical production were from herbicides. The high SD is as a result of different types of chemicals being applied on different paddocks. The diversity of chemicals is determined by the type of pest being targeted, the crop type and the FMP.
- Fertiliser production contributed to an average 47.7% of the GHG emissions on seven paddocks. The SD was 12.7%. The SD for the application of fertiliser shows that the application of fertilisers contributed to more or less the same percentage of GHG emissions per paddock. This may be the result of a more focused application rate and the use of similar fertilisers on most paddocks.
- Both chemical production and fertiliser production contributed to an average 48% of a specific paddock's GHG emissions, with an SD of 22%.
- ISE, the hotspot on seven paddocks, contributed an average 45.7% of the paddock emissions with an SD of 10.5%. The low SD shows an agreement between paddocks with regards to the ISE. In the scenarios where ISE was the hotspot, most paddocks emitted more or less the same percentage of GHGs.
- Farm machinery operation was the hotspots on only one paddock and contributed 63.4% of the total GHG emissions.
- GHG emissions from grazing and stubble burning are usually the hotspots when they are included in FMP (Biswas et al., 2010; Grant & Beer, 2006). However, in the current research, the grazing time of sheep on the paddocks was not long enough to significantly elevate the GHGs. Secondly, stubble was burned in paddocks where N_2O leaching occurred and therefore the latter became the hotspots, as N_2O is 298 times more potent than the CO_2 resulting from the combustion of stubble.

Finally the following conclusions were drawn:

- As the soil types were different for all the paddocks analysed as a variable it could not be factored into determining which soil type would be responsible for which hotspot. For accurate analyses of hotspot/soil type more of the same soil types should be used.
- Overall the wheat/wheat crop rotation presented the most hotspots. However as the other crop rotations were not numerous, no final conclusions were drawn with regards to this.
- Fertiliser production is the input category which occurs as a hotspot the most, under any soil type, crop rotation or non-leaching/leaching of N.
- ISE is the hotspot when leaching of N has occurred. In this scenario it was found mainly in the wheat/wheat crop rotation.
- Contributing to the highest percentage of GHG emissions per paddock was fertiliser transportation (69%) followed by farm machinery operation (63.4%), chemical production (49.3%), fertiliser production (47.7%) and ISE (45.7%).
- If fertiliser production is factored in with chemical production it can be said that the hotspot at which mitigation should be targeted is the chemical production input category.

5.6. CHAPTER SUMMARY

The aim of this chapter was to analyse and interpret the LCIA results. The results from the LCI were incorporated into tables and graphs to highlight the hotspots for each paddock and farm. The results were presented paddock-wise for each farming stage to identify the stage within which the highest emissions were generated and ultimately the input/output category producing the highest volume of GHGs. Each farm was then summarised to identify which paddock generated the most GHGs.

The next chapter will integrate the LCIA with the RS and GIS applications. As the analysis of the LCIA was mostly completed in this chapter, Chapter 6 will only present the integrated results and where applicable (and lacking in this chapter), analyse the results further.

CHAPTER 6

INTEGRATION OF LIFE CYCLE ASSESSMENT RESULTS INTO GEOGRAPHICAL INFORMATION SYSTEMS

This chapter discusses the integration of the results from the life cycle assessment (LCA) (Chapter 5), into the remotely sensed (RS) images and the geographical information system (GIS), in the form of the integrated spatial technology (IST). The three tools that are integrated (RS, LCA and GIS) form part of the characterisation or modelling stage of the LCIA, and are used in the final interpretation stage of the LCA, enhancing the existing LCA research for quick and easy understanding through visual representation. The IST was able to generate images covering a wide range of possible queries.

This research focuses mainly on the identification of the hotspots within each paddock and subsequently each farm, thus images or parts of images created in the IST will be presented and discussed in this chapter, as follows:

- After introducing an outline image from the IST the visible anomalies in the satellite image will be briefly commented on. Aspects such as colour differences in the satellite image, due to vegetation growth and the presence of water bodies, will be highlighted. As the satellite imagery used is dated September 2012, a brief outline of the crop for that year will be included.
- A graphical depiction of the total GHG emissions for each farm, along with a site map (where available) and a table of the GHG emissions, will be presented as an IST image.
- Each paddock will thereafter be discussed, individually, using only the relevant graphs from the IST, rather than the entire image:
    - Pre-farm and on-farm stages for both years, for a specific paddock, will be plotted on one axis in GIS to identify the stage generating the most GHGs, for example the pre-farm stage of 2010 has the tallest bar (stage hotspot).
    - A graph will be created isolating the stage with the most GHGs for the identification of the category generating the most emissions (hotspot),

for example, the chemical production input category has the tallest bar, and is thus the category hotspot. All bar graphs in this chapter were plotted in GIS to enable the development of IST for farmers to visualise both a map of the paddock and the corresponding GHG emissions, for the selection of timeous decision-making strategies in terms of GHG mitigation measures.

  - If any subdivisions (classes) exist within the category, they will be plotted on an axis to ascertain which class produced the most emissions, for example, herbicides, fungicides and insecticides, lime, fertilisers and adjuvants are all plotted on the same axis. The tallest bar will indicate the hotspot.

- Summary of the farm highlighting the hotspots.

As detailed in Chapter 3 (section 3.3.1), the red colour (false colour), in the satellite imagery represents vegetation. Chlorophyll pigment in the leaves of a plant is able to absorb visible light from sunlight, but strongly reflects near-infrared (NIR) light. As the concentration of chlorophyll in the leaf increases, the amount of reflected NIR light also increases, enhancing the red colour on the satellite image (Utah State University, 2010; Weier & Herring, 2000). The opposite is also true, with less chlorophyll pigment leading to less reflected NIR light and more absorbed visible light, resulting in diminished red colour in the satellite image until, for example with water bodies (where there is no infrared reflectance), it appears black (Lillesand et al., 2004; Mather, 2005; Utah State University, 2010; Weier & Herring, 2000). As different crops contain various levels of chlorophyll pigment, the differences in red colour are also specific to a crop. Additional factors influencing the red colour are the density of the leaves, the health of the plant and the turgidity of the plant cells (Utah State University, 2010; Weier & Herring, 2000).

The next chapter (Chapter 7) will focus on identifying cleaner production (CP) methods as mitigation strategies that may be used to reduce the emissions from each of these paddocks to reduce the overall total GHG emissions.

6.1 FARM A

Figure 6.1 is a representation of three paddocks analysed on Farm A. In 2012, canola was planted in paddocks 1 and 3, while paddock 2 was used as a pasture. In Figure 6.1 it appears that there were water bodies in paddock 1, presented by dark circles, and the canola was well established outside of these darker areas. Paddock 2 had a more even appearance with no dark areas, showing that the vegetation in this area was more evenly distributed. Paddock 3 showed an inconsistent, patchy distribution of canola, which may have been due to the gravelly soil type (Table 4.2) which could affect the underlying soil fertility. Additionally the growth stage of the vegetation differs to that in paddock 1, seen by the different hues of red. The farmer responded in the questionnaire that paddocks 1 and 3 experienced dry seeding conditions with establishment conditions for paddock 1 being ‘ideal’, whereas for paddock 3 they were ‘too dry’. This supports the observations made in the satellite image (Figure 6.1) of less vegetation being present in paddock 3.

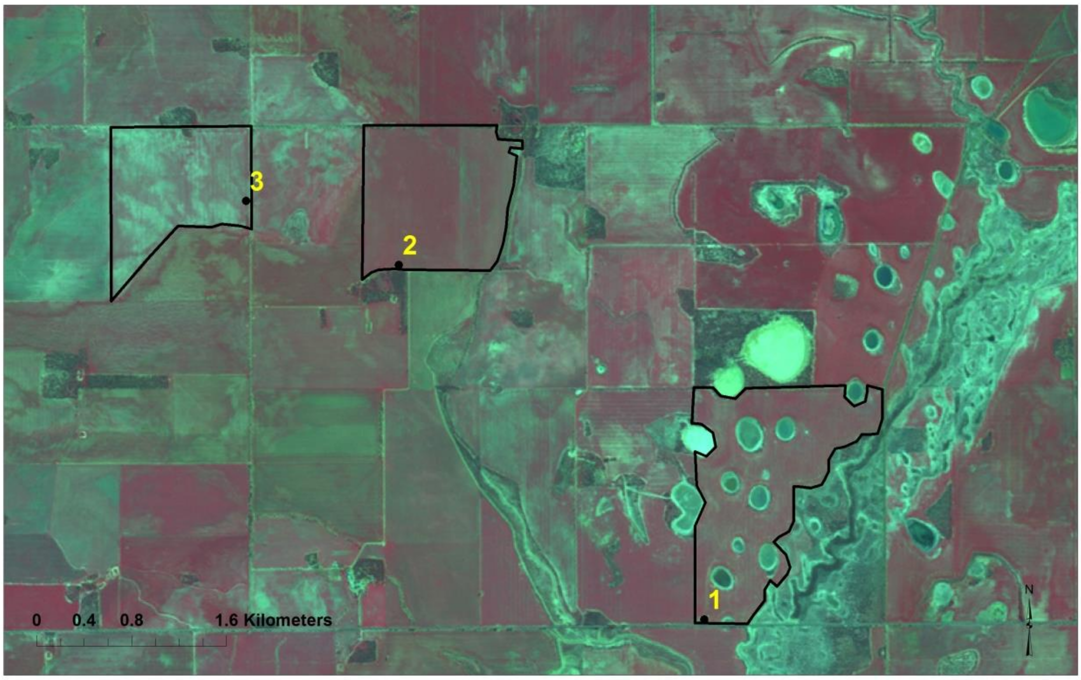
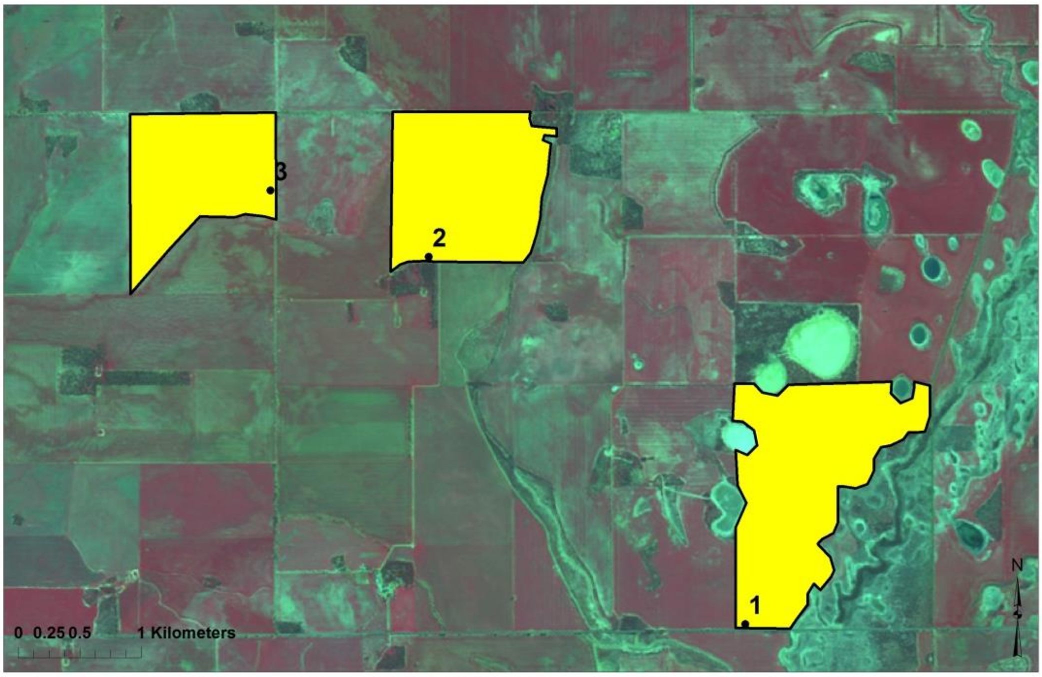
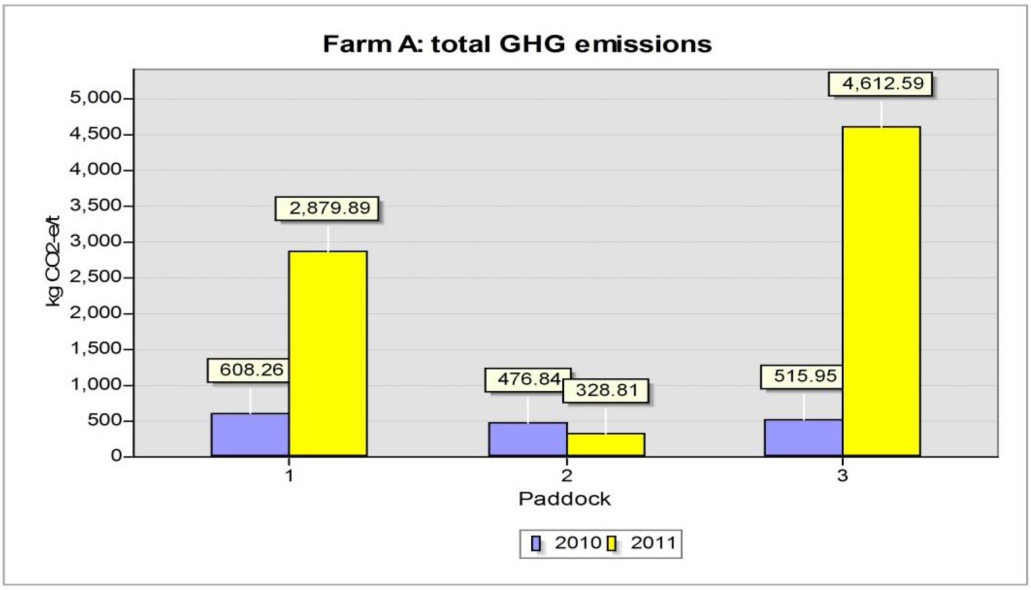


Figure 6.1. Remotely sensed image showing the three paddock outlines for Farm A in 2012

Figure 6.2 presents an image created in the IST and summarises the total GHG emissions for all three paddocks for both years in a bar graph. The data indicates that the emissions generated in paddock 3 in 2011 exceeded the GHG emissions generated in the other paddocks during this period (Chapter 5, section 5.4.1.4). Yellow was allocated to demarcate Farm A in the GIS.





	Total GHG emissions	
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
1	608.3	2879.9
2	476.8	328.8
3	515.9	4612.6

Figure 6.2. Total GHG emissions for Farm A, 2010–2011 as generated in the IST

6.1.1 Paddock 1

The image in Figure 6.3, plotted in GIS, presents the pre-farm and on-farm stages for both 2010 and 2011. The analyses for this paddock were concluded in section 5.4.1.1. The quantity of GHG emissions (in descending order) are as follows: the pre-farm stage in 2011 emitted 74.5% of the total GHGs, the pre-farm stage in 2010 emitted 13.1%, the on-farm stage in 2011 emitted 8.6% and the on-farm stage in 2010 emitted 3.8%.

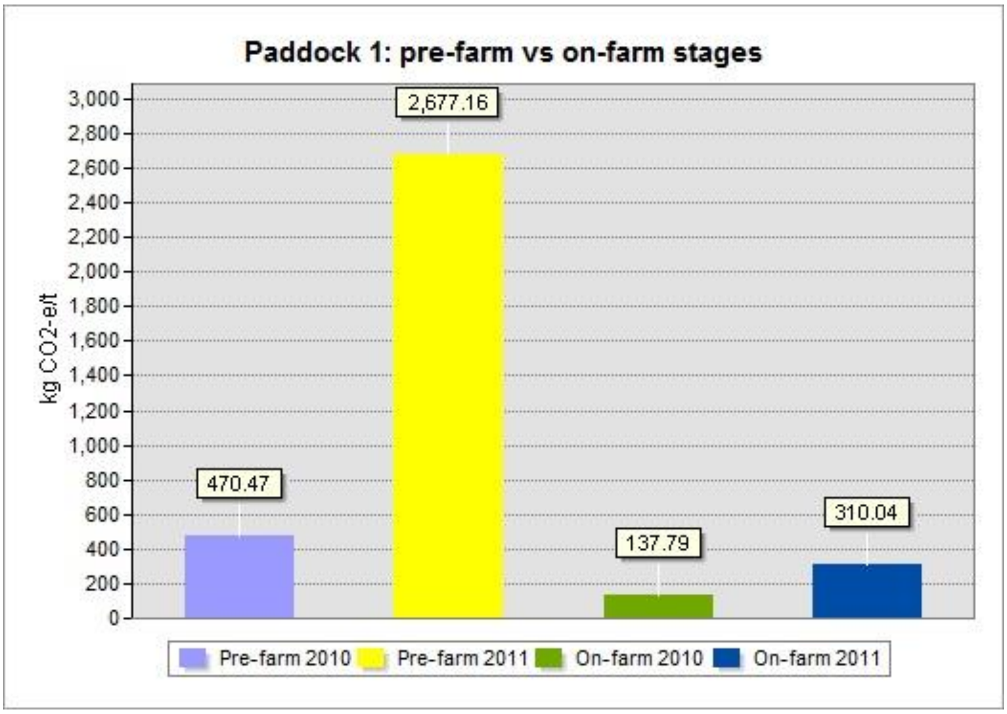


Figure 6.3. Paddock 1, pre-farm vs on-farm GHG emissions, 2010–2011

As the pre-farm stage in 2011 was identified as the hotspot in Figure 6.3, an additional figure highlighting only the categories within this farming stage was generated using GIS in the IST (Figure 6.4). Figure 6.4 shows that the transportation of fertilisers was the hotspot over the two years, generating a total of 2.26 x 10^3 kg CO_2-e/t or 84.3% of the pre-farm emissions in 2011. Chemical transportation produced 1.40x 10^2 kg CO_2-e/t (5.22%), followed by fertiliser production (1.35 x 10^2 kg CO_2-e/t, 5.1%), chemical production (1.34 x 10^2 kg CO_2-e/t, 5.0%) and farm machinery production (1.14 x 10^1 kg CO_2-e/t, 0.4%).

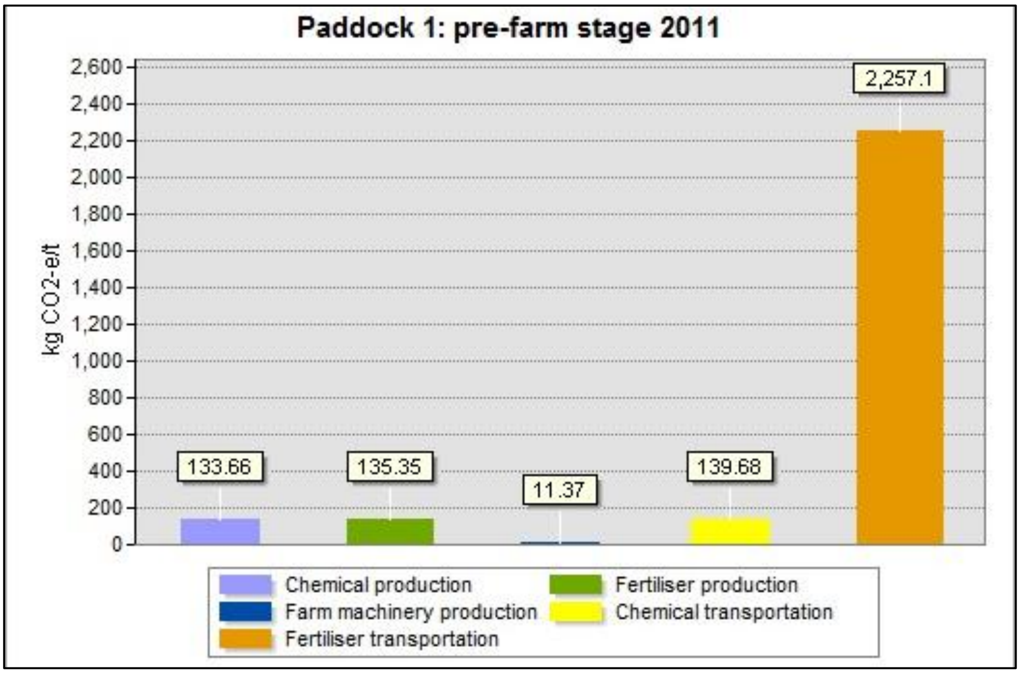


Figure 6.4. Paddock 1, pre-farm GHG emissions for 2010

6.1.2 Paddock 2

Paddock 2 emitted a total 8.06 x 10^2 kg CO_2-e/t over the period 2010 and 2011. Figure 6.5 shows that the pre-farm stage in 2010 emitted 51.4% of the total GHGs for the same period, appearing to be the overall hotspot when comparing the stages from 2010–2011. It is followed by the pre-farm stage in 2011 (27.7%), the on-farm stage in 2011 (13.1%) and finally the on-farm stage in 2011 (7.8%).

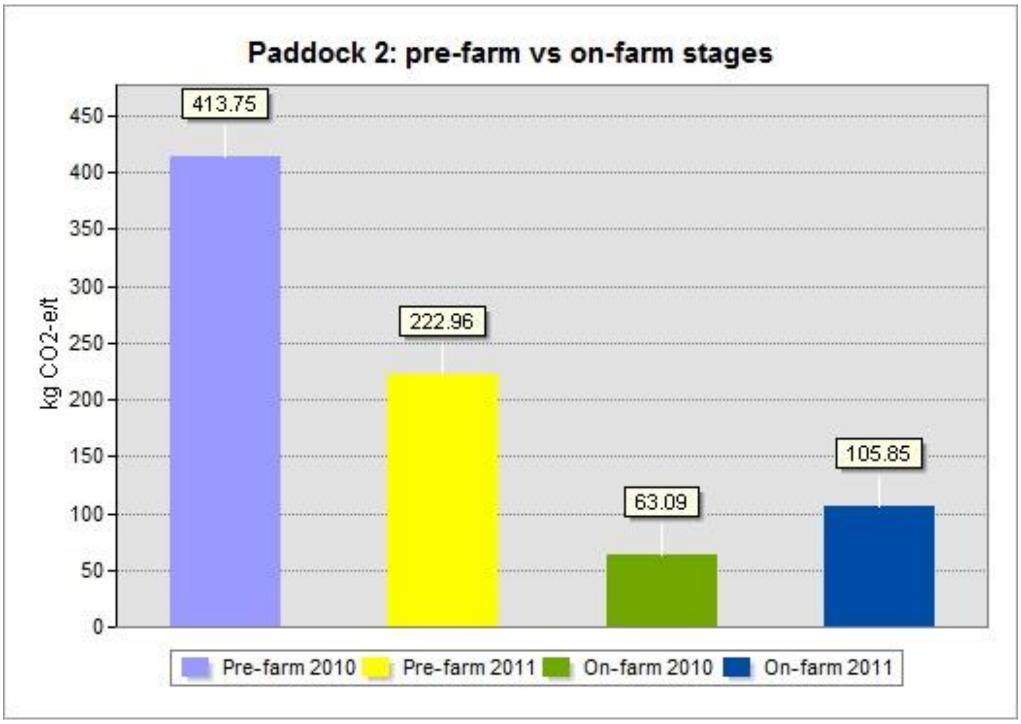


Figure 6.5. Paddock 2 pre-farm and on-farm GHG emissions, 2010–2011

Focusing on the farming stage that emitted the highest volume of GHGs as identified above, Figure 6.6 was generated using GIS in the IST. Figure 6.6 shows that within the pre-farm stage in 2010, the transportation of fertilisers generated the most GHGs. This is consistent with the analysis conducted using solely the LCA approach in section 5.4.1.3 of Chapter 5. The emissions from the transportation of chemicals totalled 2.35 x 10^2 kg CO_2-e/t or 56.9% of the total 2010 pre-farm emissions in 2010. The remaining 43.1% of emissions was divided between the transportation of chemicals (9.8%), fertiliser production (18.5%), farm machinery production (7.4%) and production of chemicals (7.3%).

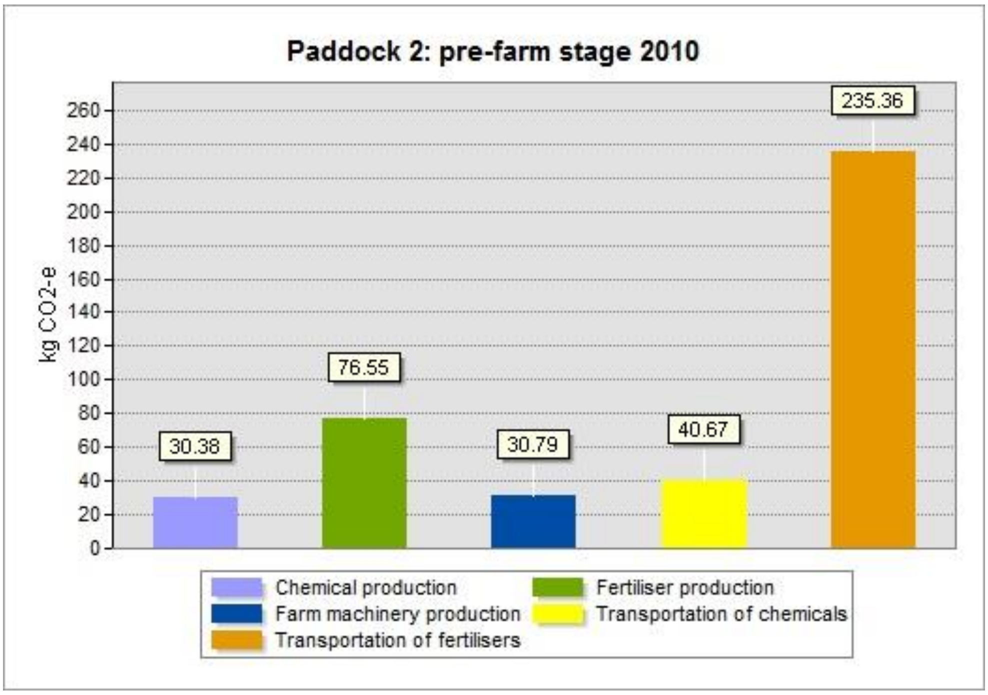


Figure 6.6. Paddock 2, pre-farm GHG emissions for 2010

6.1.3 Paddock 3

Figure 6.7 illustrates the emissions arising from both pre-farm and on-farm stages for paddock 3. The yellow bar in the graph shows that the pre-farm stage in 2011 was the hotspot on this paddock over the two years, and this is consistent with the results in Chapter 5 (section 5.4.1.4). The emissions from this stage were 81.7% of the total of the pre-farm and on-farm GHG emissions for both years (5.13×10^3 kg CO_2-e/t), followed by the on-farm stage in 2011 with 8.3%, then the pre-farm stage 2010 with 7.6% and finally the on-farm stage 2010 with 2.5% contributions.

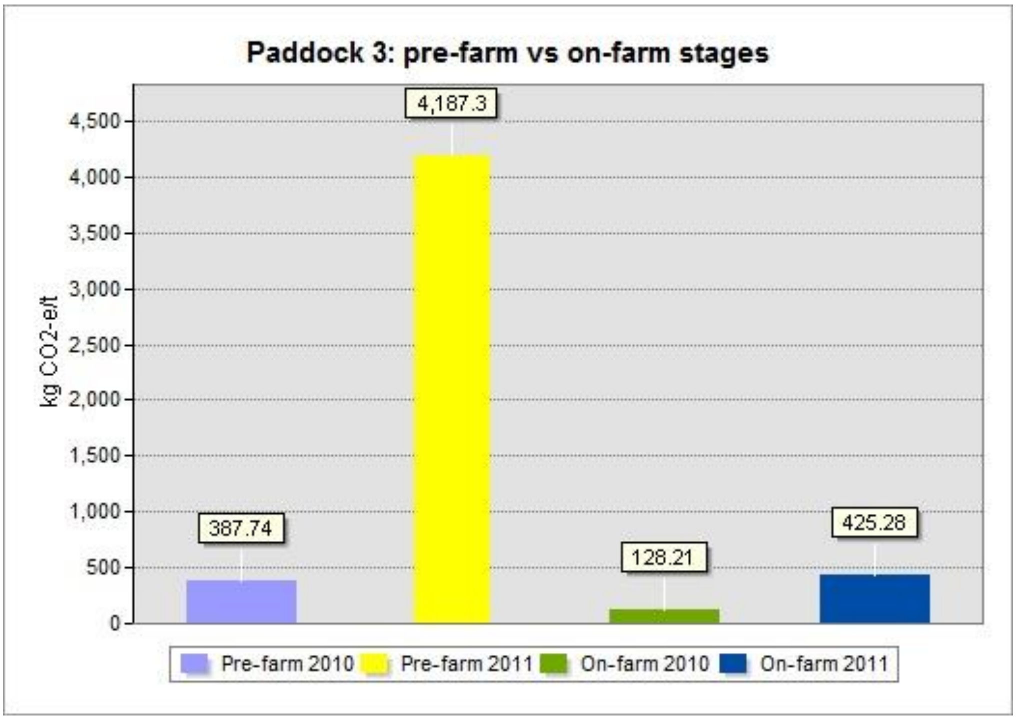


Figure 6.7. Paddock 3, pre-farm vs on-farm GHG emissions, 2010–2011

Following this observation, Figure 6.8 was generated using GIS to identify the category producing the highest level of GHGs within the pre-farm stage in 2011. The figure demonstrates that the transportation of fertilisers in 2011 generated the most GHGs for paddock 3 in the pre-farm stage of 2011, being 87.7% of the pre-farm emissions in 2011, followed by chemical transportation (6.2%), fertiliser production (4.0%), chemical production (1.8%) and the production of farm machinery (0.4%). This finding is consistent with the result obtained in the LCA (section 5.4.1.4). Additional images may be created using GIS in the IST to identify the emissions from each of the individual subclasses, for example the transportation of urea within the transportation of fertiliser class.

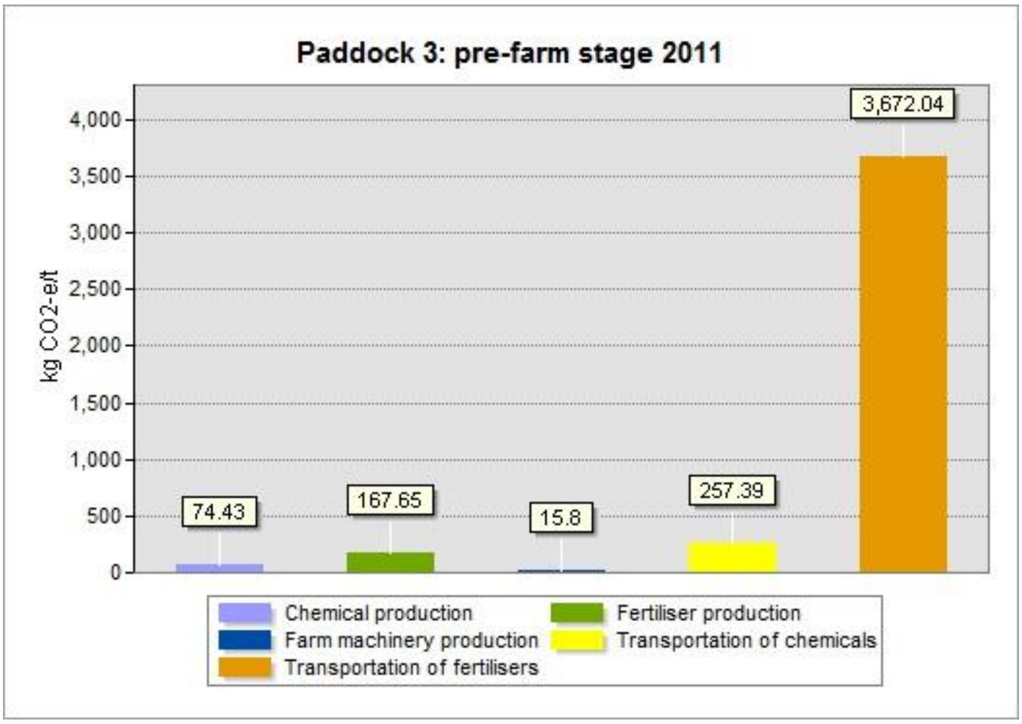


Figure 6.8. Paddock 3, pre-farm GHG emissions for 2011

6.1.4 Summary of LCA results for Farm A

The hotspot arising for grain production in paddock 1 at Farm A was due to the transportation of fertilisers (2.26 x 10^3 kg CO_2-e/t) to this paddock in 2011. The total paddock emissions amounted to 3.60 x 10^3 kg CO_2-e/t (section 5.4.1.2). For paddock 2 the transportation of fertilisers was the hotspot in 2010 with a total value of 2.35 x10^2 kg CO_2-e/t (Figure 6.6), originating solely from the transportation of the fertiliser 'DAP Extra' (section 5.4.1.3). The hotspot for paddock 3 was the transportation of fertilisers in 2011 emitting 3.67 x 10^3 kg CO_2-e/t of the total 4.19 x 10^3 kg CO_2-e/t (section 5.4.1.4). Further analysis of the information above shows that the hotspot on Farm A was the transportation of fertilisers (and more specifically the transportation of urea (section 5.4.1.4) in 2011, for paddock 3. Through this visual representation, the farmers could thus use the IST as a handy decision-making tool to choose an effective mitigation option in terms of the transportation of fertilisers, in order to further reduce GHG emissions from grain production.

6.2 FARM B

Figure 6.9 is an RS image representation of paddocks 4, 5 and 6 on Farm B in 2012. Canola was planted on paddock 4 in 2012, wheat on paddock 5 and paddock 6 was used as a pasture. Paddock 4 shows a more even colour which indicates that the vegetation density is more evenly spread over the paddock. Paddock 5 shows that there is less plant growth in the north-east corner of the paddock. The paddock is characterised by a lighter, sandier soil type (Table 4.2), which may result in lower water storage capacity and/or nutrient retention. However, the lower intensity of red in the north-east corner may be related to its association with the apparent chain of lakes through this section of the paddock, resulting in poorer plant establishment (Figure 6.9). As paddock 6 was used as a pasture, the mixture of green and red is expected due to factors such as different pasture composition or selective grazing by livestock in the green areas compared to less grazing in the red areas.

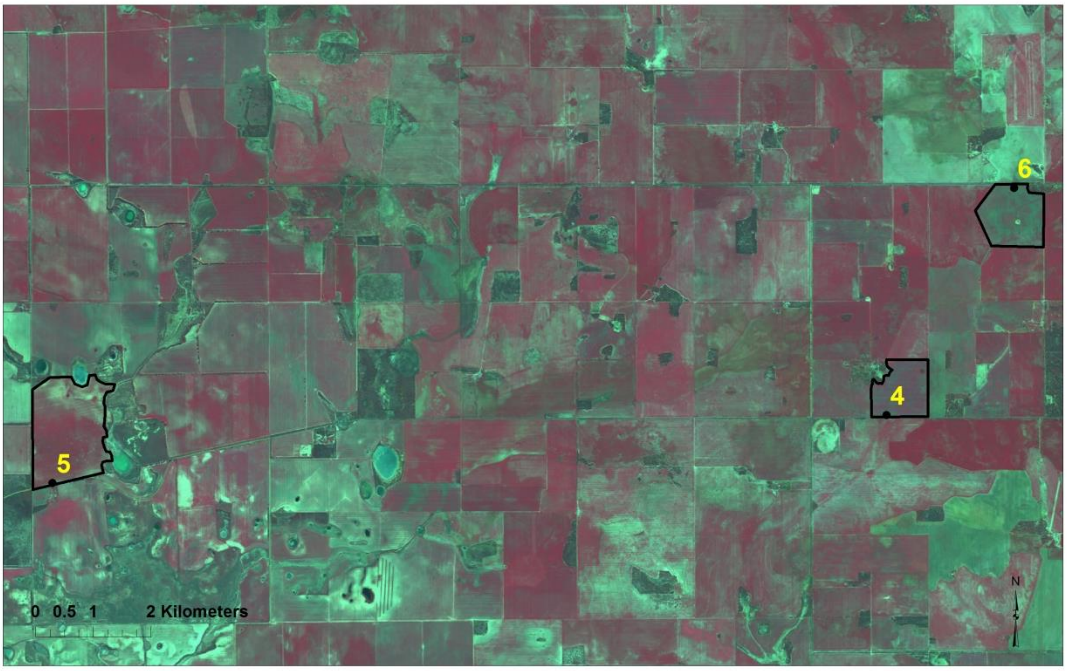
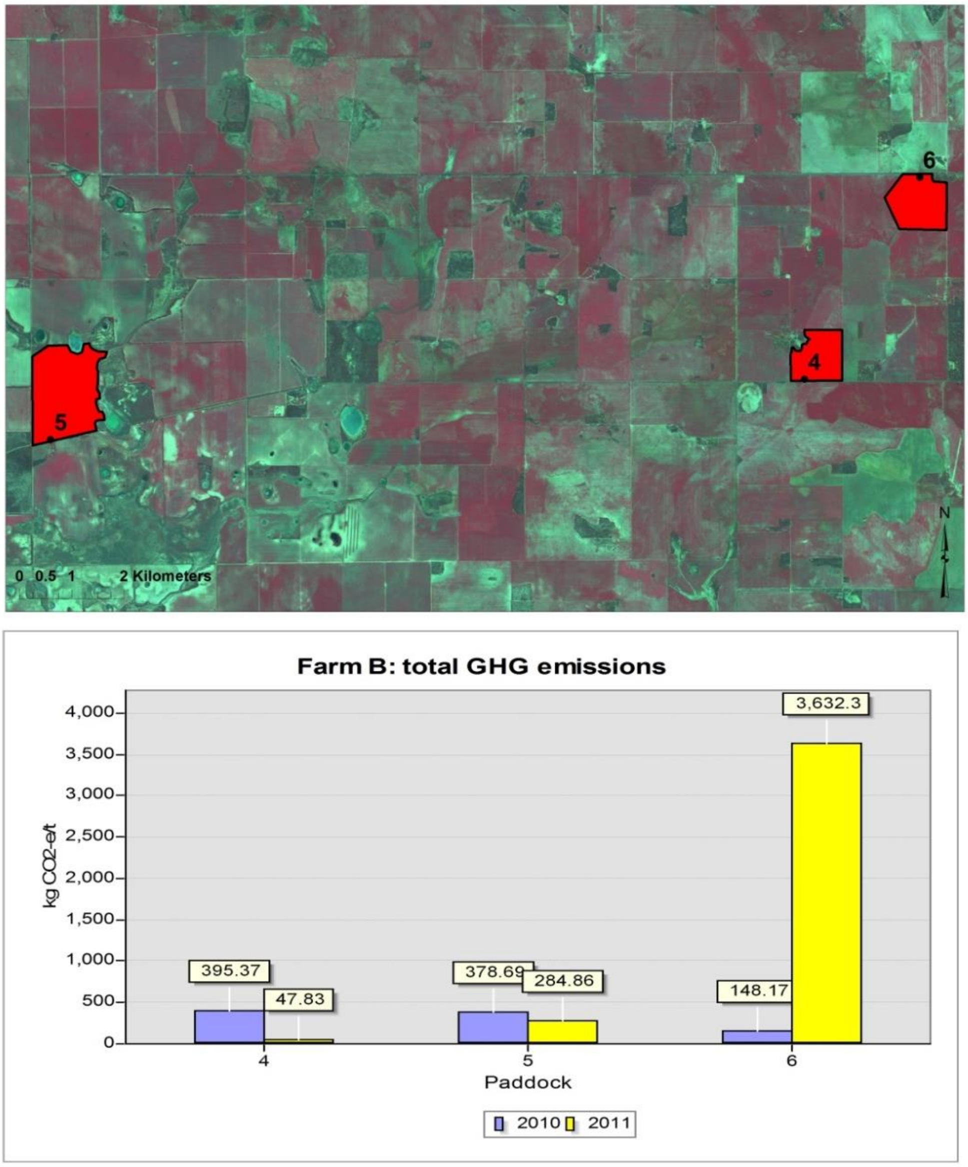


Figure 6.9. Remotely sensed image showing the paddock outlines from Farm B in 2012

Figure 6.10 is the image created in the IST for the paddocks on Farm B for both 2010 and 2011, as discussed in section 5.4.2. Red was allocated to identify the paddocks more easily in the image. The yellow and purple bars in this graph represent the total GHGs emitted by all three paddocks for both years over both farming stages and show that paddock 6 generated the highest total (3.63 x 10^3 kg CO_2-e/t) GHGs, accounting for 74% of the total 4.89 x 10^3 kg CO_2-e/t emitted. Paddock 5 emitted the second highest amount of GHGs.



Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
4	395.4	47.8
5	378.7	284.9
6	148.2	3632.3

Figure 6.10. Total GHG emissions for Farm B, 2010–2011 as generated in the IST

6.2.1 Paddock 4

Paddock 4 emitted a total of 3.95 x 10^2 kg CO_2-e/t in 2010 and 4.78 x 10^1 kg CO_2-e/t in 2011. The total GHG emissions for this paddock over the two years contributed 9%, or 4.43 x 10^2 kg CO_2-e/t, of the total emissions (4.89 x 10^3 kg CO_2-e/t) for Farm B.

Figure 6.11 is a representation of the pre-farm and on-farm emissions from paddock 4 in 2010 and 2011. The violet bar, representing the pre-farm stage in 2010, clearly shows that this farming stage was the hotspot over the two years (2010 and 2011), contributing 66.7% of the total GHG emissions (4.43 x 10^2 kg CO_2-e/t) for Farm B. The on-farm emissions for 2010 were the next highest GHG emissions (22.49% of total for Farm B, or 22% of paddock 4) followed by the on-farm emissions in 2011 (5.83% for Farm B or 5% for paddock 4), and then the pre-farm emissions in 2011 (4.96% for Farm B or 6% for paddock 4).

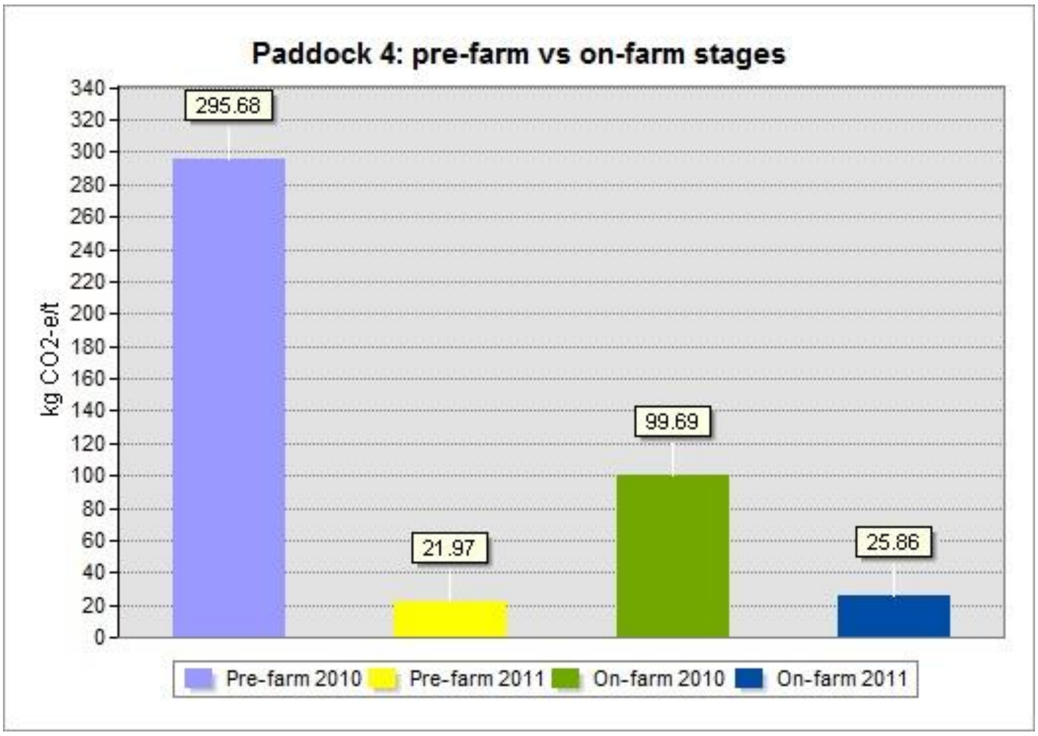


Figure 6.11. Paddock 4, pre-farm versus on-farm GHG emissions, 2010–2011

As the pre-farm stage for paddock 4 was the highest GHG emitter in 2010, Figure 6.12 was generated by isolating only this stage. The figure clearly shows that within the pre-farm stage in 2010 the hotspot was the production of fertilisers, as calculated and discussed during the LCIA (Chapter 5, section 5.4.5.2). Fertiliser production contributed to 75.2% of the pre-farm emissions in 2010 and to 56% of the total emissions (pre-farm and on-farm stages, i.e. 2.96×10^2 kg CO_2-e/t) in 2010. The percentage contributions of inputs making up the emissions from the pre-farm stage for 2010 in descending order are as follows: production of chemicals (16.2%), the transportation of fertilisers (4.3%), the production of farm machinery (3.7%) and chemical transportation (0.6%).

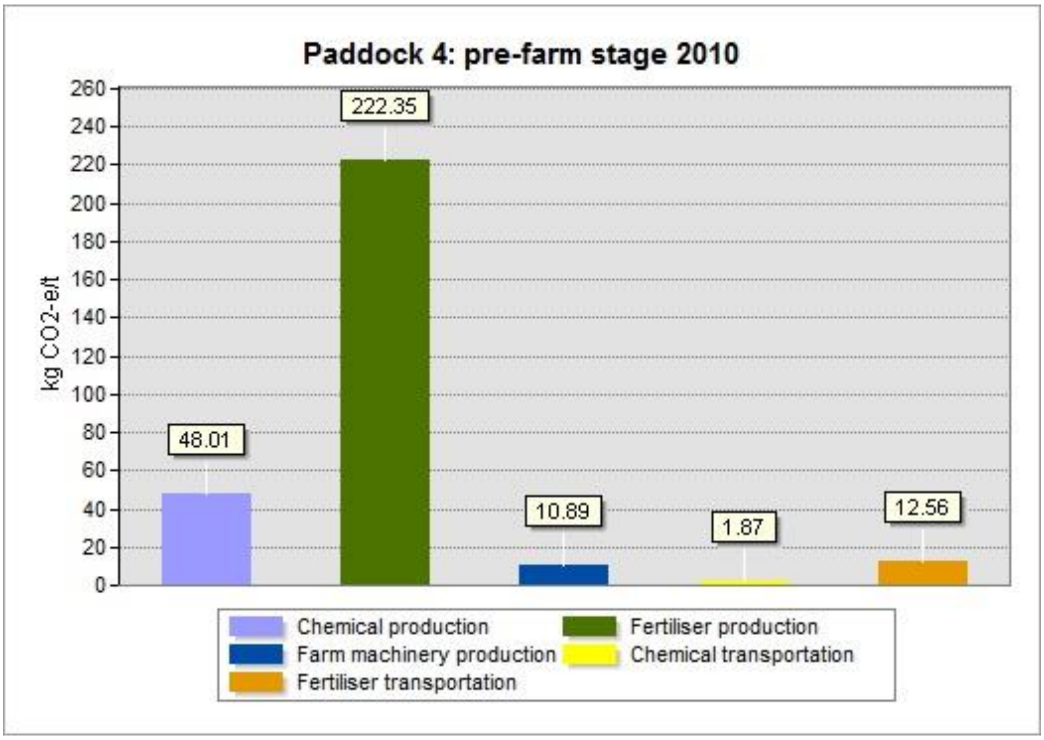


Figure 6.12. Paddock 4, pre-farm GHG emissions for 2010

6.2.2 Paddock 5

Paddock 5 contributed 14% of the total GHG emissions for Farm B, of which 43% were from the pre-farm stage in 2010, 32% from the pre-farm stage in 2011, 14% from the on-farm stage in 2010 and 11% from the on-farm stage in 2011, as depicted in Figure 6.13. The stage producing the most GHGs for this farm is thus the pre-farm stage of 2010, emitting 2.83 x 10^2 kg CO_2-e/t over the two years.

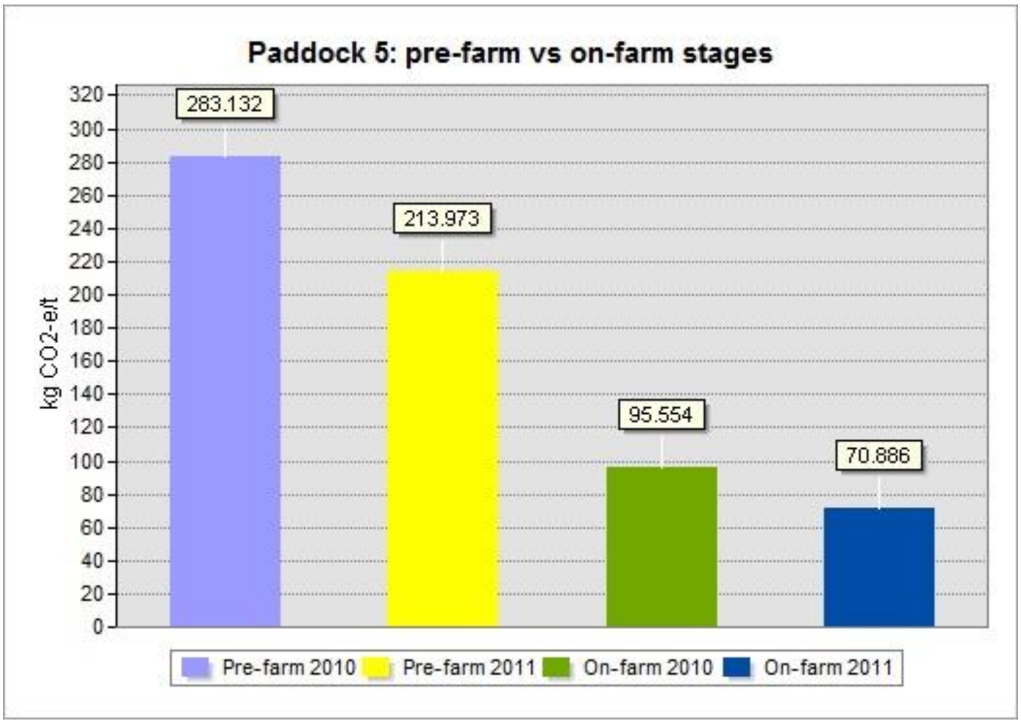


Figure 6.13. Paddock 5, pre-farm versus on-farm GHG emissions, 2010–2011

Once the stage causing the most GHG emissions was discerned, further analysis was carried out to determine the inputs or hotspots predominantly responsible for the GHG emissions. In the case of the pre-farm stage in 2010, the graph was expanded as shown in Figure 6.14. The greatest total GHG emissions in 2010 for the different categories of inputs and outputs was from the production of fertiliser in the pre-farm stage, totalling 2.29 x 10^2 kg CO_2-e/t or 81.2% of the pre-farm total of 2.83 x 10^2 kg CO_2-e/t. Fertiliser production furthermore contributed 35% of the sum of all the emissions for the paddock over the two years. Chemical production contributed 2.95 x 10^1 kg CO_2-e/t (10.4%), the transportation of fertilisers 1.24 x 10^1 kg CO_2-e/t (4.3%), farm machinery production 1.12 x 10^1 kg CO_2-e/t (4.0%) and finally the transportation of chemicals contributed 0.14% or 0.4 kg CO_2-e/t. Within the fertiliser production category, further graphical analysis may be carried out in GIS to determine which fertiliser generated the highest volume of GHGs, however this category is analysed in full in section 5.4.2.3.

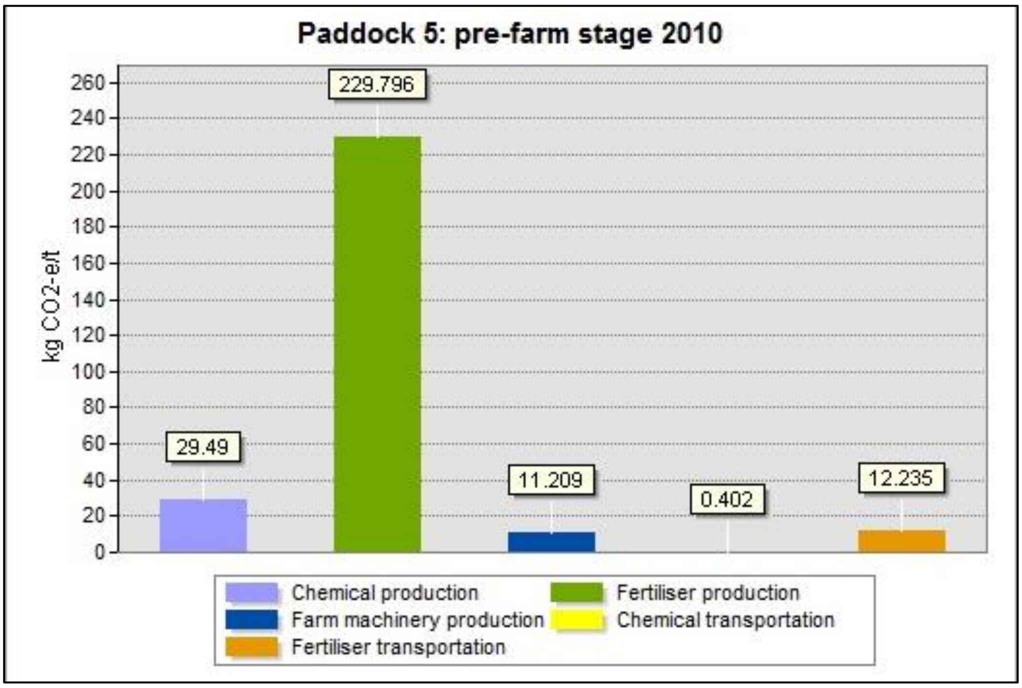


Figure 6.14. Paddock 5, pre-farm GHG emissions for2010

6.2.3 Paddock 6

The GHG emissions from paddock 6 are presented in Figure 6.15 and show that the hotspot for this paddock is the pre-farm stage in 2011, emitting a total of 3.58 x 10^3 kg CO_2-e/t or 95% of the paddock's emissions for two consecutive years 2010 and 2011, a total of 3.78 x 10^3 kg CO_2-e/t. The pre-farm stage in 2010 had the second highest emissions for all stages over both years (9.96 x 10^1 kg CO_2-e/t, 3%), followed by the on-farm emissions in 2011 (4.91 x 10^1 kg CO_2-e/t, 1%) and finally the on-farm stage in 2010 (4.85 x 10^1 kg CO_2-e/t, 1%).

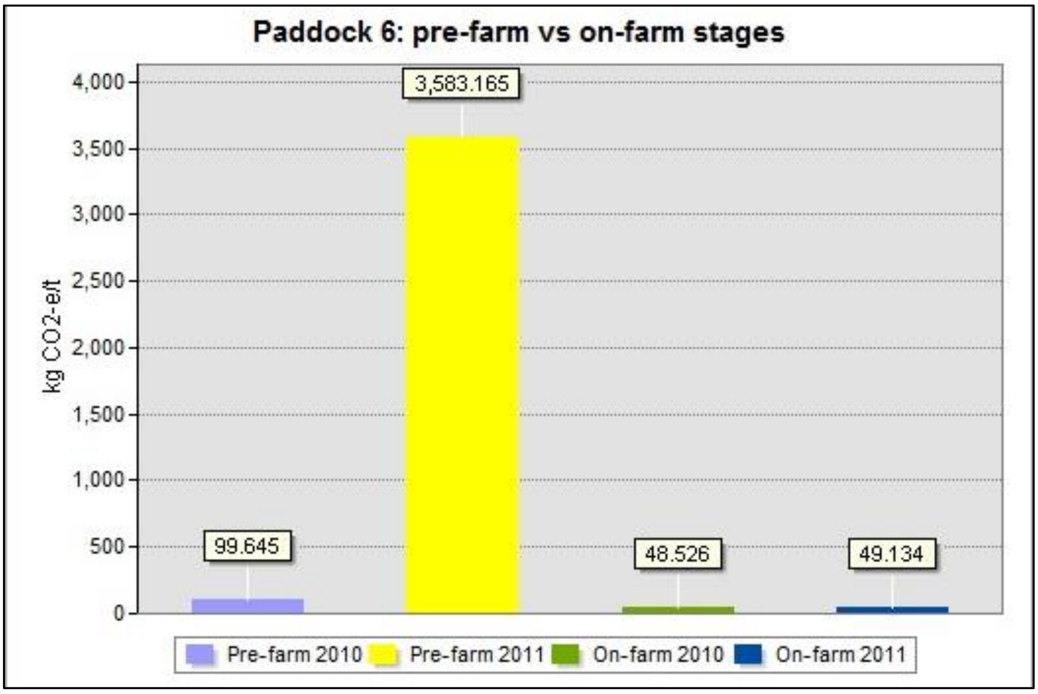


Figure 6.15. Paddock 6, pre-farm versus on-farm GHG emissions, 2010–2011

The GHG emissions from the production of chemicals in 2011 were the hotspot generated in the IST for the pre-farm stage in 2011 (Figure 6.16). The total emissions of 3.50 x 10^3 kg CO_2-e/t from this hotspot made up 97.7% of the pre-farm GHG emissions for 2011, followed by fertiliser production (2.0%). Farm machinery production, chemical transportation and fertiliser transportation together contributed to less than 0.3% of the total GHG emissions. Furthermore the production of chemicals in 2011 contributed to 35% of the overall GHG emissions for this paddock (for both stages and both years).

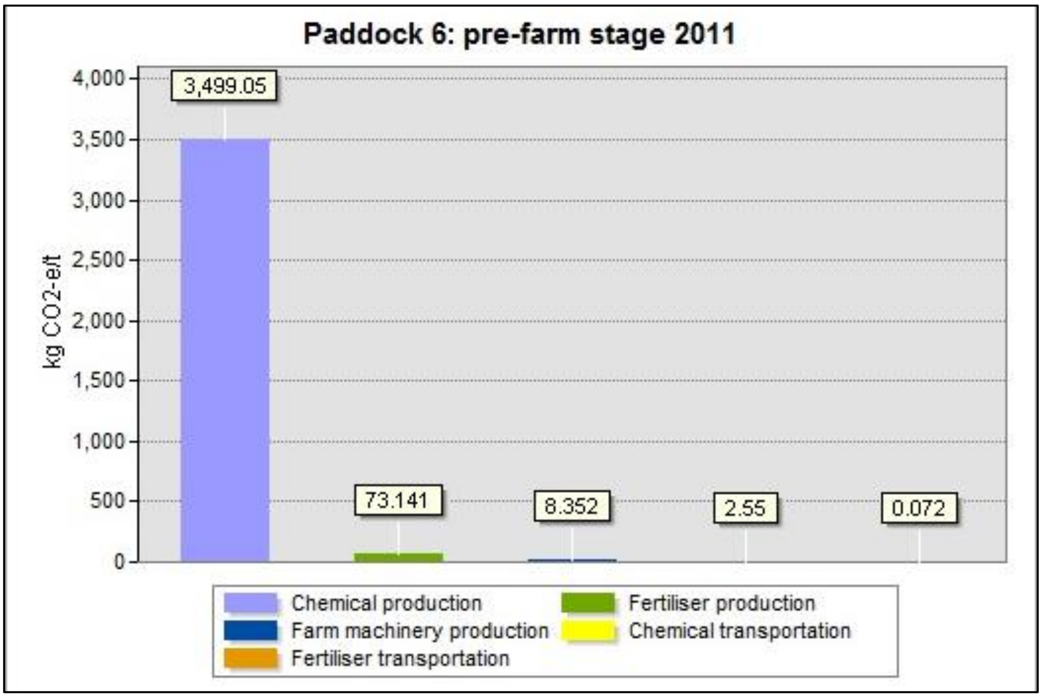


Figure 6.16. Paddock 6, pre-farm GHG emissions for 2011

To identify the class within the chemical production input category which emitted the most GHGs, an additional graph was generated (Figure 6.17), which shows that the production of herbicides for the pre-farm stage in 2011 emitted the most GHGs. The GHG emissions from herbicides made up 98% of the total chemical production (3.57×10^3 kg CO_2-e/t, including the production of fertilisers). The analyses in Chapter 5, section 5.4.2.4 were confirmed using the results from the IST, however additional graphs may be generated in GIS as part of this IST to identify exactly which herbicide contributed the most GHGs within the chemical production category.

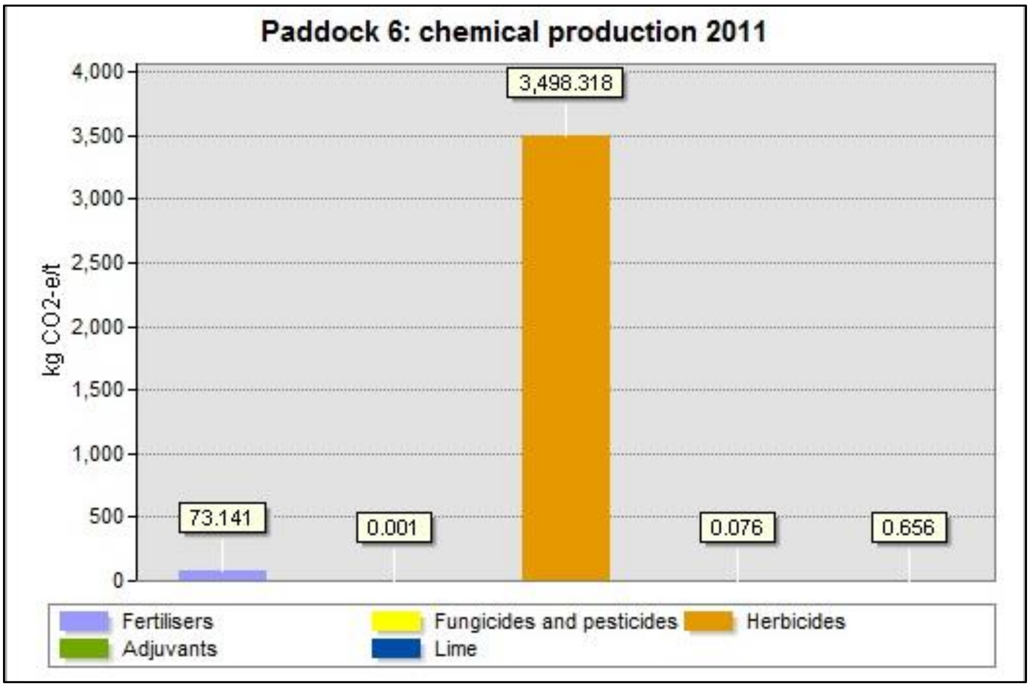


Figure 6.17. Paddock 6, chemical production GHG emissions for 2011

6.2.4 Summary of LCA results for Farm B

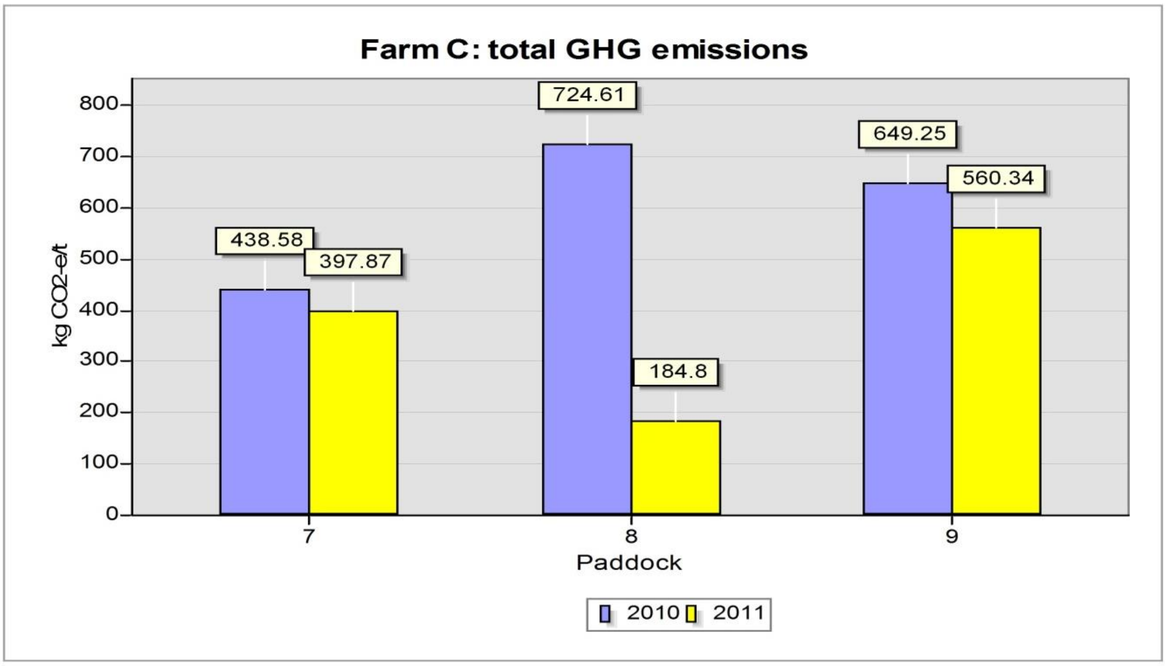
The hotspot for paddock 4 was identified as the production of fertilisers in 2010, with K-Till Extra being the fertiliser generating the most GHGs on this paddock (1.69 x 10^2 kg CO_2-e/t of the total 2.22 x 10^2 kg CO_2-e/t for fertilisers) (section 5.4.2.2). The emissions from fertiliser production, and specifically K-Till Extra, were also the hotspots for paddock 5, producing 1.82 x 10^2 kg CO_2-e/t of the overall emissions of 2.30 x10^2 kg CO_2-e/t (section 5.4.2.3). Chemical production in 2011 was the hotspot for paddock 6. The production of chemicals generated 3.50 x 10^3 kg CO_2-e/t in 2011, with the largest contributor to these emissions being the production of Logran (3.49 x 10^3 kg CO_2-e/t) (section 5.4.2.4). The aforementioned text highlights the hotspots for each paddock but also serves to show that the overall hotspot for Farm B in the research period was chemical production on paddock 6 in 2011.

The visual presentation combining soil types, paddocks, farm management practices, vegetation coverage, and carbon footprints will enable farmer B to make an efficient and timely decision to either to adopt the best existing practice or apply CP or mitigation strategies to reduce further GHG emissions.

6.3 FARM C

The boundaries of paddocks 7, 8 and 9 fell outside the area enclosed by the satellite image, approximately 24 km east of paddock 1. However as sufficient data was available the decision was made to complete the analyses and possibly generate figures in the IST without the paddock boundary demarcation.

Figure 6.18 illustrates the total GHG emissions from Farm C for all three paddocks over both years. The full analysis for this farm can be found in section 5.4.3. The graph in Figure 6.18 shows that the GHG emissions from paddock 8 in 2010 were the highest, totalling 1.33 x 10^3 kg CO_2-e/t. The second highest emitter was paddock 9 in 2010 with 6.49 x 10^2 kg CO_2-e/t. The farm emitted a total of 1.51 x 10^3 kg CO_2-e/t over all stages for both years.



Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
7	438.6	397.9
8	724.6	184.8
9	649.2	560.3

Figure 6.18. Total GHG emissions for Farm C, 2010–2011 as generated in the IST

6.3.1 Paddock 7

The pre-farm and on-farm stages for paddock 7 for both years are presented in Figure 6.19. In this graph it is apparent that the on-farm stage of 2011 was the highest emitter (2.70 x 10^2 kg CO_2-e/t or 32.3%) of the total GHGs from both stages over both years. The on-farm GHG emissions of 2010 contributed 31.3% or 2.63 x 10^2 kg CO_2-e/t of the total GHG emissions over both years and both stages, the GHG emissions from pre-farm stage in 2010 were 1.76 x 10^2 kg CO_2-e/t (21.0%), and the pre-farm stage emitted 1.28 x 10^2 kg CO_2-e/t (15.3%) of the total GHG emissions for the paddock during 2010–2011.

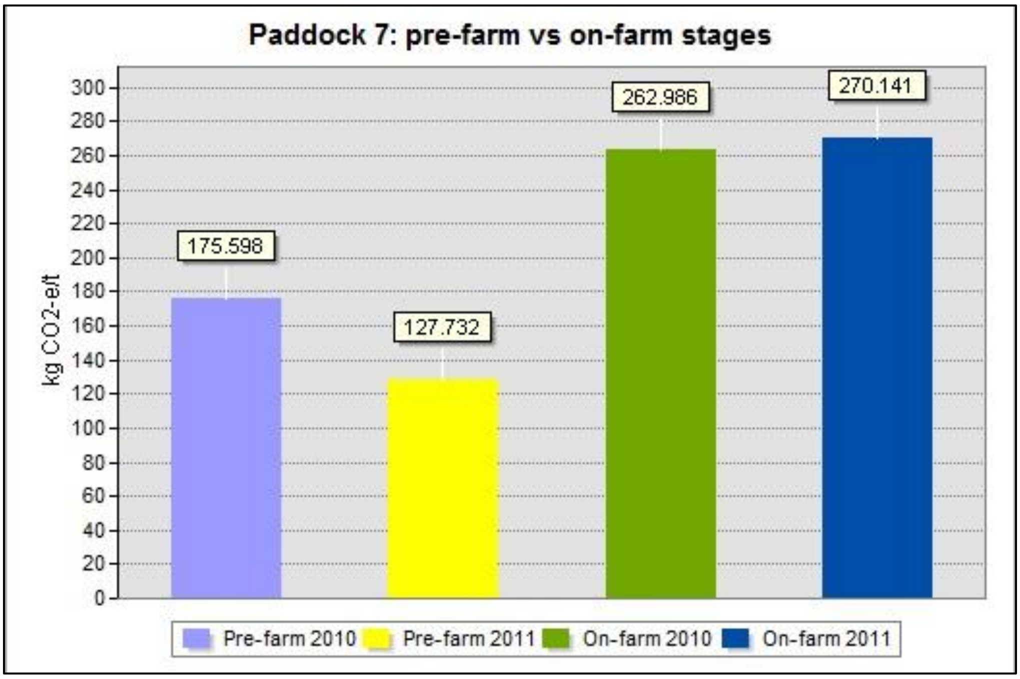


Figure 6.19. Paddock 7, pre-farm versus on-farm GHG emissions, 2010–2011

Figure 6.20 was generated using the IST to identify the hotspot within the on-farm stage of 2011. The emissions from farm machinery operation, grazing and direct soil emissions (DSE) contributed to the GHG emissions from this paddock in 2011 with values of 5.1%, 14.7% and 12.7%, respectively. The bulk of GHG emissions from the pre-farm stage in 2011 were generated as indirect soil emissions (ISE) (67.5% or 1.82 x 10^2 kg CO_2-e/t). These results agree with the analysis of results from the LCIA in Chapter 5, section 5.4.3.2. Furthermore, ISE generated 45.8% of the total GHG emissions for the paddock in 2011.

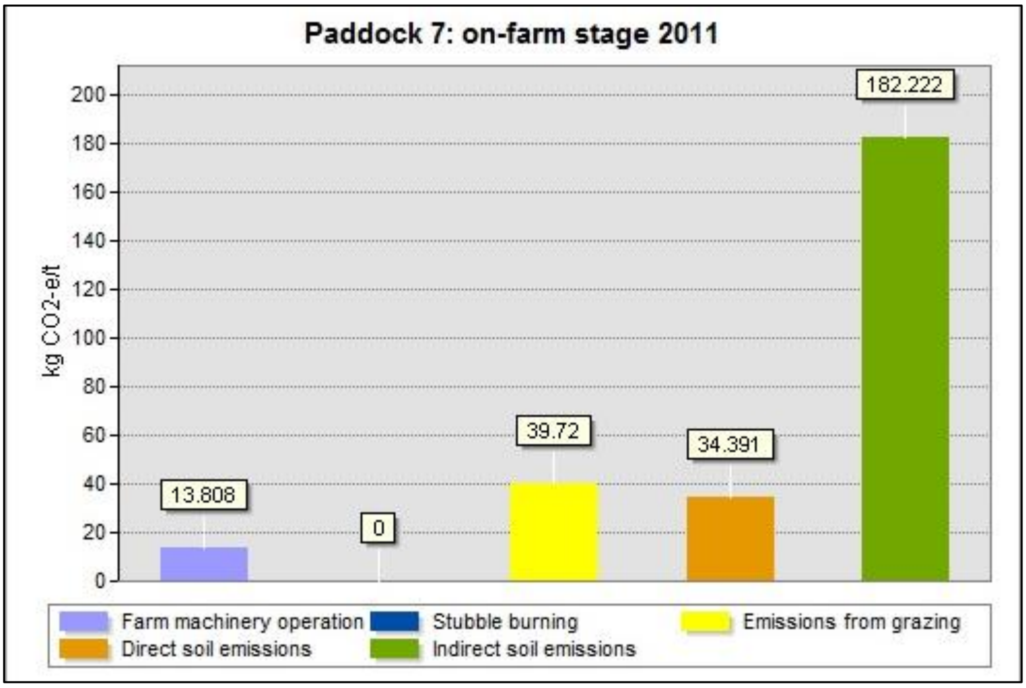


Figure 6.20. Paddock 7, on-farm GHG emissions for 2011

Figure 6.21 was generated in GIS as part of this IST to analyse the ISE and shows that the N_2O released was the major contributor of GHG emissions, with a total of 1.82×10^2 kg CO_2-e/t. The N_2O emissions made up 99.7% of the ISE emissions in 2011, 67.3% of the on-farm GHG emissions in 2011, and 21.7% of all of the emissions over the two years from this paddock.

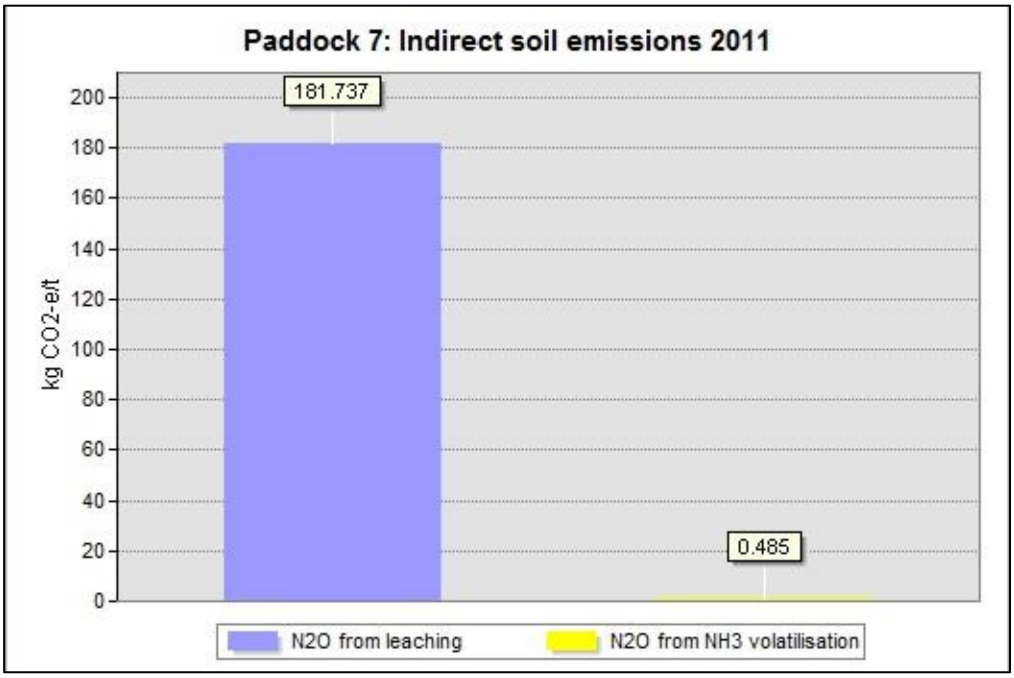


Figure 6.21. Paddock 7, indirect soil emissions for 2011

6.3.2 Paddock 8

Figure 6.22 identifies the on-farm stage for 2010 as the stage hotspot for paddock 8. It is followed by the pre-farm stage of 2010, the on-farm stage in 2011 and finally the pre-farm stage in 2011. Each of these stages emitted 44.1%, 35.6%, 14.4% and 5.9% of the total of 9.09×10^2 kg CO_2-e/t, respectively.

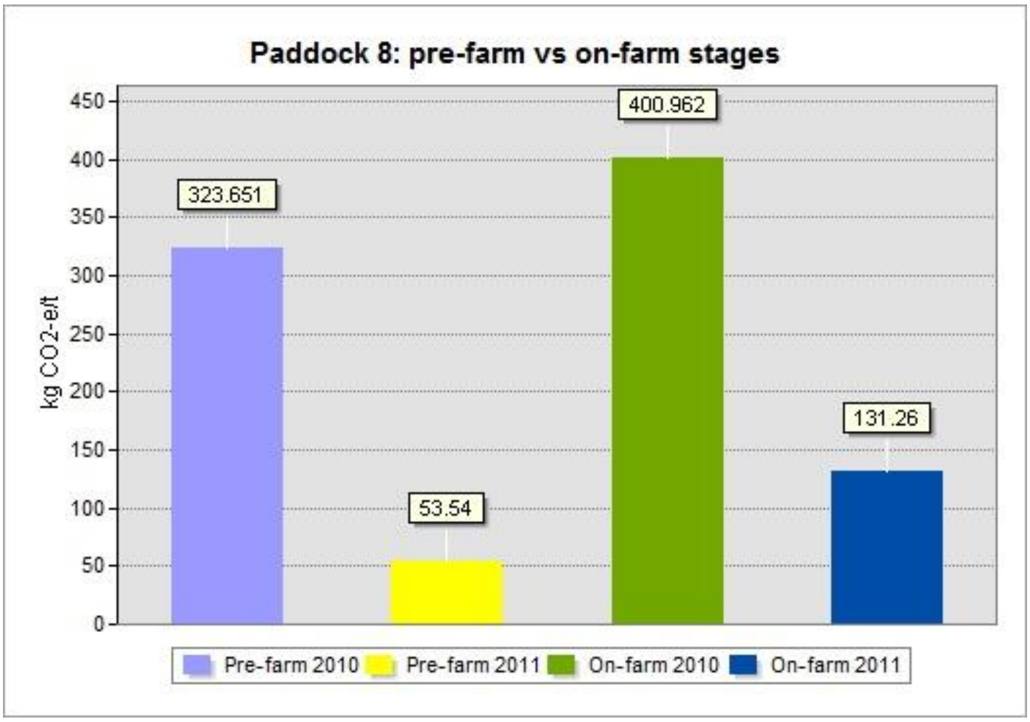


Figure 6.22. Paddock 8, pre-farm versus on-farm GHG emissions, 2010–2011

After identifying the on-farm stage of 2010 as the stage hotspot, Figure 6.23 was produced using GIS in the IST. Figure 6.23 shows that ISE was the paddock hotspot, contributing 73.0% to the total GHGs from this farming stage. It was followed by DSE (19.7%), and farm machinery operation (7.3%) (section 5.4.3.3).

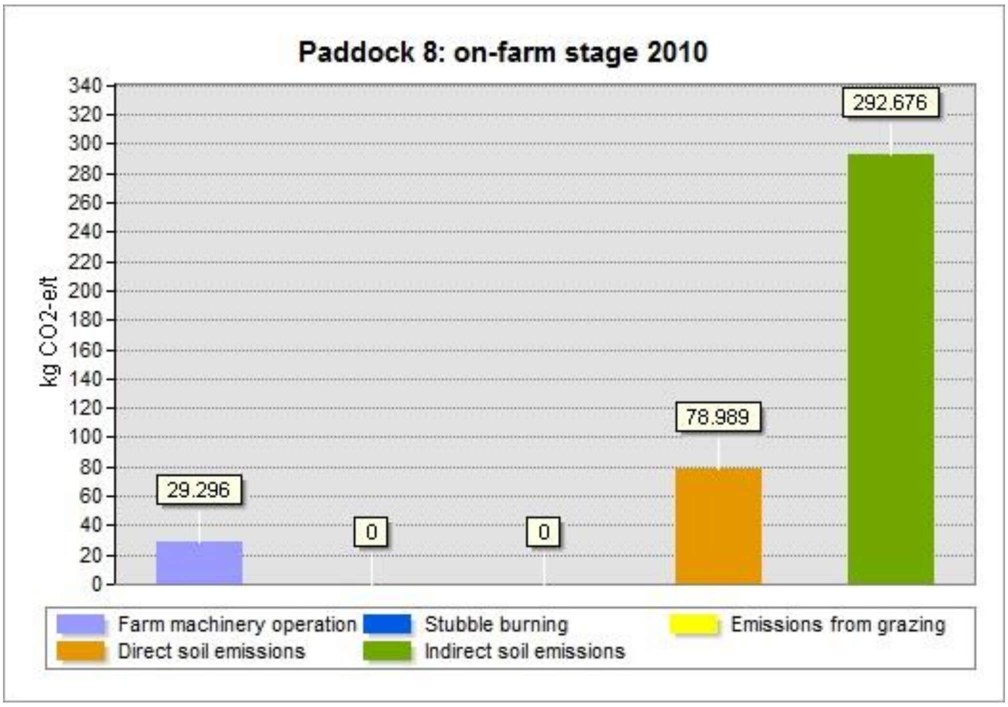


Figure 6.23. Paddock 8, on-farm GHG emissions for 2010

Figure 6.24 shows the GHG emissions from the individual classifications within the ISE output category. Emitting 2.92×10^2 kg CO_2-e/t (72.8%) of the total 4.01×10^2 kg CO_2-e/t from the on-farm stage of 2010, the quantised N_2O emissions from N leaching was the hotspot. Thereafter the emissions from NH_3 volatilisation, quantised as N_2O, emitted 7.78×10^{-1} kg CO_2-e/t (0.2% of the on-stage emissions). The ISE contributed to 40.3% of the total emissions from paddock 8 in 2010. The analysis in section 5.4.3.3 agrees with the image from the IST.

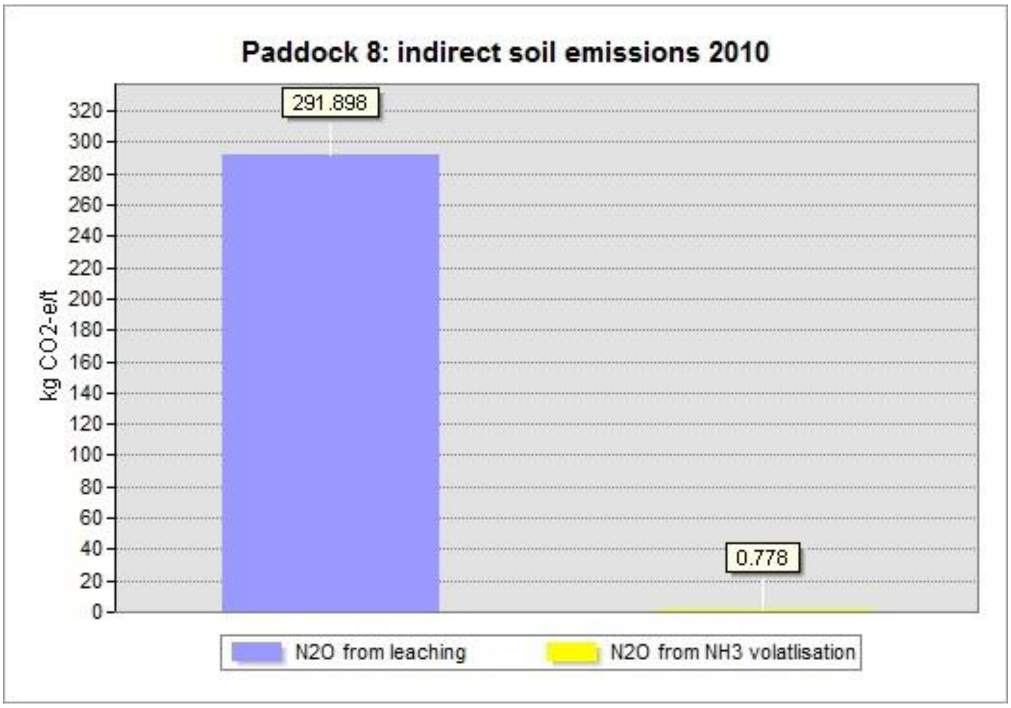


Figure 6.24. Paddock 8, indirect soil emissions for 2010

6.3.3 Paddock 9

Figure 6.25 shows that the pre-farm stage in 2011 emitted the most GHGs, totalling 3.94 x 10^2 kg CO_2-e/t or 32.6% when the four stages for paddock 9 were summed (1.21 x 10^3 kg). The on-farm stage in 2010 emitted 3.64 x 10^2 kg CO_2-e/t (30.1%), the pre-farm stage in 2010 emitted 2.85 x 10^2 kg CO_2-e/t (23.6%) and the on-farm stage in 2011 emitted 31.66 x 10^2 kg CO_2-e/t (13.7%) in total.

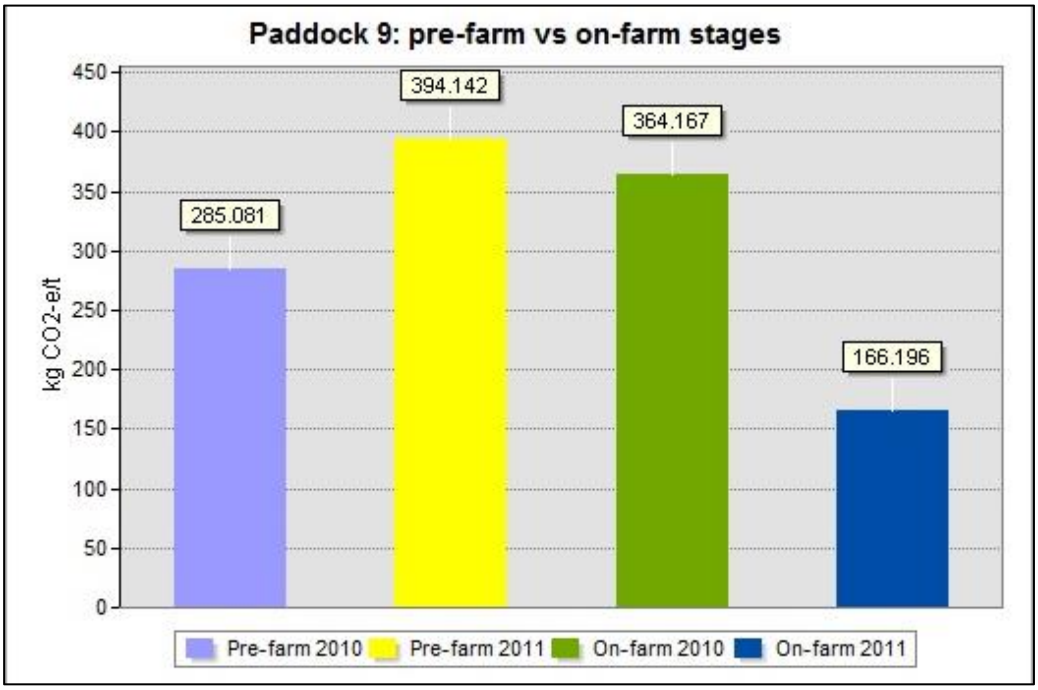


Figure 6.25. Paddock 9, pre-farm versus on-farm GHG emissions, 2010–2011

In Figure 6.26 it can be seen that the production of fertilisers category within the pre-farm stage of 2011 emitted the most GHGs, accounting for 56.8% or 2.24 x 10^2 kg CO_2-e/t of the 3.94 x 10^2 kg CO_2-e/t. The transportation of fertilisers, chemical production, farm machinery production and the transportation of chemicals produced 33.3%, 6.1%, 2.0% and 1.8% of the total GHG emissions from the pre-farm stage of 2011, respectively. The hotspot for paddock 9 is thus the production of fertilisers in 2011. Fertiliser production contributed to 40.0% of the total GHG emissions for the paddock in 2011. Additional images can be created in the IST using GIS to determine which of the fertilisers contributed the most GHGs in the production of fertilisers input category during production as discussed in section 5.4.3.4.

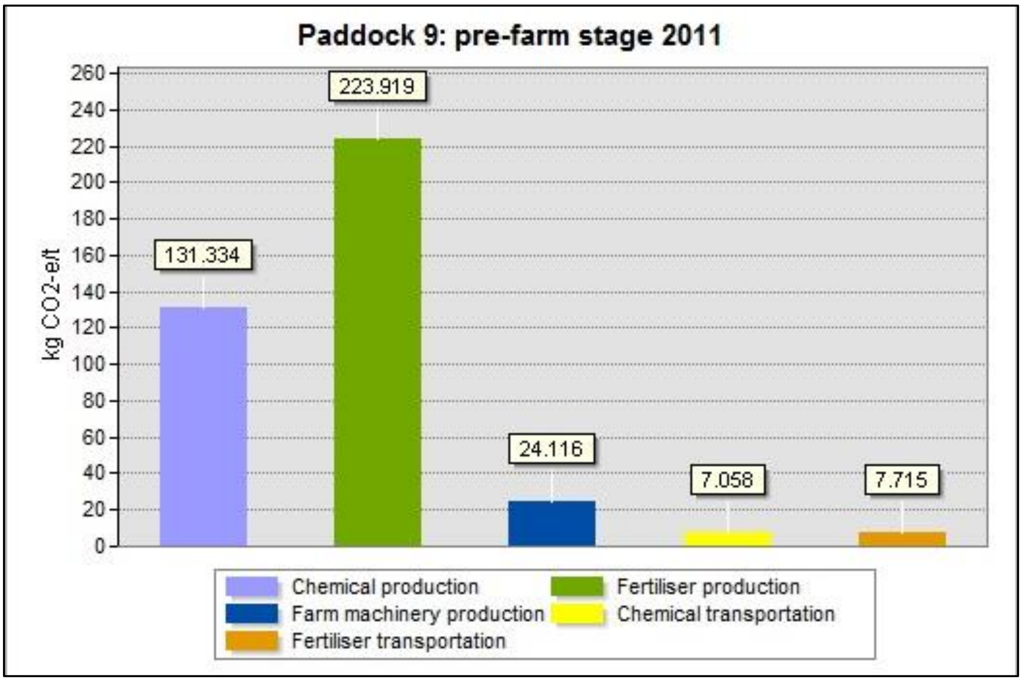


Figure 6.26. Paddock 9, pre-farm versus on-farm GHG emissions, 2010–2011

6.3.4 Summary of LCA results for Farm C

Section 6.3 highlights the hotspots identified in each paddock on Farm C. Paddock 7 generated a total of 1.82 x 10^2 kg CO_2-e/t in the ISE category of 2011 and was identified as the hotspot (section 5.4.3.2). Within this category, 1.82 x 10^2 kg CO_2-e/t was a direct result of N_2O emissions. ISE generated 2.93 x 10^2 kg CO_2-e/t on paddock 8 in 2010, and was the hotspot for this paddock over the two years, being the overall hotspot for Farm C. The production of fertilisers generated the most GHG emissions from paddock 9 during the pre-farm stage of 2011. The highest GHG emitter within this category was the production of the fertiliser ‘NPS range-Cereal’ on paddock 9, releasing 2.13 x 10^2 kg CO_2-e/t (section 5.4.3.4).

6.4 FARM D

By selecting the shapefiles of the paddocks of Farm D, Figure 6.27 was generated in the IST and shows the boundaries and shape of paddocks 10, 11 and 12. In 2012, wheat was planted in paddocks 10 and 12 and paddock 11 was used as a pasture. No further data was provided with regard to the sowing dates or the mass of the seed sown. The vegetation in paddock 10 is evenly distributed, suggesting similar growth of the crop and possibly homogenous soil conditions as indicated by the even red colour (Figure 6.27). Paddock 11 is mostly green indicating sparse vegetation, with small blocks of increased vegetation on the eastern side of the paddock. The reduced vegetation could be due to livestock grazing prior to the satellite image being taken. Paddock 12 is mostly covered with vegetation except for the north-east corner, which is green. As crop is sparse on the top right-hand corner it can be deduced that soil characteristics possibly contributed to poor growth.

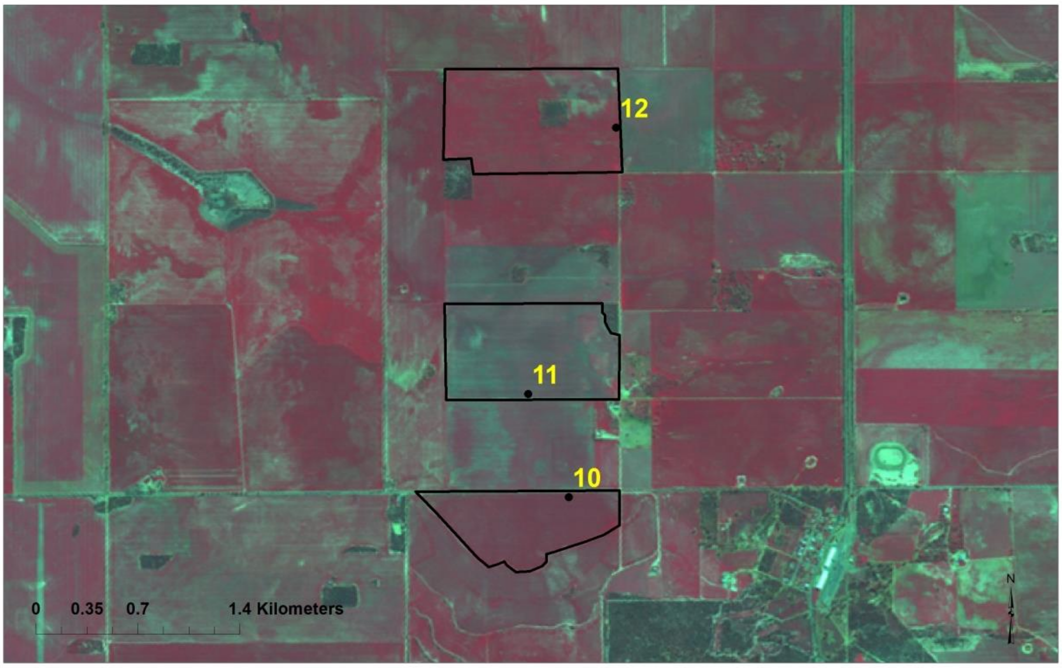
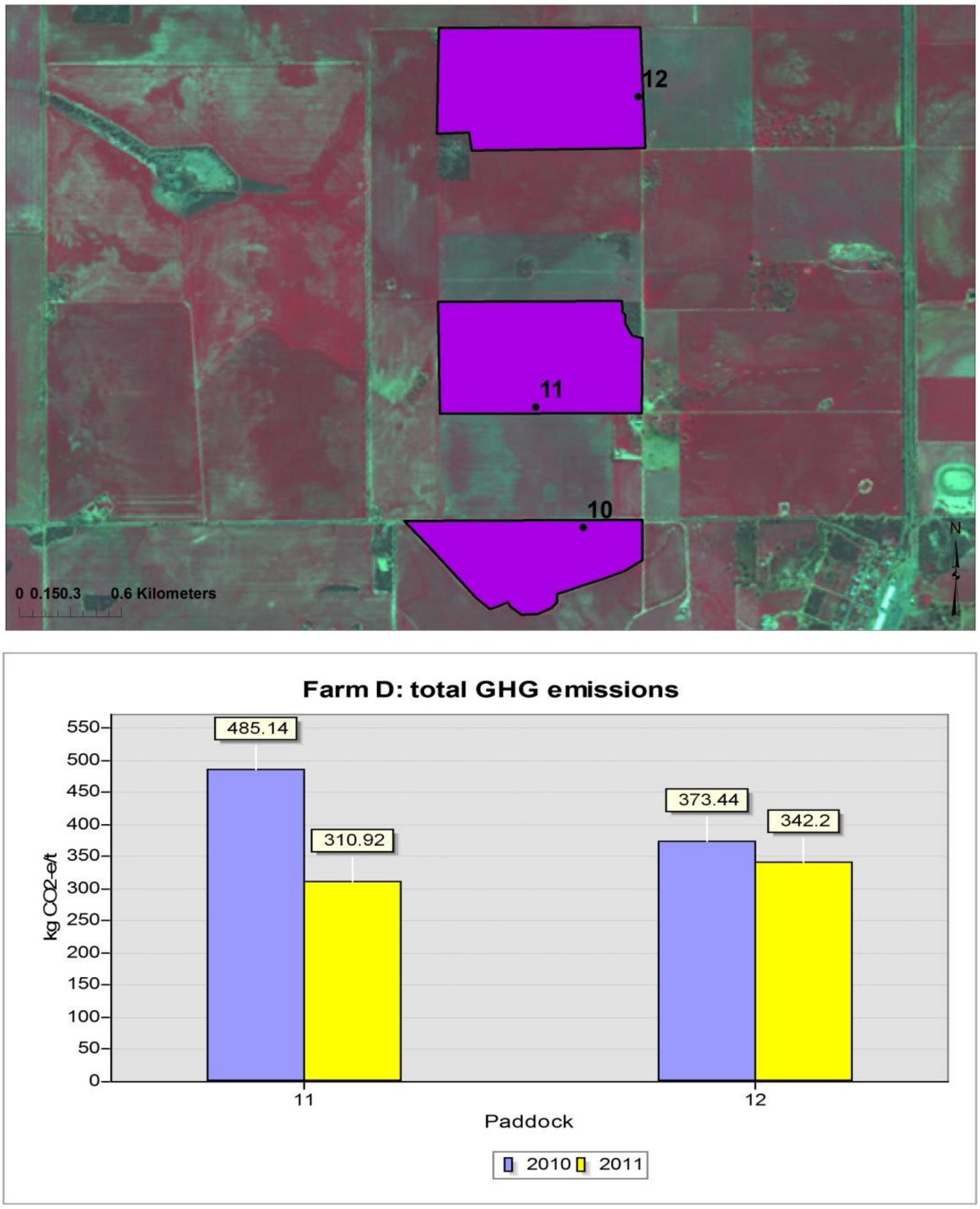


Figure 6.27. Remotely sensed image showing the paddock outlines for Farm D

As mentioned in Chapter 5, there was no analysis and imaging conducted for paddock 10 as data received were incomplete.

The paddock hotspot on Farm D is paddock 11 in 2010, followed by paddock 12 in 2011 (Figure 6.28). These two paddocks emitted 7.97 x 10^2 kg CO_2-e/t and 7.16 x

10^2 kg CO_2-e/t respectively of the total 1.51 x 10^3 kg CO_2-e/t over the two year period.



Total GHG emissions		
	2010	2011
Paddock	**kg CO_2-e/t**	**kg CO_2-e/t**
10		
11	485.1	310.9
12	373.4	342.2

Figure 6.28. Total GHG emissions for Farm D, 2010–2011 as generated in the IST

6.4.1 Paddock 11

With a total of 2.82 x 10^2 kg CO_2-e/t, the on-farm emissions in 2010 contributed 35.4% of the total 7.96 x 10^2 kg CO_2-e/t, generated in the pre-farm and on-farm stages of paddock 11, from 2010–2011. The pre-farm (2010), on-farm (2011) and pre-farm (2010) stages emitted 25.5%, 22.1% and 17.0% of the overall emissions for 2010 and 2011 over all stages, respectively. Amongst the farming stages for this paddock, the on-farm stage of 2010 was clearly the hotspot (Figure 6.29).

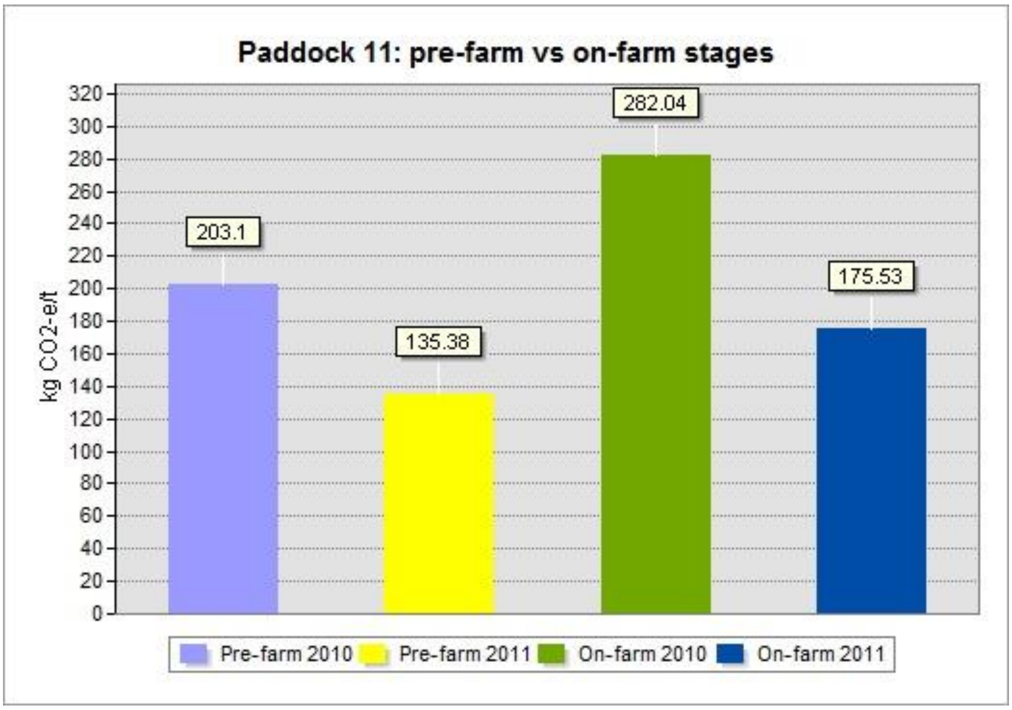


Figure 6.29. Paddock 11, pre-farm versus on-farm GHG emissions, 2010–2011

Figure 6.30 shows that the ISE (2010) output category generated the most GHG emissions for paddock 11, contributing to 44.7% of the on-farm stage emissions. Emissions from burning, emissions from grazing, DSE and emissions from the operation of farm machinery contributed 27.4%, 12.6%, 10.2% and 5.3%, respectively. The GHG emissions from the ISE output category generated 26.0% of the total paddock emissions for 2010.

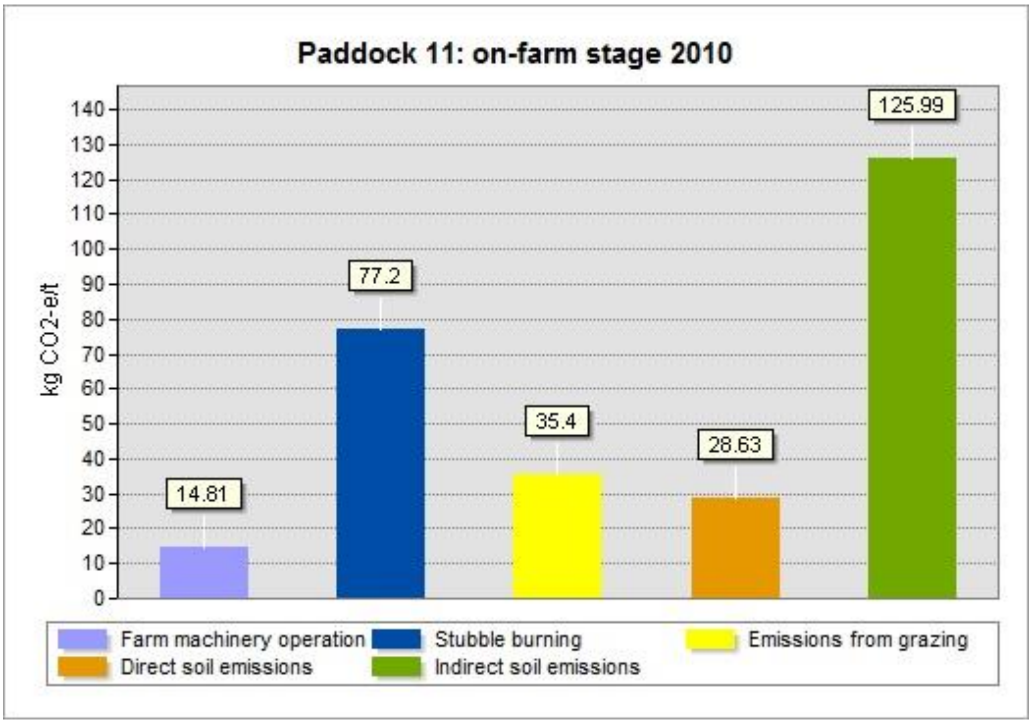


Figure 6.30. Paddock 11, on-farm GHG emissions for 2010

Figure 6.31 was created in the IST to illustrate the contribution of GHG emissions from ISE. This figure shows that soil N_2O emissions contributed to 99.7% of the ISE output category GHG emissions, 44.6% of the on-farm stage GHG emissions and 25.9% of the paddock GHG emissions for 2010.

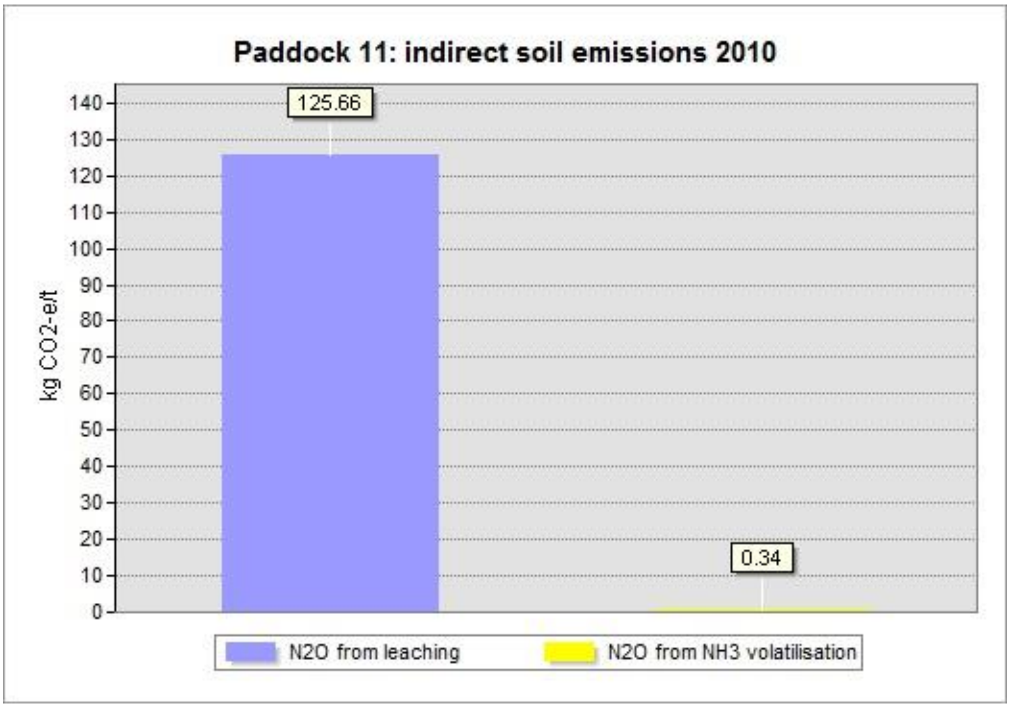


Figure 6.31. Paddock 11, ISE GHG emissions for 2010

6.4.2 Paddock 12

Figure 6.32 compares the pre-farm and on-farm stages for paddock 12, in 2010 and 2011. This paddock emitted a total of 7.16 x 10^2 kg CO_2-e/t and during this time the on-farm stage (2011) generated the highest level of GHGs, totalling 2.05 x 10^2 kg CO_2-e/t or 28.7% of the total GHG emissions over both years and both stages. The on-farm stage emitted the second highest GHGs in 2010 with a total of 1.96 x 10^2 kg CO_2-e/t or 27.4% of the total emissions from both years and stages. The two stages emitting the least GHGs for this paddock were the pre-farm stage of 2010, emitting 24.8% (1.77 x 10^2 kg CO_2-e/t), and the pre-farm stage of 2011, emitting 19.1% (1.37 x 10^2 kg CO_2-e/t) of the total GHG emissions during 2010–2011, for both stages.

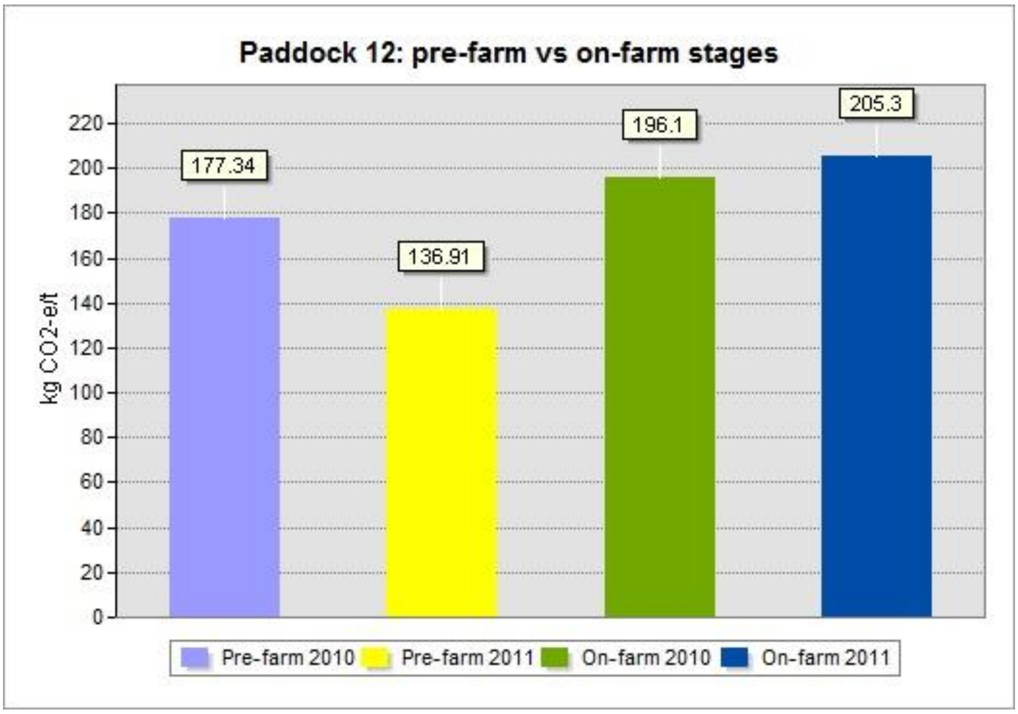


Figure 6.32. Paddock 12, pre-farm versus on-farm GHG emissions, 2010–2011

Figure 6.33 shows that the ISE output category from the on-farm stage of 2011 generated the most GHG emissions, accounting for 85.1% of the 2.05 x 10^2 kg CO_2-e/t in the on-farm stage and 51.1% of the emissions from the paddock. The other output categories contributing to GHG emissions were DSE and the operation of machinery, generating 9.97% and 4.93% of the on-farm stage GHG emissions of 2011, respectively, and 6.0% and 3.0% of the total paddock GHG emissions, respectively. Figure 6.33 supports the analysis found in section 5.4.4.3.

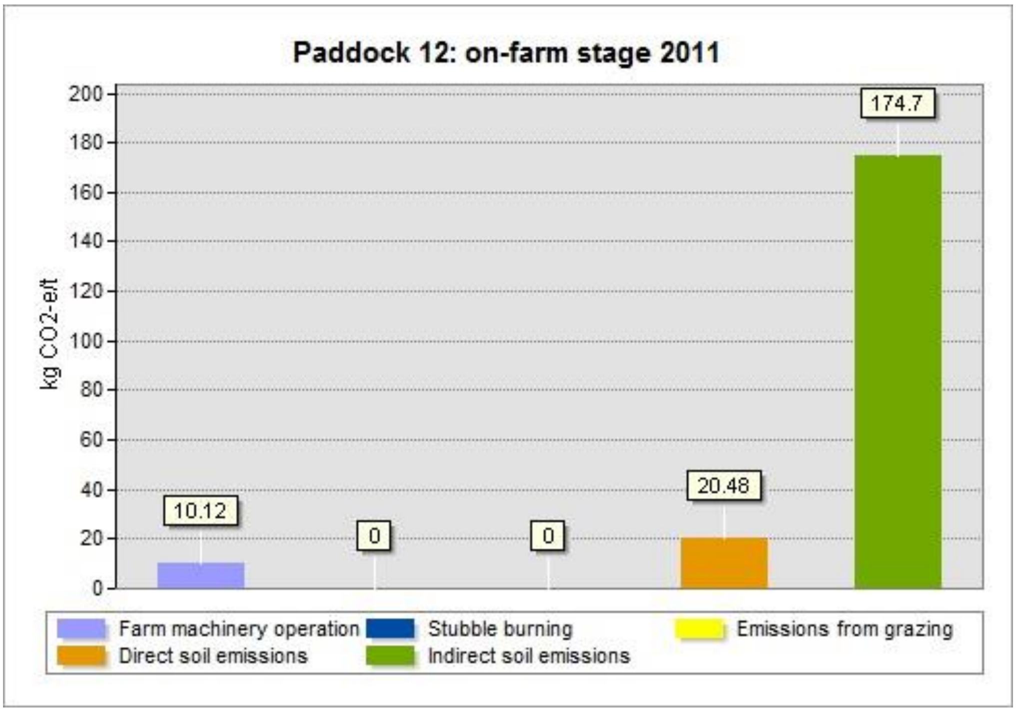


Figure 6.33. Paddock 12, on-farm GHG emissions for 2011

Figure 6.34 from the IST illustrates the hotspot within the ISE output category and shows that N_2O emissions in 2011 contributed 99.8% of GHG in the ISE output category. Furthermore it made up 84.9% of the on-farm emissions and 50.9% of the paddock emissions in 2011.

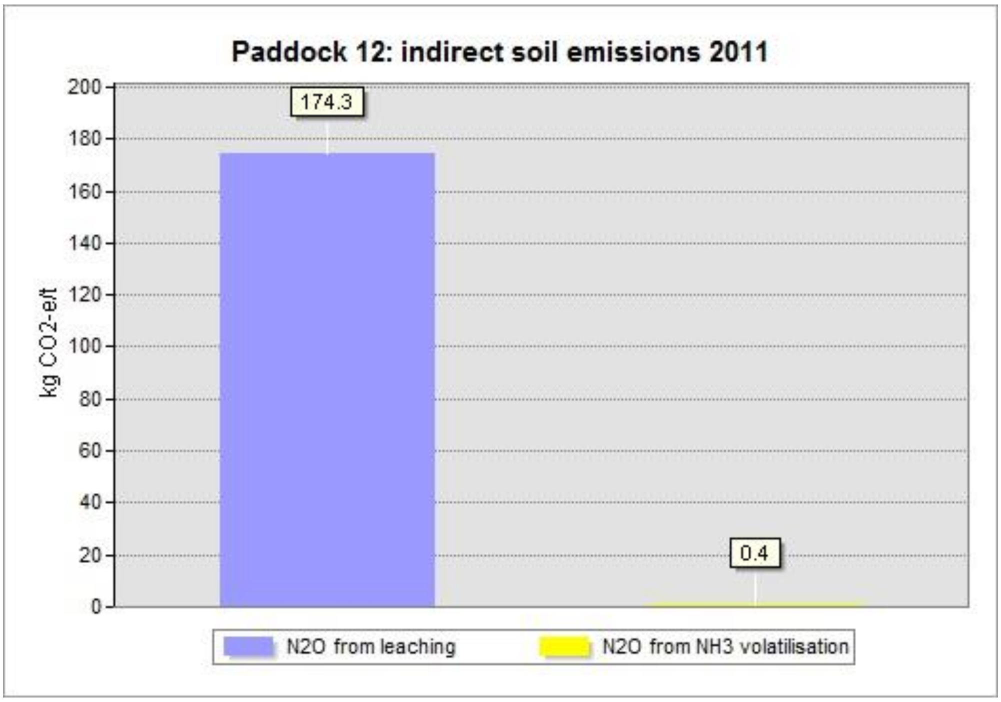


Figure 6.34. Paddock 11, ISE GHG emissions for 2011

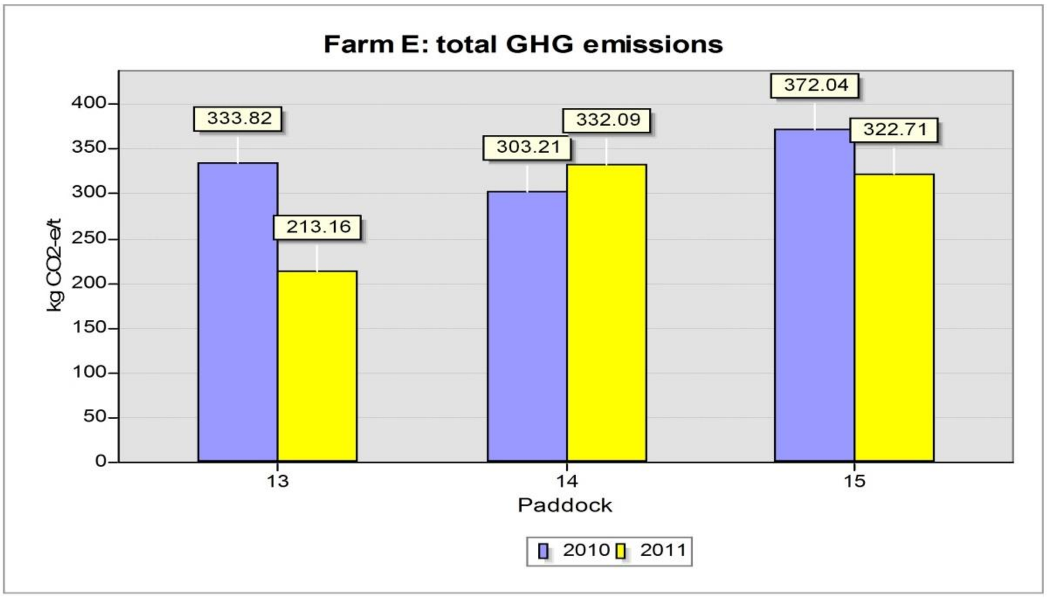
6.4.3 Summary of LCA results for Farm D

Section 6.4 presented the images generated in the IST for Farm D, specifically paddocks 11 and 12. Using solely these images, the ISE on paddock 11 in 2010 and on paddock 12 in 2011 were identified as the hotspots. These contributed 1.26×10^2 kg CO_2-e/t and 1.75×10^2 kg CO_2-e/t for paddocks 11 and 12, respectively (sections 5.4.4.2 and 5.4.4.3), and were identified as the hotspots for these two paddocks. The hotspot for Farm D was the GHG emissions from ISE in 2010 in paddock 11.

6.5 FARM E

As the boundaries of paddocks 13, 14 and 15 fell outside the area demarcated in the satellite image, no figure could be generated to show the paddock shapes or groundcover. The three paddocks lay approximately 42 km north of paddock 6. The data was not excluded from the analysis as the dataset was complete and could be used to illustrate findings from figures created with the IST, without satellite imagery.

Figure 6.35 shows the paddock hotspot on Farm E, as the pre-farm stage on paddock 15 in 2010, followed by the pre-farm stage on paddock 13 in 2010. Over the two year period this farm emitted 1.88×10^3 kg CO_2-e/t, of which paddock 15 (2010) contributed to 37.0% and paddock 13 (2010) 33.8%.



Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
13	333.8	213.2
14	303.2	332.1
15	372.0	322.7

Figure 6.35. Total GHG emissions for Farm E, 2010–2011 as generated in the IST

6.5.1 Paddock 13

Figure 6.36 compares the pre-farm and on-farm stages of paddock 13, over both years, showing that the most GHGs were generated in the pre-farm stage in 2010. Paddock 13 emitted a total 5.47 x 10^2 kg CO_2-e/t over the two years, of which the pre-farm stage (2010) contributed 41.9%, followed by the on-farm stage in 2011 (24.8%), then the on-farm stage in 2010 (19.1%) and finally the pre-farm stage in 2011 (14.1%).

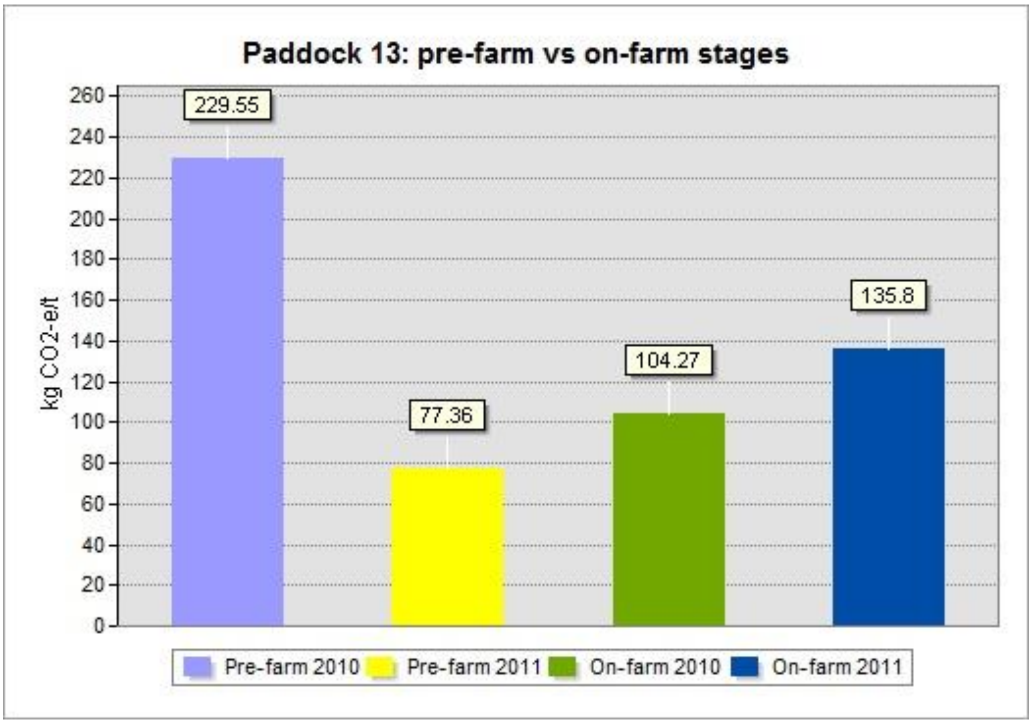


Figure 6.36. Paddock 13, pre-farm versus on-farm GHG emissions, 2010–2011

The hotspot in paddock 13, as represented by the tallest bar in Figure 6.37, was the production of fertilisers in 2010, emitting 49.4% of the pre-farm total of 2.30 x 10^2 kg CO_2-e/t and 34.0% of the total GHG emissions from this paddock.

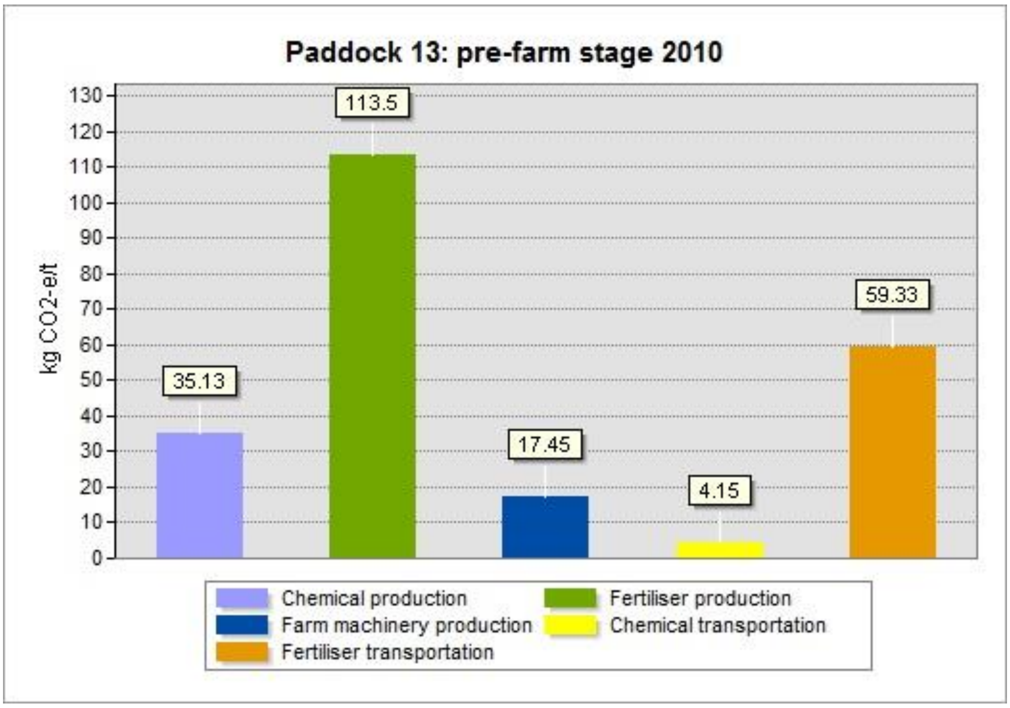


Figure 6.37. Paddock 13, pre-farm GHG emissions for 2010

6.5.2 Paddock 14

The analysis of Figure 6.38, generated for paddock 14, shows that the emissions from the on-farm stage in 2011 were the highest when compared to the other stages during 2010–2011. The breakdown of carbon footprints in terms of GHG emissions, for all stages for both years is as follows: on-farm 2011 (36.5%), pre-farm 2010 (31.9%), on-farm 2010 (15.9%) and pre-farm 2011 (15.8%).

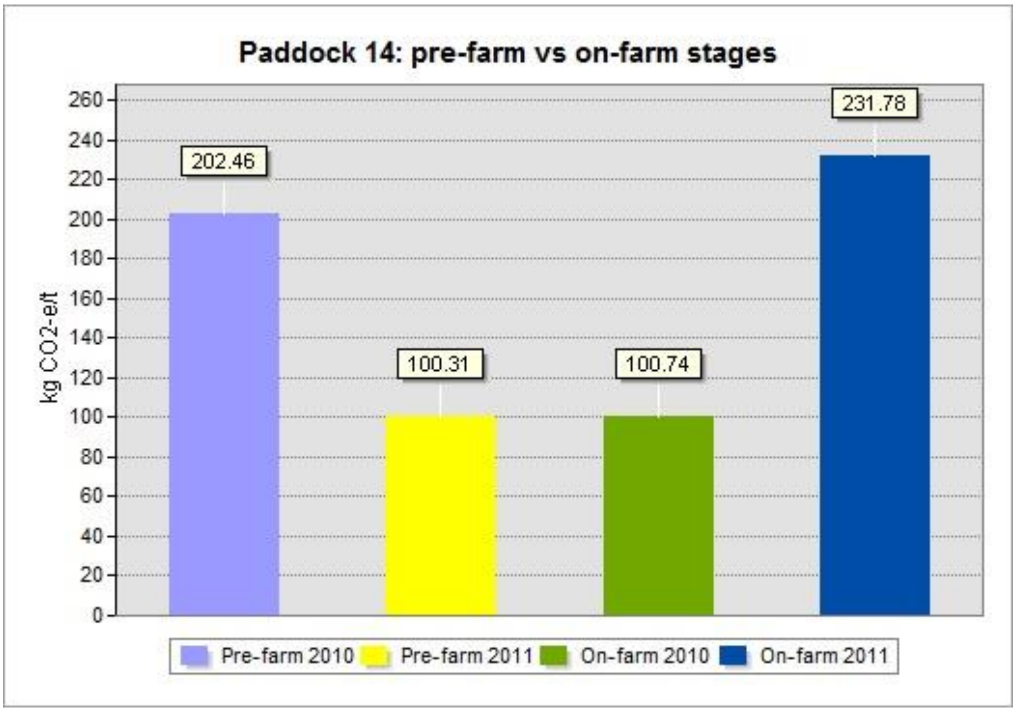


Figure 6.38. Paddock 14, pre-farm versus on-farm GHG emissions, 2010–2011

It is deduced from Figure 6.39 that the ISE in the on-farm stage 2011 was the hotspot, generating 1.71 x 10^2 kg CO_2-e/t (73.8%), followed by DSE (3.59 x 10^1 kg CO_2-e/t, 15.5%), emissions from grazing (1.58 x 10^1 kg CO_2-e/t, 6.8%) and finally the emissions from farm machinery operation (9.13 kg CO_2-e/t, 3.9%). The ISE output category contributed to 51.5% of the GHG emissions generated from this paddock in 2011.

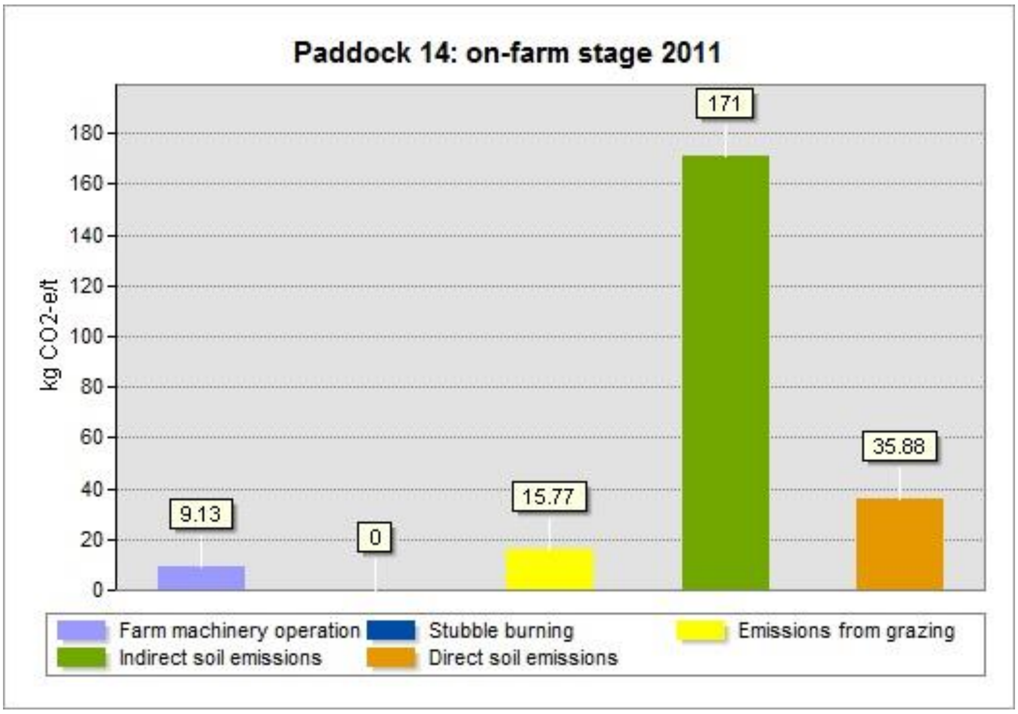


Figure 6.39. Paddock 14, on-farm GHG emissions for 2011

Figure 6.40 shows that the N_2O emissions within the ISE was the area of concern in 2011 and generated 99.7% of the emissions in the ISE output category, 73.6% of the emissions from the on-farm stage of 2011 and 51.4% of the entire paddock's GHG emissions.

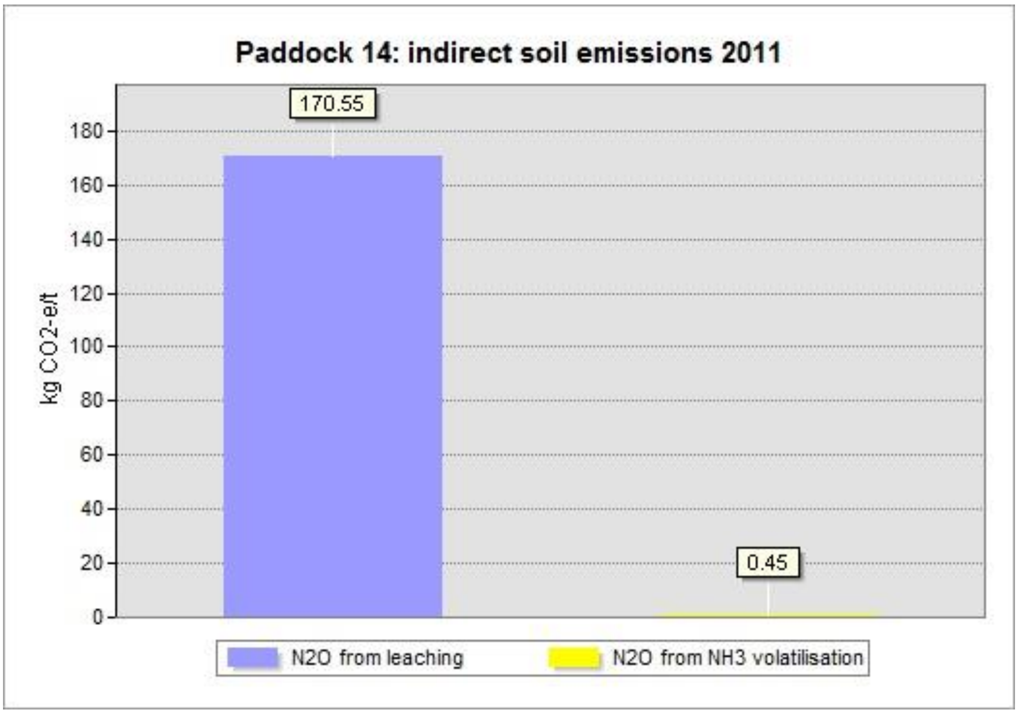


Figure 6.40. Paddock 14, indirect soil GHG emissions for 2011

6.5.3 Paddock 15

The pre-farm stage in 2010 is the stage hotspot for paddock 15, contributing 38.3% (2.66 x 10^2 kg CO_2-e/t) of the total GHG emissions from both stages and in both years (Figure 6.41). The pre-farm stage in 2011 generated 2.00 x 10^2 kg CO_2-e/t (28.8%) over the two years for both stages and 17.7% and 15.2% of GHGs were produced during the on-farm stage in 2011 (1.23 x 10^2 kg CO_2-e/t) and the on-farm stage in 2010 (1.06 x 10^2 kg CO_2-e/t).

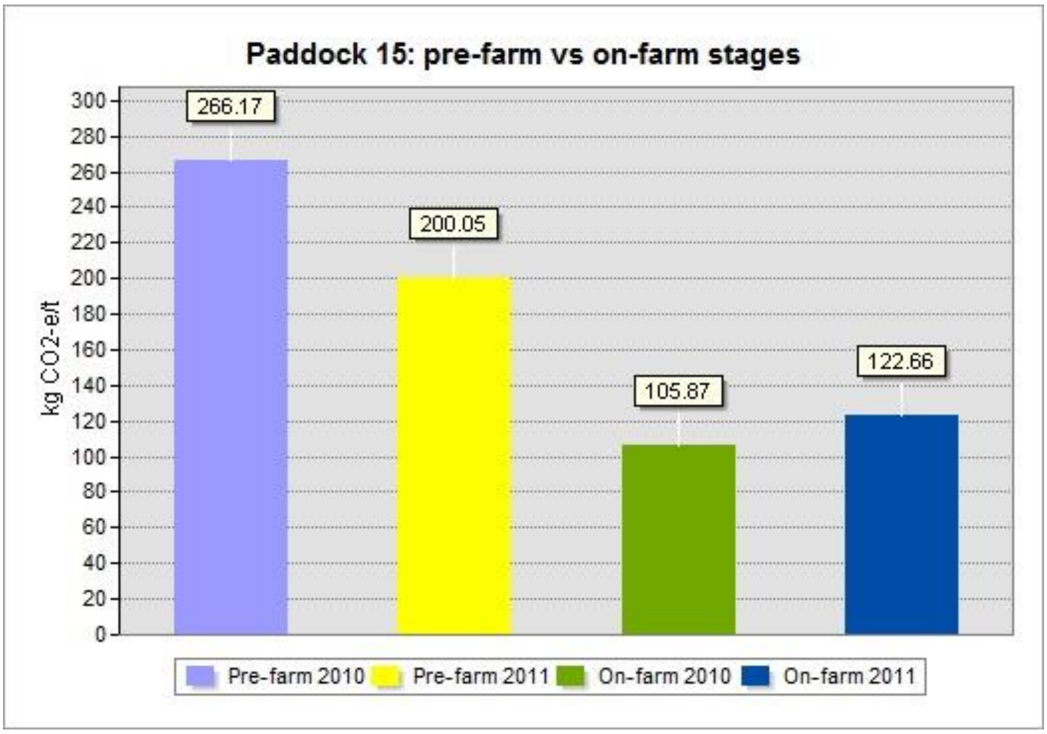


Figure 6.41. Paddock 15, pre-farm versus on-farm GHG emissions, 2010–2011

As the pre-farm stage in 2010 contributed the highest level of GHGs from paddock 15, Figure 6.42 identifies the hotspot category within this stage, as the production of fertilisers in 2010. Of the 2.66 x 10^2 kg CO_2-e/t generated in the pre-farm stage for this paddock, the production of fertiliser contributed 45.4% (1.21 x 10^2 kg CO_2-e/t) of the GHG emissions. The balance of the GHGs for the pre-farm stage were generated by the transportation of fertiliser (6.31 x 10^1 kg CO_2-e/t, 23.7%), chemical production, (5.55 x 10^1 kg CO_2-e/t, 20.9%), farm machinery production (2.11 x 10^1 kg CO_2-e/t, 7.9%) and 5.78 kg CO_2-e/t (2.2%) from chemical transportation. Overall the production of fertilisers contributed to 32.4% of the total GHG emissions from this paddock in 2010. The identification of the fertiliser that contributed the most

GHG emissions in this category was concluded in section 5.4.5.4. An additional graph, in which the GHG emissions for the production of individual chemicals are separately specified, can also be created using GIS in the IST.

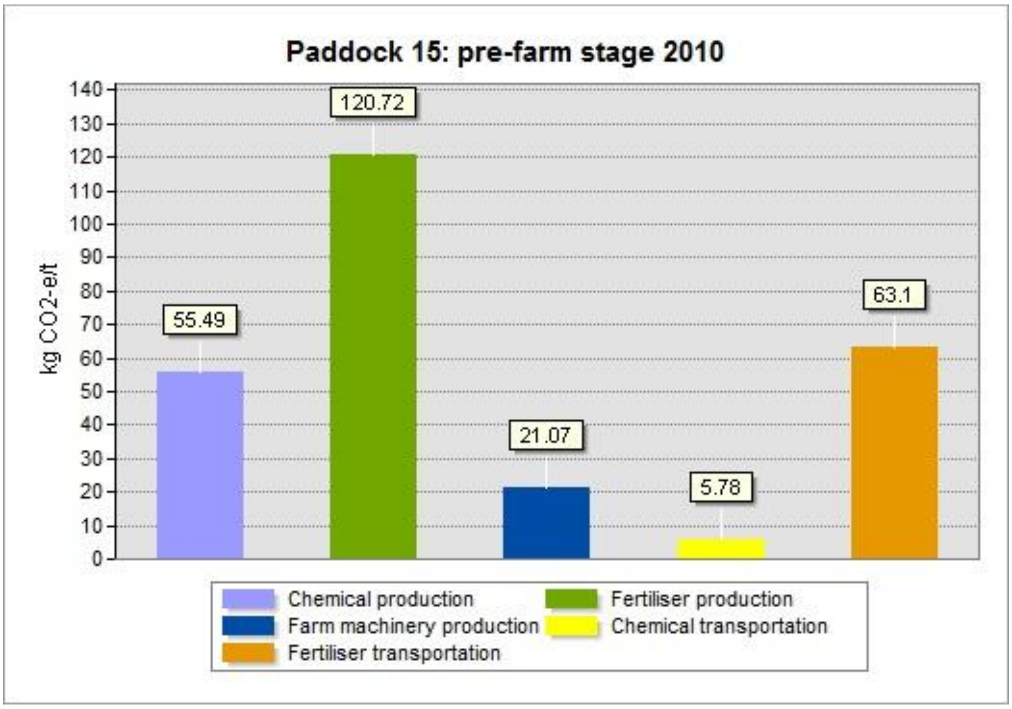


Figure 6.42. Paddock 15, pre-farm GHG emissions for 2010

6.5.4 Summary of LCA results for Farm E

The hotspots for the three paddocks from Farm E were identified visually using the IST images. The hotspot for paddock 13 was the production of fertiliser in 2010, which generated a total of 1.14 x 10^2 kg CO_2-e/t. The ISE (1.710 x 10^2 kg CO_2-e/t) from paddock 14, and more specifically N_2O (1.705 x 10^2 kg CO_2-e/t) was the hotspot in 2011 (section 5.4.5.3). In 2010 the emissions from fertiliser production presented as the hotspot for paddock 15 emitting 1.21 x 10^2 kg CO_2-e/t in that year (section 5.4.5.4). The overall hotspot for this farm was the production of fertiliser in 2010, on paddock 15.

6.6 FARM F

Figure 6.43 is an extract from the Deimos 2012 satellite image that focuses on the WANTFA area. The boundaries of the three paddocks from Farm F have been extracted from the total image by means of GIS. Wheat was planted in paddocks 16 (26/5/2012), 17 (27/5/2012) and 18 (20/5/2012). The red hue occurring in all paddocks appears to be the same, thus the deduction could be made that the growth stage of wheat was similar at the time of imaging. However, the paddocks show white and green areas which indicate an absence of vegetation. For more accurate predictions concerning the growth stages and alternative groundcover, a more advanced classification method using a RS application is recommended, such as ERDAS.

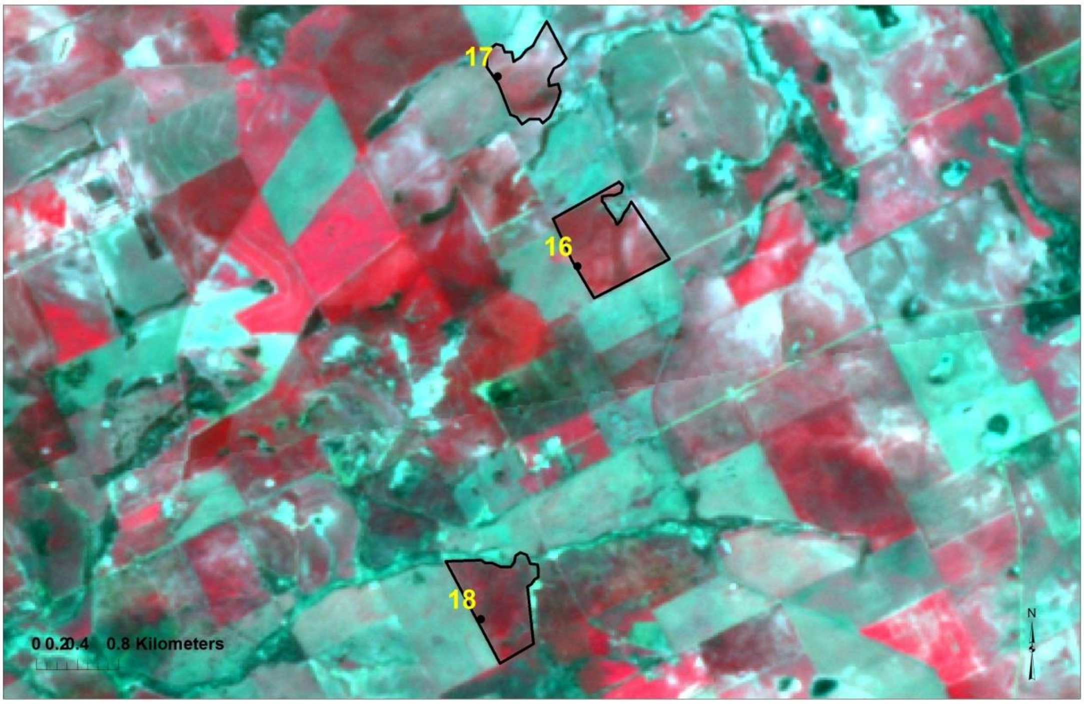
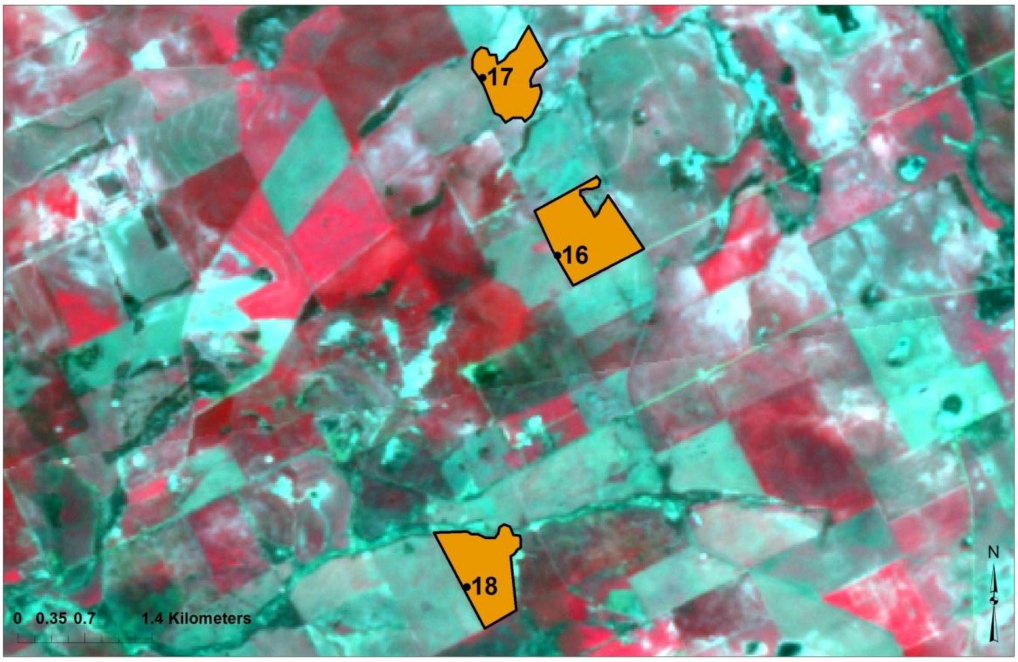
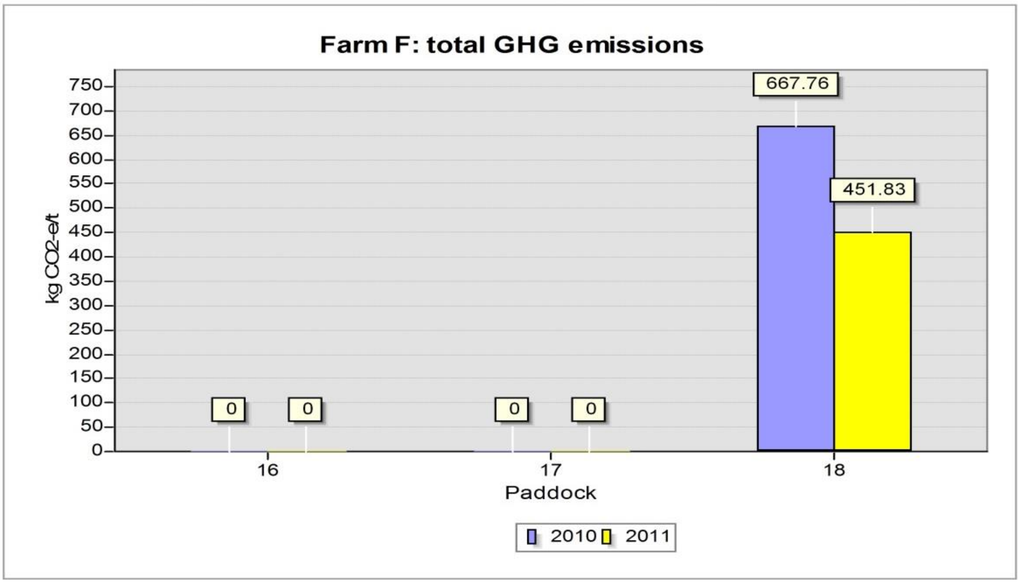


Figure 6.43. Remotely sensed image showing the paddock outlines for Farm F

In Figure 6.44 the three paddocks of Farm F are coloured in orange for identification purposes. Farm F is discussed and analysed in full in section 5.4.6. As both paddocks 16 and 17 were used as a pasture in 2011, no grain yield was available and the paddocks were excluded from further analyses.





Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
16		
17		
18	667.8	451.8

Figure 6.44. Total GHG emissions for Farm F, 2010–2011 as generated in the IST

Figure 6.45 shows the GHG emissions from the pre-farm and on-farm stages of paddock 18 for both years. It is evident from this figure that the pre-farm emissions from 2010 generated the most GHGs during the research period. A total of 1.12 x 10^3 kg CO_2-e/t was generated over the research period for paddock 18, of which 33.8% (3.78 x 10^2 kg CO_2-e/t) came from the pre-farm stage of 2010. The pre-farm stage of 2011 generated 33.6% of the total GHG emissions, the on-farm stage 2010, 25.9% and the on-farm stage in 2011 contributed 6.7% as presented in Figure 6.45.

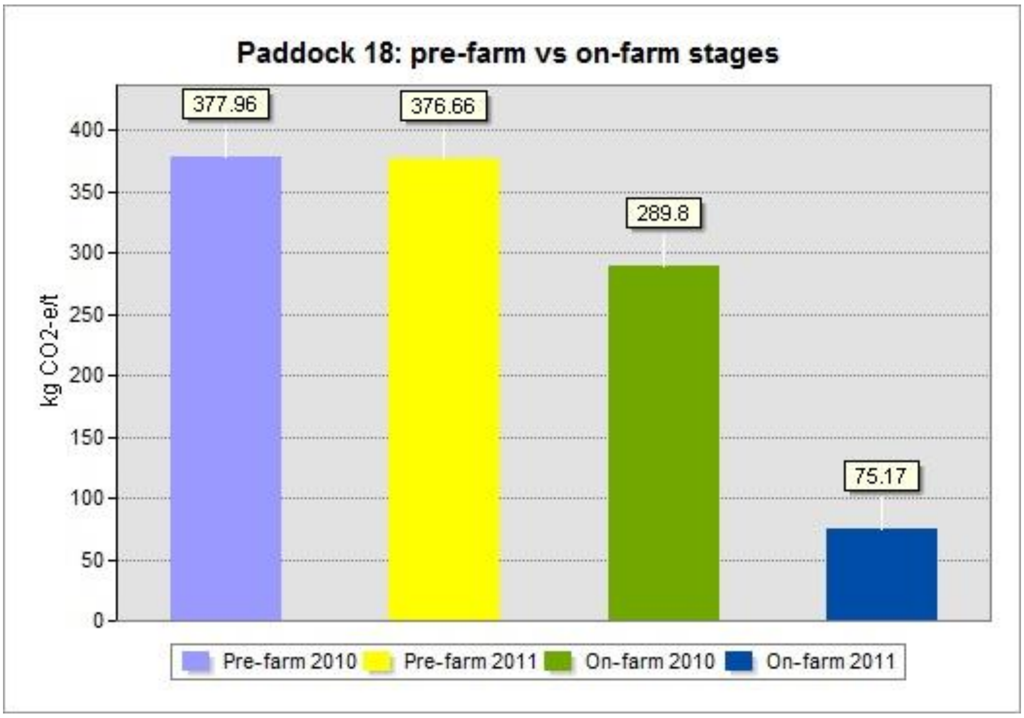


Figure 6.45. Paddock 18, pre-farm versus on-farm GHG emissions, 2010–2011

As the pre-farm stage in 2010 consists of five different input categories, the IST was used to create Figure 6.46 for further analysis and identifies the hotspot as emissions from the production of fertilisers in paddock 18. The GHG emissions from the production of fertilisers totalled 3.15 x 10^2 kg CO_2-e/t and contributed to 83.3% of the total emissions from this stage. The other 16.7% was made up of emissions from chemical production (9.6%), farm machinery production (5.2%) transportation of fertilisers (1.0%) and transportation of chemicals (0.9%). Overall the production of fertilisers generated 47.2% of the total GHG emissions from the paddock.

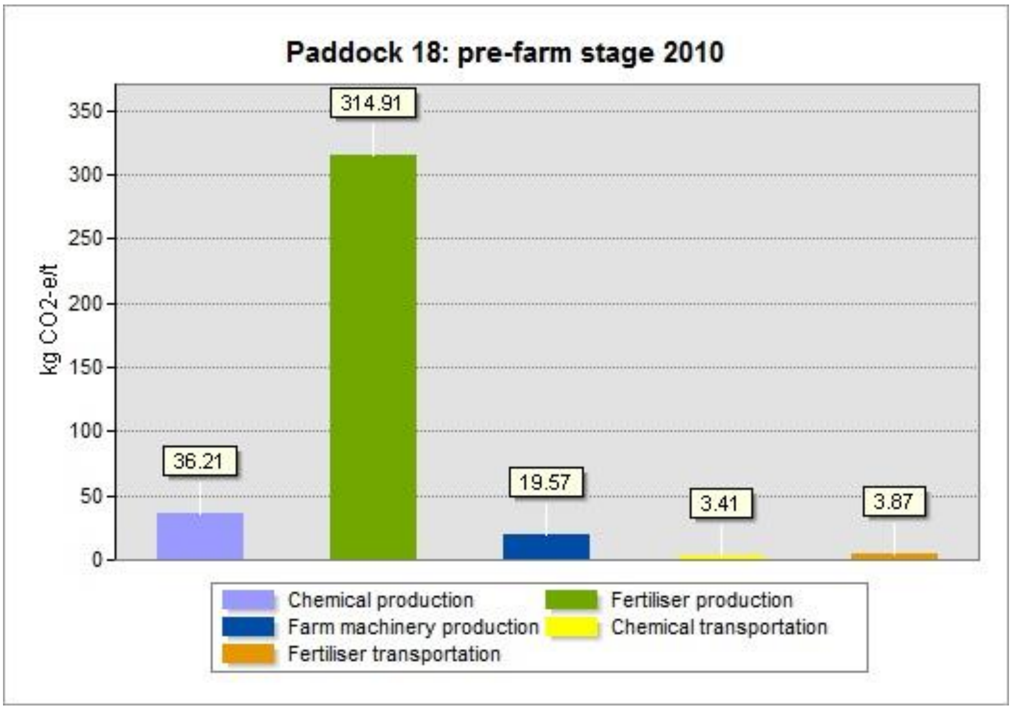


Figure 6.46. Paddock 18, pre-farm GHG emissions for 2010

The analysis of the fertiliser production input category was completed in section 5.4.6.2 where the emissions from the production of fertilisers of MAP and MaxAmFlo were identified as contributing the most GHG emissions.

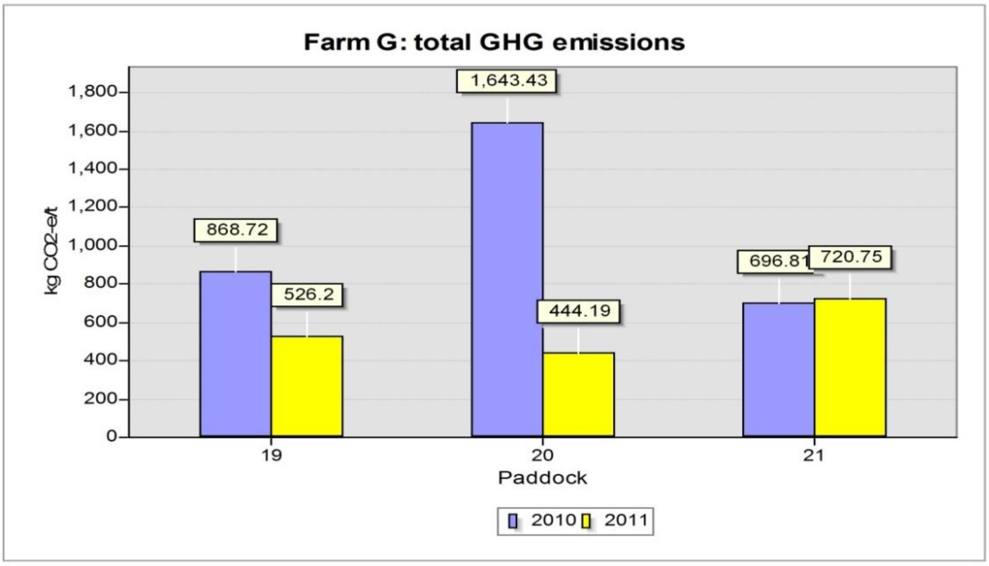
6.6.4 Summary of LCA results for Farm F

The GHG emissions from the production of fertilisers totalled 3.15 x 10^2 kg CO_2-e/t and contributed to 83.3% of the total emissions from this stage in 2010. As a result the pre-farm stage in 2010 (33.6%) appeared to be the highest contributor of GHG emissions during the 2010–2011 crop sequencing period. This will enable farmers to make a strategic decision to find alternative fertiliser management practices, such as crop rotation, selection of fertiliser with a reduced carbon footprint, as discussed in the following Chapter 7, to further mitigate GHG emissions. As both paddocks 16 and 17 were used as a pasture in 2011, these paddocks were excluded from further analyses.

6.7 FARM G

Paddocks 19, 20 and 21 lay outside the boundary of the satellite image and thus no identification could be made of their physical characteristics. Paddock 22 was the closest paddock to these three paddocks, lying approximately 12 km north-east of paddock 21. As all other data received was complete, the decision was made to include the paddocks in the analysis, however the satellite image was not included.

Figure 6.47 identified paddock 20 (2010) as the hotspot for this farm. The paddock generating the next highest level of GHGs was paddock 19 in 2010 (Figure 6.47). The farm emitted a total of 4.90 x 10^3 kg CO_2-e/t over the two years, over all stages, with paddock 20 (2010) contributing 33.5% and paddock 19 (2010) contributing 17.7% to these GHG emissions.



Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
19	868.7	526.2
20	1643.4	444.2
21	696.8	720.7

Figure 6.47. Total GHG emissions for Farm G, 2010–2011 as generated in the IST

6.7.1 Paddock 19

During 2010, the pre-farm stage generated the highest volume of GHG emissions for paddock 19 (Figure 6.48). The total emissions from this stage were 4.42 x 10^2 kg CO_2-e/t, accounting for 33.7% of the total emissions across all stages for both years for the paddock. The other three stages contributed 30.6%, 20.09% and 17.7% from the on-farm stage in 2010, on-farm stage in 2011 and pre-farm stage in 2011, respectively.

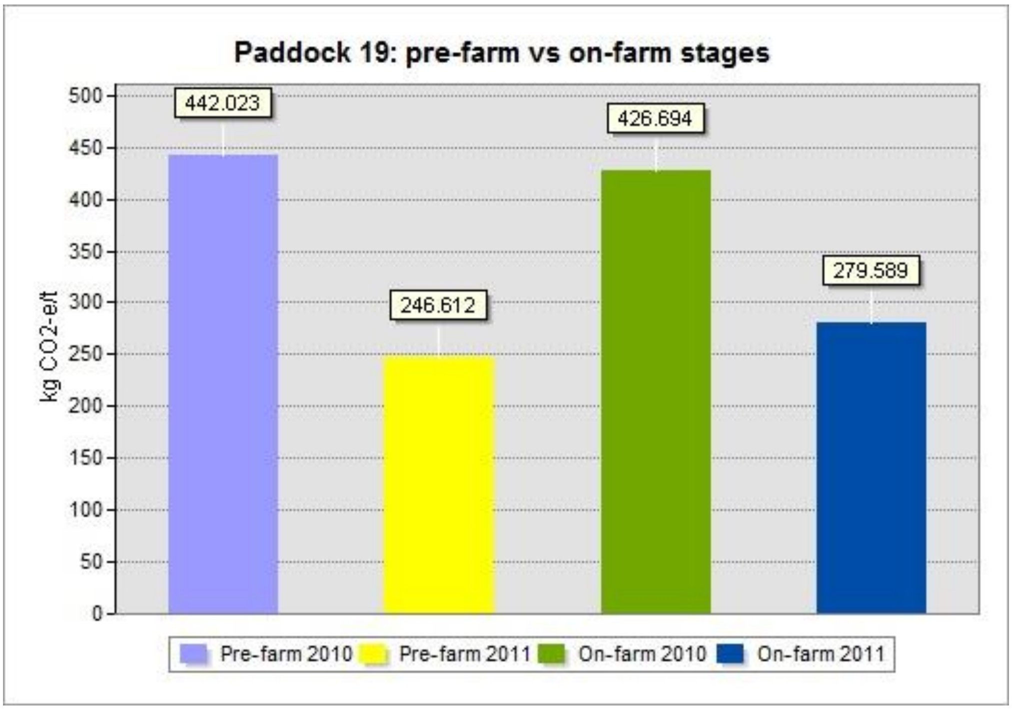


Figure 6.48. Paddock 19, pre-farm versus on-farm GHG emissions, 2010–2011

Within the pre-farm stage of 2010 the category that presented itself as the hotspot was the chemical production input category (Figure 6.49), generating 51.9% of the pre-farm GHG emissions and 26.4% of the paddock GHG emissions.

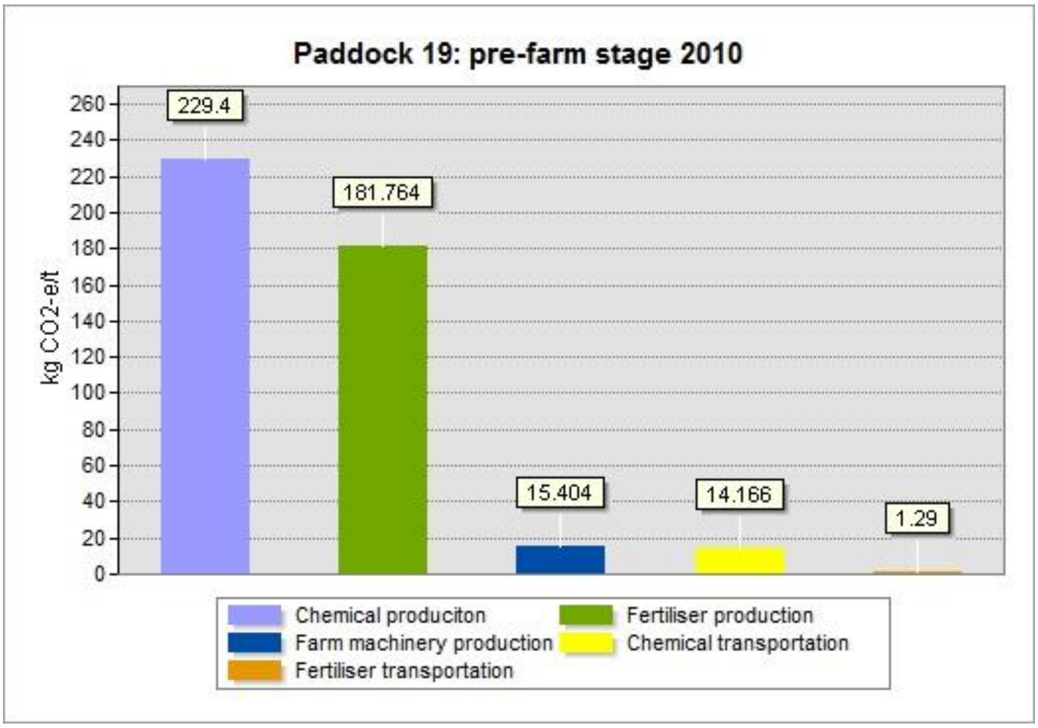


Figure 6.49. Paddock 19, pre-farm GHG emissions for 2010

Figure 6.50 was created in GIS as part of the IST to identify the overall hotspot for all chemical classes, identifying the production of herbicides as the hotspot within the chemical production input category. The production of herbicides generated 99.1% of the 2.29 x 10^2 kg CO_2-e/t from chemical production, equating to 51.4% of the pre-farm GHG emissions in 2010 and 26.2% of the emissions from the paddock for the pre-farm and on-farm stage.

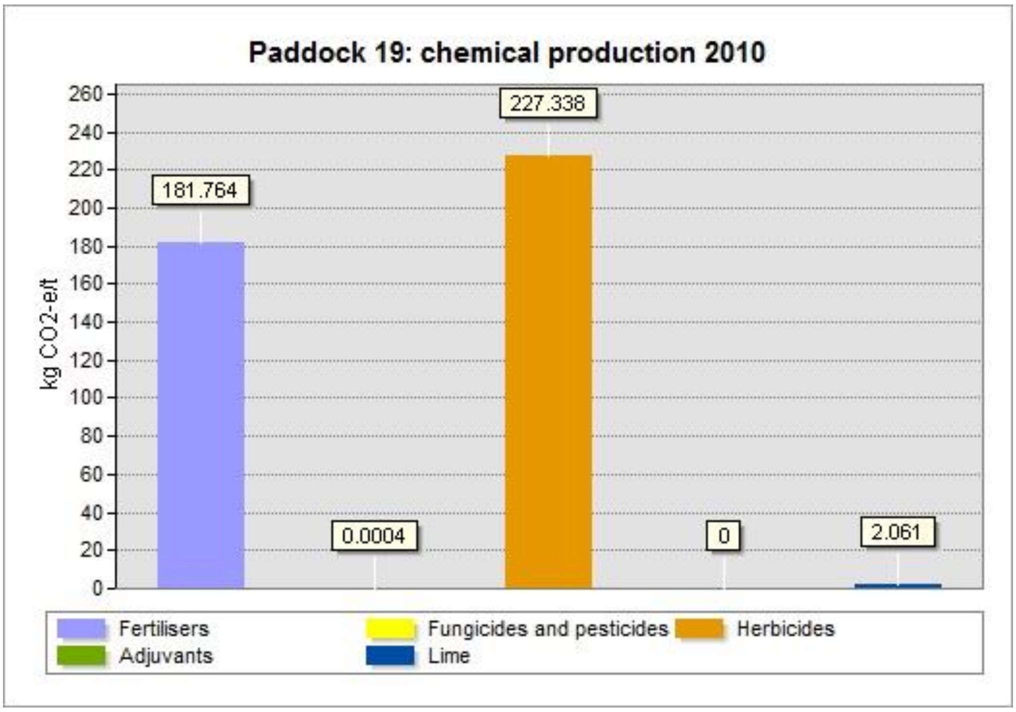


Figure 6.50. Paddock 19, chemical production GHG emissions for 2010

6.7.2 Paddock 20

Paddock 20 emitted a total of 2.09 x 10^3 kg CO_2-e/t for the years 2010 and 2011, of which 1.11 x 10^3 or 53.3% of the total GHG emissions over both years and all stages were generated by the on-farm stage of 2010 (Figure 6.51). The pre-farm stage of 2010 produced the next highest GHG emissions totalling 5.31 x 10^2 kg CO_2-e/t (25.5%), followed by the on-farm stage of 2011 with 2.66 x 10^2 kg CO_2-e/t (12.7%) and the pre-farm stage of 2011 with 1.79 x 10^2 kg CO_2-e/t (8.6%).

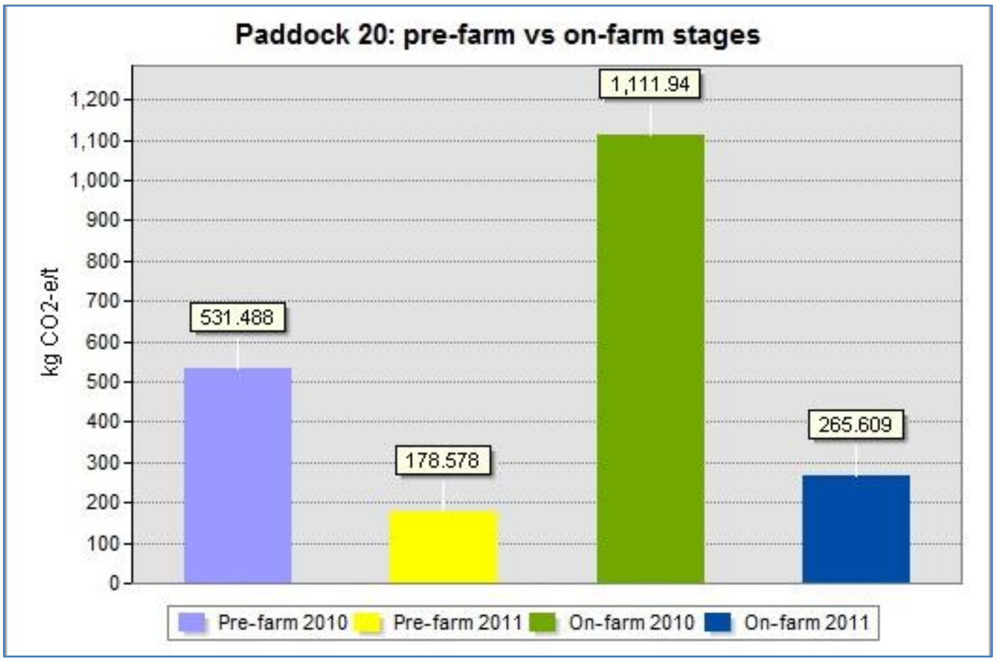


Figure 6.51. Paddock 20, pre-farm versus on-farm GHG emissions, 2010–2011

The ISE output category was identified in the on-farm stage of 2010 as the hotspot Figure 6.52, generating a total of 9.18 x 10^2 kg CO_2-e/t, accounting for 82.6% of the emissions from the on-farm stage of 2010 and 55.9% of the paddock emissions. Additionally, emissions from stubble burning contributed to 7.4% of the total emissions from the paddock, DSE to 3.4% of the emissions and farm machinery operation to 1.0%. The hotspot for the paddock was thus clearly ISE in 2010.

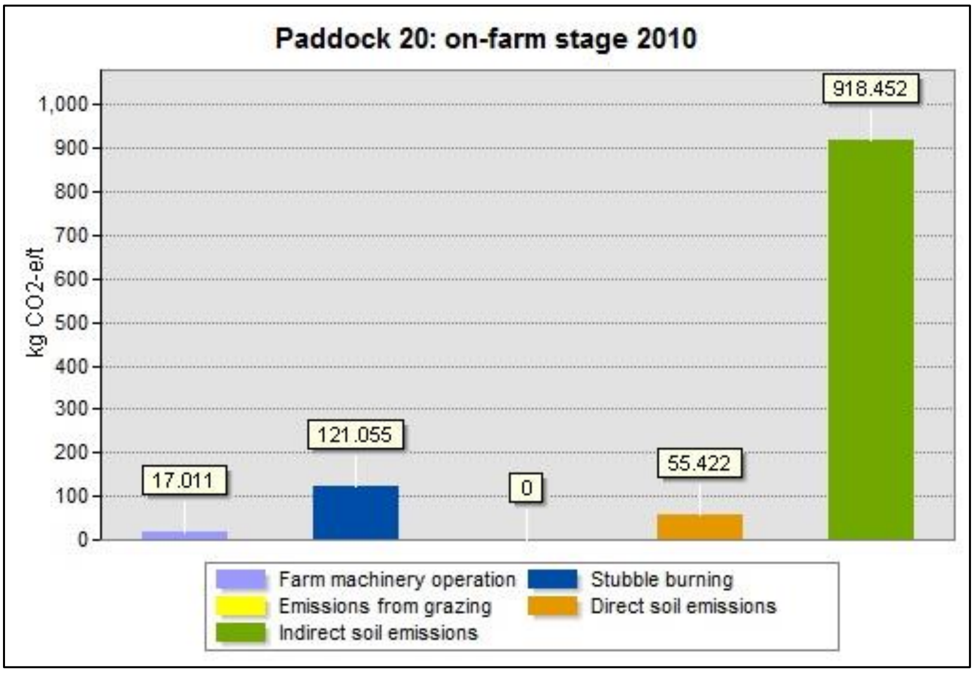


Figure 6.52. Paddock 20, on-farm GHG emissions for 2010

To further investigate the contribution of N from the leaching of NO_x and from NH_3 volatilisation, converted to N_2O, Figure 6.53 was created in the IST. This figure demonstrates that the quantised N_2O emissions generated during N transformations in the soil were responsible for 99.9% of the GHG emissions from the ISE output category. Furthermore, the converted N_2O emissions from leaching generate 82.5% of the GHG emissions in the on-farm stage of 2010 and 55.8% of the total emissions from the paddock in 2010.

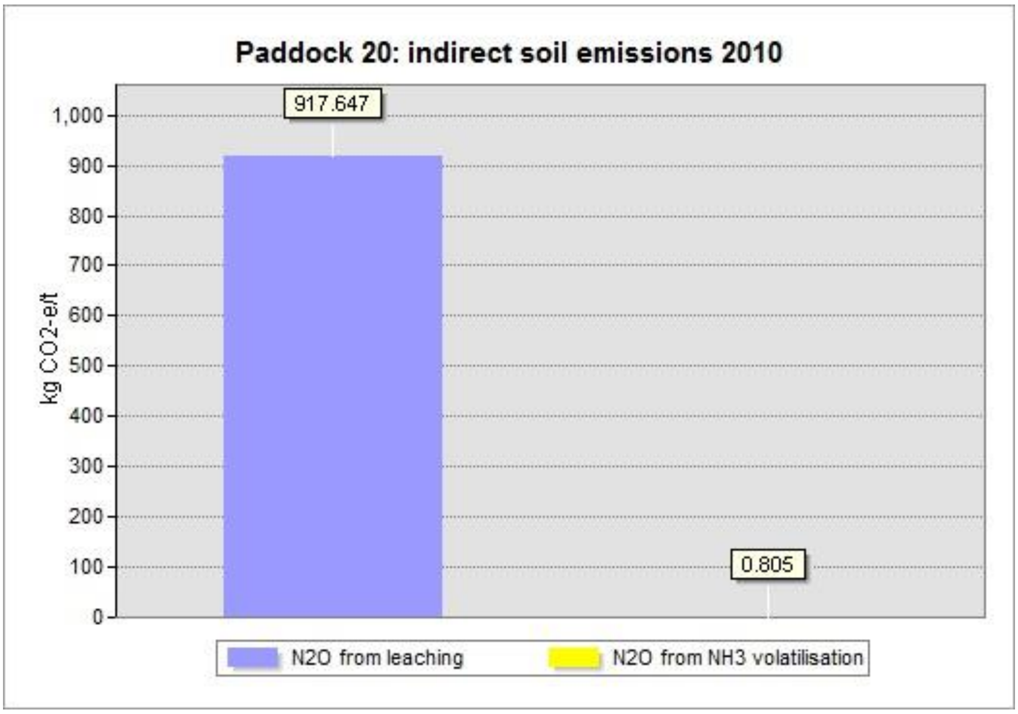


Figure 6.53. Paddock 20, indirect soil GHG emissions for 2010

6.7.3 Paddock 21

The two highest GHG emitters for paddock 21 (Figure 6.54) were the on-farm stage in 2011 followed by the pre-farm stage in 2010, generating 4.72 x 10^2 kg CO_2-e/t (33.3%) and 4.29 x 10^2 kg CO_2-e/t (30.3%), respectively. The other two stages, on-farm 2010 and pre-farm 2011, generated 2.67 x 10^2 kg CO_2-e/t (18.9%) and 2.49 x 10^2 kg CO_2-e/t (17.6%), respectively.

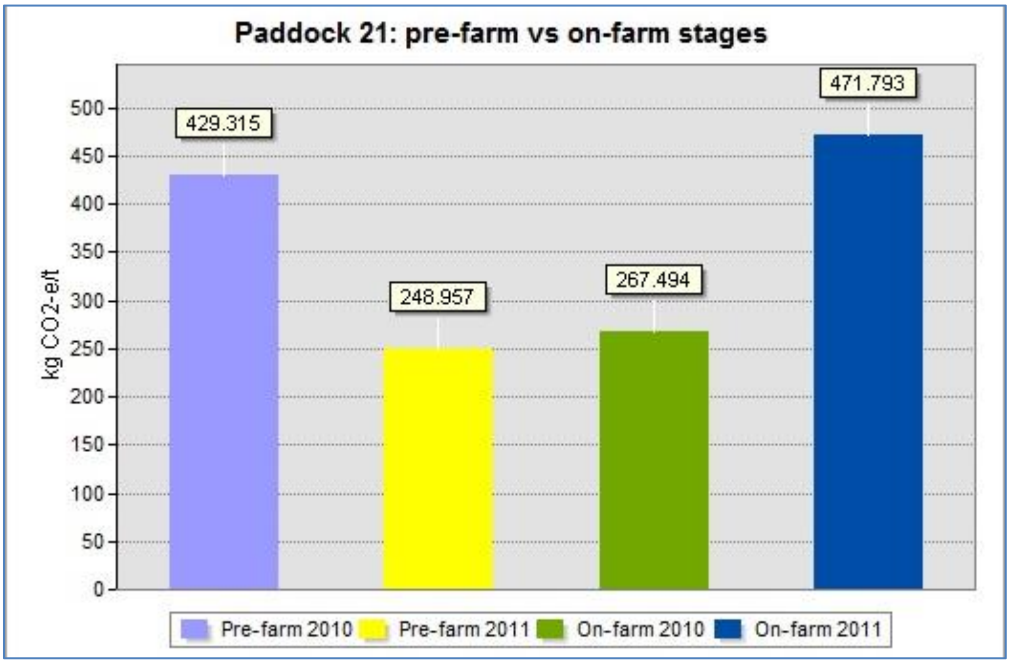


Figure 6.54. Paddock 21, pre-farm versus on-farm GHG emissions, 2010–2011

In Figure 6.55 it appears that ISE generated most of the emissions in the on-farm stage of 2011, and can thus be classified as the hotspot. The total emissions generated by the on-farm stage in 2011 were 4.72 x 10^2 kg CO_2-e/t, and the ISE made up 80.9% thereof. DSE contributed to 15.8% of the emissions and the emissions from the operation of machinery 3.2%. The percentage contribution of the GHGs from ISE to the total emissions from the paddock was 53.0%.

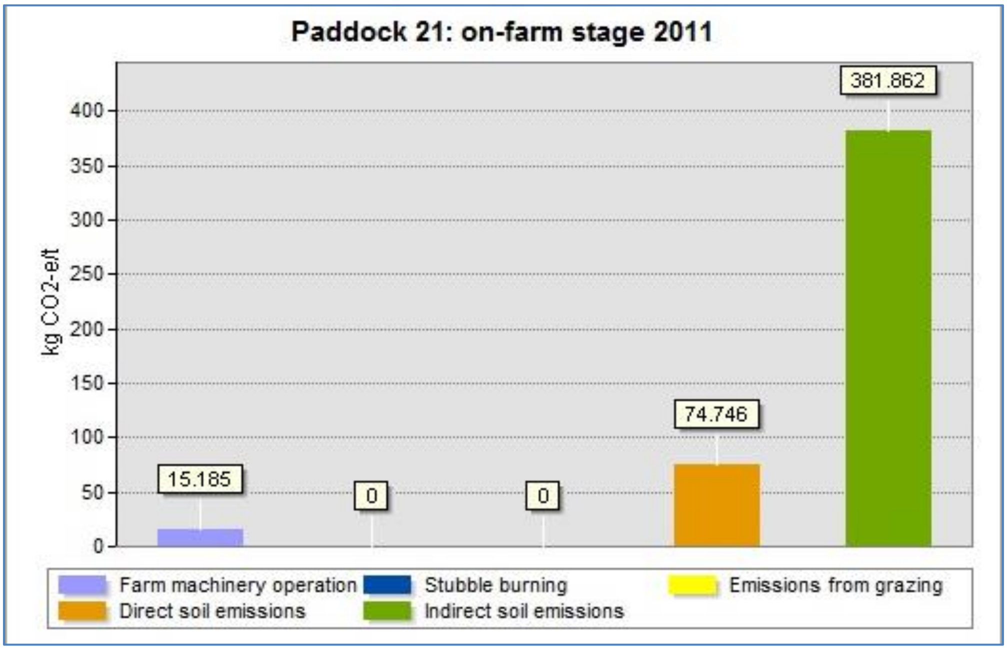


Figure 6.55. Paddock 21, on-farm GHG emissions for 2011

Consistent with all the other paddocks analysed previously, Figure 6.56 shows that the leaching of N as NO_x (converted to N_2O) in the ISE category emitted the most GHGs, totalling 99.7% of the ISE GHG emissions. Furthermore the GHG emissions from N leaching (converted to N_2O) contributed to 80.7% of the GHG emissions from the on-farm stage of 2011 and 52.8% of the GHG emissions from paddock 21 in 2011.

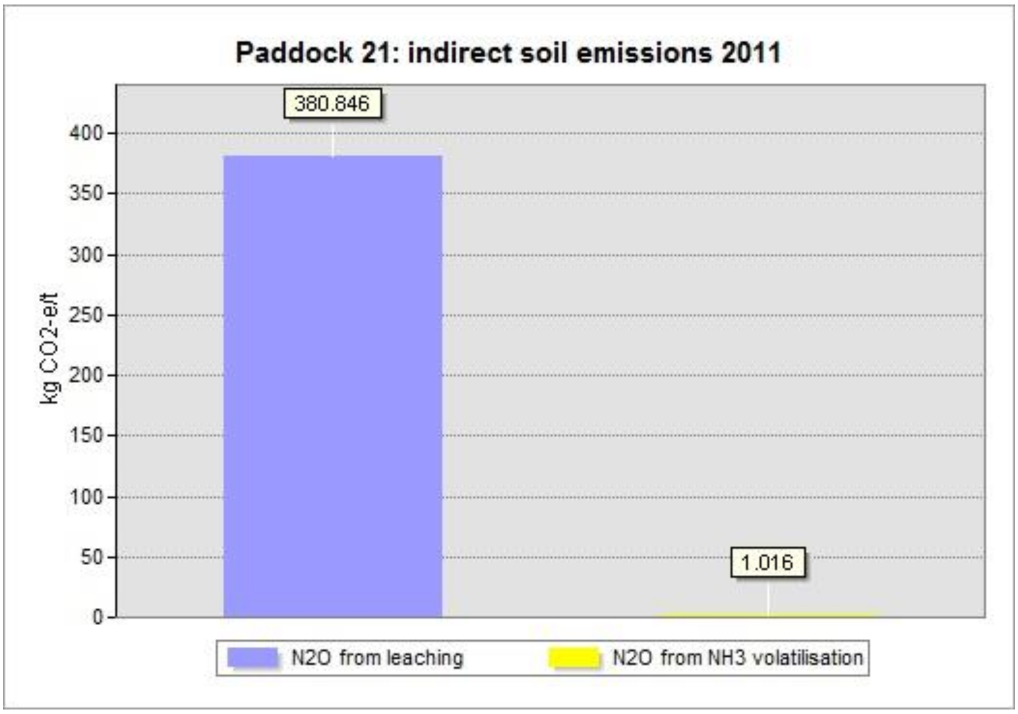


Figure 6.56. Paddock 21, indirect soil GHG emissions for 2011

6.7.3 Summary of LCA results for Farm G

The IST results for paddocks 19, 20 and 21 are presented and discussed in section 6.7. Using these visual aids (IST images), chemical production in 2010 for paddock 19, ISE in 2010 for paddock 20 and ISE in 2011 for paddock 21 were identified as hotspots. Within the chemical production input category, the production of the herbicide 'Logran' was identified as the hotspot for paddock 19 and the GHG emissions from N leaching (converted to N_2O) for paddocks 20 and 21. The overall hotspot for this farm was ISE in 2010 on paddock 29. As explained in the mitigation strategies in the following chapter, the reduction of ISE, which occurs through natural soil processes, would be a difficult task for farmers, as the only way to reduce it would be to reduce the application rate of N-fertiliser. The reduction of fertilisers on the other hand will affect productivity. In this case, the farmer would need to focus on the second highest hotspot which is chemical production.

6.8 FARM H

On Farm H, paddocks 22, 23 and 24 border each other as seen from the GIS extract (Figure 6.57). Canola was planted in paddock 22 and paddock 24 in 2012 and lupin in paddock 23. No additional data was supplied with regard to planting and establishment dates. The growth stages of the crops appear to be similar in paddocks 23 and 24 which may be related to the sandy soil profile, whereas paddock 22 is characterised by a sandy duplex (section 5.4.8), which may have more available water stored at depth for crop growth.

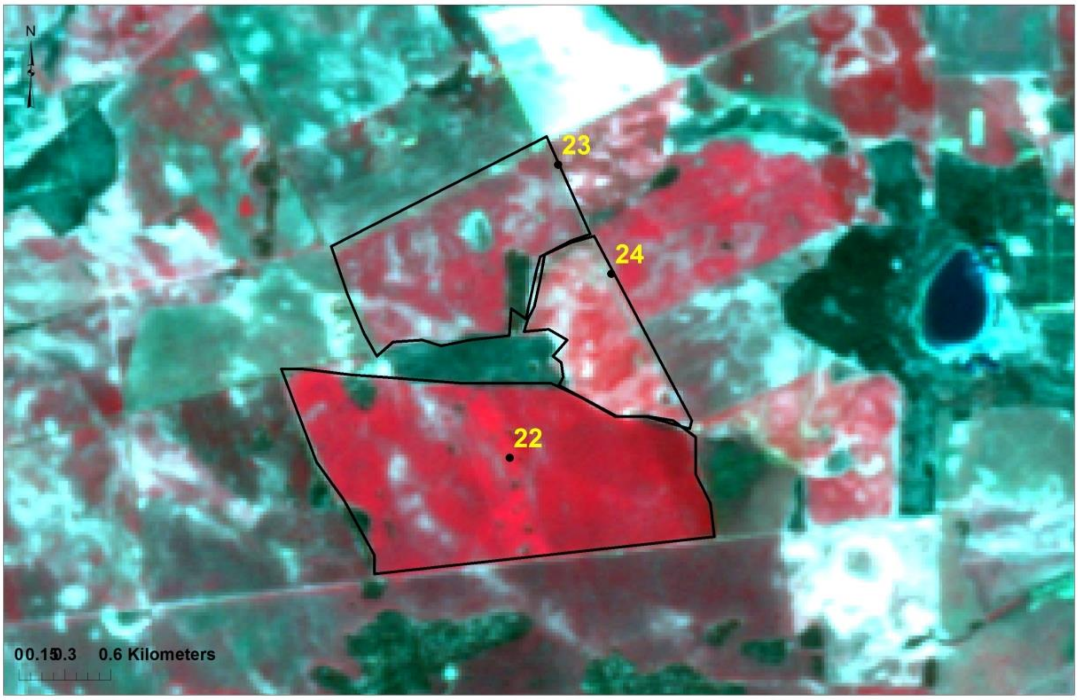
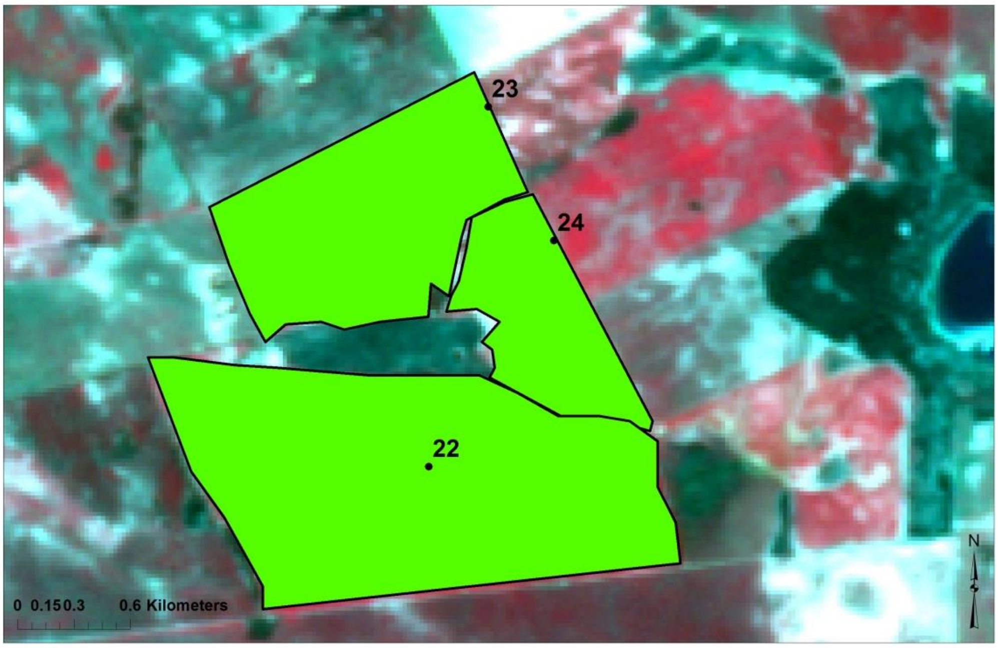
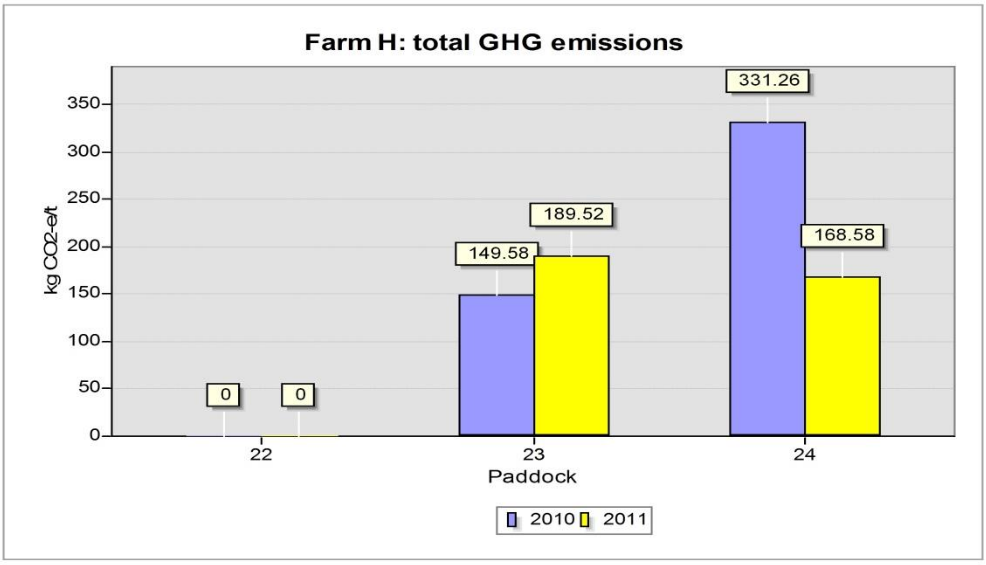


Figure 6.57. Remotely sensed image showing the paddock outlines for Farm A

The paddocks from Farm H have been shaded in green in the IST image (Figure 6.58), and these paddocks have been fully analysed and interpreted in section 5.4.8. For Farm H the most GHGs were emitted by paddock 24 (39% of the total emissions from both paddocks over both years) in 2010, followed by paddock 23 in 2011 (22% of the total emissions from both paddocks over both years).





Total GHG emissions		
	2010	2011
Paddock	kg CO_2-e/t	kg CO_2-e/t
22		
23	149.6	189.5
24	331.3	168.6

Figure 6.58. Total GHG emissions for Farm H, 2010–2011 as generated in the IST

6.8.1 Paddock 23

Figure 6.59 illustrates the GHGs emitted over the four stages of farming for paddock 23. The pre-farm stage in 2011 emitted the highest level of GHGs, totalling 1.56 x 10^2 kg CO_2-e/t. These emissions constituted 46.1% of the total 3.39 x 10^2 kg CO_2-e/t for the paddock over both years. Furthermore the on-farm stage in 2010 constituted 30.0%, the pre-farm stage in 2010 made up 14.1% and the on-farm stage in 2011 was 9.82%.

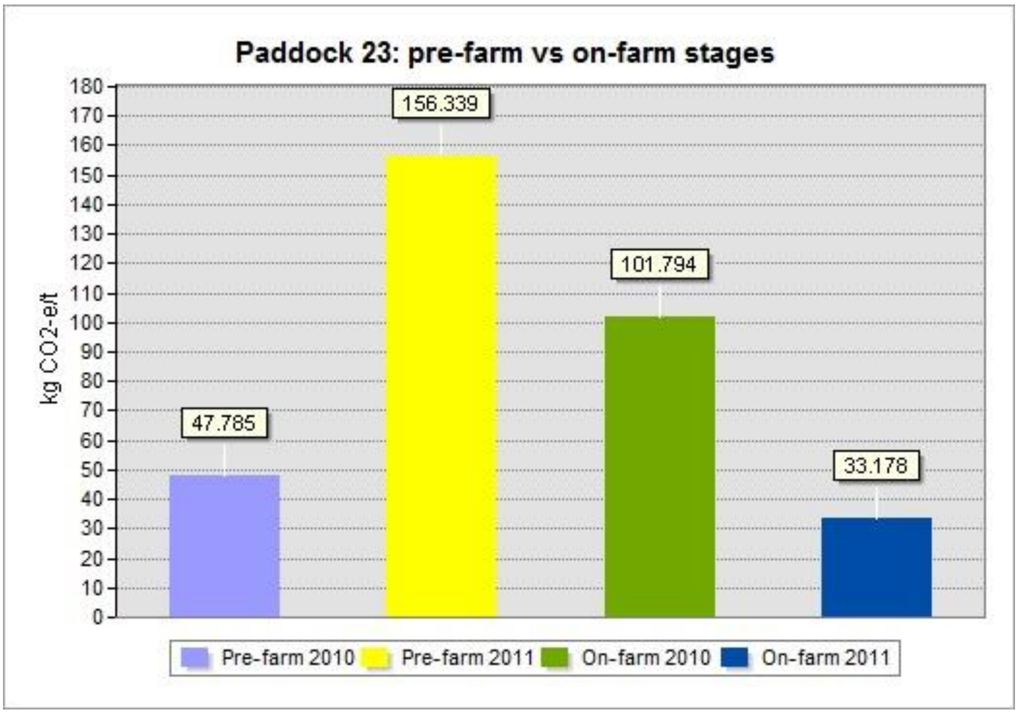


Figure 6.59. Paddock 23, pre-farm versus on-farm GHG emissions, 2010–2011

As the pre-farm stage of 2011 had the highest emissions, an additional graph was generated for this stage by expanding the categories (Figure 6.60) in the IST. The production of fertiliser in 2011 contributed a total of 1.20 x 10^2 kg CO_2-e/t (77.0%) of the GHG emissions from the pre-farm stage of 2010 and 63.5% of the paddock emissions for 2010. To further identify which fertiliser generated the most GHG emissions during production, another image focussing only on these variables could be created using GIS in the IST.

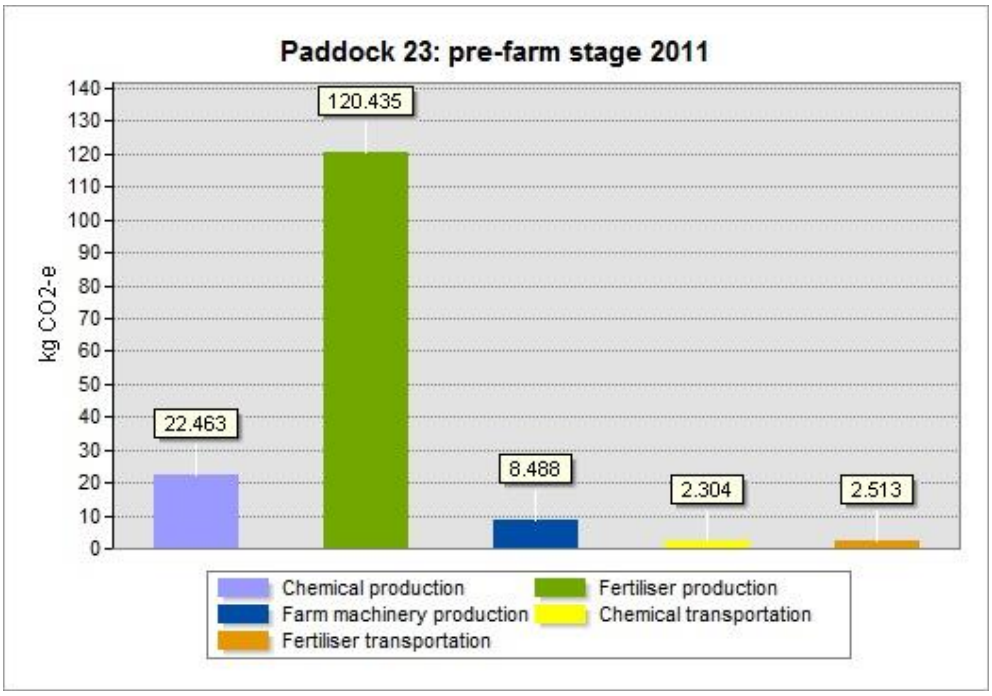


Figure 6.60. Paddock 23, pre-farm GHG emissions for 2011

6.8.2 Paddock 24

Figure 6.61 illustrates the emissions on paddock 24 for 2010 and 2011, and identifies the highest emissions from the on-farm stage in 2010. A total of 4.99 x 10^2 kg CO_2 was emitted over the research period for this paddock, of which the on-farm stage in 2010 contributed 63.4% (3.17 x 10^2 kg CO_2-e/t). The 2011 pre-farm stage contributed 27.6%, the 2011 on-farm stage 6.2% and the 2010 pre-farm stage 2.8% of GHG emissions for this paddock over both years and all stages.

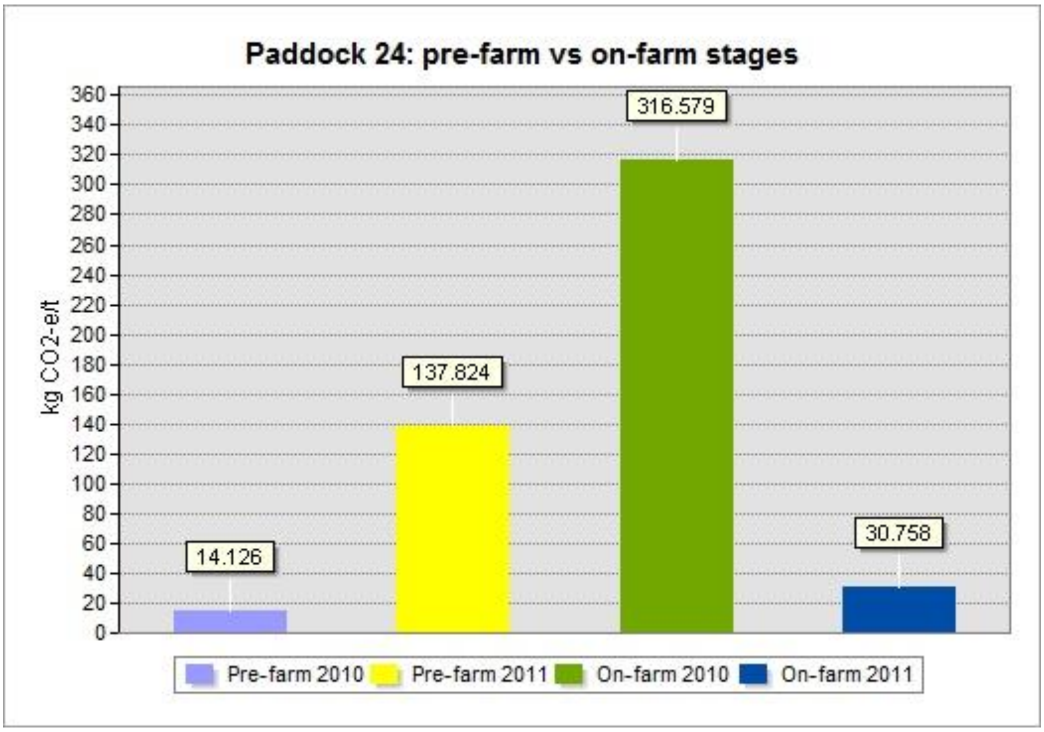


Figure 6.61. Paddock 24, pre-farm versus on-farm GHG emissions, 2010–2011

Further images expanding upon the 2010 on-farm stage illustrated the different categories to aid with identifying the hotspot in Figure 6.62. The operation of machinery in 2010 caused most of the emissions (66.3%) in the 2010 on-farm stage, and can thus be described as the hotspot. There were no emissions from grazing, stubble burning or ISE, however, DSE contributed 1.07 x 10^2 kg CO_2-e/t (33.7%) to the total of 4.99 x 10^2 kg CO_2-e/t emitted in the 2010 on-farm stage. Furthermore, the emissions from the operation of machinery contributed to 63.4% of the total GHG emissions from the paddock in 2010.

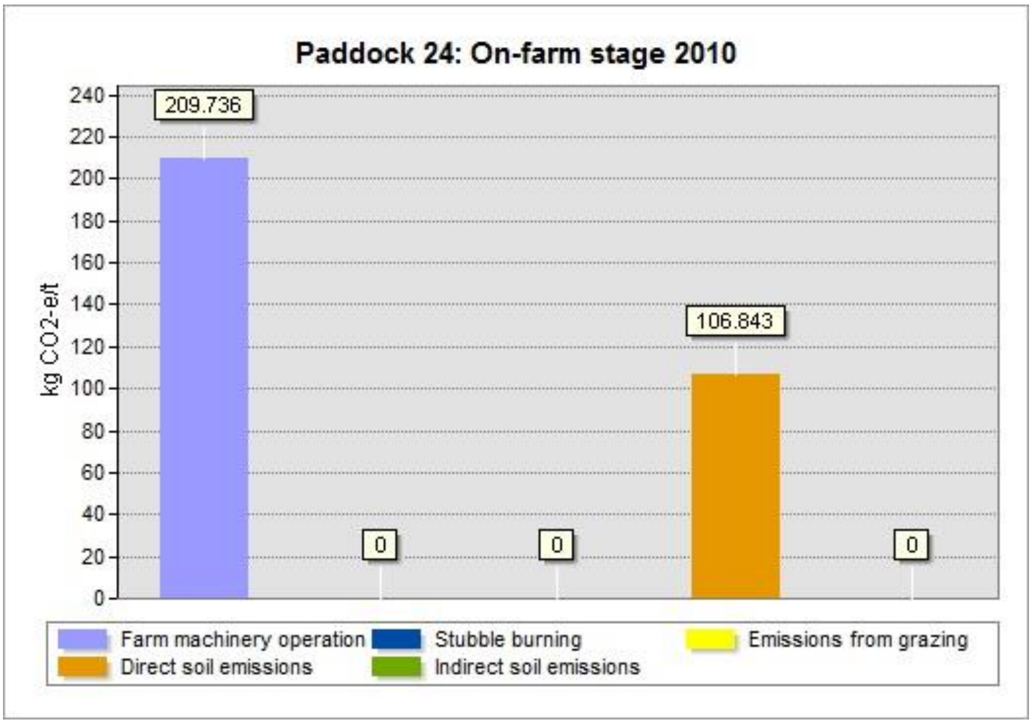


Figure 6.62. Paddock 24, on-farm GHG emissions for 2010

6.8.3 Summary of LCA results for Farm H

Paddocks 23 and 24 were the two paddocks for which IST images were generated from Farm H. These images can be seen in section 6.8 and the full discussions are in section 5.4.8. In 2011 the production of fertilisers in paddock 23 was the hotspot, emitting a total of 1.20 x 10^2 kg CO_2-e/t, and for paddock 24 it was the operation of machinery, in 2011 (2.10 x 10^2 kg CO_2-e/t). No further images were generated to ascertain which fertiliser or farm machinery was the hotspot during the production and use, respectively, thereof; however, the IST is able to generate and present these results. The overall hotspot from this farm was the operation of farm machinery in 2010.

6.9 USE OF THE INTEGRATED SPATIAL TECHNOLOGY APPROACH IN REAL WORLD APPLICATIONS

In the current analysis, the LCA data were manually inserted into the GIS to generate final outputs, for this IST approach, in the form of paddock maps and bar graphs showing GHG emissions of faming stages, inputs and outputs. Future studies will consider the development of algorithms to transfer LCA data automatically to GIS to facilitate ease of use of the IST. Furthermore it is envisaged that the IST approach may encourage the development of PC-, PDA- or smart phone-based automated tools for the user to make relevant decisions instantly, using the touch panel.

As reported by Towie (2013), the IST may have different applications in the agricultural cycle. When using the IST, factors such as the application and acquisition of chemicals (including fertilisers) could be carefully reconsidered if the tool highlights the carbon footprint thereof when captured. Options such as the replacement of N-fertilisers with alternative fertilisers, better control of application dosages, and distances the products/inputs are transported could be investigated using the IST, and if relevant, could be replaced with alternatives. The tool could investigate how the use of machinery may be reduced or better managed (possibly by less chemical applications) to reduce the emissions resulting from the production and operation of the required machinery. The emissions from livestock grazing and stubble burning could indicate how these management practices impact on GHG emissions and if reduced or eliminated how they would affect the carbon footprint of that paddock and ultimately the farm, when calculated using the IST. Furthermore the application of N-fertilisers and lime could be optimised by inputting the values into the tool in order to reduce potential GHG emissions from the soil, both directly and indirectly.

Relevant organisations, such as DAFWA in this case, could use this IST approach to maintain up-to-date records of the carbon footprints of all farms in the wheatbelt of Western Australia. Research organisations could calculate carbon footprints for various agricultural studies and applications and national organisations could integrate the IST into policy-making strategies. Finally, the IST could encourage the user to develop more informed, quicker and region-specific decision-making mitigation strategies.

6.9 CHAPTER SUMMARY

This chapter focused on using the IST images as visual aids to identify the hotspots occurring on each paddock and subsequently the hotspot from each farm as summarised in Table 6.1. In this table it can be seen that the paddock hotspots were the production of fertilisers and the ISE, and the farm hotspots were chemical production, ISE and fertiliser production. It is interesting to note that the paddocks with N leaching have ISE as the hotspot in most (six) cases, and fertiliser production in two cases, with few exceptions. For Farm A the transportation distance for fertiliser (urea) is exceptionally high (10,056 km from Iran to Kwinana) and thus it was found to be the hotspot. Heavy machinery was used on Farm H to increase the productivity through claying, and resulted in the highest emissions. Thus the integration of GIS with LCA through this IST approach would enhance the existing LCA research by enabling grain farmers to choose location specific GHG mitigation measures conveniently and efficiently (Engelbrecht et al. 2013).

Amongst the full IST images that were generated, this chapter also displayed graphs created using the IST, which can be presented as part of the IST or as individual images. It produced images which included maps, tables and graphs as well as individual graphs. It augments any existing LCA analysis in such a way that the carbon footprints for a particular paddock, soil or zone, or using a particular FMP, can be visualized together.

Table 6.1. Summary of paddock and farm hotpots

Farm	Paddock	Paddock hotspot (category)	L, SB, G	Year	Total GHGs (kg CO_2-e/t)	Farm hotspot
Farm A	Paddock 1	Fertiliser transportation	L, G	2011	2.26×10^3	No
	Paddock 2	Fertiliser transportation	L, G, SB	2010	2.35×10^2	No
	Paddock 3	Fertiliser transportation	L, G	2011	3.67×10^3	Yes
Farm B	Paddock 4	Fertiliser production		2010	2.22×10^2	No
	Paddock 5	Fertiliser production	L	2010	2.30×10^2	No
	Paddock 6	Chemical production		2011	3.50×10^3	Yes
Farm C	Paddock 7	Indirect soil emissions	L, G	2011	1.82×10^2	No
	Paddock 8	Indirect soil emissions	L	2010	2.93×10^2	Yes
	Paddock 9	Fertiliser production	G	2011	2.24×10^2	No
Farm D	Paddock 10	N/A	N/A	N/A	N/A	N/A
	Paddock 11	Indirect soil emissions	L, G, SB	2010	1.26×10^2	Yes
	Paddock 12	Indirect soil emissions	L	2011	1.75×10^2	No
Farm E	Paddock 13	Fertiliser production	G	2010	1.14×10^2	No
	Paddock 14	Indirect soil emissions	L, G	2011	1.71×10^2	No
	Paddock 15	Fertiliser production	G	2010	1.21×10^2	Yes
Farm F	Paddock 16	N/A	N/A	N/A	N/A	N/A
	Paddock 17	N/A	N/A	N/A	N/A	N/A
	Paddock 18	Fertiliser production	L	2010	3.15×10^2	Yes
Farm G	Paddock 19	Chemical production	L, SB	2010	2.29×10^2	No
	Paddock 20	Indirect soil emissions	L, SB	2010	9.18×10^2	Yes
	Paddock 21	Indirect soil emissions	L	2011	3.82×10^2	No
Farm H	Paddock 22	N/A		N/A	N/A	N/A
	Paddock 23	Fertiliser production	L	2011	1.20×10^2	No
	Paddock 24	Farm machinery operation	L	2010	2.10×10^2	Yes

Note: ‘L’= leaching, ‘G’ = grazing, ‘SB’ = stubble burning

The next chapter, Chapter 7, will introduce different CP methods for the mitigation of GHGs in the agricultural sector. Thereafter each paddock will be focused on individually to identify strategies that may be used to mitigate the emissions from the paddocks and farms as presented in Table 6.1.

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CHAPTER 7

GHG MITIGATION USING CLEANER PRODUCTION STRATEGIES

This chapter will discuss the cleaner production (CP) strategies introduced in the literature review (i.e. Chapter 2) that may be applied to 'hotspots' as identified in Chapters 5 and 6 to mitigate greenhouse gas (GHG) emissions from grain production. Thereafter these CP methods will be assimilated into the integrated spatial technology (IST), using examples, to suggest possible GHG mitigation methods. The use of IST prior to finalising the relevant farm management practice (FMP) will enable the farmer or decision-maker to determine the level of GHGs emitted on the farm. The alternatives can then be investigated by entering them into the IST to enable the results to be compared with the initial assessment so that a best practice option may be selected.

Each of the farms will be discussed individually using appropriate mitigation measures that have been identified using the results from the research. This research focused primarily on mitigating the GHG emissions from the hotspot initially identified, but will suggest methods for the input/output category contributing the second (or even third) highest emissions if the hotspot contributed to more than 20% of the paddock's total GHG emissions (Biswas, Engelbrecht, & Rosano, 2013a; Biswas, Thompson, & Islam, 2013b; Denham, Biswas, Solah, & Howieson, in press). The hotspots addressed were those identified using the methodology specified in Chapter 6.

The application of these mitigation measures is only theoretical and where any substitutions (especially chemicals and fertilisers) have been made it should be noted that these have not been proven to be the best economic alternative, the best option, or suitable for the specific agronomic practices; the options were selected on the basis that they may be suitable as mitigation options. Each farmer would need to ascertain which chemicals and fertilisers are suitable to the FMP employed as well as the soil conditions of that paddock. In addition, changes have been assumed to be linear without taking external influencing factors into consideration. Furthermore, a change in one variable could alter the total GHGs for that specific input/output category, hence the percentage contribution of each input/output category to the paddock emission would change and in so doing the hotspot would also change. Finally, no cost, financial or economic factors have been taken into consideration in relation to CP strategy implementation as they do not fall within the scope of this PhD research.

7.1 CLEANER PRODUCTION

According to van Berkel (2007), CP is best achieved by systematically reviewing a company, or in this scenario, a farm's operations, products and processes, and from there developing an applicable strategy for implementation. Each situation needs to be evaluated as a unique entity and the CP practices adjusted to fit the methods used in that situation (Engelbrecht et al., 2013; van Berkel, 2007).

The following text presents the five CP strategies using examples from reviewed literature for explanation purposes. These examples are not applicable to farming in general and not specifically to Western Australian agriculture.

7.1.1 Product modification (on-site processing)

According to van Berkel (2007), product modification takes place when the features of a product are changed in such a way as to reduce its life cycle environmental impacts. Biswas et al. (2011) expand further on this concept to state that it is the development of product types and categories that require less processing inputs and/or transport steps to the consumer. Examples used by Biswas et al. (2011) for the grain supply chain include the on-site processing of grains to enable the reduction of transportation emissions and the use of genetically engineered plants to possibly reduce the use of pesticides and increase crop yields.

7.1.2 Input substitution (use of alternatives)

Input substitution is the use of alternatives which reduce GHG emissions (Biswas et al., 2010; van Berkel, 2002; van Berkel, 2007). It is, for example, the production of alternative and renewable energy sources by delivering grain products for the generation of fuel for on-farm and transportation purposes, the use of earthworms to reduce the need for chemicals in grain production and solar energy in the place of electrical energy for irrigation (Biswas et al., 2011). Where livestock forms part of the FMP the feed should be highly digestible and of good quality in order to reduce the GHG emissions (specifically the methane (CH_4) production) originating through digestion. For pasture-fed animals this is achieved through managing the pastures with grazing rotations, which optimises the feed value. Alternatively, the breed of animal can be substituted with one that produces less emissions or the animal numbers could be reduced (Rebbeck et al., 2007). Other alternatives which have been highlighted by Reddy (2015) include the use of legume crops which increase nitrogen (N) in the soil, the use of improved crop varieties which increase pasture yield, the use of precision farming methods that focus on the placement of chemicals in the soil to increase the more efficient uptake of the chemical by the plant, the use of newer chemicals such as slow release fertilisers which release the right amount of N throughout the growing cycle and the elimination of burning practices.

7.1.3 Technology modification

Technology modification is used for the improvement of production facilities (van Berkel, 2007). These improvements can take place throughout the grain supply chain by addressing modifiable aspects such as farm machinery, the production of agro-chemicals and other inputs and the transportation of the inputs (Biswas et al., 2011). An example of technology modification includes the use of zero or minimum tillage practices which reduces emissions from machinery (Biswas et al., 2011; Khakbazan et al., 2009; Lal, 2004). Minimum or zero tillage by Australian farmers has been found to be productive and profitable and leads to a more sustainable cropping system. Inputs such as fuel, pesticides and fertilisers decrease when these tillage systems are used, thereby reducing the emission of GHGs downstream (Khan, 2008). Rebbeck et al. (2007) support these authors by stating that energy efficient equipment should be purchased and used and reduced tillage systems should be implemented.

7.1.4 Good housekeeping

Good housekeeping is the improvement of operational, maintenance and management procedures (van Berkel, 2007). By practicing good housekeeping, the overall consumption of agricultural inputs as well as the production and application of these inputs, which may cause harmful environmental emissions, can be reduced (Barton et al., 2014; Biswas et al., 2011; Dikgwatlhe, Chen, Lal, Zhang, & Chen, 2014; Khakbazan, 2009; Lal, 2004). Examples of good housekeeping mentioned by Biswas et al. (2011), Khan (2008) and Rebbeck, (2007) include the use of crop rotation plans which focus on preventing the overuse of chemical fertilisers and N-fertilisers which are responsible for the loss of N to soil and air through leaching and volatilisation, the astute use of pesticides and preventative maintenance of farm machinery, the use of maintenance registers on machinery, the judicious use of water (where applicable), staying abreast of current developments, not resisting change and the effective preventative management of chemical spillages. Another example could be the use of precision agriculture (PA), that can reduce the use of inputs by applying monitoring and mapping techniques to supply exact amounts of inputs to crops, at exactly the right time and place (Biswas et al. 2011).

7.1.5 On-site recycling and re-use

On-site recycling focuses on the recovery, recycling and re-use of nutrients, packing material, energy and water during the agricultural cycle (Biswas et al., 2011; van Berkel, 2007). Specific examples focus on the re-use of environmentally friendly packing materials and the purification and disinfection of wastewater before irrigation (Biswas et al., 2011). Khan (2008) states that bulk purchasing should be considered, and if possible the packaging should be returned to the supplier or re-used. For the reduction of storage space, flexible packaging manufactured from recycled materials could be requested and products sourced from local manufacturers and suppliers. For example, an alternative fertiliser from Kwinana, Western Australia could be used instead of urea from Asia.

7.2 FARM A

The FMPs employed on Farm A were similar for both years, with the exception of the sheep grazing in 2011 on all three paddocks, and no stubble burning in 2010 on paddocks 1 and 3 (Chapter 5). The hotspots identified in Chapter 6 for this farm are fertiliser transportation for paddocks 1 and 3 and chemical transportation for paddock 2 (Table 6.1 and Table 7.1). Input substitution and good housekeeping CP strategies were selected to mitigate the GHGs from these hotspots.

7.2.1 GHG mitigation for paddock 1

The hotspot for paddock 1 was the transportation of fertilisers in 2011, contributing 75.6% of the paddock's total emissions. However from 2010 to 2011 there was an increase in these GHG emissions (Chapter 5, Table 5.2). Table 5.3 furthermore identifies urea as the hotspot in the transportation of fertilisers input category. As urea was transported from Asia to Australia, international transportation emission factors were allocated to that portion of the transportation, and national transportation factors were applied to the ratio of transport occurring within Australia (Appendix F, Table F.8). The urea was transported for a total distance of 10,309 km, of which 97.5% (generating 3.58 x 10^3 kg CO_2-e/t) was international transportation.

To mitigate the GHG emissions from the use of urea, alternative sources of N, such as crop rotations with legumes or the replacement of urea with alternative fertilisers were considered. Organic (manure) or chemical fertilisers are both effective means of replacing N in the soil (Lal, 2004; Ryan, 2010). As organic fertilisers have low N content compared to chemical fertilisers, a very large volume of these fertilisers would need to be applied to the paddock to obtain the same equivalence of N. In the wheatbelt of Western Australia, where cropping is the main agricultural enterprise, there is limited access to livestock manure and hence any benefit would be negated by increased transportation costs and emissions from fuel combustion in trucks (Department of Environment and Primary Industries (DEPI), 2015; Lal, 2004; Ryan, 2010). The use of organic fertilisers will thus not be discussed. As the crop grown in 2010 was not a legume, sourcing N through N-fixation legumes was not considered for this paddock either.

Table 7.1. Presentation of the top hotspots and corresponding cleaner production strategies for Farm A

<table>
<tr><th rowspan="2">Paddock (year)</th><th rowspan="2">Paddock hotspots (% contribution)</th><th rowspan="2">Type of CP strategy</th><th colspan="3">Overall GHG for the top hotspots only</th><th colspan="3">Overall GHG emissions for the paddock</th></tr>
<tr><th>Existing emissions (kg CO_2-e/t)</th><th>Emissions after CP (kg CO_2-e/t)</th><th>Percentage reduction</th><th>Existing emissions kg CO_2-e/t</th><th>Emissions after CP kg CO_2-e/t</th><th>Percentage reduction</th></tr>
<tr><td rowspan="3">1 (2011)</td><td>Transportation of fertilisers (75.6%)</td><td>Input substitution</td><td>2.26×10^3</td><td>3.83×10^2</td><td>83.1%</td><td rowspan="3">2.99×10^3</td><td>1.13×10^3</td><td>62.2%</td></tr>
<tr><td>ISE* (8.8%)</td><td>-</td><td>2.62×10^2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Transportation of chemicals (4.7%)</td><td>-</td><td>1.40×10^2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">2 (2010)</td><td>Transportation of fertilisers (49.4)</td><td>Input substitution</td><td>2.35×10^2</td><td>1.29×10^2</td><td>45.1%</td><td rowspan="3">4.77×10^2</td><td>3.35×10^2</td><td>29.8%</td></tr>
<tr><td>Fertiliser production (16.1%)</td><td>-</td><td>9.64×10^1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Chemical production (8.5%)</td><td>-</td><td>8.88×10^1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">3 (2011)</td><td>Transportation of fertilisers (77.6%)</td><td>Input substitution</td><td>3.67×10^3</td><td>6.23×10^2</td><td>83.00%</td><td rowspan="3">4.61×10^3</td><td>1.74×10^3</td><td>62.3%</td></tr>
<tr><td>ISE (7.3%)</td><td>-</td><td>3.36×10^2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Transportation of chemicals (5.6%)</td><td>-</td><td>2.57×10^2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

*ISE is indirect soil emissions

A CP mitigation strategy considered for this paddock was input substitution and the effect thereof on the transportation of fertilisers. In Australia, Flexi-N (UAN), MAP and DAP are the fertilisers that are commonly used to replace urea (Elders, 2015), with N contents of 32%, 11.6% and 17.5%, respectively (Appendix E, Table E.1). In this scenario, although Flexi-N has the closest N content and is formulated in Kwinana (270 km away from Farm A) and the dosage could possibly be increased, it was not used as a theoretical replacement as the farmer had already applied it on this paddock in 2011. DAP was the fertiliser with the next closest N content and thus a calculated mass of 105 kg was used to theoretically replace urea (see Appendix H, Equations H.1−H.2 for example of calculation). The theoretical dosage (105 kg/ha) applied was calculated based on the N content of each of the chemicals and the actual dosage (40 kg/ha) of urea. The dosage was required for the calculation of the distance over which that specific amount of fertiliser or chemical would be transported from origin to application. The results showed that if urea was theoretically replaced with DAP, the GHG emissions from the transportation of fertilisers would decrease by 83.1%. The total GHG emissions would in turn be reduced by 60.5% to 1.18 x 10^3 kg CO_2-e (Table 7.1).

7.2.2 GHG Mitigation for paddock 2

Using the method described in Chapter 6 (Section 6.1) the fertiliser transportation input category of 2010 was found to be the overall hotspot for this paddock from 2010 to 2011 contributing to 29.2% of the overall GHG emissions. Furthermore this input category contributed to 49.4% of the paddock's emissions in 2010. The recommended CP method for mitigation purposes focused on the transportation of fertilisers is input substitution (Table 7.1).

The only fertiliser used on this paddock in 2010 was DAP Extra (17.5% N), which emitted 16% of the total paddock emissions in 2010 and was formulated in Kwinana, Western Australia.

Fertilisers used as an alternative to DAP as a source of N in Western Australia include urea (46% N), Flexi-N (32% N) and MAP (11% N) (Appendix E, Table E.1). For mitigation purposes MAP was chosen to theoretically replace DAP, as the percentage N in MAP (11% N) is closer to that of DAP (17.5%) than the other fertilisers (Appendix E, Table E.1). On substituting the calculated theoretical dosage of 66.6 kg/ha MAP on the basis of N content, in the place of 45 kg DAP, an increase in GHG emissions in both fertiliser transportation (32.5%) and paddock GHG emissions (32.1%) was observed. The use of IST thus demonstrates that substituting DAP with MAP is not a viable option.

Flexi-N (32% N) was used as an additional alternative (also formulated in Kwinana, Western Australia), with a theoretical application rate of 22.89 kg/ha. As DAP has a high phosphorus (P) content and Flexi-N contains no P the soil test results from DAFWA (Appendix H, Table H.1) were consulted to ascertain whether there was a P deficiency in the soil. As the phosphorus (P) levels in the soil were 33 mg P/kg soil in the 0–10 mm soil horizon (using Colwell testing), and were considered marginal (Blaesing, 2006), no additional source of P was considered (Appendix H, Table H.1). The GHG emissions from this substitution showed an overall reduction in the paddock GHGs by 29.8%, and the fertiliser transportation input category by 45.1% (Table 7.7) as the load of fertiliser was almost halved. These two options demonstrate that the IST can be used by the decision-maker to select the best option to mitigate GHGs which in this scenario was the replacement of DAP with Flexi-N.

7.2.3 GHG mitigation for paddock 3

In 2011 the hotspot for paddock 3 was identified as the transportation of fertilisers, and more specifically the transportation of urea. This paddock was similar to paddock 1 and thus the same reasoning from section 7.2.1 was applied. The transportation of fertilisers contributed 79.6% of the paddock emissions for 2011 (Table 7.1).

After theoretically substituting 50 kg urea with 131 kg DAP the overall GHG emissions from the paddock were reduced by 62.3% and the emissions from the transportation of fertilisers were reduced by 83.0% (Table 7.1).

7.2.4 Summary of mitigation measures for Farm A

In the preceding section the focus was on theoretically mitigating the GHG emissions from the transportation of fertilisers. The CP strategy employed was input substitution which resulted in a reduction in the GHGs from the paddocks by 62.2%, 29.8% and 62.3%, respectively. As the fertiliser actually applied and the fertiliser theoretically applied on paddock 2 were both freighted from Kwinana, Western Australia, it can be seen that distance is not the only factor that determines the GHG emissions from transportation. In this scenario the adjustment of the application rate almost halved the fertiliser requirement which in turn reduced the GHG emissions. The alternative input for both paddocks 1 and 3, however, altered the GHG emissions due to the distance changing for the urea replacement. It can thus be concluded that by using input substitution strategies, the GHG emissions from transportation of fertilisers could be reduced by more than 25% on all three paddocks.

7.3 FARM B

The FMP for the three paddocks on Farm B were the same for both years, however the type of grains sown differed (Table 5.9). In 2010 wheat was planted in three paddocks, while in 2011, barley, lupin and wheat were planted in paddocks 4, 5 and 6, respectively (Table 5.9). No livestock were grazed on the stubble and no stubble burning took place. The planting of different grains requires different FMPs which the farmer applied and have essentially been considered in this research. The hotspots were the production of fertiliser for paddocks 4 and 5 and chemical production for paddock 6 (Table 7.2). Following is a short discussion of mitigation measures through appropriate CP strategies that the farmer could apply to each of these paddocks (Table 7.2).

7.3.1 GHG mitigation for paddock 4

On analysing the results obtained from the IST it was noticed that the hotspot was the production of fertilisers in 2010, contributing to 56.2% of the paddock emissions for 2010 (Table 5.10, Figure 6.13). Furthermore, the production of fertilisers input category contributed to 75.2% of the pre-farm emissions in 2010 and to 50.2% of the total emissions in both stages from 2010 to 2011. The two fertilisers used in this paddock in 2010 were K-Till Extra (10% N) and urea (46% N), emitting 1.69 x 10^2

kg CO_2-e/t and 5.31 x 10^2 kg CO_2-e/t, respectively (Table 7.2) (Appendix E, Table E.1 and Appendix G, Table G.8). The soil type on this paddock, yellow Chromosol, is characterised by deficiencies in N and P (Moore, 2001).

The CP methods considered for mitigation purposes on this paddock were input substitution and good housekeeping, focusing on reducing GHG emissions from fertiliser production and DSE.

7.3.1.1 Input substitution for GHG mitigation from DSE

By theoretically replacing K-Till Extra (9% N, 11% P) with a fertiliser with similar N content, such as MaxAmRite (12.8% N, 17.7% P) (Appendix E, Table E.1), a reduction in GHG emissions was apparent. This is an input substitution strategy. The theoretical dosage for MaxAmRite was calculated at 70.3 kg/ha/year, using the percentage N content and the actual dosage of K-Till Extra (90 kg/ha/year) to maintain nutrient balance in N deficient soil (Appendix H, Equation H.1−H.2). As K-Till Extra has a potassium (K) content of 11.2% and MaxAmRite contains no K, the soil test results in Appendix H (Table H.1) were consulted. The test results showed a K content of 104 mg K/kg soil, and thus K was not a requirement in this growing season. For cereal crops soil K levels should not fall below 45-50 mg K/kg soil (Department of Agriculture, 2015) and for legumes 50−80 mg K/kg soil, (Quinlan & Wherrett, 2015). MaxAmRite produced 1.09 x 10^2 kg CO_2-e/t compared to the 1.69 x 10^2 kg CO_2-e/t from K-Till Extra using these dosages. The input category production of fertilisers was reduced by 29.7% which in turn reduced the overall GHG emissions of the paddock by 17.2% (Table 7.2).

After production of fertiliser, DSE was the next highest GHG output category in 2010. DSE contributed to 21.1% of the paddock emissions in 2010 and no reduction in GHG emissions was observed through input substitution. This is due to the N-fertiliser addition remaining constant as the calculation was based on the dosage and percentage N content (Table 7.2). DSE reduction using low dosages of N fertilizer is therefore not practicable in a N deficient soil.

Table 7.2. Presentation of the top hotspots and corresponding cleaner production strategies for Farm B

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
4 (2010)	Fertiliser production (56.2%)	Input substitution	2.22×10^2	1.56×10^2	29.7%	3.95×10^2	3.27×10^2	17.2%
	DSE* (21.1%)	Good housekeeping	8.33×10^1	4.18×10^1	49.8%		3.11×10^2	21.5%
	Chemical production (12.1%)	-	4.80×10^1	-	-		-	-
5 (2010)	Fertiliser production (60.7%)	Input substitution	2.30×10^2	1.59×10^2	30.9	3.79×10^2	3.05×10^2	19.5%
	DSE (21%)	Good housekeeping	7.95×10^1	5.48×10^1	31.1%		3.28×10^2	13.5%
	Chemical production (7.8%)	-	2.95×10^1	-	-		-	-
6 (2011)	Chemical production (96.3%)	Input substitution	3.50×10^3	1.15×10^1	99.7%	3.63×10^3	1.44×10^2	96.0%
		Good housekeeping		2.51×10^3	28.3%		2.64×10^3	27.0%
	Fertiliser production (2.0%)	-	7.31×10^1	-	-		-	-
	DSE (1.0%)	-	3.75×10^1	-	-		-	-

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

*DSE is direct soil emissions

7.3.1.2 Good housekeeping for GHG mitigation from DSE

The most effective way to reduce DSE would be the removal of lime applications as a good housekeeping strategy. However, in Western Australia the soils are characteristically acidic which increases the toxicity of aluminium to the plants and reduces the grain yield (Gazey & Ryan, 2015), thus the removal of lime could not be considered a CP strategy for this paddock. As the application of urea also contributes to DSE the next option was the reduction of the application rate of urea. Urea could be replaced with other fertilisers as specified in section 7.2.1.1 as an input substitution strategy (Barton et al., 2014; Khakbazan et al., 2009). To apply this strategy and investigate the effect thereof on DSE it was assumed that in the previous growing season legumes (2009) had been grown in this paddock, thus increasing the residual N. On average it has been found that legumes fix about 100 kg N/ha, thereby reducing the N-fertiliser application requirement by 40–80 kg N/ha (GRDC, 2014c). The farmer had applied 130 kg/ha/yr urea (59.8 kg N) in two applications; 90 kg/ha/yr urea (41.4 kg N) was applied with the seed (in the soil) and 40 kg/ha/yr urea (18.4 kg N) (data received from DAFWA) later in the season (top-dressed). Based on the aforementioned assumption the 90 kg/ha/yr was discounted (fertiliser input was reduced by 69.2%) as N was already in the soil. The DSE was thus reduced by 21.3% in the paddock and the DSE output category reduced by 49.8% (Table 7.2).

It must be noted that residual N from a previous growing season also contributes to the overall GHG emissions (Barton et al., 2014; Wang & Dalal, 2015). This N allocation however has not been factored into the calculation of GHGs from this theoretical application as no lupin yield from the previous season (as it was an assumption) was available to calculate the N-allocation. In calculating the residual N allocation, for incorporating GHG emissions from N-production originating from lupin in the previous year, the variables required are the amount of N-fertiliser saved, the amount of N in the above-ground lupin biomass and the amount of N in the below-ground lupin-biomass based on the formula (Equation 7.1) from Barton et al. (2014).

$$Allocation\ factor = \frac{Nfert_{saved}}{Lupin\ N_{AG} + Lupin\ N_{BG}}$$ **Equation 7.1**

Where 'Nfert$_{saved}$' is the amount of fertiliser saved (kg N/ha), 'Lupin N$_{AG}$' is the amount of N in the above ground biomass of the lupin (shoots) (kg N/ha) and 'Lupin N$_{BG}$' is the amount of N in the below ground biomass of the lupin (roots) (kg N/ha). The numerical values of these variables were adapted from the Barton et al. (2014) study as this was carried out in south-western Australia.

7.3.2 GHG mitigation for paddock 5

Similar to paddock 4, the two input/output categories emitting more than 20% of the paddock's GHGs were fertiliser production and DSE. The CP strategies considered for the mitigation of these GHGs were input substitution for fertiliser production and good housekeeping for DSE. The soil type on this paddock, Orthic Tenosol, is characteristically deficient in N and P (Moore, 2001).

7.3.2.1 Input substitution for GHG mitigation from fertiliser production

The input category fertiliser production in 2010 was the hotspot for paddock 5 over the research period, contributing to 81.2% of the pre-farm emissions and 60.7% of the paddock GHG emissions. The emissions totalled 2.30 x 10^2 kg CO_2-e/t, of which the fertiliser K-Till Extra (9% N, 11% P) (Appendix E, Table E.1) contributed 64.4% and the fertiliser urea 14.0% of the fertiliser production input category. As with paddock 4 (section 7.4.2), MaxAmrite (12% N, 17.7% P) was selected to be the theoretical fertiliser replacement. When K-Till Extra (90 kg/ha/year) was replaced with MaxAmrite (70.3 kg/ha/year) (Appendix H, Equation H.1−H.2), the following reductions in GHG emissions were noticed: the GHG emissions from the input category fertiliser production were reduced to 30.9% (Table 7.2), the input category fertiliser transportation was reduced by 17.2%, the pre-farm stage reduced by 25.8% and the paddock emissions were reduced by 19.5% (Tables 5.10 and 5.11, Table 7.2). The fertiliser transportation emissions have been stated here as they changed when the amount of fertiliser substituted and thus influenced all other emissions downstream.

7.3.2.2 Good housekeeping for DSE mitigation

The good housekeeping strategy referred to in section 7.3.1.2, adjusting the application rate of urea, was theoretically applied to this paddock. This adjustment can be performed by PA practices as elaborated on in 7.1.4. Using the same consideration as section 7.3.1.2, the first application of 50 kg/ha/yr (fertiliser input was reduced by 45.5%) of urea was discounted, meaning that only 60 kg/ha/yr was applied as a theoretical good housekeeping strategy. The paddock GHG emissions were then theoretically reduced by 13.5% and the DSE output category by 68.9% when the fertiliser application rate was reduced by 45.5% (Table 7.2).

7.3.3 GHG mitigation for paddock 6

The hotspot for paddock 6 over both years was the production of chemicals in 2011. The total GHG emissions in this input category were calculated to be 3.50 x 10^3 kg CO_2-e/t (Table 5.10). The total GHG emissions for this paddock in 2011 were 3.63 x 10^3 kg CO_2-e/t (Table 5.10). Closer inspection shows that within the input category chemical use the production of herbicides was the hotspot, emitting 96.4% of the total paddock emissions (Tables 5.10 and 5.11). Two CP strategies were investigated for mitigation of GHG emissions, namely input substitution and good housekeeping.

7.3.3.1 Input substitution for GHG mitigation from chemical production

As Logran was identified as the herbicide emitting the most GHGs (3.491 x 10^3 kg CO_2-e/t), the same procedure was followed as documented in section 7.3.2. On substituting Logran (15 g/ha/year) with the recommended average dose of Avadex (1.8 l/ha/year) the GHG emissions from the input category production of chemicals decreased to 4.26 x 10^2 kg CO_2-e/t. Consequently, the category transportation of chemicals was reduced by 43.1% and overall GHG emissions were reduced by 95.9% (Table 7.2).

7.3.3.2 Good housekeeping for chemical production GHG mitigation

The actual dosage of Logran to this paddock was 15.0 g/ha. The recommended dosage, according to the Australian Pesticides and Veterinary Medicines Authority (APVMA), of this herbicide is 6.5–15.0 g/ha (APVMA, 2014). A good housekeeping strategy focuses on optimising the dosage of a specific chemical. To investigate the effect of reducing the actual dosage, a theoretical dosage midway between the minimum and maximum dosage was selected (10.75 g/ha). Assuming that the management of the targeted weeds did not require a larger dosage, the theoretical dosage could reduce the paddock GHG emissions by 27.0% (Table 7.2).

7.3.4 Summary of mitigation measures for Farm B

The hotspots for the paddocks on this farm were fertiliser production (paddocks 4 and 5) and chemical production (paddock 6). In selecting mitigation strategies for these paddocks input substitution CP strategies were considered. For paddocks 4 and 5 reductions of 17.2% and 19.5% respectively were realised and for paddock 6 a reduction of 96.0%. Good housekeeping was also considered for paddock 6 wherein a reduction of 27.0% occurred. The GHGs from these paddocks were altered due to the selection and theoretical application of chemicals and fertilisers from national and more local sources (Table 7.2).

The next highest GHG emitter for paddock 4 and paddock 5 was DSE, for which good housekeeping was selected. By assuming a legume rotation in the year prior to growing wheat, thus allowing for a reduction in the application of urea (70% in paddock 4 and 45% in paddock 5), GHGs were reduced by 21.5% and 13.5%, respectively.

For this farm the CP strategy which reduced the GHG emissions the most per paddock, was input substitution (Table 7.2).

7.4 FARM C

The FMPs for Farm C are summarised in Table 5.14. This table shows that the farmer planted wheat in all three paddocks in 2010, and oats, wheat and lupin in paddocks 7, 8 and 9 respectively in 2011. The practice of stubble burning was not employed on these paddocks and there was no grazing on paddocks 8 and 9 in 2010. The three highest categories identified for the application of mitigation using CP methods were ISE (2010) on paddock 7 and paddock 8, and the production of fertilisers (2011) for paddock 9.

The ISE are dependent on the interaction of variables that can be manipulated with those that cannot be manipulated. The variables that can be manipulated include the type, the placement (place and method) in the soil, the application time and the application rate of the fertilisers (Gregorich, Janzen, Helgason, & Ellert, 2015; Snyder, Bruulsema, Jensen, & Fixen, 2009) and the effect of N availability to the crop (Barton et al., 2013; Gregorich et al., 2015; Snyder et al., 2009) . In contrast, those that cannot be manipulated include climatic conditions such as rainfall and temperature, soil type, soil organic carbon content, soil drainage, micro-organism population densities in the soil and the N-supplying (residual N) capacity of the soil (Gregorich et al., 2015; Snyder et al., 2009).

For the purpose of identifying mitigation strategies it was decided to focus on reducing the application rate of the fertiliser as this is a good housekeeping strategy and the simplest for demonstrating the workability of the IST. Altering the type of fertiliser is an input substitution strategy which is related to the GHG emissions from fertiliser production, and is discussed where relevant. The time and the placement of the fertiliser are dependent on the soil and climatic conditions, thus cannot be manipulated using the IST.

However, on reviewing the literature no conclusion could be reached as to how the yield would be influenced when N application was reduced, considering that non-manipulative factors influence application rates to a large extent (Gregorich et al., 2015; Khakbazan et al., 2009; Lehuger, Gabrielle, Laville, Lamboni, Loubet, & Cellier, 2011; Snyder et al., 2009). Yield reductions were reported in the literature with the decreased application of N-fertilisers (Barton et al., 2013; De Gryze, Lee, Ogle, Paustian, & Six, 2011; Kim, Seo, Kraus, Klatt, Haas, Tenhunen, & Kiese, 2015; Liu et al., 2015; Wang & Dalal, 2015), and other literature showed that no significant changes in crop yield could be expected if N-fertiliser application was reduced (Khakbazan et al., 2009; Lehuger et al., 2011). Residual N in the soil from previous cropping seasons combined with current N applications are required at optimal levels so as not to experience lower crop yields (Malhi, Nyborg, Solberg, Dyck & Puurveen, 2011; Shah, Shah, Peoples, Schwenke, & Herridge, 2003; Yang, Zhao, Huang, & Lv, 2015). Snyder et al. (2009) states that reducing N-fertiliser rates is not an appropriate management option for the reduction of ISE as it could decrease the productivity of the soil. Furthermore the enhancement of soil productivity optimises crop production and is affected by FMP (Snyder et al., 2009), thus attention should be given to reducing ISE by focusing not only on the variables that can be manipulated but also on those that cannot be manipulated, and thus mitigation of ISE was excluded.

Table 7.3 presents the hotspots for each paddock and selected CP strategies used for mitigation.

7.4.1 GHG mitigation for paddock 7

In 2011 the ISE from paddock 7 presented as the hotspot for 2010 and 2011. However, based on the argument presented in section 7.1, no mitigation strategies for ISE were included in this chapter as by incorporating ISE mitigation N applications are reduced which will in turn affect the soil productivity (denominator) and increase GHG emissions and loss of profit.

The next highest GHG contributor on this paddock was the fertiliser production input category and the application of input substitution methods were considered to mitigate the GHGs from this input category.

Even though paddocks may have the same Et/P and fertiliser as a hotspot the mitigation potential of substituting for an alternate fertiliser will differ due to actual dosages and N content (Gregorich et al., 2015). As the substitution of one fertiliser for another has been demonstrated to be a workable mitigation method in other paddocks (for example paddocks 3, 4 and 5) the substitution of the fertiliser generating the most GHGs for an alternative is investigated here.

Table 7.3. Presentation of the top hotspots and corresponding cleaner production strategies for Farm C

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
7 (2011)	ISE (38%)	Discussed in section 7.4	1.82×10^2	Discussed in Section 7.4	Discussed in Section 7.4	3.98×10^2	Discussed in Section 7.4	Discussed in Section 7.4
	Fertiliser production (23%)	Discussed in section 7.4	9.65×10^1					
		Input substitution	9.65×10^1	6.58×10^1	31.8%		3.67×10^2	7.8%
	Fertiliser transportation (11%)	-	4.38	-	-			
8 (2010)	ISE (40.4%)	Discussed in section 7.4	2.93×10^2	Discussed in Section 7.4	Discussed in Section 7.4	7.25×10^2	Discussed in Section 7.4	Discussed in Section 7.4
	Fertiliser production (25.2%)	Input substitution	1.83×10^2	1.61×10^2	12.0%		6.50×10^2	10.3%
	Transportation of fertilisers (12.0%)	-	-	-	-		-	-
9 (2011)	Fertiliser production (40.0%)	Input substitution	2.24×10^2	2.14×10^2	4.46%	5.60×10^2	5.50×10^2	1.8%
	Chemical production (23.4%)	Good housekeeping	1.31×10^2	8.86×10^1	32.4%		5.17×10^2	7.7%
	DSE 15.4%)	-	-	-	-		-	-

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

During 2011 the fertiliser generating the most GHGs was MaxAmRite (17.2% of the total GHGs from paddock 7). The fertiliser AgYield Extra was selected as a theoretical replacement as the soil type (red Kandosol) is typically deficient in N and P and in addition to supplying N and P, AgYield Extra (17.2% N, 17.8% P, 3.8% S) (Appendix E, Table E.1) has similar concentrations of N and P to MaxAmRite (12.8% N, 17.7% P, 7.4% S). After theoretically replacing the actual dosage of 50 kg/ha/year of MaxAmRite with 37.2 kg/ha/year (Appendix H, Equation H.1−H.2) of AgYield Extra, the total GHGs from the paddock were reduced by 7.8%. The theoretical dosage was calculated based on the % N in each of the fertilisers and the actual dosage of the original fertiliser (Table 7.3). In south-western Australia, to maintain the level of S in the soil a dosage rate of 1–10 kg S/ha is advised (Croppro.com, 2015). As the S content in Agyield Extra is 3.8 % and the theoretical application rate of 37.2 kg applies 1.4 kg S/ha from Agyield Extra, content was assumed not to be compromised, given that the soil S levels were adequate.

7.4.2 GHG mitigation for paddock 8

The overall hotspot for this paddock was ISE, however based on the discussion in section 7.1, no mitigation strategies were considered for this output category. The next highest GHG emitting category was the production of fertilisers category and CP strategies were investigated to mitigate GHG emissions from this input category.

The fertiliser generating the most GHGs in 2010 was MAP SZC (11.6% N, 20% P, 5.5% S) (9.78×10^1 kg CO_2-e) (Appendix E, Table E.1). As MaxamRite had a similar N, P and S content it was used to theoretically replace MAP SZC. By substituting the actual application rate of 25 kg/ha/yr (2.9 kg N/ha/yr) of MAP SZC with 22.6 kg/ha/yr (2.9 kg N/ha/yr) (Appendix H. Equation H.1−H.2) of MaxamRite, the paddock GHG emissions were reduced by 10.3% and fertiliser production GHG emissions were reduced by 12.0% (Table 7.3).

7.4.3 GHG mitigation for paddock 9

Fertiliser production contributed to 40% of the total GHG emissions on paddock 9 in 2011. Muriate of potash (MOP) and 'NPS range-Cereal' were the fertilisers used. The fertiliser MOP (potassium chloride) has no N content (50% K and 46% chloride) and is commonly used when the K content of the soil is low (Agrow Australia, 2015) (Appendix E, Table E.1). For cereal crops soil K levels should not fall below 50 mg K/kg soil and for legumes 50−80 mg K/kg soil, (Quinlan & Wherrett, 2015). The K level for this paddock using the Colwell test was 23 mg K/ kg soil, in the 20–40 mm soil horizon, and no results were available for the 0-10 mm horizon (Appendix H, Table H.1). By contrast, the fertiliser known as NPS range-Cereal is a nitrogenous fertiliser (N-fertiliser) with an N content of 12.5% (and no K), and was considered the hotspot in this paddock (Table 7.3), and thus mitigation measures focused on NPS range-Cereal.

7.4.3.1 Input substitution for fertiliser production GHG mitigation

By replacing 55 kg/ha/year of NPS range-Cereal fertiliser (N = 12.5%) with 53.7 kg/ha/year MaxAmRite (N = 12.8%) (Appendix H, Equation H.1−H.2), on the basis of theoretical dosages at similar N contents (Appendix E, Table E.1), a reduction of 1.0×10^{-1} kg CO_2-e/t was realised for the paddock in 2011. Theoretically the GHG emissions from the input category fertiliser production were reduced by 4.7% to 2.03×10^{2} from 2.13×10^{2} kg CO_2-e/t, and the paddock GHG emissions by 1.8% (Table 7.3).

7.4.3.2 Good housekeeping for chemical production GHG mitigation

In addition to the production of fertilisers the production of chemicals contributed 23.4% of the overall paddock GHG emissions in 2011. Within the chemical production input category the production of herbicides was identified as the biggest GHG contributor, and the herbicide 'Verdict 120' was of the greatest concern, contributing to 15.3% of the paddock emissions. The mitigation measures for the production of chemicals are the same as those for fertilisers and include input substitution, technology modification and good housekeeping methods as discussed in section 7.3.3. On investigating the dosages it was found that the farmer applied 0.4 ml/ha in 2011 and the recommended dosage of Verdict 120 for Lupins was 0.15–0.20 ml/ha. Thus an additional mitigation measure, by incorporating a good housekeeping strategy, was investigated for this paddock in 2011. By reducing the dosage to 0.2 ml/ha (good housekeeping) the paddock GHG emissions were reduced by 7.7% (Table 7.2).

7.4.4 Summary of mitigation measures for Farm C

This section summarises the mitigation measures for Farm C. The hotspots for paddocks 5, 6 and 7 were ISE, chemical production and fertiliser production respectively. The second highest GHG emitter was fertiliser production, followed by ISE and chemical production respectively. Input substitution and good housekeeping CP strategies were investigated to ascertain whether GHGs could be mitigated. The total GHG reduction per paddock ranged from 1.8% to 45.6% (Table 7.3).

Based on the mitigation results obtained for the three paddocks on Farm C no conclusive recommendations could be made as to the best mitigation practice for this farm. The results showed one or more CP strategies could be applied and thus the farmer would need to make informed choices by considering which impact category would reduce the GHGs on the farm the best. For paddock 7, input substitution of fertilisers showed an immediate potential reduction of 7.8%, however methods for the mitigation of ISE were not investigated thus no conclusive recommendations could be identified on the mitigation of ISE. The theoretical application of input substitution in the chemical production input category on paddock 8 allowed for a reduction of GHGs by 45.6%. This paddock also required the identification of strategies to mitigate ISE. On paddock 9 when good housekeeping strategies were applied to the chemical production input category, the GHGs were reduced by 7.8% compared to the 1.8% reduction due to input substitution in the fertiliser production input category.

It could be recommended, however, that the farmer focus on fertiliser use on all three paddocks, as the use and transportation of fertilisers was identified as a common element which could mitigate GHGs if altered.

7.5 FARM D

The FMPs for Farm D are tabulated in Table 5.21 and include full paddock stubble burn on paddock 11 in 2010 and windrow stubble burning on paddock 12 in 2010. Sheep were grazed on both paddocks in 2010 but not in 2011. Wheat was planted and harvested in 2010 on both paddocks, and in 2011 barley on paddock 11 and wheat on paddock 12. The hotspots were identified as ISE for paddocks 11 and 12 in 2010 (Chapter 5, section 5.4.4).

Table 7.4 presents the hotspots for each paddock and selected CP strategies used as mitigation measures.

7.5.1 GHG mitigation for paddock 11

The total GHGs generated by ISE in 2010 were 26.0% of the paddock GHG emissions for 2010 (Table 6.1), and the N_2O emissions from leaching generated 99.7% of the ISE GHG emissions and 25.9% of the paddock GHG emissions. Fertiliser production, which also caused the ISE, generated 27.6% of the paddock emissions in 2010. Although fertiliser production was higher than the ISE GHG emissions, ISE was identified as the hotspot using the method described in Chapter 6.

The CP method considered here for mitigation purposes is input substitution for the reduction of GHGs from fertiliser production.

The soil type (brown Kandosol) for this paddock is characterised by deficiencies in N and P, thus mitigation strategies focused on these deficiencies as well as on the percentage of N content in the fertiliser applied (Agras 16.1% N, 9.1% P). Agyield Extra (17.2% N, 17.8% P) (Appendix E, Table E.1) was thus selected as a theoretical alternative. After theoretically applying 93.6 kg of Agyield Extra (vs 100 kg of Agras) (Appendix H, Equation H.1−H.2), to this paddock a reduction of 2.3% was noticed for the paddock GHG emissions and a reduction of 6.7% in the fertiliser production input category (Table 7.4).

Table 7.4. Presentation of the top hotspots and corresponding cleaner production strategies for Farm D

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
11 (2010)	ISE (26.0%)	Discussed in section 7.4	1.26×10^2	Discussed in Section 7.4	Discussed in Section 7.4	4.85×10^2	Discussed in Section 7.4	Discussed in Section 7.4
	Fertiliser production (27.5%)	Input substitution	1.34×10^2	1.25×10^2	6.7%		4.74×10^2	2.3%
	Stubble burning (15.7%)	-	7.72×10^1	-	-		-	-
12 (2011)	ISE (51.1%)	Good housekeeping	1.75×10^2	Discussed in Section 7.4	Discussed in Section 7.4	3.42×10^2	Discussed in Section 7.4	Discussed in Section 7.4
	Fertiliser production (31.2%)	Good housekeeping	1.07×10^2	9.80×10^1	8.4%			
		Input substitution	1.07×10^2	9.69×10^1	9.4%		3.32×10^2	2.9%
	DSE (6%)	-	2.05×10^1	-	-		-	-

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

7.5.2 GHG mitigation for paddock 12

In 2011 ISE contributed to 51.1% of the total GHG emissions for 2011 on this paddock. Within this category the N_2O emissions from leaching accounted for 99.8% of the total GHG emissions in the ISE category and 51.0% of the overall GHG emissions in 2011 on the paddock. Fertiliser production contributed to 31.2% of the total GHG emissions from this paddock in 2011, thus input substitution was considered.

The two fertilisers used on this paddock in 2011 were Agras (16.1% N, 9.1% P, 14.3% S) and Flexi-N (32% N) (Appendix E, Table E.1). Generating 23.5% of the paddock's GHG emissions, Agras was the fertiliser contributing the most GHGs in the fertiliser production input category and thus the focus was on reducing the GHG emissions from this fertiliser. The soil type was red Kandosol, characterised by deficiencies in N and P, thus the same replacement option was selected as for paddock 11 (section 7.5.1.1). After theoretically applying 93.6 kg of Agyield Extra the paddock GHG emissions were reduced by 2.9% and the fertiliser production input category by 9.4% (Table 7.4). Soil tests showed that the S content was 5.81 mg S/kg soil in the 0–10 mm soil horizon, and should be above 5 mg S/kg soil to maintain crop health (Croppro.com, 2015) (Appendix H, Table H.1), hence the theoretical application rate of 93.6 kg Agyield (providing 3.55 kg S/ha),) should not have compromised crop growth due to the reduced level of S.

7.5.3 Summary of mitigation measures for Farm D

The hotspots for paddocks 11 and 12 were ISE, followed by fertiliser production. The CP strategy selected was the input substitution method for the production of fertiliser input category. By substituting one fertiliser for another on these paddocks the GHG emissions were reduced by 2.3% and 2.9%. Although the change in GHGs was not significant, the use of input substitution is an alternative that could be considered, especially if additional data regarding other fertilisers were to be made available on the IST.

7.6 FARM E

For Farm E the FMP were the same for all three paddocks in both years, differing only for paddock 15 which was used solely for pasturing in 2011. Sheep were grazed and no stubble burning carried out on all three for both years. The hotspots were identified as ISE on paddock 14 and for paddocks 13 and 15 it was the production of fertilisers.

Table 7.5 presents the hotspots for each paddock and selected CP strategies used as mitigation measures.

7.6.1 GHG mitigation for paddock 13

In 2010 the fertiliser production input category was identified as the hotspot for this paddock over the two years, generating 33.9% of the total GHG emissions for this paddock in 2010. The CP strategy selected for investigating the mitigation of GHGs was good housekeeping.

The only fertiliser used on this paddock in 2010 was DAP (17.5% N), emitting 34% of the total paddock emissions in 2010. Alternative fertilisers used to substitute DAP as a source of N in Western Australia include urea (46% N), Flexi-N (32% N) and MAP (11% N). For mitigation purposes MAP was chosen to theoretically replace DAP as the percentage N in MAP (11% N) is closer to DAP (17.5%) than the other fertilisers (Appendix E, Table E.1). A theoretical application rate of 95.5 kg was calculated for MAP, using the actual application rate of DAP (60 kg/ha/year) and the percentage of N content in DAP (Appendix H, Equation H.1−H.2). On substitution into the spreadsheets the GHG emissions from fertiliser production increased by 10%. The use of IST thus demonstrates that substituting DAP with MAP is not a viable option.

Table 7.5. Presentation of the top 'hotspots and corresponding cleaner production strategies for Farm E

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
13 (2010)	Fertiliser production (34%)	Input substitution	1.14×10^2	3.39×10^1	70.3%	3.34×10^2	2.27×10^2	32.0%
	Transportation of fertilisers (17.8%)		5.93×10^1	-	-		-	-
	DSE (15.3%)	-	5.12×10^1	-	-		-	-
14 (2011)	ISE (51.5%)	Discussed in section 7.4	1.71×10^2	Discussed in Section 7.4	Discussed in Section 7.4	3.32×10^2	Discussed in Section 7.4	Discussed in Section 7.4
	Fertiliser production (27.4%)		5.84×10^1					
		Input substitution		3.92×10^1	32.9%		3.03×10^2	8.7%
	Transportation of fertilisers (11.5%)	-	2.45×10^1	-	-		-	
15 (2010)	Fertiliser production (33.7%)	Input substitution	1.21×10^2	7.63×10^1	36.9%	3.72×10^2	3.15×10^2	15.3%
	Transportation of fertilisers (17%)	-	6.31×10^1	-	-		-	-
	Chemical production (14.9%)	-	5.55×10^1	-	-		-	-

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

Flexi-N was used as an additional alternative, with a theoretical application rate of 32.8 kg/ha. As Flexi-N contained no P and DAP 1.2% P, the soil test results (Appendix H, Table H.1) were consulted to ascertain the P levels of the soil. The P levels in the soil were 37 mg P/kg soil in the 0–10 mm soil horizon (as supplied by DAFWA, using Colwell testing), and considered marginal (Blaesing, 2006), thus no additional source of P may be required. The GHG emissions from this substitution showed an overall reduction in the paddock GHGs by 32.0%, and the fertiliser production input category by 70.3% (Table 7.5). These two options demonstrate that the IST can be used by the decision-maker to select the best option to mitigate GHGs, which in this scenario was the replacement of DAP with Flexi-N.

7.6.2 GHG mitigation for paddock 14

The output category ISE in 2011 presented as the overall hotspot for paddock 14 for the time period 2010–2011. As noted in section 7.4 it will not be included in the mitigation analyses. The production of fertilisers, however, was considered and the CP strategy applied was input substitution.

As stated in section 7.2.1.1 Flexi-N, MAP and DAP are the N fertilisers most commonly used in Australia to replace urea. As DAP was the fertiliser emitting the bulk of the GHG emissions in fertiliser impact category (72.4% for DAP vs 27.6% for urea, the mitigation strategy focused on replacing DAP. After ascertaining in section 7.6.1.1 that MAP was not the best alternative Flexi-N was selected as the substitute. No P replacement was considered for this paddock as the soil P was determined to be 30 mg/kg, which is marginal (see section 7.6.1) (Appendix H, Table H.1). The theoretical replacement dosage of Flexi-N was calculated at 35.5 kg/ha based on percentage N in the chemicals (Appendix H, Equation H.1−H.2). By theoretically replacing DAP with Flexi-N the GHG emissions from fertiliser production were reduced by 32.9% and the paddock emissions by 8.7% (Table 7.5).

7.6.3 GHG mitigation for paddock 15

The production of fertilisers in 2010, generating a total of 1.21 x 10^2 kg CO_2-e/t, was the hotspot for paddock 15 during 2010–2011. The only fertiliser used on this paddock in 2010 was DAP. The two categories with the next highest GHG emissions for this paddock are the transportation of fertilisers (17.0% of paddock GHG emissions) and chemical production (14.9% of the total GHG from the paddock in 2010).

For mitigation purposes the theoretical substitution of DAP (17.5% N) with MaxAmFlo (22% N) was considered. Both these existing and alternative chemicals are distributed from Kwinana thus there are no additional emissions associated with the transportation of alternative chemicals. As the soil tests showed P content of 38 mg P/kg soil, falling within the marginal range MaxAmFlo (containing no P) could be applied in this growing season, however a P-fertiliser should be applied in future growing seasons. The theoretical dosage of MaxAmFlo (47.7 kg) was calculated by taking the percentage N composition into account and applying equivalent amounts of N as with MAP (Table 7.5) (Appendix E, Table E.1; Appendix H, Equation H.1−H.2).

The application of this theoretical mitigation measure showed a reduction in the GHG emissions from the individual fertiliser through to the overall paddock emissions. The production of fertilisers input category was reduced from 1.21 x 10^2 kg CO_2-e/t to 7.63 x 10^1 kg CO_2-e/t, resulting in mitigation of GHGs by 36.9%. As fertiliser transportation is influenced by the fertiliser used as well as the dosage applied, the CP strategy input substitution also allowed for a 20.4% reduction of GHG emissions from this input category. The overall paddock emissions were reduced by 15.3% (Table 7.5).

7.6.4 Summary of mitigation measures for Farm E

Fertiliser production was the hotspot for paddocks 13 and 15 and the second highest GHG generator for paddock 14. Input substitution was selected as the CP strategy to mitigate GHGs from fertiliser production, resulting in a reduction by 32%, 8.7% and 15.3%, respectively. These differences can be related to the different types of fertilisers applied to the paddocks as well as to the N content, climatic conditions and application rates. The transportation of fertilisers was the next highest GHG emitter for paddocks 13 and 15. The GHGs from the transportation of fertilisers will be affected by the application dosage of the fertiliser and the distance transported. ISE was the hotspot for paddock 14.

Overall this farm exhibited hotspots that were all related to the dosage of fertilisers. The farmer, therefore, would need to ascertain the best type of FMP for the use of fertilisers on these paddocks to ascertain the best method to mitigate GHGs on this farm.

7.7 FARM F

Wheat was planted in 2010 in three paddocks at Farm F and no grazing or stubble burning practices were carried out. In 2011, paddocks 16 and 17 were used as pastures for sheep but the stubble was not burned. In the case of paddock 18, canola was planted, stubble was burned and sheep were not grazed. The hotspots identified for these paddocks were fertiliser production in 2010 for all three paddocks, followed by ISE and DSE.

Table 7.6 presents the hotspots for each paddock and selected CP strategies used as mitigation measures.

7.7.1 Mitigation for paddock 18

The hotspot for this paddock as identified in Chapter 6, section 6.3.3 was the production of fertilisers in 2010, emitting 47.2% of the total paddock GHG emissions. The next highest GHG emitter was ISE, generating 34.4% of the overall paddock emissions for 2010.

Table 7.6. Presentation of the top hotspots and corresponding cleaner production strategies for Farm F

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
18 (2010)	Fertiliser production (47.2%)	Input substitution	3.15×10^2	2.27×10^2	27.9%	6.68×10^2	5.57×10^2	16.6%
	ISE (34.4%)	Discussed in section 7.4	2.30×10^2	Discussed in section 7.4	Discussed in section 7.4		Discussed in section 7.4	Discussed in section 7.4
	DSE (6.1%)	-	4.07×10^1	-	-		-	-

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

Similar to paddock 17, MaxAmFlo was the fertiliser generating the most GHGs and therefore a calculated mass of 47.30 kg/ha/year of Flexi-N was used to theoretically replace the actual dose of 70 kg/ha/year of MaxAmFlo (Appendix H, Equations H.1−H.2). Through this theoretical substitution the GHG emissions for the paddock in 2010 were reduced by 16.6% (Table 7.6).

The soil tests showed an S content of 7.12 mg S/kg soil in the 0–10 mm soil horizon, which falls above the required level of 5 mg S/kg soil for maintaining crop health (Croppro.com, 2015; see section 7.4.1) (Appendix H, Table H.1). In the current growing season the theoretical application of Flexi-N, which does not contain any S, would not compromise the crop but may impact on crop health in subsequent seasons as S is depleted in the soil. It would be advisable to add S in future growing seasons, however it should be noted that the addition of S will increase GHG emissions.

7.7.2 Summary of mitigation measures for Farm F

The hotspot for all paddocks was fertiliser production followed by ISE. For fertiliser production input substitution methods were considered whereby one fertiliser was substituted with another fertiliser. This substitution was based on the N and P content of the fertilisers and the theoretical dosage was calculated using the percentage of N content and actual dosage.

As the GHGs emitted by these paddocks are all related to fertiliser use (ISE included) the farmer would need to make a decision based on fertiliser application in order to reduce the carbon footprint of this farm.

7.8 FARM G

Wheat was planted in all three paddocks at Farm G in 2010 and 2011. The farmer did not graze any livestock on the land in these years and paddocks 19 and 20 were burned in 2010. During the study period the hotspots were paddock burn in 2010 for paddock 19 and 20 and ISE in 2011 for paddock 21 (Table 7.7).

Table 7.7. Presentation of the top hotspots and corresponding cleaner production strategies for Farm G

Paddock (year)	Paddock hotspots (% contribution)	Type of CP strategy	Overall GHG for the top hotspots only			Overall GHG emissions for the paddock		
			Existing emissions (kg CO_2-e/t)	Emissions after CP (kg CO_2-e/t)	Percentage reduction	Existing emissions kg CO_2-e/t	Emissions after CP kg CO_2-e/t	Percentage reduction
19 (2010)	Chemical production (26.4%)	Input substitution	2.29×10^2	1.07×10^2	53.3%	8.69×10^2	7.42×10^2	14.6%
	ISE (32.1%)	Good housekeeping	2.79×10^2	2.09×10^2	25.1%		7.51×10^2	13.6%
	Fertiliser production (20.9%)		1.82×10^2	1.36×10^2	25.3%			
		Input substitution		1.36×10^2	25.3%		8.23×10^2	5.3%
20 (2010)	ISE (55.9%)	Discussed in section 7.4	9.18×10^2	Discussed in section 7.4	Discussed in section 7.4	1.64×10^3	Discussed in section 7.4	Discussed in section 7.4
	Fertiliser production (15.9 %)	-	2.61×10^2	-	-		-	-
	Chemical production (15.1%)	-	2.48×10^2	-	-		-	-
21 (2011)	ISE (53.0%)	Good housekeeping	3.82×10^2	2.55×10^2	33.2%	7.21×10^2	5.10×10^2	29.3%
	Fertiliser production (28.2%)	Input substitution	2.03×10^2	1.56×10^2	23.2%		6.73×10^2	6.7%
		Good housekeeping	2.03×10^2	1.35×10^2	33.5%		5.10×10^2	29.3%

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

7.8.1 GHG mitigation for paddock 19

The hotspot for paddock 19 (2010) was identified as chemical production, contributing 26.4% of the paddock's GHG emissions. Other areas of concern in 2010 were the production of fertilisers (20.9% of the paddock emissions) and ISE (32.1% of the paddock emissions). Theoretically ISE is the actual hotspot when consulting the tables (Tables 5.37, 5.38 and 7.7), however chemical production was identified by the IST as the hotspot (using the method specified in Chapter 6).

CP strategies considered for mitigation the GHGs from paddock 19 are input substitution for both chemical and fertiliser production.

The theoretical substitution of the herbicide Logran (the highest GHG emitter) with 1.8 l/ha herbicide Avadex, which is based on the same factors as described in Paddock 1 (section 7.2.2.1), would result in a reduction of 14.6% in total GHGs for the paddock in 2010.

The fertiliser Agstar Trace (14.2% N) generated 15.3% of the GHGs from the paddock in 2010 and was thus the fertiliser selected for theoretical replacement. As the brown Kandosol soil on paddock 19 is characterised by deficiencies in N and P, the fertiliser DAP was selected to theoretically replace Agstar Trace. DAP (17.5% N) is manufactured by the same company as Agstar Trace and can be used for N and P replacement (Appendix E, Table E.1). The soil tests showed a sulphur (S) content of 7.36 mg S/kg soil in the 0–10 mm soil horizon, whereas the minimum required level for crop health is 5 mg S/kg soil (Croppro.com, 2015; see section 7.4.1) (Appendix H, Table H.1). In the current growing season the theoretical application of DAP, which does not contain any S, would not compromise the crop but may impact on crop health in subsequent seasons as S is depleted in the soil. S should thus be added to the soil in the following season. The calculated dosage (based on percentage N of both fertilisers) and actual dosage of Agstar Trace was 64.9 kg/ha/year. This theoretical dosage enabled the GHG emissions from the paddock to be reduced by 5.3% for the year (Table 7.7).

7.8.2 GHG mitigation for paddock 20

On consulting Table 7.7 it was found that ISE was the overall hotspot for the paddock in 2010, contributing 55.9% of the total GHG emissions, followed by fertiliser production generating 15.9% of the paddock GHG emissions. For the previous paddocks, the hotspots contributing to less than 20% of the paddock GHG emissions were excluded, thus no additional mitigation measure will be considered for this paddock (section 7.4).

7.8.3 GHG mitigation for paddock 21

ISE in 2011 was identified as the hotspot for paddock 21 during 2010–2011, contributing 53% of the paddock GHG emissions. The next highest GHG emitter was fertiliser production, generating 28.2% of the total GHGs from the paddock in 2011 (Table 7.7).

The method considered for mitigating the GHG emissions from fertiliser production was substitution with an alternative fertiliser.

Generating a total of 73.4% of GHGs in the production of fertilisers input category, MacroPro Extra was the hotspot. As MacroPro Extra generated the most GHGs it was decided to theoretically replace the actual dosage of 100 kg/ha with 68.8 kg/ha of Agstar Extra. Agstar Extra was selected as its composition is similar to MacroPro Extra in terms of N, P and S (Appendix E, Table E.1). Orthic Tenosol, the soil type for this paddock, is deficient in these nutrients. The soil analysis for the 20–40 mm horizon gave a result of 69 mg K/kg soil (Colwell), which falls in the optimal range of 50–100 mg K/kg soil (Blaesing, 2006) (Appendix H, Table H.1). This means that the soil should have adequate K for crop growth, however in future growing seasons additional K-fertiliser may be required. This CP strategy enabled the GHG emissions from this paddock in 2011 to be mitigated by 6.7% and 23.2% for the fertiliser production input category (Table 7.7).

7.8.4 Summary of mitigation measures for Farm G

The hotpot for paddock 19 was chemical production, followed by ISE and then fertiliser production. Paddocks 20 and 21 had ISE as the hotspot and fertiliser production as the second highest GHG emitter.

For chemical production and fertiliser production, input substitution with alternatives was considered as a CP strategy. After theoretically substituting with selected alternatives for paddocks 19 and 20, the GHGs from the paddocks were reduced with 14.6 and 6.7%, respectively (Table 7.7).

The hotspots identified on these paddocks are mainly related to the application of N-fertilisers, and the decision-maker would need to consider the fertiliser type, application rate, N-content and soil type to reduce the carbon footprint of the farm.

7.9 FARM H

The FMPs for the two paddocks analysed on this farm included mouldboard[1] ploughing on paddock 23 and claying on paddock 24, both in 2010. In addition wheat was planted in both paddocks for both years, there was no stubble burning and no livestock were grazed. The hotspot for paddock 23 was the production of farm machinery in 2010 and for paddock 24, farm machinery operation was the hotspot in 2010 (Table 7.8).

7.9.1 GHG mitigation for paddock 23

The hotspot for paddock 23 was fertiliser production in 2011, emitting 24.1% of the total 5.00 x 10^2 kg CO_2-e/t for this paddock over the research period. Fertiliser production contributed to 63.5% of the paddock emissions for 2011 and the next highest GHG emitter on this paddock for 2011 was DSE, generating 11.9% of the paddock emissions.

[1] Mouldboard ploughing is a form of ploughing in which the soil is completely inverted.

Table 7.8. Presentation of the top hotspots and corresponding cleaner production strategies for Farm H

<table>
<tr><th rowspan="2">Paddock (year)</th><th rowspan="2">Paddock hotspots (% contribution)</th><th rowspan="2">Type of CP strategy</th><th colspan="3">Overall GHG for the top hotspots only</th><th colspan="3">Overall GHG emissions for the paddock</th></tr>
<tr><th>Existing emissions (kg CO_2-e/t)</th><th>Emissions after CP (kg CO_2-e/t)</th><th>Percentage reduction</th><th>Existing emissions kg CO_2-e/t</th><th>Emissions after CP kg CO_2-e/t</th><th>Percentage reduction</th></tr>
<tr><td rowspan="3">23 (2011)</td><td>Fertiliser production (63.5%)</td><td>Input substitution</td><td>1.20×10^2</td><td>1.18×10^2</td><td>1.7%</td><td rowspan="3">1.90×10^2</td><td>1.88×10^2</td><td>1.1%</td></tr>
<tr><td>Direct soil emissions (11.9%)</td><td></td><td>2.26×10^1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Chemical production (11.9%)</td><td>-</td><td>2.25×10^1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">24 (2010)</td><td>Farm machinery operation (63.4)</td><td>Discussed in section 7.9.2</td><td>2.10×10^2</td><td>Discussed in section 7.9.2</td><td>Discussed in section 7.9.2</td><td rowspan="3">3.31×10^2</td><td>Discussed in section 7.9.2</td><td>Discussed in section 7.9.2</td></tr>
<tr><td>DSE (32.3%)</td><td>Discussed in section 7.9.2</td><td>1.07×10^2</td><td>Discussed in section 7.9.2</td><td>Discussed in section 7.9.2</td><td>Discussed in section 7.9.2</td><td>Discussed in section 7.9.2</td></tr>
<tr><td>Farm machinery production (3.0%)</td><td>-</td><td>9.98</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Note: Inputs or outputs contributing less than 20% of the total emission were not considered under cleaner production strategies

The fertiliser NPS range-Cereal (12.5% N, 17.7% P, 6.9% S) was identified as the fertiliser generating 6.60 x 10^1 kg CO^2-e (34.8% of the paddock emissions) for 2011 and was thus selected for theoretical replacement with Maxamrite (12.8% N, 17.7% P, 7.4% S). MaxAmRite has a similar N, P and S content to NPS range-Cereal (Appendix E, Table E.1). The theoretical dose of 73.3 kg/ha Maxamrite was substituted into the spreadsheet in the place of NPS range-Cereal (74 l/ha or 75.5 kg/ha) (Appendix H, Equation H.1−H.2). Overall, the paddock GHG emissions were reduced by 1.1% and fertiliser production GHG emissions were reduced by 1.7%. Although the reduction was small, the IST showed that by substituting with an alternative fertiliser GHG mitigation was possible, however for larger reductions in GHGs other fertilisers can be investigated.

7.9.2 GHG mitigation for paddock 24

In 2010, paddock 24 was subjected to a machinery use intensive practice, namely claying. During the claying procedure, clay is spread over the paddock as a strategy to increase soil moisture, retain nutrients and overcome water repellence. It is a top-dressing procedure wherein the clay is mechanically spread and ‘smudged’ into the paddock soil (pers. comm., Brockman, 2014, DAFWA, Albany; Brockman, 2015). As with mouldboard ploughing (section 7.10.2), claying is only conducted on an ad hoc basis (pers. comm., Brockman, 2014, DAFWA, Albany); it is expensive and time consuming and may not benefit all paddocks However the benefits of claying have been shown to last up to 15 years (Brockman, 2010; GRDC, 2011b). Due to the claying procedure the output category farm machinery operation was the hotspot for 2010, producing 63.4% of the total 3.31 x 10^2 kg CO_2-e/t from the entire paddock.

The output category farm machinery operation focuses on the combustion of fuel as a source of GHG emissions. The total emissions generated from burning fuel will be dependent on the area treated, the fuel consumption of the machinery, the header widths of the machinery and the speed at which the machinery operates. As the aforementioned factors are all fixed variables in this PhD study, the mitigation measures did not focus on altering these aspects. Furthermore, as no historical data were available for the 2009 growing season for this paddock, no mitigation measures were proposed; however, possible mitigation measures were identified and are discussed. Claying is essentially a good housekeeping CP strategy.

The largest benefit from increasing the clay content in the soil is the increase in crop yields which vary in Western Australia from 20% to 130% (Brockman, 2010; GRDC, 2011b). As the crop yield increases, the GHG emissions per tonne decreases (the denominator that is larger will allow for greater distribution of the numerator). The wetting capacity and the water holding capacity of soil improves when clay is incorporated into sandy soils, thus water availability to the crops increases (Brockman, 2010; GRDC, 2011b). Furthermore, as clay has a higher pH, the pH of the sandy soil is adjusted; the clay improves the organic content of the sandy soil, and compaction and erosion are reduced due to improved aggregation of the clay particles, amongst other benefits (Brockman, 2010; GRDC, 2011b).

Following the output category farm machinery operation, the DSE generated 32.3% of the GHG emissions, which was as a result of the residual lime in the soil. Lime is essential to increase soil pH, which is inherently low in yellow Kandosols. It is therefore not advisable to decrease the application rate of lime, thus no mitigation measure was considered for DSE.

7.9.3 Summary of mitigation measures for Farm H

Mouldboard ploughing and claying were the two FMPs used on this farm in 2010, and both are practices that are only carried out on an ad hoc basis. Mitigation measures were proposed for these paddocks as specified above. However, by mouldboard ploughing or claying the soil in these paddocks, the GHG emissions in future growing seasons will be mitigated due to the increase in anticipated crop yields and reduced GHG emissions from chemical or fertiliser use. If mitigation strategies result in the loss of productivity there is generally overall no GHG saving benefit (Biswas, 2015). Reduced fertiliser applications could furthermore result in lower ISE and DSE at the loss of productivity, which increase rather than decrease GHG emissions. When historical data are available, the paddocks could be modelled using the GHG emissions from other growing seasons (not from 2010) for comparative purposes, in order to investigate which input/output categories would change and how the changes would take place. Furthermore the practice of mouldboard ploughing and claying could be modelled over a ten-year period as the benefits are not generalised on the basis of the current season, but could impact on all the seasons thereafter.

7.10 CHAPTER SUMMARY

After identifying the hotspot on each paddock, this chapter endeavoured to theoretically apply CP strategies to determine the viability of GHG mitigation strategies. The most common CP strategies used were input substitution where one chemical was replaced with another, and good housekeeping which mostly focused on adjusting application dosages. It was mostly found that the use of fertilisers (18 out of 20 paddocks) was responsible either directly (production and transportation of fertilisers) or indirectly (ISE) for the elevated GHG emissions. By focusing on using alternative fertilisers, adjusting the dosage or using a fertiliser with lower N content, these GHG emissions could be mitigated. However it should be noted that crop growth can be affected by the nutrient balance in the soil and thus all chemical (including fertilisers) applications should be based on soil nutrient testing and not conducted haphazardly.

This chapter has attempted to identify different mitigation strategies that could be used on each of the paddocks to bring about a reduction in GHG emissions. The theoretical values generated from the application of cleaner production strategies could all be entered into the IST to generate additional figures for comparative purposes. However it should be kept in mind that these are only theoretical results and actual changes to any of the variables would need to be based on the conditions of the paddock as well as the envisaged FMPs.

Another factor to bear in mind is that if one variable is altered to adjust the emissions from a specific input/output category, other downstream GHG emissions may also change. This in turn will modify the results in the categories and the hotspot may change as well.

The next chapter is the final chapter wherein the conclusions and recommendations of this study are documented.

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CHAPTER 8

CONCLUSIONS

This chapter synthesises the analyses in the preceding chapters around each objective in Chapter 1, and provides recommendations based on the use of an integrated spatial technology (IST) appraoch in agriculture. Thereafter conclusions were drawn based on the synthesis and recommendations.

8.1 SYNTHESIS

In completing the synthesis of this study, all ideas, concepts and objectives were fused within the aim of the study. The aim of the research, as stated in Chapter 1, section 1.3, **was the development of a tool (integrated spatial technology (IST)) that could assist with the identification of mitigation measures, based on cleaner production strategies, in the grain sector of agriculture**. The five objectives as stated in Chapter 1 to arrive at the aim of this research, were addressed as follows:

8.1.1 Objective 1: To identify the study area in a geographical information system using geographical co-ordinates and remote sensing

The identification of the study area in this research was important as it defined the space and scope within which the research was conducted. The Department of Food and Agriculture Western Australia (DAFWA) allocated 44 out of the total of 144 paddocks from the DAFWA crop rotation project, which covered a large area throughout the wheatbelt of Western Australia, to this PhD research.

The study area was refined by registering the geographical co-ordinates onto the two available pre-processed satellite images and only extracting those falling within, or close to, the boundaries of the satellite images. Remote sensing (RS) images are available in pre-defined sizes and formats as determined by sensors on board the satellite. Using the geographical information system (GIS) the locations of the 24 paddocks were identified and where possible, outlined. Thus, this objective was successfully achieved as its primary goal was to identify the paddocks within the study area delineated by the satellite imagery.

8.1.2 Objective 2: To calculate the carbon footprints of individual paddocks and farms using an LCA approach

A full life cycle assessment (LCA) focuses on the entire 'cradle to gate' analysis of a system. It also includes all the impact categories as defined by the International Organization for Standardization (ISO) (ISO, 2006). The research objective for this study was to determine the carbon footprint, which impacts on climate change, for the pre-farm and on-farm stages of an agricultural system. Although the post-farm stage was excluded and only climate change was considered, the same methodology was applied as for a full LCA in which all impact categories are considered (Curran, 2006).

The data gathered, using an LCA approach, was outlined in Chapter 3. Thereafter, all input and output data for each paddock were separated into pre-farm or on-farm stages and separate life cycle inventories (LCI) were compiled. Emissions factors for global warming potentials (GWP) for inputs and outputs were then sourced from literature and used to calculate the carbon dioxide equivalents (CO_2-e) for each input and output category for each paddock. This was the basis of the GHG analysis. Finally, the CO_2-e were summed to quantise the overall carbon footprint of each paddock. Ultimately the carbon footprint of each farm was identified and interpreted.

The carbon footprints of the paddocks ranged from 4.78 x 10^1 kg CO_2-e/t (paddock 4 in 2011) to 4.61 x 10^3 kg CO_2-e/t (paddock 3 in 2011). In 2010, paddock 6 emitted the least GHGs overall (1.48 x 10^1 kg CO_2-e/t) and paddock 20 was the overall hotspot (1.64 x 10^3 kg CO_2-e/t). The paddock hotspot for 2011 was paddock 3 (4.61 x 10^3 kg CO_2-e/t) and the paddock with the lowest carbon footprint was paddock 4 (4.78 x 10^1 kg CO_2-e/t). The overall carbon footprints for the farms ranged from 4.42 x 10^2 kg CO_2-e/t (Farm H, 2011) to 8.23 x 10^3 kg CO_2-e/t (Farm A, 2011). The farm with the lowest carbon footprint in 2010 was Farm F (6.68 x 10^2 kg CO_2-e/t) while Farm G had the highest carbon footprint (3.21 x 10^3 kg CO_2-e/t). In 2011, Farm H had the lowest carbon footprint (4.42 x 10^2 kg CO_2-e/t) and Farm A the highest carbon footprint (8.23 x 10^3 kg CO_2-e/t).

This objective was successful as the IST was able to determine the carbon footprints at both farm and paddock levels.

8.1.3 Objective 3: To identify the hotspots on each paddock and farm after integrating the LCA, RS and GIS

Hotspot is a colloquial term which in this research refers to an input/output category, farming stage or paddock generating the most greenhouse gases (GHGs). The carbon footprints of each input/out category, farming stage, paddock and farm were calculated using an LCA approach. After completing the quantisation of the life cycle impact assessment (LCIA) for each paddock, the carbon footprints were compiled. Thereafter, by consulting the carbon footprint tables and the LCIA graphs and tables for each paddock, the area generating the most GHGs was identified. The carbon footprints and LCIA data were then uploaded into GIS.

By superimposing GIS layers onto the satellite image, different data could be selected for inclusion in the required visual representations. The image created in the GIS could include individual or grouped paddock outlines according to the selected satellite image, climatic variables such as temperature and transpiration, maps, graphs and tables.

To identify the hotspots, the paddock outlines as well as a graph of the paddock and the relevant table of CO_2-e, were selected for inclusion in the image. Through further variable selections and manipulation the final image illustrated the hotspot of the input/output category, paddock or farm.

Out of the 20 paddocks analysed, fertiliser production and indirect soil emissions were the hotspots on six paddocks each, with an average GHG hotspot contribution to total paddock emissions of 45.1% and 47.2% respectively. Chemical production was the hotspot on three paddocks (56.8% contribution), chemical transportation on one paddock (51.4% contribution) and fertiliser transportation on two paddocks (77.6% contribution). Farm machinery operation and farm machinery production were the hotspots on one paddock each, contributing an average of 63.4% and 86.1% to the overall GHG emissions from those paddocks respectively.

This objective was achieved by integrating the LCA, and more specifically the carbon footprint and LCIA results, into the GIS. After the integration of the three tools it was possible to identify the hotspot. Through this visual representation, the farmers could thus use the IST as a handy decision-making tool to choose an effective mitigation option in terms of the transportation of fertilisers, in order to further reduce GHG emissions from grain production.

8.1.4 Objective 4: To propose mitigation measures based on cleaner production strategies for each paddock and farm

As cleaner production (CP) strategies concentrate on mitigating GHGs at the source, it was important to pinpoint the origin of the hotspot for each paddock or farm. For most of the paddocks the source of the GHG emissions was related to nitrogenous fertiliser (N-fertiliser) applications (14 of 20 paddocks). Thus, after identifying N-fertilisers as the source of the emissions in the farming system using the IST, the CP strategies were considered.

For example, to mitigate the GHG emissions from N-fertiliser use, input substitution and good housekeeping alternatives were found to be effective CP strategies. These strategies mainly consisted of the substitution of one N-fertiliser for an alternative N-fertiliser contributing less to the overall GHG emissions, and crop rotations which included legumes were found to be applicable for the majority of the paddocks. In theoretically applying the mitigation options based on CP strategies, additional images were able to be generated in the IST. These images could then be compared with the original scenarios and the differences between the two analysed. In turn this comparison could enable the farmer to make informed decisions regarding the selection of farm management practices.

This objective was successful in identifying which of the five existing CP strategies were predominantly required for south-western Australia's farming systems. The IST also proved to be successful in applying mitigation measures based on the CP strategies.

8.1.5 Objective 5: To present the integrated tools as a product that can be used by farmers, the industry and academic institutions alike

The application of mitigation measures requires information to be processed and presented to the farmer, so that informed decisions can be made. The IST is able to show the user the source of the hotspot, the level of the GHG emissions in relation to the rest of the area examined, and propose possible GHG mitigation methods based on CP strategies. However, although the IST is easy to use it is not yet freely accessible or automated.

To encourage the use of the IST, it is necessary to address the accessibility and the automation of the tools. Firstly the Excel spreadsheets should be accessible in such a way that the user is requested to enter or select the required input data (e.g. application rates of fertilisers, type of chemical used, machinery passes over a paddock). Thereafter, the calculation of the CO_2-e will automatically occur through the linked worksheets. Secondly, an interface needs to be established between the Excel worksheets and the GIS application. The relevant input data and the calculated variables will then be transferred to the satellite imagery for modelling. Finally, the user will be requested to make choices as to which information should be displayed so that final images can be created and printed for decision-making purposes. To address accessibility issues, factors such as web-based programmes or applications could be considered, the tool could be made accessible for mobile smart-phone users, or tablet-based applications could be devised.

As the Excel spreadsheets have been developed and the generation of the images in GIS have proven to be successful, the objective can be considered to have been partially achieved. However, as the automation and the accessibility of the tool has not yet been addressed, more research is required to achieve this objective in its entirety.

8.1.6 Section summary

The general aim of this research was to establish whether LCA, RS and GIS could be integrated and used as a tool to propose GHG mitigation measures to the cropping sector in south-western Australia.

As all objectives were achieved, it can be concluded that the aim of the research was met. There are improvement opportunities for two objectives (Objectives 4 and 5), however these did not affect the development of the tool. To further enhance Objective 4, additional research is required to enable the identification of additional mitigation measures specifically for the reduction of GHGs from N-fertiliser applications (including indirect soil emissions and direct soil emissions). Objective 5 requires the development of an interface that will allow for the spontaneous transfer of data from one application to another. Accessibility issues will be partially resolved when the interface has been developed. For the complete resolution of accessibility issues, programmes need to be designed and made available for marketing.

8.2 RECOMMENDATIONS

The overall shortcomings of the research, shortcomings have been specified as part of the recommendations to achieve the aforementioned objectives, others are specified below:

- Based on the research conducted it was obvious that farming is a complex system which is influenced by the farm management practice employed in previous seasons, the current growing season and will also be influenced by future plans. For example the soil health is influenced in the short-term and long-term by crop rotations, and/or chemical applications such as lime or fertilisers. It is therefore recommended that the IST be used calculate the GHG emissions on, for example, a five year future based scenario taking the previous years into consideration and then plan accordingly.
- The identification of a study area could be problematic if there is no access to high quality satellite imagery that has been pre-processed before inclusion in the GIS. Other means of identifying the study area need to be explored, such as Google Earth, and how these can be integrated into the IST tool.

- The development of an LCI is a time-consuming task, especially if data records are incomplete. The farmers should be encouraged to maintain comprehensive records to eliminate the need for assumptions and for quicker identification of potential hotspots.
- As the emission factors for the production of chemicals were based on generic values, the GHG emissions calculated in the production of chemicals input category and transportation of chemicals input category are only estimates. To calculate more accurate results for each chemical, a local emissions factor database needs to be developed based on actual fieldwork research.
- The GHG emissions from the application of N-fertilisers were the hotspot in most of the paddocks, whether through indirect soil emissions, direct soil emissions, transportation or the production process. Alternatives should be investigated to lower these GHG emissions and could include the use of crop rotations involving legumes and organic fertilisers, adjusting the application rates, applying slow release fertilisers or using N-fertilisers with a lower N content. The use of fertilisers with lower N content was not investigated in this research as fertiliser application is usually based on the N content of the soil prior to planting (not within the scope of the research), and usually lower N content would mean that more fertiliser would need to be applied, thus increasing GHG emissions. Alternatively the production of urea in Australia could be investigated, which will reduce the GHG emissions from transporting urea from Asia or the urea with the lowest carbon footprint (transportation-wise) needs to be sourced for grain production.
- The research focused on an area in south-western Australia, and the tool developed was successful in modelling the GHG emissions from this area. For comparative purposes, and to establish whether the GHG emission is similar to other farming regions, the tool should be used in other national and international agricultural applications. Furthermore it should be extended not only to cropping systems but to pastures and horticultural applications as well.
- Future research can apply the findings of this current research to identify mitigation strategies for a particular crop grown, in particular soil, under

certain agro-climatic conditions. For example, Biswas et al. (2008) identified fertiliser as the hotspot in one tonne of wheat production in the semi-arid climate of south-western Australia. Following this, the Grain Research Development Corporation of Australia provided funding to grow wheat in a legume-wheat rotation system and reduce the amount of fertiliser application thereby reducing the overall GHG emissions from wheat production. The recently completed LCA by this funded project shows that GHG emissions are reduced due to the use of crop rotation (Barton et al. 2014)

- The tool should be extended to include the post-farm stage in the agricultural cycle as GHG emissions are generated in the processing, storage and transportation of the crops from the farm gate to the point of distribution.
- As the IST has been used to model carbon footprints resulting from agriculture it could possibly be used to model other impact categories specified in the LCA methodology such as eutrophication, water scarcity and land use amongst others. It is recommended that this opportunity be explored.
- One of the main criteria of a CP strategy is that it should be economically feasible. In future research, this model could be enhanced further by incorporating an economic analysis to assess cost-effective mitigation strategies.
- Detailed information on grazing animals, such as the lifetime of the animals and the amount of live weight gained during short term grazing during the fallow land period needs to be determined to allocate GHG emissions to co-products.
- The practice of mouldboard ploughing and claying was introduced to the paddock during the time of this PhD research. Furthermore this practice could be modelled over a ten-year period as the benefits are not isolated to the current season, but impacts on all the seasons thereafter.
- The IST approach at the current stage is heavily dependent on the use of surrogate emission factors of chemicals due to absence of emission factors of local brands. A need exists for additional funding into research to estimate the emission factors of locally produced chemicals to perfectly represent the local situation and to enhance the IST approach.

8.3 CONCLUSION

In 2011, the redundant *Clean Energy Act 2011* (Cth) of Australia was initiated. As part of the Act the Carbon Farming Initiative (CFI) was devised and introduced to enable landowners to quantify and control the emissions of GHGs during farming. In the future, by quantifying and controlling these GHG emissions, the farmer would be able to generate and sell carbon credits using approved methodologies. The methodologies that were developed only focused on mitigating GHGs in a few farming systems, and no methodology was available for the farmer to quickly and easily establish level of GHGs or test alternative strategies.

This study thus assumed the responsibility for developing a tool that could enable farmers to calculate the anticipated GHG emissions from an already established crop or an anticipated crop. In developing this tool, other proven tools (LCA, GIS and RS) were integrated to form a unit that would be presented as the IST.

The thesis has thus described the successful development and testing of the IST framework using actual field data.

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APPENDIX A

PUBLICATION OF THEORETICAL FRAMEWORK

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An evaluation of integrated spatial technology framework for greenhouse gas mitigation in grain production in Western Australia

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ABSTRACT

The International Panel on Climate Change (IPCC) predicts an increase of 0.2 °C per decade for the next two decades in global temperatures and a rise of between 1.5 and 4.5 °C by the year 2100. Related to the increase in world temperatures is the increase in Greenhouse Gases (GHGs) which are primarily made up of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and fluorinated gases. In 2004, the GHGs from agriculture contributed 14% of the overall global GHGs made up mainly of methane (CH_4) and nitrous oxide (N_2O) emissions. In Australia, the dominant source of CH_4 and N_2O emissions for the year ending June 2012 was found to be from the agricultural sector. With the recent introduction of the Clean Energy Act 2011, the agricultural sector of Australia is expected to develop appropriate GHG mitigation strategies to maintain and improve its competitiveness in the green commodity market. This paper proposes the use of Integrated Spatial Technologies (IST) framework by linking Life Cycle Assessment (LCA), Remote Sensing (RS) and Geographical Information Systems (GIS). The IST approach also integrates and highlights the use of Cleaner Production (CP) strategies for the formulation and application of cost-effective GHG mitigation options for grain production in Western Australia (WA). In this study, the IST framework was tested using data from an existing study (the baseline study) and two mitigation options. The analysis results revealed production and use of fertiliser as the "hotspot", and for mitigation purposes was replaced with pig manure in option 1, whereas option 2 emphasised crop rotation system/s.

1. Introduction

The International Panel on Climate Change (IPCC) predicts an increase of 0.2 °C per decade for the next two decades in global temperatures and rise of between 1.5 and 4.5 °C by the year 2100 (IPCC, 2007). According to the World Bank these higher temperatures can cause changes in precipitation, rising sea levels and weather-related disasters which in turn can pose risks for agriculture, food and water supplies (World Bank, 2012). Related to the increase in world temperatures is the increase in greenhouse gases(GHGs) which are primarily made up of CO_2, N_2O, CH_4 and fluorinated gases (EPA, 2013).

In 2004, the GHGs from agriculture contributed 14% of the overall global GHGs made up mainly of CH_4 and N_2O emissions (EPA, 2013). The GHGs originate from the use and production of agrochemicals, such as fertilisers, along with the use of other agricultural inputs (such as agrochemicals) and farm machinery operations (Adler et al., 2007; Anderson, 2011; CSIRO, 2010; Ugalde et al., 2007).

In Australia, the dominant source of CH_4 and N_2O emissions is agriculture, accounting for 16% (86.5 Million Tons (Mt) CO_2-e (carbon dioxide equivalents)) of total national GHG emissions in 2010 and 16.4% (90.1 Mt CO_2-e) for year ending June 2012. The total national GHG emissions for 2012 were 551 Mt CO_2-e (AuGOV, 2012; DCCEE, 2012). For 2010 these agricultural GHG emissions can be attributed to enteric fermentation in livestock (67% of agricultural GHG emissions), manure management (4% of agricultural GHG emissions), rice cultivation (0.2% of agricultural GHG emissions), agricultural soils (17% of agricultural GHG emissions), savannah burning (11% of agricultural GHG emissions) and field burning of agricultural residues (0.4% of agricultural GHG emissions) (NGGI, 2012; DCCEE, 2013).

The production of grain in WA, despite its legacy of poor soils and low rainfall, has resulted in 40–50% of the annual grains production for Australia. This growth is concentrated in the Wheatbelt areas where mostly wheat, barley and lupins are produced (ABS, 2006; Biswas et al., 2008; DLGRG, 2007; Islam, 2009; Van Gool, 2009).

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Abbreviations

CFI	Carbon farming initiative
CH_4	methane
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalents
CP	Cleaner Production
DAFWA	Department of Agriculture and Food, Western Australia
GHG	Greenhouse Gas
GIS	Geographical Information Systems
IPCC	International Panel on Climate Change
IST	Integrated Spatial Technology
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
N_2O	nitrous oxide
RS	Remote Sensing
SLCA	Streamlined LCA
SPOT	Systeme Pour l'Observation de la Terre
WA	Western Australia

In July 2012, the Australian government commenced with carbon pricing by introducing the Clean Energy Act 2011 (CEA, 2011). This act is directed to respond to the climate change impacts by reducing environmental pollution and to drive the transformation of the Australian economy to a clean energy future (CEA, 2011; CELP, 2012; Johnson, 2011; Packham and Vasek, 2011). Within this act, a Carbon Farming Initiative (CFI) has been designed specifically for the land sector to reduce pollution and to manage the impact of climate change on the Australian economy and landscape (CFI, 2012). This initiative has been designed for farmers and landholders to generate carbon credits and sell these credits in the carbon market. It is anticipated that the CFI will create a new source of revenue by implementing projects that restore degraded soils and landscapes or the adoption of farm management practices that build carbon stores and reduces harmful greenhouse gases (CFI, 2012). Currently, the approved methodologies for the CFI include manure management in piggeries, establishing environmental plantings, the capture and combustion of landfill gas and the management of savannah fires, but others may be proposed in the future (CFI, 2012).

As the worldwide population escalates and more pressure is applied to farmers for increased agricultural productivity, management of their carbon footprint (or life cycle GHG emissions) becomes paramount (Biswas et al., 2010; NGGI, 2010). Without negating the importance of these above-mentioned methodologies other options should also be investigated and developed to assist farmers to reduce their pollution and manage their carbon footprint, thereby generating carbon credits and reducing harmful GHG emissions. The implementation of carbon footprint mitigation and CP strategies into all facets of agricultural production, especially grain production, could assist in reducing chemical and fertiliser use, transportation costs, energy use and in the quantification of the environmental benefits pertinent to the overall Australian production systems. Thus, this research has attempted to develop a tool for grain growers and policy makers to mitigate GHG emissions from grain production.

Numerous environmental management tools, including Life Cycle Assessment (LCA), Remote Sensing (RS) and Geographical Information Systems (GIS) have been widely-used, separately, to address the aforementioned GHG mitigation issues (Ahammed and Nixon, 2006; Biswas et al., 2008; Grant and Beer, 2008; Biswas et al., 2010, 2011; Yousefi-Sahzabi et al., 2011). However, the integration of these tools could possibly offer accurate but also time and cost effective means for assessing GHG mitigation strategies from the agricultural sector and therefore warrants further investigation. The Integrated Spatial Technology (IST) framework has been developed to integrate these tools with CP strategies to aid with the formulation and application of cost-effective GHG mitigation options pertinent to the WA grain industry. As part of the IST, an internet site which calculates the carbon footprint will be developed. This internet site will allow farmers to select different combinations of inputs (chemicals, machinery etc.) at different farming stages (pre-farm, on-farm) thereby allowing them to make informed choices based on soil type, farm management practices and climate. The IST will initially only focus on calculating and presenting the carbon footprint in an easily understandable manner but may later be extended to include other environmental impacts.

The IST framework (Fig. 1) primarily consists of two stages. Stage one involves the use of remotely sensed data originating from the satellite images and aerial photographs as an input to a GIS. In the GIS other data layers such as paddock and farm boundaries, corresponding rainfall, temperature, soil types and administrative shire boundaries are stored. Stage two involves the application of a Streamlined LCA (SLCA)-based approach to calculate the carbon footprint of the paddock. The SLCA approach has been considered as current research which considered cradle-to-gate studies, ignored activities after the production stage (Todd and Curran, 1999). This carbon footprint is integrated with RS-based GIS so that CP strategies are able to be identified as mitigation measures for the quantification of environmentally benign and cost-effective farm management practices for the selected paddocks.

RS is defined as the science and art of obtaining information about various objects (targets) on earth with the help of a device placed onboard a number of aerial and space-borne platforms. Remotely sensed data are being used worldwide for a number of agricultural and livestock applications including crop area estimation, crop type identification, crop yield estimation and crop sequence monitoring and pastures growth rates (Lillesand et al., 2004; Mkhabela et al., 2011; Mo et al., 2005; Peña-Barragán et al., 2011; Yang et al., 2011; Donald et al., 2012). GIS on the other hand, has emerged as a tool for capturing, editing and analysing multi-layered environmental and ancillary data layers along with its geographic location and temporal variation. This tool enables diversified users to establish and analyse scientific relationships between different data layers entered into the database (Lillesand et al., 2004). Integration of RS data with GIS enables the user to generate varied scale outputs. These outputs may vary across paddock,[1] farm,[2] shire,[3] and larger,[4] administrative boundaries and can be used to illustrate a wide variety of geo-referenced data layers such as agricultural practices, climatic zones, soil types, agricultural crops and pasture types and its temporal and spatial distributions. It has also been used to model GHG emissions from Chinese rice paddies (Yao et al., 2006) and the annual direct biogenic GHG emissions from the European agriculture (Freibauer, 2003).

[1] A paddock is field or plot of land, on a farm, enclosed by fencing or defined by natural boundaries. Livestock or different crops can be raised or grown on each (Oxford, 2013).

[2] A farm is an area of land (within the shire) and its buildings, used for growing crops and rearing animals (Oxford, 2013).

[3] A shire is a rural district having its own local council (Dict, 2013). Each state and territory is made up of a number of shires.

[4] The administrative boundaries of Australia are made up of the six states with their own constitution, namely Western Australia, New South Wales, Queensland, South Australia, Tasmania, Victoria and two states with limited self-governance, namely Australian Capital Territory Northern Territory (AusGov, 2013).

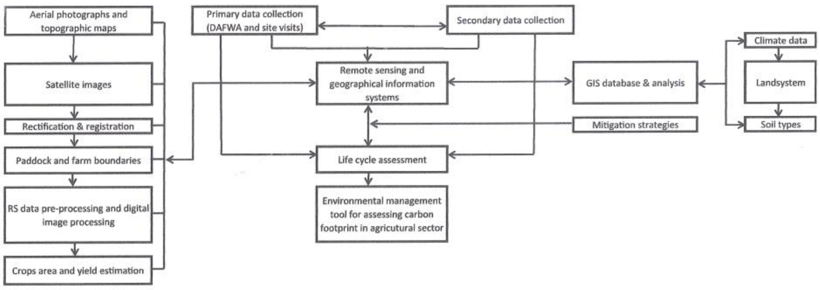


Fig. 1. Flow diagram showing Integrated Spatial Technology Approach.

LCA is a tool for the systematic evaluation of the environmental impacts of a product or service system through all stages of its life cycle i.e. from the raw material acquisition, through production and use to waste management. It is used to evaluate and implement opportunities to bring about environmental improvements by comparing existing products and developing new products (ISO, 2006). It has been used by various researchers in the agricultural sector to investigate aspects such as N_2O emissions from nitrogen fertiliser applications, methane emissions from livestock, CO_2 emissions arising from agricultural energy use, CO_2 emissions from vegetation sinks and the manufacture of products such as corn chips following the production of maize (Barton & Biswas, 2008; Barton et al., 2011; CLAN, 2006; Grant and Beer, 2008; GRDC, 2011). The SLCA (Streamlined LCA) is accomplished by limiting the scope of the study (e.g. determining the GHG emissions from one tonne of wheat production instead of one loaf of bread production) in order to support decision making for a particular group (Todd and Curran, 1999). The current research has applied this SLCA approach to enable grain growers, who are in the middle of the supply chain, to take appropriate strategies for mitigating GHG emissions from grain production.

There are other environmental impacts, such as eutrophication, acid rain, eco-toxicity, water pollution, which may result from the production of these products, (Adler et al., 2007; Finnveden et al., 2009) however, only global warming impacts have been considered because of governments recent climate change policy (carbon pricing) and Australia's commitment for meeting GHG emission targets (DCC, 2006). Like Finkbeiner et al. (2011), this research considers carbon footprints in terms of an LCA, with the limited focus on one impact category only, i.e. climate change. All methodological requirements and principles of the LCA can be applied to estimate carbon footprints, as evidenced by local and international literature (Biswas et al., 2008, 2010, 2011; Brock et al., 2012; Grant and Beer, 2008; Finkbeiner et al., 2011; Ghafooria et al., 2006; Gunady et al., 2012; Kim et al., 2009).

Cleaner production attempts to reduce wastes and emissions at the source by making more efficient use of natural resources. CP production is the continuous application of an integrated preventative environmental strategy to process, products and services to increase efficiency and reduce risks to humans and the environment (Van Berkel, 2002). Prevention practices generally employed to bring about CP are product modification (on site processing), input substitution (use of alternatives), technology modification, good housekeeping (reduction of energy, raw materials etc.) and recycling and reuse (packing material, water) (Biswas et al., 2010; Van Berkel, 2002; Van Berkel, 2007). By integrating CP into the IST framework, users could select alternatives which focus on one or more of the above mentioned practices. Thereby they should be able to ascertain whether, for example, by choosing an alternative product, or a product using a different production method, their carbon footprint could be altered.

The following sections present the development of the IST framework, the testing of the framework using a hypothetical example, the results obtained for the hypothetical example and conclusions and recommendations.

2. Methods and materials

The methodology is presented as two separate sections. In the first section the theoretical IST framework methodology is explained and the progress in the development thereof detailed. The second section makes use of data from a case study to illustrate the workability of the IST framework.

2.1. Outline of the integrated spatial technology framework methodology

Currently, the above mentioned IST framework is being developed in collaboration with the Department of Agriculture and Food Western Australia (DAFWA) and some farmers in the central Wheatbelt region of WA. This IST framework involves three key steps i.e. data collection, data processing and data integration.

Prior to and divorced from the IST development, DAFWA initiated a comprehensive crop sequencing project involving 144 paddocks located across different rainfall zones of WA. This crop sequencing project is scheduled to collect and analyse data over a period of five years (2010–2015). To ascertain a true picture of the factors of production used and specific management practices applied for the production of agricultural crops, structured questionnaires were prepared by the DAFWA field staff and distributed (for years 2010–2012) to all participating farmers for each selected paddock. These questionnaires provide data on critical aspects of farming and farm management practices such as paddock and farm details, land preparation methods, seed and sowing information, farm machinery use, chemical use, fertiliser use, crop rotations and the consequent crop yields obtained specific to the adopted farm management practices.

For the evaluation of the IST framework, 44 paddocks were selected by DAFWA from the initial 144 paddocks and geographic locations provided. The geographic locations for these 44 paddocks were registered on two medium resolution SPOT (Systeme Pour l'Observation de la Terre) satellite images acquired in September

2012. This registration allowed for the identification of a final sample of 24 paddocks (nine farmers) falling within the boundaries of the satellite images.

DAFWA provided the crop sequencing questionnaires to be used in the IST framework validation for this final sample of 24 paddocks. All applicable data was extracted from the crop sequencing questionnaires and an additional primary data collection questionnaire was generated and distributed. This second questionnaire addressed data required for the IST framework that was not included in the initial crop sequencing questionnaire. Overall the data requirements from both questionnaires included detailed information (paddock-wise) on the inputs used and management practices applied for the production of different crops for 2010–2011. Additionally, face to face interviews and field site visits were scheduled (November 2012) to discuss these questionnaires and to collect field data using a hand-held GPS and multispectral radiometer. These field-based data sets will be used as an input for the classification of remotely sensed data i.e. the identification and mapping of agricultural crops at specific paddock and farm levels as well as for input for carbon footprint calculations in the SLCA.

The second step of the IST framework focuses on the processing of the collected data in three tiers. Firstly, using advanced digital image processing methods and GIS analysis, a series of ground control points will be identified in 2013, from the satellite images, aerial photographs and 1:50 000 topographic maps of the study area. This will enable the accurate demarcation of individual paddocks and farm boundaries on remotely sensed images. This in turn will allow the application of advanced image classification techniques (Lillesand et al., 2004) for the identification, mapping, quantification and accuracy assessment of agricultural crops sown by the participating farmers during the 2012 crop calendar. With the advent of medium to high resolution remotely sensed images with improved spatial (sub-meter) and spectral resolution, and the introduction of advanced digital image processing techniques, this has enabled scientists to accurately identify and map agricultural crops at paddock and farm level (Ahmad, 2010; Ahmad et al., 2010).

Secondly, working in a GIS environment, the RS data based crops classification results will be cross-checked (overlayed) with the paddock-wise detailed information provided by the participating farmers and the ground-data collected during field surveys. Using the above mentioned data layers, the subsample i.e. 24 paddocks will be stratified according to the rainfall gradient, soil type and specific farm management practices such as minimum till, crop rotation etc., adapted for the production of agricultural crops (e.g. wheat, barley, lupin, peas and oats etc.). This attempt will result in an inventory list describing full details of inputs used and outputs produced at a paddock and or farm level along with the details of farm management practices applied.

Thereafter, in the next tier, the following four steps were conducted to carry out the SLCA (Biswas et al., 2008; Gunady et al., 2012): 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation (as presented in the 'Results' section of this paper).

The goal was to mitigate the GHG emissions from the grain production under different soil and climatic conditions. This was achieved by establishing the functional unit, which is the production of one tonne of grain. This functional unit helps carry out a mass balance for developing a life cycle inventory (LCI). A life cycle inventory (LCI) consists of totalling the amount of each input (e.g. fertilizers, pesticides, machinery etc.) and output (e.g. crop yield, emissions) for processes which occur during the life cycle of a product. Undertaking an LCI is a necessary initial step in order to carry out a carbon footprint analysis.

The input and output data in LCI were inserted into the Simapro 7.3 software, a software program developed by Pré -Consultants in the Netherlands, to calculate GHG from, or carbon footprint of wheat production. The carbon footprint assessment of wheat production for pre-farm and on-farm activities included two stages. The first calculated all the GHG emissions produced in each process and the second converted these gases (CO_2, CH_4, N_2O) to CO_2 equivalents (Biswas et al., 2008). The input/output data of LCI were linked to relevant emission databases in Simapro 7.3. The Australian GHG emission database for agricultural inputs will be used to calculate the GHG emissions from the grain industries. Where emission factors are not available in the Australian database, other databases such as the EcoInvent database or CML methodology, will be used as surrogates for calculating equivalent values, alternatively equivalent values will be calculated using manufacturer supplied data. As part of the SLCA approach flow diagrams will be generated to illustrate all inputs used (e.g. fertilizers, pesticides, machinery etc.) and outputs produced (e.g. crop yield, emissions) in the life cycle stages of crops production. Normally an impact assessment assesses about nine environmental impacts and forms part of the SLCA, but will not be included here as the focus is on global warming impact (or carbon footprint) only. The SLCA has been used here as a tool to capture all GHG emissions in the product cycle.

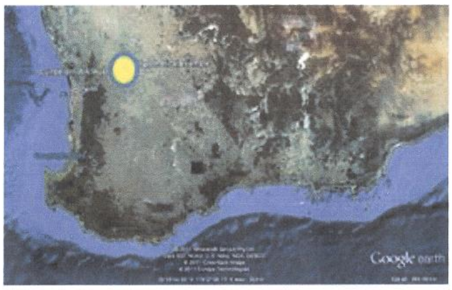
The last stage of this framework involves the integration of carbon footprint information with the RS- and GIS-based database. This will allow for the identification and reporting of the geographic location of the most significant "hotspots". Such a database also allows the scientific analysis and evaluation of the alternative mitigation measures pertinent to different production zones. Finally, the LCI-based data will be fed into a RS and GIS database to determine and map the spatial distribution of agricultural system related carbon footprints for different zones prevalent in the sample used. Such a consolidated IST database analysis will assist in generating geo-referenced hotspots (carbon footprints) for the selected paddocks and farms. The final output may be produced, using colour graduated schemes or bar graphs for the agro-ecological zone, farm management practices and corresponding carbon footprints.

The above mentioned approach provides a feasible framework to accurately identify and quantify dynamic carbon footprints. Therefore with IST, natural resource managers will be equipped with a tool to evaluate alternative mitigation strategies for different agro-ecological and environmental zones, enabling thereby reduced carbon footprints with a minimum level of GHG emissions and the identification of CP strategies to be incorporated into the WA production system pertinent to specific agronomic environments.

2.2. Application of IST methodology to an existing case study

Workability of the above explained IST framework was evaluated for the identification of appropriate farm management practices for wheat production in a WA based case study. This was carried out by using datasets associated with a previously completed study by Biswas et al. (2008), here named as the baseline study. The datasets involved are pertinent to a small paddock area and may not be representative of a larger West Australian based zone but are considered sufficient to test IST workability.

Using the given geographical co-ordinates from Biswas et al. (2008) the generalised location of the study area was identified using RS methods (Fig. 2a) and marked with a yellow circle. By clicking on the yellow marker and allowing the software to enlarge (zoom in) the area, the detailed location and shape of the paddock was highlighted (Fig. 2b). In Biswas et al. (2008) the area was identified as having a semi-arid climate with an annual rainfall of 368 mm, which mainly falls in the winter months. Mean daily temperatures varied between 11.4 and 25.1 °C. The soil is free



a) Geographic location of the base line study area in Western Australia.

b) Exact location of the paddock used for the baseline study.

Fig. 2. Geographic location of the baseline study paddock.

draining sandy soil overlying poor draining clay (Biswas et al. (2008). In the IST framework, as different data layers and attribute data sets are geo-referenced, just by "clicking" on the yellow circle users would be able to display the full features of the target study area in terms of its exact location, size, soil type, rainfall, crops grown, management practices applied etc.

For this paddock Biswas et al. (2008) quantified CO_2, N_2O and CH_4 emissions associated with per tonne of wheat produced at the[5]pre-farm,[6]on-farm stages and[7]post-farm stages of production. In testing the IST framework only the pre-farm and on-farm stages were considered (Fig. 3). In the pre-farm stage the production of inputs (fertiliser, pesticides etc.), transportation of inputs and manufacture of farm machinery were quantified. In the on-farm stage, land preparation, the use of farm machinery and paddock emissions were studied (Biswas et al., 2008) (Fig. 2a–b). The goal and scope for this project was the reduction of the carbon footprint resulting from the WA grain industry and was limited to pre-farm and on-farm (cradle to gate) activities. The system boundary was determined to be a specific paddock in the agricultural region of Cunderdin, Western Australia (WA), as referred to above. For the baseline study, the functional unit (e.g. GHG emissions from 1 tonne of wheat production from 0.37 ha) was fixed and the corresponding factors of production and data requirements (i.e. chemicals, energy, emissions etc.) decided on (Biswas et al., 2008).

In compiling and calculating the inventory the relevant emission factors were mostly obtained from the Australian Life Cycle Inventory database for the production of chemical inputs such as pesticides and fertilisers. As no emission factor was available for super-phosphate it was generated by obtaining required information from the phosphate manufacturer. A USA input–output database was used to assess the GHGs from the manufacture of farm machinery and the Australian LCA database was used for farm machinery operation (Biswas et al., 2008). The CO_2, N_2O and CH_4 emissions of inputs and outputs were converted to CO_2 equivalents (CO_2-e) by multiplying the measured value with the current conversion factors, (1 for CO_2, 25 for CH_4 and 298 for N_2O) (CC, 2013; IPCC, 2007a). These CO_2-e values of all inputs and outputs were then summed to determine the resulting carbon footprint. These CO_2–e values of inputs and outputs enabled the identification of 'hotspots' or inputs or outputs causing the significant emissions.

Associated literature review (Biswas et al., 2011; Chadwick et al., 2011; Hansen et al., 2006), presented two options that could be used to reduce GHG emissions from the baseline study. Option 1 included the use of organic fertiliser in the pre-farm stage, whereas option 2 involved crop rotation methods in the on-farm stage. Both of these options were applied for validating the workability of the IST framework.

Option 1 applied *input substitution*, i.e. the substitution of urea with organic fertilizer such as pig manure containing an equivalent amount of nitrogen. Data on GHG emissions during the anaerobic production of the pig manure were extracted from Hansen et al. (2006) and Chadwick et al. (2011). This data were applied to the baseline study with the underlying assumption that the pig manure produced is in close proximity to the paddock in question, the manure was distributed on the land using the same machinery used for fertiliser spreading and wheat yield was assumed to be the same as in the baseline scenario.

Option 2 considered wheat rotation with legumes (lupins) which is regarded worldwide as an established source of enhancing nitrogen in the soil (Shah et al., 2003; Biswas et al., 2011), termed a *good housekeeping* CP strategy (Biswas et al., 2011). The sowing of wheat after lupins harvest allows for the reduced application of urea fertilizer (Shah et al., 2003). For the baseline study, research reported by Bowden and Burgess (1993) was used for assessing this mitigation strategy. It was assumed that the lupins yield on the paddock was 1.2 t/ha and the residual organic nitrogen from the lupin totalled 46 kg N/ha, thus for the following year the urea fertilizer usage could be reduced by 15.84%.

Using the geo-referenced location from the baseline study, the calculated values from both Option 1 and Option 2 were separately integrated into the RS and GIS based database. This allowed for the mapping of the carbon footprints of both options thus generating three datasets (baseline study, option 1 and option 2). These three datasets allowed the comparative analyses of all three options using the same consolidated output method.

3. Results

As to date there are no results available for the DAFWA-collaborated study, only the results for the validation of the IST framework, using a hypothetical example (integrated with a case study), are presented here.

The results obtained in the baseline study are tabulated in Table 1. These results show that most of the GHG emissions were generated in the pre-farm stage (134.34 kg CO_2-e vs 133.51 kg

[5] Pre-farm includes all processes, such as soil preparation, chemical production, machinery production, chemical applications etc. required up to the sowing of the seed.

[6] On-farm includes all emissions resulting from the growing of the crops as well as the use of required machinery for chemical applications and harvesting.

[7] The post-farm stage includes emissions resulting after the harvesting of the crop for e.g. from electricity required for storage purposes.

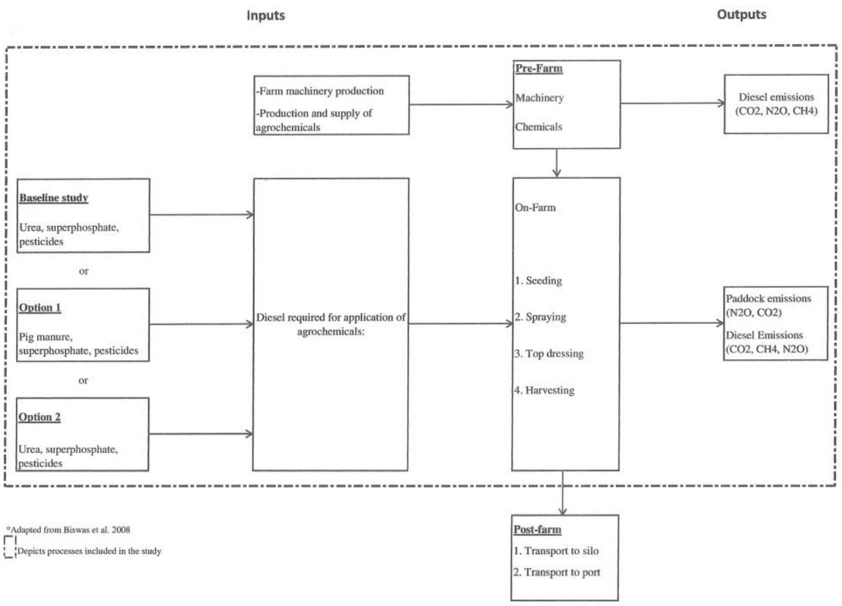


Fig. 3. Life cycle inventory diagram showing the inputs and outputs for the pre-farm and on-farm stages.

CO_2-e). In this stage the production and supply of urea was identified as a 'hotspot' (it has the highest overall GHG emissions) i.e. 37.48% of the total GHG emissions and 74.73% of the pre-farm GHG emissions. In order to reduce these GHG emissions the use of urea fertilizer required further investigation. In the on-farm stage, the CO_2 emissions from the paddock soil were due to urea hydrolysis and amounted to the highest of the on-farm emissions i.e.81 kg CO_2-e or 60.67%. The examination of alternative mitigation measures which focused on the reduction of GHGs generated from the use of urea was therefore required.

Using input substitution the use of pig manure as fertiliser was considered for option 1 as expounded upon previously. Table 2 presents the results obtained when urea is substituted with pig manure in the same farming practice as the baseline study. Overall

Table 1
Total carbon footprint for each of the agricultural stages in the baseline study.

Stages	Baseline						Total kg CO_2-e
	Greenhouse gases			kg CO_2-e[a]			
	CO_2 (kg)	N20 (kg)	CH4 (kg)	CO_2 kg CO_2-e	N2O	CH4	
Pre-farm							
Farm Machinery Production	0.93	5E-05	1E-04	0.93	0.01	3E-03	0.95
Production and supply of urea	79.25	0.05	0.25	79.25	14.90	6.25	100.40
Production and supply of superphosphate	2.93			2.93			2.93
Production and supply of pesticide	17.15	0.04	0.04	17.14	11.92	1.00	30.06
Subtotal	*100.26*	*0.09*	*0.29*	*100.25*	*26.83*	*7.25*	*134.34*
On-farm							
N2O emissions from paddock (Barton and Biswas, 2008)		0.09			26.82		26.82
CO_2 emissions from paddock (IPCC, 2006)	81.00			81.00			81.00
Diesel supply and utilization for spraying ferilizer	4.65	1E-04	6E-04	4.65	0.03	0.02	4.69
Diesel supply and utilization for spraying herbicide	2.32	5E-05	3E-04	2.32	0.01	0.01	2.34
Diesel supply and utilization for spraying seeds	9.24	2E-04	1E-03	9.24	0.06	0.03	9.32
Diesel supply and utilization for harvesting	9.24	2E-04	1E-03	9.24	0.06	0.03	9.32
Subtotal	*106.45*	*0.09*	*3E-03*	*106.45*	*26.98*	*0.07*	*133.51*
Grand totals	206.71	0.18	0.29	206.70	53.82	7.33	267.84

[a] kg CO_2-e: Carbon dioxide equivalent.

Table 2
Calculated carbon footprint resulting from the use of mitigation strategies – option 1, product substitution.

Stages	Option 1						Total kg CO_2 equ-
	Greenhouse gases			kg CO_2 equ-			
	CO_2	N_20	CH_4	CO_2	N_2O	CH_4	
	(kg)	(kg)	(kg)	kg CO_2 equ-			
Pre-farm							
Farm Machinery Production	0.93	5E-05	1E-04	0.93	0.01	3E-03	0.95
Production and supply of manure	22.91	0.05	0.75	22.91	14.21	18.68	55.80
Production and supply of superphosphate	2.93			2.93			2.93
Production and supply of pesticide	17.15	0.04	0.04	17.14	11.92	1.00	30.06
Subtotal	*43.92*	*0.09*	*0.79*	*43.91*	*26.15*	*19.68*	*89.73*
On-farm							
N_2O emissions from paddock (Barton and Biswas, 2008)		0.51			152.43		152.43
CO_2 emissions from paddock (IPCC, 2006)							0.00
Diesel supply and utilization for spreading manure	4.65	1E-04	6E-04	4.64	0.03	0.02	4.68
Diesel supply and utilization for spraying herbicide	2.32	5E-05	3E-04	2.31	0.01	0.01	2.33
Diesel supply and utilization for spraying seeds	9.24	2E-04	1E-03	9.23	0.06	0.03	9.31
Diesel supply and utilization for harvesting	9.24	2E-04	1E-03	9.23	0.06	0.03	9.31
Subtotal	*25.45*	*0.51*	*3E-03*	*25.41*	*152.59*	*0.07*	*178.07*
Grand totals	69.37	0.60	0.79	69.32	178.74	19.75	267.81

*kg CO_2-e: carbon dioxide equivalent.

the results show that there is an insignificant change in the total CO_2-e when urea is substituted with pig manure, 267.84 kg CO_2-e vs 67.81 kg CO_2-e. However on closer inspection there is a reduction of 44.61 kg CO_2-e in the pre-farm stage and an increase of 44.56 kg CO_2-e in the on-farm stage.

In option 2 the use of lupins as a crop rotation was considered, this allowed for the reduction in the application of urea. The results (Table 3) reveal an overall GHG emissions decrease of 5.38% when compared to the baseline study. In this scenario the GHGs from the on-farm stage decreased from 133.51 kg CO_2-e to 119.93 kg CO_2-e (10.17%) and in the pre-farm stage from 134.34 kg CO_2-e to 133.50 kg CO_2-e (0.63%).

The results from all three options were entered into the IST for the generation of the output as depicted in Figs. 4 and 5, and as discussed above. In Fig. 4 a–c graphs are generated to facilitate the identification of the hotspots. In Fig. 4a the CO_2 emissions from chemicals (production and supply) accounts for 50% of the total emissions or 99.3 kg CO_2-e. Fig. 4b portrays the emissions from option 1 in which manure replaces urea. It can be seen that the N_2O emissions from the paddocks is the highest in this scenario (52.4 kg CO_2-e or 57%). In option 2, using a lupin-wheat rotation to reduce the use of urea, 99.3 kg CO_2-e for CO_2 emissions for chemical production and use is generated (52%).

The final figure (Fig. 5) generated by the IST illustrates the pre-farm, on-farm stages and total CO_2-e emission values for all three options on one axis for comparison purposes. In this figure it is clear that in the pre-farm stage Option 1 has the least emissions (90 kg CO_2-e), in the on-farm stage Option 2 emits the least GHGs (120 kg CO_2-e) and overall the total GHG emissions for option 2 is the lowest (253 kg CO_2-e).

4. Discussions

The following discussion is based on the results obtained during the validation of the IST framework using the hypothetical example. As this study has not been carried out with the intention to explain the reasons behind the change in results, no explanation

Table 3
Calculated carbon footprint resulting from the use of mitigation strategies – option 2, crop rotation.

Stages	Option 2						Total kg CO_2 equ-
	Greenhouse gases			kg CO_2 equ-			
	CO_2	N_20	CH_4	CO_2	N_2O	CH_4	
	(kg)	(kg)	(kg)	kg CO_2 equ-			
Pre-farm							
Farm Machinery Production	0.93	5E-05	1E-04	0.93	0.01	3E-03	0.95
Production and supply of urea	66.70	0.05	0.21	79.25	15.05	5.26	99.56
Production and supply of superphosphate	2.93			2.93			2.93
Production and supply of pesticide	17.15	0.04	0.04	17.14	11.92	1.00	30.06
Subtotal	*87.71*	*0.09*	*0.25*	*100.25*	*26.98*	*6.26*	*133.50*
On-farm							
N_2O emissions from paddock (Barton and Biswas, 2008)		0.09			26.82		26.82
CO_2 emissions from paddock (IPCC, 2006)	68.17			68.17			68.17
Diesel supply and utilization for spraying fertilizer	3.91	8E-05	5E-04	3.91	0.03	0.01	3.95
Diesel supply and utilization for spraying herbicide	2.32	5E-05	3E-04	2.32	0.01	0.01	2.34
Diesel supply and utilization for spraying seeds	9.24	2E-04	1E-03	9.24	0.06	0.03	9.32
Diesel supply and utilization for harvesting	9.24	2E-04	1E-03	9.24	0.06	0.03	9.32
Subtotal	*92.88*	*0.09*	*3E-03*	*92.88*	*26.98*	*0.07*	*119.93*
Grand totals	180.59	0.18	0.25	193.13	53.96	6.33	253.4

*kg CO_2-e : carbon dioxide equivalent.

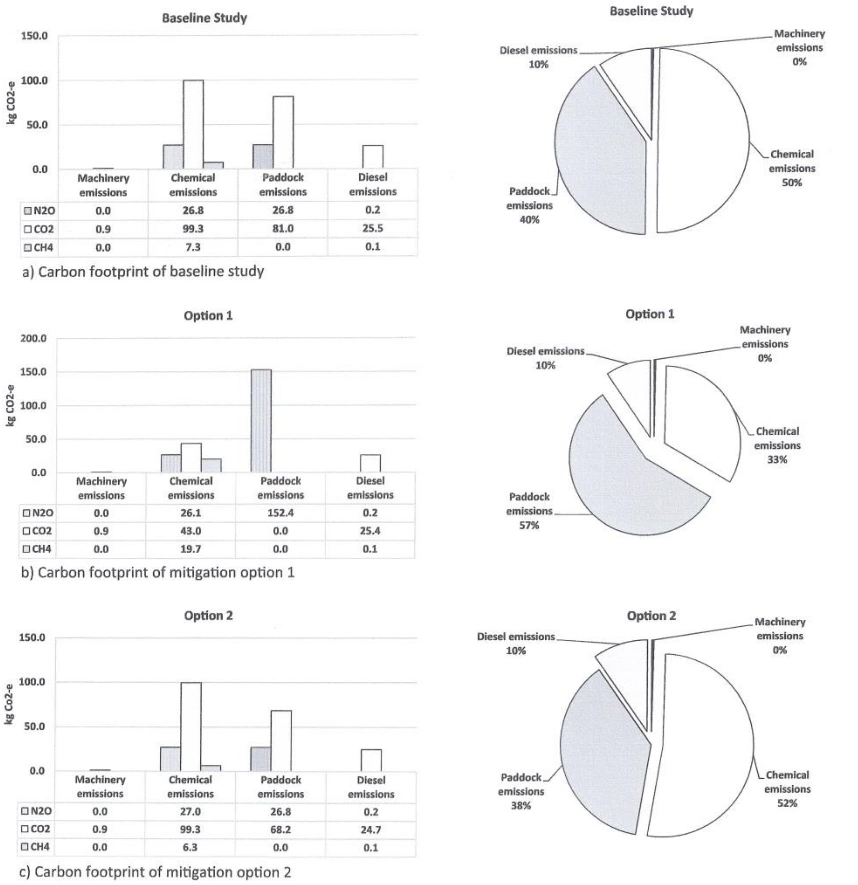


Fig. 4. IST framework database output.

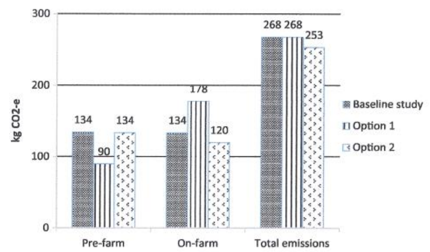


Fig. 5. Comparative GHG output for the pre-farm, on-farm and total emissions.

is given as to why there is a change in the emissions. The discussions focus on the workability of the IST framework.

The hypothetical testing of the IST framework, using a case study and calculated results from other projects, shows the successful integration of RS, GIS and SLCA with CP as mitigation measures. Fig. 3a and b respectively show the location and shape of the paddock in question. Further multi-layer data manipulation of these figures could, for example, highlight unique characteristics of the study area. These characteristics could include amongst others soil type, management practices adapted, crop sequence used and/or the rainfall/temperature gradient for the study area.

The graphical output in the IST framework (Fig. 4 a–c and Fig. 5) was generated by clicking on the yellow circle in Fig. 2b. The graphs highlighted in Figs. 4–5 are based on the calculated results presented in Tables 1–3.

In each of the Fig. 4 a–c the bar graph presents the GHG emissions for the baseline study, option 1 and option 2 by source (machinery, chemical (includes agro-chemicals and fertilisers), paddock and diesel emissions) and GHG emissions (CO_2, N_2O and CH_4). The baseline study results (Fig. 4a) revealed that, the production of chemicals (including fertilisers) resulted in the highest emission of CO_2 as CO_2-e (99.3 kg CO_2-e). Option 1 (Fig. 4b), showed N_2O emissions originating from the paddock as the hotspot (152.4 kg CO_2-e) whereas option 2 (Fig. 4c), revealed chemical (including fertilisers) associated CO_2 emissions (99.3 kg CO_2-e) as the highest. When examining the baseline study (Table 1) it was observed that the CO_2 emissions accounted for 77.2% of the total GHG emissions. It was also apparent that by altering one aspect in the production line it could change the consequent emissions of the individual GHGs. For example, by substituting N-fertilizer with an organic fertiliser the GHG paddock emissions may increase, but the GHG emissions from the other input agrochemicals decrease. Alternatively, by using crop sequencing methods (option 2) GHG chemical emissions may increase but GHG emissions from the paddock decrease.

Each emission category is also depicted as a part of a pie graph in Fig. 4a–c. In each graph the CO_2-e are summed across all categories and shows GHG percentage contribution. By presenting the data as a pie graph the user is able to recognise the emission category with the most GHGs at a glance. For the baseline study the emissions arising from chemical production was the highest (50%). For option 1 the paddock emissions resulted in 57% of the total emissions and in option 2, the overall emissions from the production of chemicals (which includes fertilisers) was also the highest (52%).

The analytical view of the bar graphs in Fig. 4, reveal that the IST framework is a tool that can assist with the identification of the hotspots at micro (paddock) level and highlights the impact of alternative mitigation measures applied in reducing GHG emissions.

In Fig. 5, nine resultant bars are grouped into the two stages namely pre-farm and on-farm GHG emissions and the third set of bars represents the sum of the GHG emissions from these two stages as CO_2-e. Analysis of the first set of bars (pre-farm) reveals that the highest GHG emissions are attributed to option 2 in the baseline study. As Option 1 generates the least GHG emissions the user could conclude that using pig-manure in the pre-farm stage would aid with the reduction of GHGs. The second set of bars represents the on-farm stage, with the highest emissions generated when pig manure is used and the least GHG emissions resulting from the use of a crop rotation system. As these results appear to be contradictory, the third set of results could be considered as they illustrate the sum of all of the stages. In this scenario the user could deduce that if crop rotation systems were used to produce the same amount of wheat, on the same area of land, as in the baseline study, the GHG emissions could be reduced by 9.4% (12 kg CO_2-e).

For this hypothetical example it can thus be concluded that by using the IST an alternative mitigation method could be selected. In this scenario it is apparent that if an alternative mitigation method was to be considered for the baseline study agricultural practice, that option 2 should be preferred over option 1.

5. Conclusions and recommendations

The introduction of Clean Energy Act 2011 and the CFI precipitates a need for the development of tools designed to assess mitigation measures in Agriculture. In this study an IST framework has been presented in which RS, GIS and SLCA are integrated to highlight carbon footprint hotspots and as a means for identifying the underlying contributing factors. The key feature of the proposed framework is its ability to be applied on a micro scale (paddock and/or farm level). This enables individual property holders to make a strategic decision to evaluate their farming activities thereby facilitating with the alteration of farming practices to reduce GHG emissions.

Theoretically, the IST framework has been developed to integrate environmental management tools to generate output which summarises various scenarios. It offers an alternative tool that can assist farmers with the identification of the hotspots at micro and macro level and shows that if mitigation measures are identified and applied, it could aid the farmer in reducing GHG emissions. Moreover when the data is broken down into smaller categories (e.g. chemical emissions, machinery emissions etc.) and the corresponding layers are generated for each of these categories, it could eventually even aid with the identification of other aspects (such as individual contribution to GHGs, eutrophication and other impacts) at a paddock level to larger scales. Other advantages include multi-layer data manipulation, for example the study area can be highlighted as per its unique characteristics such as mapping by soil type, management practices adapted, crop sequence used and/or the rainfall/temperature gradient in which the study area falls.

Considering the current carbon-constrained economy, the framework has been developed to address only carbon footprint modelling, but has the potential to include other relevant impacts identified during the SLCA. These impacts could include aspects such as water scarcity, land use changes etc., and may also be applied to other primary industries sectors such as livestock and horticulture. It is envisaged that in future, the proposed IST framework may encourage the development of PC, PDA or iPhone based automated tools. Furthermore, future research could improve this framework by incorporating an economic analysis for determining the cost-effective GHG mitigations strategies.

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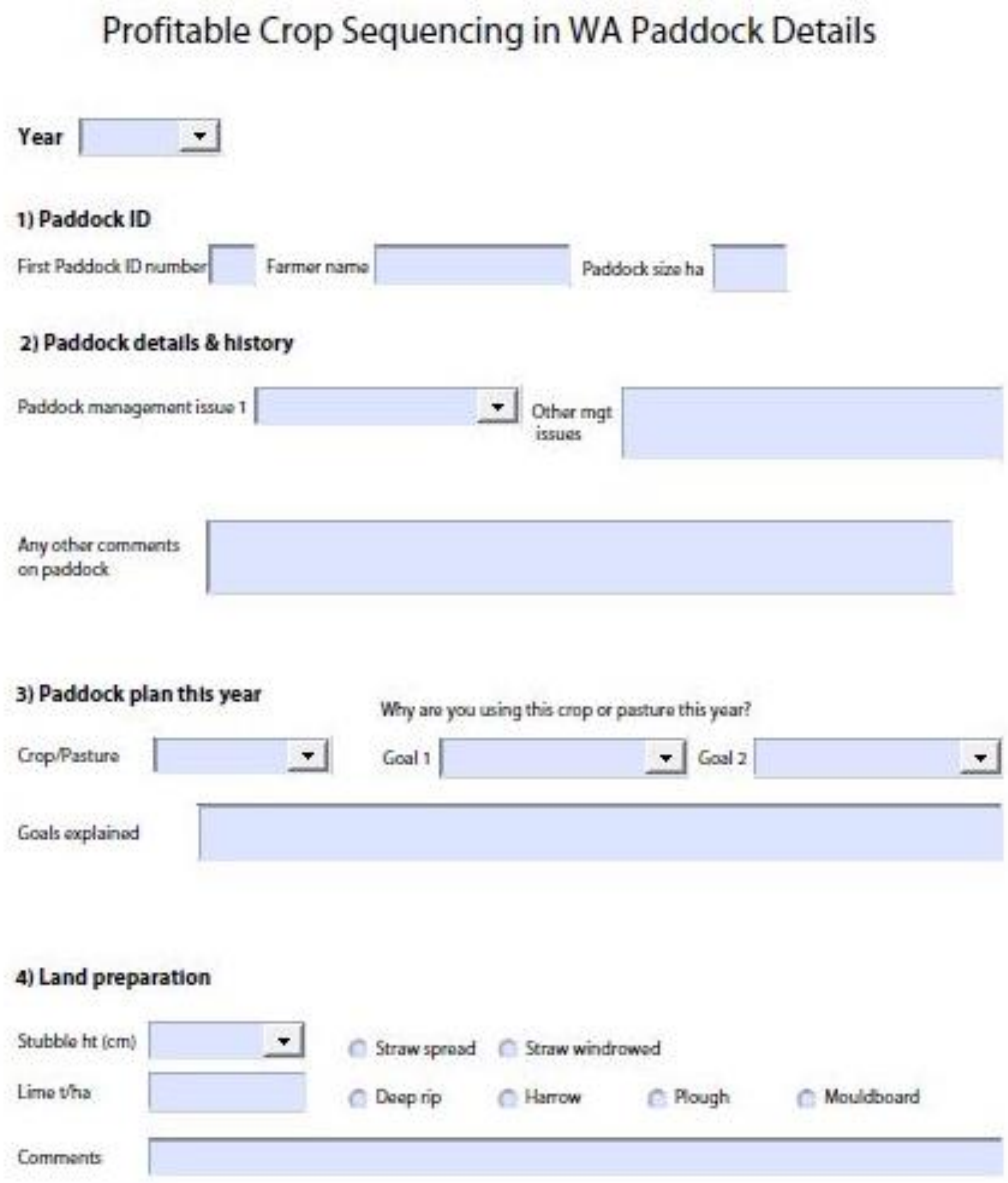
APPENDIX B

TEMPLATE OF CROP SEQUENCING QUESTIONAIRE FROM DAFWA



Profitable Crop Sequencing in WA Paddock Details

Year

1) Paddock ID

First Paddock ID number | Farmer name | Paddock size ha

2) Paddock details & history

Paddock management issue 1 | Other mgt issues

Any other comments on paddock

3) Paddock plan this year

Why are you using this crop or pasture this year?

Crop/Pasture | Goal 1 | Goal 2

Goals explained

4) Land preparation

Stubble ht (cm) | Straw spread | Straw windrowed

Lime t/ha | Deep rip | Harrow | Plough | Mouldboard

Comments

5) Stock management

Stock numbers Breed Stock class Date in Date out

Stock numbers Breed Stock class Date in Date out

Stock numbers Breed Stock class Date in Date out

Stock numbers Breed Stock class Date in Date out

Stock numbers Breed Stock class Date in Date out

Stock numbers Breed Stock class Date in Date out

Supplemental feeds

Sup feed 1 Amount per day Days Lick Trail

Sup feed 2 Amount per day Days Lick Trail

6) Seed

Variety Germination % Certified Nutrient conc test Disease tested

Rhizobia inoculation Peat or granular Rate L or kg per T

Comments

7) Planting machinery

Knife point Disc GPS guidance used Seed placed between last years rows

Full cut Harrow Culti-trash Variable rate Row spacing(cm)

Comments Total metres seeding bar, farm

8) Crop establishment

Seed rate kg/ha Sowing date Establishment date

Soil moisture at sowing Establishment conditions

Rating of establishment Very poor Poor OK Good Excellent

Comments

9) Fertiliser

Fert 1 name | Application date | Placement | Rate kg or L/ha
N% P% K% S% Ca% Mg% Cu% Zn% Mo% Mn%

Fert 2 name | Application date | Placement | Rate kg or L/ha
N% P% K% S% Ca% Mg% Cu% Zn% Mo% Mn%

Fert 3 name | Application date | Placement | Rate kg or L/ha
N% P% K% S% Ca% Mg% Cu% Zn% Mo% Mn%

Fert 4 name | Application date | Placement | Rate kg or L/ha
N% P% K% S% Ca% Mg% Cu% Zn% Mo% Mn%

Fert 5 name | Application date | Placement | Rate kg or L/ha
N% P% K% S% Ca% Mg% Cu% Zn% Mo% Mn%

Did defficiency or toxicity limit yield? No Minor Moderate Severe Failure | Nutrient 1

Comments | Nutrient 2

10) Weed Management

Known Herb Resistance1 | Known Herb Resistance2

Known Herb Resistance3 | Known Herb Resistance4

Suspect Herb Resistance1 | Suspect Herb Resistance2

Target weed 1 [▼] Target weed 2 [▼] Target weed 3 [▼]

Integrated weed management (IWM) stratagies you used for this crop or pasture

IWM effectivness rating: Excelent, ok, none

Autumn ○ Paddock burn ○ Windrow burn — Burn effectivness [▼]

Autumn ○ Autumn Tickle ○ Delay sowing ○ Knock down ○ Double knock — KD effectivness [▼]

Spring ○ Swath hay or for harvest ○ Crop top ○ Spray top ○ Fallow — Seed set control [▼]

Harvest ○ Windrow — Chaff cart (capacity/T) [▼] ○ Destructor — Seed capture [▼]

IWM Comments [ ]

Herbicide comments [ ]

Did weeds in crop/pasture limit yield? ○ No ○ Minor ○ Moderate ○ Severe ○ crop/pastue failure

Which weeds? Weed 1 [▼] Weed 2 [▼] Weed 3 [▼]

11) Disease management

Target fungi1 [▼] Target fungi2 [▼]

Target nematode [▼] Target virus [▼]

Integrated disease management (IDM) practices done for this years crop or pasture

○ Control summer weeds ○ seed testing ○ Variety choice ○ Delay sowing ○ Tillage

○ Seed btw row ○ isolation from past stubble ○ Isolation from pasture paddocks ○ Retain stubble ○ Destroy stubble

How many years has it been since this crop or pasture species was grown in this paddock? [▼]

Distance from closest paddock of the same species (m) [▼]

IDM Comments [ ]

Did fungi, nemotodes or virus limit yield? ○ No ○ Minor ○ Moderate ○ Severe ○ crop/pastue failure

Suspected fungi/nematode/virus [ ]

Disease comments [ ]

12) Insect and other invertebrate pest management

Target insect/pest1 Target insect/pest2

Did invertebrate pests limit yield? No Minor Moderate Severe crop/pastue failure

Suspected invertebrate pest

Invertebrate pest comments

Pest control applications

Fungicide seed dressing

Product Rate g or ml/tonne

Fungicide in furrow

Product Rate g or ml/ha

Tank mix 1 Please use actual product if in list. If not use generics. Enter name of insecticide fungicide; or herb if required

Herb 1 Rate ml or g/ha

Herb 2 Rate ml or g/ha

Herb 3 Rate ml or g/ha

Herb 4 Rate ml or g/ha

Insectic Rate ml or g/ha

Insectic Rate ml or g/ha

Fungici Rate ml or g/ha

Other Rate ml or g/ha

Application time i.e.Summer Pre em, PSPE, Post, pre harvest

Application date

Application method Boom, plane, mist wick wipe

Crop stage Weed stage Efficacy Mix cost $/ha

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser setion

Tank mix 2

Herb 1		Rate ml or g/ha	
Herb 2		Rate ml or g/ha	
Herb 3		Rate ml or g/ha	
Herb 4		Rate ml or g/ha	
Insectic		Rate ml or g/ha	
Insectic		Rate ml or g/ha	
Fungici		Rate ml or g/ha	
Other		Rate ml or g/ha	

Application time i.e.Summer Pre em, PSPE, Post, pre harvest		Application date		Application method Boom, plane, mist wick wipe			
Crop stage		Weed stage		Efficacy		Mix cost $/ha	

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

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Tank mix 3

Herb 1		Rate ml or g/ha	
Herb 2		Rate ml or g/ha	
Herb 3		Rate ml or g/ha	
Herb 4		Rate ml or g/ha	
Herb 5		Rate ml or g/ha	
Insectic		Rate ml or g/ha	
Fungici		Rate ml or g/ha	
Other		Rate ml or g/ha	

Application time		Application date		Application method			
Crop stage		Weed stage		Efficacy		Mix cost $/ha	

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

Tank mix 4

Herb 1 Rate ml or g/ha

Herb 2 Rate ml or g/ha

Herb 3 Rate ml or g/ha

Herb 4 Rate ml or g/ha

Herb 5 Rate ml or g/ha

Insecti Rate ml or g/ha

Fungici Rate ml or g/ha

Other Rate ml or g/ha

Application time i.e.Summer Pre em, PSPE, Post, pre harvest

Application date

Application method Boom, plane mist wick wipe

Crop stage Weed stage Efficacy Mix cost $/ha

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

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Tank mix 5

Herb 1 Rate ml or g/ha

Herb 2 Rate ml or g/ha

Herb 3 Rate ml or g/ha

Herb 4 Rate ml or g/ha

Herb 5 Rate ml or g/ha

Insectic Rate ml or g/ha

Fungici Rate ml or g/ha

Other Rate ml or g/ha

Application time Application date Application method

Crop stage Weed stage Efficacy Mix cost $/ha

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

Tank mix 6

Herb 1 — Rate ml or g/ha
Herb 2 — Rate ml or g/ha
Herb 3 — Rate ml or g/ha
Herb 4 — Rate ml or g/ha
Herb 5 — Rate ml or g/ha
Insectic — Rate ml or g/ha
Fungici — Rate ml or g/ha
Other — Rate ml or g/ha

Application time i.e.Summer Pre em, PSPE, Post, pre harvest

Application date

Application method Boom, plane, mist wick wipe

Crop stage — Weed stage — Efficacy — Mix cost $/ha

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

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Tank mix 7

Herb 1 — Rate ml or g/ha
Herb 2 — Rate ml or g/ha
Herb 3 — Rate ml or g/ha
Herb 4 — Rate ml or g/ha
Herb 5 — Rate ml or g/ha
Insectic — Rate ml or g/ha
Fungici — Rate ml or g/ha
Other — Rate ml or g/ha

Application time — Application date — Application method

Crop stage — Weed stage — Efficacy — Mix cost $/ha

Note; if liquid fertiliser is a part of the tank mix please enter details in fertiliser section

13) Yield and quality grain and hay

Hectare yield t/ha | Paddock yield t/ha | Long term yield for this species

Grade | Protein % | Screenings | Stainings | Black point | Falling no

Oil % | Moisture % | Foreign material % | Unmillable % | Weeds

Hay yield kg/ha | Hay quality

Yield comments

Quality comments

14) Economics

Crop

Farm gate $/tonne (hay/grain)

Grain handling $/t

Variable costs ($/ha)

Paddock prep | Seed | Fertiliser

Pesticides | Herbicide | Fungicide | Insecticide

Machinery | Labour

Estimated total varaiable cost $/ha

Sheep

Wool Cut kg/head | Wool Cut Av. Micron

15) Decision making: Tactical management of this paddock in this year

When did you first decide what crop or pasture to use on this paddock?

Did the crop or pasture used change from the original decision?

If the paddock plan changed at sowing please answer the questions below

From what

To what

What was the major consideration?

Comments on tactics for this paddock

16) Farmer comments on paddock (open ended questions)

How did the paddock perform?

○ Very poor ○ Poor ○ Average ○ Good ○ Very good

Did you learn much from what happened in this paddock this year?

○ No ○ Unsure ○ Yes

What things of interest did you notice?

At the start of the yr you said your goal was xxx do you think you achieved it?

○ No ○ Unsure ○ Yes

Why or why not?

Would you use the same strategy again?

○ No ○ Yes

Why or why not

What are your thoughts on the paddock for next year?

Any other comments

17) Agronomists comments

Agronomists comments. Please note major observations

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APPENDIX C

QUESTIONAIRE FOR ADDITIONAL INFORMATION

General Information

Farmers name	Click here to enter text.
Contact details (telephone number and email address)	Click here to enter text.
Paddock name	Click here to enter text.
Location of paddock (co-ordinates)	Click here to enter text.
Size of paddock	Click here to enter text.
Average rainfall 2010 2011 2012	 Click here to enter text. Click here to enter text. Click here to enter text.
Do you use irrigation?	Yes ☐ No ☐
If yes give consumption in litres 2010 2011 2012	 Click here to enter text. Click here to enter text. Click here to enter text.

Crop information

Soil preparation methods 2010 2011 2012	 Click here to enter text. Click here to enter text. Click here to enter text.	
Crops grown 2010 2011 2012 Other (indicate for all years)	 Choose an item. Choose an item. Choose an item.	
Weight of seed sown 2010 2011 2012	 Click here to enter text. Click here to enter text. Click here to enter text.	Unit Choose an item. Choose an item. Choose an item.
Crop yield per paddock 2010 2011 2012	kilogram (kg) Click here to enter text. Click here to enter text. Click here to enter text.	

Stock information

 2010 2011 2012	Type of stock (e.g. cows, sheep) Click here to enter text. Click here to enter text. Click here to enter text.	Average carcass weight (kg) Click here to enter text. Click here to enter text. Click here to enter text.
 2010 2011 2012	Number of stock Click here to enter text. Click here to enter text. Click here to enter text.	

Machinery Information

	Machinery used (Select all)			Weeks used per year			Number of applications per year		
	2010	2011	2012	2010	2011	2012	2010	2011	2012
Seeder	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Swather	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Topdresser	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Harvester	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Sprayer	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Other	☐	☐	☐	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.	Choose an item.
Specify other	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Machinery Information

	Fuel consumption (l/km)			Speed of vehicle during use (km/hr)			Number of passes per hectare		
	2010	2011	2010	2011	2012	2012	2010	2011	2012
Seeder	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Swather	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Topdresser	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Harvester	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Sprayer	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Other	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.
Specify other	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Choose an item.	Choose an item.	Choose an item.

Chemicals information

Names of chemicals used						
	2010		2011		2012	
Fertilisers	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Fungicides	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Herbicides	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Innoculants	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Lime	Choose an item.		Choose an item.		Choose an item.	
Oils	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Pesticides	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Rhizobiums	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Other - Specify	Click here to enter text.		Click here to enter text.		Click here to enter text.	
Rate of chemical application						
	2010		2011		2012	
	Dosage	Unit	Dosage	Unit	Dosage	Unit
Fertilisers	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Fungicides	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Herbicides	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Innoculants	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Lime	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Oils	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Pesticides	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Rhizobiums	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.
Other - specify	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.	Click here to enter text.	Choose an item.

Chemical supplier			
	2010	2011	2012
Fertilisers	Click here to enter text.	Click here to enter text.	Click here to enter text.
Fungicides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Herbicides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Innoculants	Click here to enter text.	Click here to enter text.	Click here to enter text.
Lime	Click here to enter text.	Click here to enter text.	Click here to enter text.
Oils	Click here to enter text.	Click here to enter text.	Click here to enter text.
Pesticides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Rhizobiums	Click here to enter text.	Click here to enter text.	Click here to enter text.
Other - specify	Click here to enter text.	Click here to enter text.	Click here to enter text.

How was chemical transported/delivered to the farm			
	2010	2011	2012
Fertilisers	Click here to enter text.	Click here to enter text.	Click here to enter text.
Fungicides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Herbicides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Innoculants	Click here to enter text.	Click here to enter text.	Click here to enter text.
Lime	Click here to enter text. Click here to enter text.	Click here to enter text.	Click here to enter text.
Oils	Click here to enter text.	Click here to enter text.	Click here to enter text.
Pesticides	Click here to enter text.	Click here to enter text.	Click here to enter text.
Rhizobiums	Click here to enter text.	Click here to enter text.	Click here to enter text.
Other-specify	Click here to enter text.	Click here to enter text.	Click here to enter text.

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APPENDIX D

SAMPLE CALCULATIONS FOR CLAYING

Examples of equations required for claying

The claying process consists of the following activities:

1. Removal of topsoil from the clay pit
2. The scalping of the clay
3. Transporting the clay from the clay pit to the paddock
4. Tipping the clay onto the paddock
5. Spreading the clay on the paddock
6. Incorporating the clay into the paddock soil

All information with regards to the claying process was obtained from DAFWA (pers. comm, Brockman, Albany, Western Australia, 2014)

1. Removal of topsoil from the clay pit.

The topsoil is removed to a depth of 500 cm. The clay pit dimensions are usually 36 m x 50 m x 4 m. The clay requirement per is 72 m^3/ha.

The first calculation is the clay requirement for the paddock, then the calculation of how many clay pits need to be excavated to obtain this amount of clay.

Area of the paddock to be "clayed" was 120 ha, the distance between the clay pit and the paddock was 1.5 km and a D7, 220 HP bulldozer, travelling at 5 km/hr was used to remove the topsoil.

The clay requirement for the paddock, based on 72 t/ha.

$$\boldsymbol{Clay_{needed} = Clay_{rec} \times Area_{paddock}} \qquad \textbf{Equation D.1}$$

Where '$Clay_{needed}$' is the clay that will be needed to cover the paddock (m^3), '$Clay_{rec}$' is the recommended volume of clay (m^3/ha) and '$Area_{paddock}$' is the area of the paddock to be covered in clay (ha)
Thus: $Clay_{needed}$ = 72 m^3/ha x 120 ha = 8640 m^3

To calculate the clay from one pit:

$$\boldsymbol{Volume_{clay} = Length_{pit} \times Breadth_{pit} \times Depth_{pit}} \qquad \textbf{Equation D.2}$$

Where 'Volume$_{clay}$' is the volume of the clay obtained from the pit (m^3), 'Length$_{pit}$' is the length of the pit (m), 'Breadth$_{pit}$' is the depth of the pit (m) and 'Depth$_{pit}$' is the depth of the pit (m).
Thus: Volume$_{clay}$ =36 m x 50 m x 4 m = 7200 m^3

To calculate how many pits should be excavated:

$$\boldsymbol{Pits = \frac{Clay_{needed}}{Volume_{clay}}} \qquad \textbf{Equation D.3}$$

Where 'Pits' is the number of clay pits to be excavated, 'Clay$_{needed}$' is the amount of clay required for the paddocks (m^3/ha) and 'Volume$_{clay}$'is the volume of clay from one pit (m^3/ha)
Thus: Pits = 8640 m^3/7200 m^3=1.2 pits

The following calculations focus on the removal of the topsoil. Topsoil is removed to a depth of 5m, from the clay pit. The volume removed per hour is 350 m^3/hr.

$$\boldsymbol{Volume_{topsoil} = Length_{pit} \times Breadth_{pit} \times Depth_{topsoil}} \qquad \textbf{Equation D.4}$$

Where 'Volume$_{topsoil}$' is the volume of the topsoil removed (m^3) per pit, 'Length$_{pit}$' is the length of the pit (m), 'Breadth$_{pit}$' is the depth of the pit (m) and 'Depth$_{topsoil}$' is the depth of the topsoil removed (m).
Thus: Volume$_{topsoil}$ =36 m x 50 m x 5 m = 9000 m^3

$$\boldsymbol{Time_{topsoil} = \frac{Volume_{topsoil} \times Pits}{Volume_{hour} \times Area_{paddock}}} \qquad \textbf{Equation D.5}$$

Where 'Volume$_{topsoil}$' is the volume of the topsoil removed (m^3) from multiple pits, 'Pits' is the number of clay pits to be excavated and 'Volume$_{hour}$'.is the volume of clay removed in one hour (m^3/hr)
Thus: Time$_{topsoil}$ = (9000 m^3 x 1.2 pits) / 350 m^3/hr x 120 ha= 0.26 hr/ha

The distance travelled to complete the removal of the topsoil, when the bulldozer travels at 5 km/hr.

$$Distance_{topsoil} = \frac{Volume_{topsoil} \times Pits}{Volume_{hour}} \times Speed \qquad \textbf{Equation D.6}$$

Where 'Distance$_{topsoil}$' is the total distance travelled to remove the topsoil (km), Volume$_{topsoil}$' is the volume of the topsoil removed (m^3) from multiple pits, 'Pits' is the number of clay pits to be excavated and 'Volume$_{hour}$'.is the volume of clay removed in one hour (m^3/hr) and speed is the speed of the machine (km/hr
Thus: Distance$_{topsoil}$=((9000 m^3 x 1.2)/350m^3/hr)x 5 km/hr = 154.25 km

Thereafter Equations 3.10-3.15 are used to calculate the cost and fuel use of the machinery used to remove the topsoil.

2. Scalping of the clay

The scalping of the clay includes the removal of the clay from the clay pit, from which the topsoil has been removed. A 185 HP carry grader is used to remove 150 t/ha of clay, travelling at 5 km/hr and using 31 km/hr of fuel.

$$Distance_{pit} = Pit_{length} \times \left(\frac{Pit_{breadth}}{Header_{width}}\right) \div 1,000 \qquad \textbf{Equation D.7}$$

Where 'Distance$_{pit}$' is the distance travelled when excavating clay from one pit (km), Pit$_{length}$' is the length of the pit (m), 'Pit$_{breadth}$' is the breadth of the pit (m) and 'Header$_{width}$' is the width (m) of the implement used

$$Pit_{time} = \frac{Distance_{pit}}{speed} \qquad \textbf{Equation D.8}$$

Where, 'Pit$_{time}$' (hrs) is the time taken to complete one pit, 'Distance$_{pit}$' (km)is the distance travelled when excavating clay from one pit and 'speed' is the speed of the machine (km/hr)

$$Distance_{total} = Distance_{pit} \times Pits \qquad \textbf{Equation D.9}$$

Where, 'Distance$_{total}$' is the totalled distance covered to scalp clay for multiple pits (km), 'Distance$_{pit}$' is the distance travelled when excavating one pit (km), and 'pits' is the number of clay pits required to obtain clay from.

Then use equation from 3.10 – 3.15 to calculate the cost and fuel cost of the machinery required for the scalping of clay.

3. Transporting the clay from the clay pit to the paddock

A 30 t dump truck travelling at 30 km/hr, fuel use 2.5 l/km. AUD 260,000, lifetime is 10 years, travels 70,000 km/yr

$$\boldsymbol{Dump_{trips} = \frac{Clay_{total}}{Truck_{volume}}}$$ **Equation D.10**

Where, '$Dump_{trip}$' is the total number of trips to transport the clay from the clay pit to the paddock, '$Clay_{total}$' is the total volume of clay required (t) and '$Truck_{volume}$' is the volume of the truck (t)

$$\boldsymbol{Distance_{totalpp} = Distance_{pp} \times Dump_{trips}}$$ **Equation D.11**

Where, '$Distance_{totalpp}$' is the total distance travelled between the pit and the paddock (km), '$Distance_{pp}$' is the distance between the pit and the paddock (km) and '$Dump_{trips}$' is the total number of trips to transport the clay from the clay pit to the paddock

$$\boldsymbol{Time_{totalpp} = \frac{Distance_{totalpp}}{speed}}$$ **Equation D.12**

Where '$Time_{totalpp}$' is the total time is the taken to transport the clay from the pit to the paddock (hrs), '$Distance_{totalpp}$' is the total distance travelled between the pit and the paddock (km) and 'speed' is the actual speed of the machinery (km/hr)

$$\boldsymbol{Fuel_{totalpp} = Distance_{totalpp} \times Fuel_{cons}}$$ **Equation D.13**

Where, '$Fuel_{totalpp}$' is the total fuel used when travelling between the pit and the paddock (l), '$Distance_{totalpp}$' is the total distance travelled between the pit and the paddock (km) and '$Fuel_{cons}$' is the fuel consumption of the machine (l/km)

$$\boldsymbol{Distance_{pp/ha} = \frac{Distance_{totalpp}}{Area_{paddock}}}$$ **Equation D.14**

Where, '$Distance_{pp/ha}$' is the distance travelled between the paddock and pit (km/ha), per hectare, '$Distance_{totalpp}$' is the total distance travelled between the pit and the paddock (km) and '$Area_{paddock}$' is the paddock area (ha).

$$Transport_{totalpp} = \frac{Time_{totalpp}}{Area_{paddock}}$$ **Equation D.15**

Where 'Transport$_{totalpp}$' is the time taken to transport the clay (hrs/ha), 'Time$_{totalpp}$' is the total time is the taken to transport the clay from the pit to the paddock (hrs) and 'Area$_{paddock}$' is the paddock area (ha).

Then use equations 3.9-3.15 to complete the calculations

4. Tipping the clay onto the paddock

The same machinery is used for tipping the clay as for the transportation of the clay between the clay pit and the paddock. Thus only the calculation of the fuel consumption is required.

$$Area_{hour} = \frac{1}{\frac{100 \times \frac{100}{Header_{width}}}{\frac{1000}{speed}}}$$ **Equation D.16**

Where, 'Area$_{hour}$' is the area covered by tipping in one hour (ha/hr), 'Header $_{width}$' is the header width (m) and 'speed'is the speed the machinery moves at (km/hr).

$$Tipping_{td} = \frac{\frac{100\,m}{Header_{width}} \times 100\,m \times Area_{paddock}}{1000\,m}$$ **Equation D.17**

Where 'Tipping$_{td}$' is the total distance travelled when tipping (km), 'Header$_{width}$ is the width of the header (m) and 'Area$_{paddock}$' is the area of the paddock (ha)

$$Tipping_{\ tt} = \frac{100\,m \times \frac{100\,m}{Header_{width}}}{1000\,m} \times \frac{1}{speed} \times Area_{paddock}$$ **Equation D.18**

Where 'Tipping$_{tt}$' is the total time taken to complete tipping on the whole paddock (m^3/km/hrs), Header$_{width}$ is the width of the header (m), speed is the speed the machinery travels at (km/hr) and 'Area$_{paddock}$' is the area of the paddock (ha)

$$Tipping_{days} = \frac{Tipping_{\ tt}}{8}$$ **Equation D.19**

Where, 'Tipping$_{days}$' is the number of days required to complete the tipping, based on an eight hour day, 'Tipping$_{tt}$' is the total time taken to complete tipping on the whole paddock (hrs)

$$\boldsymbol{Tipping_{fuel} = Fuel_{cons} \times Tipping_{td}}$$ **Equation D.20**

Where 'Tipping$_{fuel}$' is the fuel used to complete the tipping (l), 'Tipping$_{td}$' is the total distance travelled when tipping (km), and 'Fuel$_{cons}$' is the fuel consumption of the machinery (l/km)

$$\boldsymbol{Fuel_{ha} = \frac{Tipping_{fuel}}{Area_{paddock}}}$$ **Equation D.21**

Where, 'Fuel$_{ha}$' is the fuel required to complete tipping on one hectare (l/ha), 'Tipping$_{fuel}$' is the fuel used to complete the tipping (l) and 'Area$_{paddock}$' is the area of the paddock (ha)

Then use equations 3.6 – 3.15 to complete the required calculations.

5. Spreading the clay onto the paddock

A tractor is used, pulling a Lehman scraper of width 10 m. The fuel use of the tractor is 0.7 l/ha when travelling at 25 km/hr. The total fuel use for the spreading of the clay is calculated using the following equations.

$$\boldsymbol{Spreading_{distance} = \frac{\frac{100\ m}{Header_{width}} \times 100\ m}{1000\ m}}$$ **Equation D.22**

Where 'Spreading$_{distance}$' is the total distance covered when spreading the clay and 'Header$_{width}$' is the header width of the implement

$$\boldsymbol{Spreading_{time} = \frac{Spreading_{distance}}{speed}}$$ **Equation D.23**

Where 'Spreading$_{time}$' is the time taken to complete the spreading of the clay (hrs,) 'spreading$_{distance}$' is the total distance (m) covered when spreading the clay and 'speed' is the tractor speed (km/hr)

$$\boldsymbol{Spreading_{ha} = Spreading_{distance} \times speed}$$ **Equation D.24**

Where 'Spreading$_{ha}$' is the time taken to complete spreading on one hectare (hrs/ha), 'spreading$_{distance}$' is the total distance (km) covered when spreading the clay and 'speed' is the tractor speed (km/hr)

$$Spreading_{fuel} = \frac{Spreading_{ha} \times Fuel_{km}}{Spreading_{time}}$$ **Equation D.25**

Where, 'Spreading$_{fuel}$' is the fuel used to complete the spreading on one hectare (l/ha/km), 'Spreading$_{ha}$' is the 'Spreading$_{ha}$' is the time taken to complete spreading on one hectare (hrs/ha), 'Fuelkm' is the fuel use per km (l/km)and 'Spreading$_{time}$' is the time taken to complete spreading on one hectare (hrs)

$$Fuel_{hr} = 1hr \times \frac{Spreading_{fuel}}{Spreading_{ha}}$$ **Equation D.26**

Where, 'Fuel$_{hr}$ is the fuel used in one hour (l/hr), 'Spreading$_{fuel}$' is the fuel used to complete the spreading on one hectare (l/ha) and 'Spreading$_{ha}$' is the time taken to complete spreading on one hectare (hrs/ha)

$$Fuel_{total} = \frac{Fuel_{cons}}{Spreading_{ha}}$$ **Equation D.27**

Where, 'Fuel$_{total}$' is the total fuel used (l/ha) when spreading, 'Fuel$_{cons}$' is the tractor fuel consumption (l/hr) and 'Spreading$_{ha}$' is the time taken to complete spreading on one hectare (ha/hr)

The cost of the tractor and the cost of the Lehman scraper are determined by applying Equations 3.6-3.15.

6. Incorporating the clay into the paddock soil

The clay is incorporated into the paddock soil using a 57 series spading machine at the back of a tractor. The header width of the spading machine is 2 m, the tractor travels at 9 km/hr and the fuel consumption is 34 l/hr. The machinery is used for an average of 1000 hrs/yr, for 12 yrs. The grain yield is 2.8 t/ha. Equations 3.6-3.15 are used to do the calculations.

For example:

Equation 3.6: D_{ha} = 100 m / 2 m x 100 m / 1000 m = 5 km/ha

Equation 3.7: TD = 5 km / ha x 1 = 5 km/ha

Equation 3.8: OT = 5 km/ha / 9 km/hr = 0.56 hr/ha

Equation 3.9: LM = 1000 hrs/yr x 12 years = 12,000 hrs

Equation 3.10: $Cost_{hr}$ = 200,000 AUD / 12,000 hrs = 16.67 AUD/hr

Equation 3.11: $Cost_{ha}$ = 0.56 hr/ha x 16.67 AUD/hr

Equation 3.12: $Cost_{yield}$ = 16.67 AUD/hr / 2.8 t/ha = 5.95 AUD/hr/t

Equation 3.13: $Cost_{AUD\ 1998}$ = 5.95 AUD/hr/t / $(1 + 2.98\%)^{(0.6049)}$ = 4.18 AUD/t

Equation 3.14: $Cost_{USD\ 1998}$ = 4.18 AUD/t x 0.6049 USD/AUD = 2.52 USD/t

Equation 3.15: $Fuel_t$ = 34 l/hr x 0.56 hr/ha / 2.8 t/ha = 6.8 l/hr/t

APPENDIX E

CLASSIFICATION OF CHEMICALS USED FOR LCA ANALYSIS

All chemicals were classified according to APVMA classifications. All data was extracted from the MSDS and the labels from the APVMA website (APVMA, 2014).

Table E.1. Fertilisers and percentage nitrogen in the fertiliser

Fertiliser	% N	%P	%K	%S
AgFlow Extra	12.7	17.7	-	5.6
AgNP	11.0	22.2	-	1.2
Agras	16.1	9.1	-	14.3
Agstar Extra	14.1	14.1	-	9.2
Agstar Trace	14.2	14.0	-	9.5
Agyield Extra	17.2	17.8	-	3.8
Copper (Stratosol)	13.9	-	-	-
DAP SZC	17.2	18.4	-	5.0
DAP	17.5	20.0	-	1.2
Flexi -(also known as UAN)	32.0	-	-	-
K-till Extra	10.2	12.0	11.2	6.0
Macropro Extra	9.7	11.2	11.2	10.2
Macropro Plus	10.0	14.0	8.4	8.0
MAP	11.2	22.8	-	1.2
MAP SZC	11.6	20.0	-	5.5
MaxAmFlo	22.0	-	-	6.2
MaxAmRite	12.8	17.7	-	7.4
NPS Range-Cereal	12.5	17.7	-	6.9
UAN (also known as Flexi- N)	32.0	-	-	-
Urea	46.0	-	-	-

Table E.2. Adjuvants used in the study, showing active ingredients, density and dosage range

Adjuvant	Active ingredient	Mass	Density (g/ml)	Dosage range (unit, min, max)		
Ammonium Sulphate	Ammonium sulphate	417 g/l	1.77	ml/ha	2	2
Hasten	Ethyl and Methyl esters	704 g/l	0.9	ml/ha	500	1,000
LI 700	Soyal phospholipids	350 g/l	1.035	ml/ha	100	500
Uptake	Paraffinic oil	582 g/l	0.875	ml/ha	250	250
Wetter BS 1000	Alcohol Alkoxylate	1000 g/l	1.003	ml/ha	10	40

Table E.3. Insecticides and pesticides used in the study, showing active ingredients, density and dosage range

Insecticides and pesticides	Active ingredient	Mass (g/l)	Density (g/ml)	Dosage range (unit,min, max)		
Fastac/Dominex	Alpha cypermethrin	100	0.93	ml/ha	120	200
Alphasip duo/Alpha duo/Scud/Sonic	Alpha cypermethrin	100	0.93	ml/ha	50	400
Astral/Talstar	Bifenthrin	100	0.93	ml/ha	50	200
Saboteur/Rogor	Dimethoate	400	1	ml/ha	75	800
Dividend	Difenoconazole	80	1.092	ml/ha	100	260
	Metalaxyl-m	20				
Folicur	Tebuconazole	430	1.12	ml/ha	145	290
Le-Mat	Omethoate	290	1.05	ml/ha	100	300
Lorsban	Chlorpyifos	500	1.075	ml/ha	500	1,500
Premis	Triticonazole	25	1.06	ml/ha	100 ml/100 kg seed	
	Cypermethrin	4				
Prosaro 420	Prothioconazole	50	1.115	ml/ha	150	375
	Tebuconazole	50				
Raxil	Prothioconazole	62.5	Solid	ml/ha	15	
	Tebuconazole	37.5				
Tilt/Bumper	Propiconazole	250	0.98	ml/ha	150	500
Vincit	Flutriafol	250	1.03	ml/ha	200	400

Table E.4. Herbicides used in the study, showing active ingredients, density and dosage range

Herbicides	Active ingredient	Mass (g/l)	Density (g/ml)	Dosage range (unit,min, max)		
Ally	Metsulfuron-methyl	600	1.47	ml/ha	5	7
Amine 625	2,4-d as dimethylamine salt	625	1.25	ml/ha	640	1,400
Amine 720	2,4-d as dimethylamine salt	720	1.23	ml/ha	170	1,100
Atlantis	Mesosulfuron-methyl	30	1.03	ml/ha	330	330
Atragranz, Atradex or Gesaprim	Atrazine	600	1.1	ml/ha	830	3,300
Avadex	Tri-allate	500	Solid	g/ha	1600	2,000
Brodal	Diflunican	500	1.175	ml/ha	100	200
Bromicide/Buctril	Bromoxynil	200	1.08	ml/ha	750	2,400
Crusader	Pyroxsulam	25	1.04	ml/ha	500	500
	Cloquintocet-mexyl	75				
Diurex	Diuron	900	1.092	ml/ha	275	550
Dual	Metolachlor	720	1.045	ml/ha	300	500
Eclipse	Metosulam	100	1.05	ml/ha	35	50
Ester 600	2,4-D Amine	600	1.11	ml/ha	950	3,700
Ester 680	2,4-D Amine	680	1.14	ml/ha	800	1,500
Ester 800	2,4-D Amine	800	1.22	ml/ha	500	2,800
Garlon	Triclopyr	75	1.135	ml/ha	200	750
	Hexyloxypropylamine salt	25				
Gladiator	Glyphosate	450	1.2	ml/ha	800	1,600
Gramoxone	Paraquat	250	1.12	ml/ha	1200	2400
Jaguar	Bromoxynil	90.9	1.078	ml/ha	350	1100
	Diflunican	9.09				
Kamba	MCPA	80.9	1.116	ml/ha	1000	4,000
	Dicamba	0.19				
Lexone/Sencor	Metribuzin	750	0.55	ml/ha	100	200
Logran	Triasulfuron	750	Solid	g/ha	6.5	35
Lorsban	Chlorpyrifos	500	1.075	ml/ha	350	900
MCPA LVE 500	MCPA as the 2-ethyl hexyl ester	500	1.02	ml/ha	500	2,100
MONZA	Sulfosulfuron	750	Solid	g/ha	20	25
Optimax	Glyphosate	540	1.36	ml/ha	340	2700
Oxyfluorfen	Oxyfluorfen	240	1.08	ml/ha	75	75
Polo/MCPA LVE 570	MCPA present as 2 ethyl hexyl ester	570	1.06	ml/ha	440	1,800
Precept	MCPA as 2 ethylhexyl ester	71.4	1.05	ml/ha	1000	2,000
	Pyrasulfotole	28.6				
Roundup	Glyphosate	360	1.17	ml/ha	2000	3,000
Select/Status	Clethodim	240	0.95	ml/ha	150	500
Simagranz, Gesatop	Simazine	600	1.15	ml/ha	830	3,300
Simazine	Simazine	900	1.15	ml/ha	550	2,200
Sprayseed/Brown out	Paraquat	250	1.17	ml/ha	1200	1,600
Terbyne	Terbuthylazine	750	1.19	ml/ha	700	1,400
Tigrex	MCPA as ethyl hexyl ester	90.9	0.995	ml/ha	250	1,000
	diflunican	9.09				
Topik	Clodinafop-propargyl	240	1.08	ml/ha	65	210
	Cloquintocet-mexyl	60				
Treflan/TriFlurX	Trifluralin	480	1.116	ml/ha	800	2,000
Trifluralin	Trilfluralin	600	1.116	ml/ha	640	2,000
Velocity	Bromoxynil as esters	84.84	Solid	g/ha	500	1,000
Verdict/Asset	Haloxyfop	130	1.15	ml/ha	200	300

APPENDIX F

INVENTORY LISTS

Table F.1 Stubble decomposition

Farm	Paddock	2010						2011					
		Starting mass of stubble	Stubble remaining before grazing	Stubble after grazing	Stubble before burning	Stubble remaining after burning	Total stubble decomposed	Starting mass of stubble	Stubble remaining before grazing	Stubble after grazing	Stubble before burning	Stubble remaining after burning	Total stubble decomposed
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
A	1	1.22.E+03	1.22.E+03	1.22.E+03	1.07.E+03	5.88.E+02	1.53.E+02	4.49.E+03	4.38.E+03	3.87.E+03	3.54.E+03	3.54.E+03	2.16.E+02
	2	1.21.E+03	1.21.E+03	1.21.E+03	1.06.E+03	5.84.E+02	1.52.E+02	2.82.E+03	2.61.E+03	2.40.E+03	2.34.E+03	1.29.E+03	2.77.E+02
	3	5.54.E+02	5.54.E+02	5.54.E+02	4.85.E+02	2.67.E+02	6.93.E+01	2.95.E+03	2.80.E+03	2.46.E+03	2.39.E+03	2.39.E+03	2.18.E+02
B	4	2.66.E+03	2.66.E+03	2.66.E+03	2.33.E+03	2.33.E+03	3.32.E+02	4.95.E+03	4.95.E+03	4.95.E+03	4.33.E+03	4.33.E+03	6.19.E+02
	5	1.49.E+03	1.49.E+03	1.49.E+03	1.30.E+03	1.30.E+03	1.86.E+02	5.19.E+03	5.19.E+03	5.19.E+03	4.54.E+03	4.54.E+03	6.48.E+02
	6	2.15.E+03	2.15.E+03	2.15.E+03	1.88.E+03	1.88.E+03	2.69.E+02	3.80.E+03	3.80.E+03	3.80.E+03	3.33.E+03	3.33.E+03	4.75.E+02
C	7	2.61.E+03	2.42.E+03	2.24.E+03	2.13.E+03	2.13.E+03	3.08.E+02	4.05.E+03	3.65.E+03	3.39.E+03	3.35.E+03	3.35.E+03	4.47.E+02
	8	1.37.E+03	1.37.E+03	1.37.E+03	1.20.E+03	1.20.E+03	1.72.E+02	6.70.E+03	6.20.E+03	5.07.E+03	4.88.E+03	4.88.E+03	6.93.E+02
	9	6.85.E+02	5.99.E+02	5.99.E+02	5.24.E+02	5.24.E+02	1.61.E+02	1.62.E+03	1.58.E+03	1.45.E+03	1.30.E+03	1.30.E+03	1.85.E+02
D	10	-	-	-	-	-	-	-	-	-	-	-	-
	11	1.14.E+03	1.11.E+03	9.24.E+02	8.55.E+02	3.42.E+01	9.78.E+01	2.11.E+03	2.11.E+03	2.11.E+03	1.79.E+03	1.79.E+03	3.16.E+02
	12	8.44.E+02	8.23.E+02	6.15.E+02	5.68.E+02	3.13.E+02	6.72.E+01	3.67.E+03	3.67.E+03	3.67.E+03	3.12.E+03	3.12.E+03	5.51.E+02
E	13	1.16.E+03	1.13.E+03	1.03.E+03	9.26.E+02	9.26.E+02	1.32.E+02	4.37.E+03	4.15.E+03	4.01.E+03	3.81.E+03	3.81.E+03	4.19.E+02
	14	7.16.E+02	6.98.E+02	5.99.E+02	5.54.E+02	5.54.E+02	6.28.E+01	5.15.E+03	4.63.E+03	4.51.E+03	4.51.E+03	4.51.E+03	5.15.E+02
	15	6.23.E+02	6.07.E+02	5.28.E+02	4.75.E+02	4.75.E+02	6.84.E+01	3.91.E+03	3.91.E+03	3.69.E+03	2.86.E+03	2.86.E+03	8.31.E+02
F	16	-	-	-	-	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-	-	-	-	-
	18	1.10.E+03	1.10.E+03	1.10.E+03	9.31.E+02	9.31.E+02	1.64.E+02	1.06.E+04	1.06.E+04	1.06.E+04	9.27.E+03	5.10.E+03	1.32.E+03
G	19	1.47.E+03	1.47.E+03	1.47.E+03	1.29.E+03	5.15.E+01	1.84.E+02	5.26.E+03	5.26.E+03	5.26.E+03	4.47.E+03	4.47.E+03	7.90.E+02
	20	2.20.E+03	2.20.E+03	2.20.E+03	1.93.E+03	7.70.E+01	2.75.E+02	5.47.E+03	5.47.E+03	5.47.E+03	4.65.E+03	4.65.E+03	8.21.E+02
	21	1.43.E+03	1.43.E+03	1.43.E+03	1.22.E+03	1.22.E+03	2.15.E+02	3.92.E+03	3.92.E+03	3.92.E+03	3.33.E+03	3.33.E+03	5.87.E+02
H	22	-	-	-	-	-	-	-	-	-	-	-	-
	23	2.09.E+03	2.09.E+03	2.09.E+03	1.72.E+03	1.72.E+03	3.65.E+02	4.66.E+03	4.66.E+03	4.66.E+03	3.96.E+03	3.96.E+03	6.99.E+02
	24	1.48.E+03	1.48.E+03	1.48.E+03	1.22.E+03	1.22.E+03	2.59.E+02	3.50.E+03	3.50.E+03	3.50.E+03	2.97.E+03	2.97.E+03	5.24.E+02

Table F.2 Inventory list and GHG emissions (kg CO2-e/t) from grazing sheep

Farm	Paddock	2010					2011				
		Initial stubble load	Total stubble grazed	Remaining stubble	GHG emissions from enteric emissions	GHG emissions from manure decomposition	Initial stubble load	Total stubble grazed	Remaining stubble	GHG emissions from enteric emissions	GHG emissions from manure decomposition
		kg/ha	kg/ha	kg/ha	kg CO2-e/t	kg CO2-e/t	kg/ha	kg/ha	kg/ha	kg CO2-e/t	kg CO_2-e/t
A	1	-	-	-	-	-	4.38E+03	5.09E+02	3.87E+03	1.73E-01	3.21E-03
	2	-	-	-	-	-	2.61E+03	2.06E+02	2.40E+03	1.36E-01	1.30E-03
	3	-	-	-	-	-	2.80E+03	3.49E+02	2.46E+03	1.21E-01	2.20E-03
C	7	2.42E+03	1.71E+02	2.24E+03	2.33E+00	1.08E-03	3.65E+03	2.57E+02	3.39E+03	3.49E+00	1.62E-03
	8	-	-	-	-	-	6.20E+03	1.13E+03	5.07E+03	1.53E+01	7.11E-03
	9	-	-	-	-	-	1.58E+03	1.34E+02	1.45E+03	1.37E+00	8.46E-04
D	11	1.11E+03	1.88E+02	9.24E+02	2.55E+00	1.18E-03	-	-	-	-	-
	12	8.23E+02	2.08E+02	6.15E+02	2.83E+00	1.31E-03	-	-	-	-	-
	13	1.13E+03	9.93E+01	1.03E+03	1.35E+00	1.39E-03	4.15E+03	1.43E+02	4.01E+03	1.95E+00	2.00E-03
E	14	6.98E+02	9.93E+01	5.99E+02	1.35E+00	1.39E-03	4.63E+03	1.23E+02	4.51E+03	2.14E+00	1.72E-03
	15	6.07E+02	7.96E+01	5.28E+02	1.08E+00	1.12E-03	3.91E+03	2.23E+02	3.69E+03	3.03E+00	3.12E-03
	16										

Note: This table only contains paddocks and farms, where sheep were grazed

Table F.3 Inventory list and GHG emissions from the burning of stubble

Farm	Paddock	2010						2011					
		Type of paddock burn	Starting mass of stubble	Mass of fuel burnt	Stubble remaining after burning	CH_4 emissions from burning	N_2O emissions from burning	Type of paddock burn	Starting mass of stubble	Mass of fuel burnt	Stubble remaining after burning	CH_4 emissions from burning	N_2O emissions from burning
		kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
A	1	windrow	1.07E+03	4.81E+02	5.88E+02	5.75E-04	1.25E-03	-	-	-	-	-	-
	2	windrow	1.06E+03	4.78E+02	5.84E+02	5.72E-04	1.24E-03	windrow	2.34E+03	1.05E+03	1.29E+03	1.23E-03	2.66E-03
	3	windrow	4.85E+02	2.18E+02	2.67E+02	3.37E-04	7.31E-04	-	-	-	-	-	-
D	10	-	-	-	-	-	-	-	-	-	-	-	-
	11	paddock	8.55E+02	8.21E+02	3.42E+01	2.07E-01	4.49E-01	-	-	-	-	-	-
	12	windrow	5.68E+02	2.56E+02	3.13E+02	5.80E-02	1.26E-01	-	-	-	-	-	-
F	16	-	-	-	-	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-	-	-	-	-
	18	-	-	-	-	-	-	windrow	9.27E+03	4.17E+03	5.10E+03	5.52E-03	1.20E-02
G	19	paddock	1.29E+03	1.24E+03	5.15E+01	1.56E-01	3.38E-01	-	-	-	-	-	-
	20	paddock	1.93E+03	1.85E+03	7.70E+01	3.49E-01	7.59E-01	-	-	-	-	-	-
	21	-	-	-	-	-	-	-	-	-	-	-	-

Note: This table only contains paddocks and farms, where stubble was burned

Table F.4. Inventory list for cost of Machinery (USD/t) at 1998 price for 2010 and 2011

	Paddock	Seeding USD/t	Swathing USD/t	Spraying USD/t	Top-dressing fertiliser USD/t	Top-dressing lime USD/t	Harvesting USD/t	Claying USD/t	Mould board ploughing USD/t
2010	1	2.71	-	0.81	-	14.86	11.35	-	-
	2	2.96	-	0.29	-	17.69	12.38	-	-
	3	2.59	-	0.52	-	13.60	10.85	-	-
	4	1.74	-	0.80	1.45	0.52	7.27	-	-
	5	1.86	-	0.34	1.56	0.56	7.80	-	-
	6	1.48	-	0.27	1.24	0.45	6.22	-	-
	7	2.24	-	0.92	-	0.11	9.36	-	-
	8	3.98	-	0.55	-	0.20	16.64	-	-
	9	3.25	-	0.89	-	0.16	13.62	-	-
	10	-	-	-	-	-	-	-	-
	11	1.99	-	0.25	-	0.60	8.32	-	-
	12	1.79	-	0.44	-	0.54	7.49	-	-
	13	3.67	-	0.56	-	1.84	12.80	-	-
	14	3.30	-	0.25	-	1.66	11.52	-	-
	15	3.90	-	0.60	2.72	1.96	13.62	-	-
	16	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-
	18	2.56	-	0.55		0.22	12.24	-	-
	19	2.08	-	0.45	4.21	0.01	9.92	-	-
	20	1.76	-	0.19	3.56	0.01	8.39	-	-
	21	1.55	-	0.17	3.14	0.01	7.40	-	-
	22	-	-	-	-	-	-	-	-
	23	1.84	-	-	-	-	6.88	-	39.32
	24	2.26	-	-	-	-	8.43	0.71	-
2011	1	1.26	-	0.50	2.10	3.19	5.26	-	-
	2	1.78	-	0.35	-	6.41	7.45	-	-
	3	1.63	-	0.49	2.74	5.40	6.84	-	-
	4	1.27	-	0.23	1.07	0.38	5.33	-	-
	5	1.52	-	0.70	1.27	0.46	6.37	-	-
	6	1.39	-	0.25	1.16	0.42	5.81	-	-
	7	1.63	-	0.97	1.36	0.08	6.81	-	-
	8	1.02	-	0.61	-	0.05	4.28	-	-
	9	4.47	-	2.67	-	0.22	18.72	-	-
	10	-	-	-	-	-	-	-	-
	11	1.15	-	0.57	0.97	0.35	4.83	-	-
	12	1.19	-	0.59	1.00	0.36	4.99	-	-
	13	1.26	1.81	0.19	2.64	0.63	4.41	-	-
	14	1.26	1.81	0.10	1.76	0.63	4.41	-	-
	15	2.39	3.43	0.18	1.67	1.20	8.35	-	-
	16	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-
	18	2.43	-	0.53	5.18	0.21	11.62	-	-
	19	0.90	-	0.10	3.63	0.01	4.28	-	-
	20	0.85	-	0.09	3.45	0.01	4.07	-	-
	21	1.31	-	0.14	7.97	0.01	6.26	-	-
	22	-	-	-	-	-	-	-	-
	23	1.10	-	0.10	1.94	1.94	4.11	-	-
	24	0.95	-	0.09	1.67	1.67	3.54	-	-

Table F.5. Inventory list for machinery fuel use for use, 2010 and 2011

Year	Paddock	Seeding l/hr/t	Swathing l/hr/t	Spraying l/hr/t	Top-dressing fertiliser l/hr/t	Top-dressing lime l/hr/t	Harvesting l/hr/t	Claying l/hr/t	Mould boarding l/hr/t
2010	1	3.16E+00	-	8.23E-01	-	2.18E+00	4.30E+00	-	-
	2	3.44E+00	-	2.99E-01	-	2.60E+00	4.70E+00	-	-
	3	3.02E+00	-	5.25E-01	-	2.00E+00	4.12E+00	-	-
	4	2.02E+00	-	8.09E-01	2.14E-01	7.69E-02	2.76E+00	-	-
	5	2.17E+00	-	3.47E-01	2.29E-01	8.25E-02	2.96E+00	-	-
	6	1.73E+00	-	2.77E-01	1.82E-01	6.57E-02	2.36E+00	-	-
	7	2.60E+00	-	6.25E-01	-	2.75E-02	3.55E+00	-	-
	8	4.63E+00	-	3.70E-01	-	4.89E-02	6.31E+00	-	-
	9	3.79E+00	-	6.06E-01	-	4.00E-02	5.17E+00	-	-
	10	-	-	-	-	-	-	-	-
	11	2.31E+00	-	1.85E-01	-	8.80E-02	3.16E+00	-	-
	12	2.08E+00	-	3.33E-01	-	7.92E-02	2.84E+00	-	-
	13	3.56E+00	-	5.70E-01	-	2.71E-01	4.86E+00	-	-
	14	3.21E+00	-	2.56E-01	-	2.44E-01	4.37E+00	-	-
	15	3.79E+00	-	6.06E-01	4.00E-01	2.88E-01	5.17E+00	-	-
	16	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-
	18	2.98E+00	-	7.83E-01		4.70E-02	4.64E+00	-	-
	19	2.42E+00	-	6.35E-01	9.15E-01	9.15E-02	3.76E+00	-	-
	20	2.05E+00	-	2.68E-01	7.73E-01	7.73E-02	3.18E+00	-	-
	21	1.80E+00	-	2.37E-01	6.82E-01	6.82E-02	2.81E+00	-	-
	22	-	-	-	-	-	-	-	-
	23	2.15E+00	-	-	-	-	2.61E+00	-	9.01E-01
	24	2.63E+00	-	-	-	-	3.20E+00	7.55E+01	-
2011	1	1.46E+00	-	5.09E-01	3.09E-01	4.68E-01	1.99E+00	-	-
	2	2.07E+00	-	3.61E-01	-	9.41E-01	2.83E+00	-	-
	3	1.90E+00	-	4.96E-01	4.02E-01	7.92E-01	2.59E+00	-	-
	4	1.48E+00	-	2.37E-01	1.57E-01	5.63E-02	2.02E+00	-	-
	5	1.77E+00	-	7.09E-01	1.87E-01	6.73E-02	2.42E+00	-	-
	6	1.62E+00	-	2.59E-01	1.71E-01	6.14E-02	2.20E+00	-	-
	7	1.89E+00	-	6.59E-01	2.00E-01	2.00E-02	2.58E+00	-	-
	8	1.19E+00	-	4.14E-01	-	1.26E-02	1.62E+00	-	-
	9	5.21E+00	-	1.81E+00	-	5.50E-02	7.10E+00	-	-
	10	-	-	-	-	-	-	-	-
	11	1.34E+00	-	4.30E-01	1.42E-01	5.11E-02	1.83E+00	-	-
	12	1.39E+00	-	4.44E-01	1.47E-01	5.28E-02	1.89E+00	-	-
	13	1.23E+00	2.45E+00	1.96E-01	3.88E-01	9.31E-02	1.67E+00	-	-
	14	1.23E+00	2.45E+00	9.80E-02	2.59E-01	9.31E-02	1.67E+00	-	-
	15	2.32E+00	4.64E+00	1.86E-01	2.45E-01	1.76E-01	3.17E+00	-	-
	16	-	-	-	-	-	-	-	-
	17	-	-	-	-	-	-	-	-
	18	2.83E+00	-	7.44E-01	1.13E+00	4.46E-02	4.41E+00	-	-
	19	1.04E+00	-	1.37E-01	7.89E-01	3.95E-02	1.62E+00	-	-
	20	9.92E-01	-	1.30E-01	7.50E-01	3.75E-02	1.54E+00	-	-
	21	1.53E+00	-	2.00E-01	1.73E+00	5.77E-02	2.37E+00	-	-
	22	-	-	-	-	-	-	-	-
	23	1.28E+00	-	1.46E-01	4.21E-01	4.21E-01	1.56E+00	-	-
	24	1.10E+00	-	1.26E-01	3.62E-01	3.62E-01	1.34E+00	-	-

Table F.6. Adjuvants, showing the distance portion allocation to a farm in Dalwallinu

Name of adjuvant		Hasten	LI 700	Sulphate of Ammonia / AMS / Liquid ammo	Uptake	Wetter 1000 / BS 1000
Producer/Formulator		Victorian Chemicals	4 Farmers	CSBP	DOW	Cropcare
Country/Town/Region of origin		Coolaroo, Victoria	Welshpool, Perth	Kwinana, Western Australia	Altona, Victoria	Melbourne, Victoria
Density (when in liquid form)		0.9	1.035	1.77	0.875	1.003
International journey						
Method of transport						
Place of manufacture to distributor (km)						
From within Australia to WA (km)		Coolaroo to Kwinana			Altona to Kwinana	Melbourne to Kwinana
Method of transport		30 t truck			30 t truck	30 t truck
Distributor to distributor (km)		3,492			3,449	
From WA to the town		Kwinana to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	96	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		3,745	114	253	3,702	253
Allocation of journey	National portion (%)	100	100	100	100	100
	International portion (%)	0	0	0	0	0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.7. Fungicides, showing the distance portion allocation to a farm in Dalwallinu

Name of fungicide		Dividend	Lorsban	Prosaro	Raxil	Tilt / Bumper	Vincit
Producer/Formulator		**Syngenta**	**4Farmers**	**Bayer**	**Bayer**	**Syngenta**	**Cropcare**
Country/Town/Region of origin		**Kwinana, Western Australia**	**Welshpool, Western Australia**	**Pinkenba, Queensland**	**Pinkenba, Queensland**	**Brisbane, Queensland**	**Kwinana, Western Australia**
Density (when in liquid form)		**1.092**	**1.075**	**1.115**	**Solid**	**0.98**	**1.03**
International journey							
Method of transport							
Place of manufacture to distributor (km)							
From within Australia to WA (km)				Pinkenba to Kwinana	Pinkenba to Kwinana	Brisbane to Kwinana	
Method of transport				30 t truck	30 t truck	30 t truck	
Distributor to distributor (km)				4,392	4,392	3,616	
From WA to the town		Kwinana to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	252	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		253.4	270.4	4,645.4	4,645.4	3,869.4	253.4
Allocation of journey	**National portion (%)**	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion

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Table F.8. Fertilisers, showing the distance portion allocation to a farm in Dalwallinu

Name of fertiliser		Ag Flow Xtra	AgNP	Agras	Agstar Extra	Agstar Trace	Agyield Extra	NPS range-Cereal
Producer/Formulator		CSBP	CSBP	CSBP	CSBP	CSBP	CSBP	Summit
Country/Town/Region of origin		Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia
Density (when in liquid form)								1.02
Nitrogen content (%)		12.7	11	16.1	14.1	14.2	17.2	12.5
International journey								
Method of transport								
Place of manufacture to distributor (km)								
From within Australia to WA								
Method of transport								
Distributor to distributor (km)								
From WA to the town		Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	235	235	235	235	235	236
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		253.4	253.4	253.4	253.4	253.4	253.4	254.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.8 (cont.). Fertilisers, showing the distance portion allocation to a farm in Dalwallinu

Name of fertiliser		Copper (Stratosol Copper)	DAP (diammonium phosphate)	DAP SZC	Flexi N (UAN)	K Till Extra	Macropro Plus	MAP (mono ammonium phosphate)
Producer/Formulator		CSBP	CSBP	Summit	CSBP	CSBP	CSBP	CSBP
Country/Town/Region of origin		Kwinana , Western Australia	Kwinana , Western Australia	Mount Isa, Queensland	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia	Kwinana , Western Australia
Density (when in liquid form)		1.5	0.93		1.32			
Nitrogen content (%)		13.9	17.5	17.2	32	10	10	11.2
International journey								
Method of transport								
Place of manufacture to distributor (km)								
From within Australia to WA				Mount Isa to Kwinana				
Method of transport				30 t truck				
Distributor to distributor (km)				4,008.0				
From WA to the town		Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	235	235	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		253.4	253.4	4,261.4	253.4	253.4	253.4	253.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.8 (cont.). Fertilisers, showing the distance portion allocation to a farm in Dalwallinu

Name of fertiliser		MAPSZC	MAXamFLO	MAXamRite	MOP (muriate of potash)	Sodium molybdate	Urea	Zinc/ Manganese
Producer/Formulator		Summit	Summit	Summit	CSBP	Micro Brothers	Syngenta or CSBP	CSBP
Country/Town/Region of origin		Mount Isa, Queensland	Mount Isa, Queensland	Mount Isa, Queensland	Kwinana , Western Australia	Kwinana , Western Australia	Iran to Kwinana	Kwinana , Western Australia
Density (when in liquid form)			1.77					1.8
Nitrogen content (%)		11.1	22	12.8			46	
International journey							Shipped from Asia to Kwinana	
Method of transport								
Place of manufacture to distributor (km)							10,056	
From within Australia to WA		Mount Isa to Kwinana	Mount Isa to Kwinana	Mount Isa to Kwinana				
Method of transport		30 t truck	30 t truck	30 t truck				
Distributor to distributor (km)		4,008	4,008	4,008				
From WA to the town		Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	235	235	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		4,261.4	4,261.4	4,261.4	253.4	253.4	10,309.4	253.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	2.5	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	97.5	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.9. Herbicides, showing the distance portion allocation to a farm in Dalwallinu

Name of herbicide		Ally	Amine 625	Amine 720	Atragranz/ Atradex/ Gesaprim	Avadex	Brodal	Bromicide / Buctril	Clethodim/ Status/ Select	Crusader	Diurex
Producer/Formulator		4 Farmers	4 Farmers	4 Farmers	Cropcare	4Farmers	Bayer	Bayer	Sumitomo	DOW	Cropcare
Country/Town/Region of origin		Hendra, Queensland	Welshpool, Western Australia	Welshpool, Western Australia	Kwinana, Western Australia	Welshpool, Western Australia	Pinkenba, Queensland	Kwinana, Western Australia	Kwinana, Western Australia	Altona, Victoria	Kwinana, Western Australia
Density (when in liquid form)		1.47	1.25	1.23	1.1	Solid	1.175	1.08	0.95	1.04	1.092
International journey											
Method of transport											
Place of manufacture to distributor (km)											
From within Australia to WA		Hendra to Kwinana		Port Muar to Kwinana			Pinkenba to Kwinana			Altona to Kwinana	
Method of transport		30 t truck		30 t truck			30 t truck			30 t truck	
Distributor to distributor (km)		4,384					4,392			3,449	
From WA to the town		Kwinana to Dalwallinu	Welshpool to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	252	252	235	252	235	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		4,637.4	270.4	270.4	253.4	270.4	4,645.4	253.4	253.4	3,702.4	253.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.9 (cont.). Herbicides, showing the distance portion allocation to a farm in Dalwallinu

Name of herbicide	Dual	Ester 600	Ester 680	Ester 800	Garlon	Gladiator 450	Gramoxone	Glyphosate 450	Jaguar	Kamba
Producer/Formulator	**Syngenta**	**4Farmers**	**4 Farmers**	**4 Farmers**	**DOW**	**Cropcare**	**Syngenta**	**Nufarm**	**Bayer**	**Ravensdown**
Country/Town/Region of origin	**Brisbane, Queensland**	**Welshpool, Western Australia**	**Welshpool Western Australia**	**Welshpool, Western Australia**	**Altona, Victoria**	**Kwinana, Western Australia**	**Kwinana, Western Australia**	**Kwinana, Western Australia**	**Kwinana, Western Australia**	**Hendra, Queensland**
Density (when in liquid form)	**1.045**	**1.11**	**1.14**	**1.22**	**1.135**	**1.2**	**1.12**	**1.2**	**1.078**	**1.116**
International journey										
Method of transport										
Place of manufacture to distributor (km)										
From within Australia to WA	Brisbane to Kwinana				Altona to Kwinana					Hendra to Kwinana
Method of transport	30 t truck				30 t truck					30 t truck
Distributor to distributor (km)	3,616				3,449					4,384
From WA to the town	Kwinana to Dalwallinu	Welshpool to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)	235	252	235	235	235	235	235	235	235	235
From the town to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm		Dalwallinu to the farm	Dalwallinu to the farm
Method of transport	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)	3,869.4	270.4	253.4	253.4	3,702.4	253.4	253.4	253.4	253.4	4,637.4
Allocation of journey – National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Allocation of journey – International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.9 (cont.). Herbicides, showing the distance portion allocation to a farm in Dalwallinu

Name of herbicide		Lexone / Sencor	Logran	MCPA LVE	MCPA LVE 570/ Polo LVE 570	Monza	Optimax 540	Precept	Roundup 360	Simazine	Simagranz/ Gesatop
Producer/Formulator		DOW	Syngenta	4Farmers	Cropcare	Monsanto	Cropcare	Bayer	Nufarm	Cropcare	Cropcare
Country/Town/Region of origin		Altona, Victoria	Melbourne, Victoria	Welshpool, Western Australia	Kwinana, Western Australia	Laverton, Victoria	Kwinana, Western Australia	Pinkenba, Queensland	Kwinana, Western Australia	Kwinana, Western Australia	Kwinana, Western Australia
Density (when in liquid form)		0.55	Solid	1.02	1.05	Solid	1.36	1.05	1.17	1.15	1.15
International journey											
Method of transport											
Place of manufacture to distributor (km)											
From within Australia to WA		Altona to Kwinana	Melbourne to Kwinana			Laverton to Kwinana		Pinkenba to Kwinana			
Method of transport		30 t truck	30 t truck			30 t truck		30 t truck			
Distributor to distributor (km)		3,449	3,311			3,342		4,392			
From WA to the town		Kwinana to Dalwallinu	Kwinana to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	235	252	235	235	235	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm		Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		3,702.4	3,564.4	270.4	253.4	3,595.4	253.4	4,645.4	253.4	253.4	253.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.9 (cont.). Herbicides, showing the distance portion allocation to a farm in Dalwallinu

Name of herbicide		Sprayseed/ Brownout	Terbyne	Tigrex	Topik	Treflan	Trifluralin 600	Triflurx	Velocity	Verdict
Producer/Formulator		Sygenta	Sipcam	Bayer	Syngenta	DOW	Cropcare	Cropcare	Bayer	4 Farmers
Country/Town/Region of origin		Kwinana, Western Australia	Geelong, Victoria	Kwinana, Western Australia	Brisbane, Queensland	Altona, Victoria	Kwinana, Western Australia	Kwinana, Western Australia	Pinkenba, Brisbane	Welshpool, Western Australia
Density (when in liquid form)		1.17	1.19	0.995	1.08	1.116	1.116	1.116	Solid	1.15
International journey										
Method of transport										
Place of manufacture to distributor (km)										
From within Australia to WA			Geelong to Kwinana		Brisbane to Kwinana	Altona to Kwinana			Pinkenba to Kwinana	
Method of transport			30 t truck		30 t truck	30 t truck			30 t truck	
Distributor to distributor (km)			3,428		3,616	3,449			4,392	
From WA to the town		Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		235	235	235	235	235	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		253.4	3,681.4	253.4	3,869.4	3,702.4	253.4	253.4	4,645.4	253.4
Allocation of journey	National portion (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.10. Insecticides, showing the distance portion allocation to a farm in Dalwallinu

Name of insecticide		Fastac/Dominex	Astral/Talstar	Alphasip Duo/Alhpa duo/Scud/Sonic	Premis	Saboteur, Rogor	Folicur	Lemat
Producer/Formulator		**4 Farmers**	**Cropcare**	**4 Farmers**	**Cropcare**	**Cropcare**	**Bayer**	**Ravensdown**
Country/Town/Region of origin		**Welshpool, Western Australia**	**Brisbane, Queensland**	**Welshpool, Western Australia**	**Murarrie, Queensland**	**Brisbane, Queensland**	**Pinkenba, Queensland**	**Hendra, Queensland**
Density (when in liquid form)		**0.93**	**0.93**	**0.93**	**1.06**	**1**	**1.12**	**1.05**
International journey								
Method of transport								
Place of manufacture to distributor (km)								
From within Australia to WA			Brisbane to Kwinana		Murarie to Kwinana	Brisbane to Kwinana	Pinkenba to Kwinana	Melbourne to Kwinana
Method of transport			30 t truck		30 t truck	30 t truck	30 t truck	30 t truck
Distributor to distributor (km)			3,616		4,393	3,616	4,392	2,491
From WA to the town		Welshpool to Dalwallinu	Kwinana to Dalwallinu	Welshpool to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu	Kwinana to Dalwallinu
Method of transport		30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck	30 t truck
Distributor to town in WA (km)		252	235	252	235	235	235	235
From the town to the farm		Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm	Dalwallinu to the farm
Method of transport		1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute	1 t ute
To farm (km)		18.4	18.4	18.4	18.4	18.4	18.4	18.4
Total distance transported (km)		270.4	3,869.4	270.4	4,646.4	3,869.4	4,645.4	2,744.4
Allocation of journey	**National portion (%)**	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	International portion (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Table F.11. Lime, showing the distance portion allocation to a farm in Dalwallinu

Lime		Lime
Producer/Formulator		**Aglime**
Country/Town/Region of origin		**Port Denison, Western Australia**
Density (when in liquid form)		**Solid**
International journey		
Method of transport		
Place of manufacture to distributor (km)		
From within Australia to WA (km)		
Method of transport		
Distributor to distributor (km)		
From WA to the town		Port Denison to Dalwallinu
Method of transport		30 t truck
Distributor to town in WA (km)		262
From the town to the farm		Dalwallinu to the farm
Method of transport		1 t ute
To farm (km)		18.4
Total distance transported (km)		280.4
Allocation of journey	**National portion (%)**	100.0
	International portion (%)	0.0

*Note: This table shows the distance allocations to a farm in Dalwallinu, the distances are allocated in the same manner to any other farm. Where no distance allocations were made in the table it means that there was no freighting for that portion.

Appendix F.12. Climatic variables – calculating the emission factors

Farm	Paddock	2010						2011					
		Annual rainfall (mm)	Et min (mm)	Et max (mm)	Average EtT/P (mm)	Emission factor	Leaching/ not leaching	Annual rainfall (mm)	Et min (mm)	Et max (mm)	Average Et/P (mm)	Emission factor	Leaching/ not leaching
A	1	201.0	300	400	1.7	0.3	leaching	271.2	300	400	1.3	0.3	leaching
	2	201.0	300	400	1.7	0.3	leaching	271.2	300	400	1.3	0.3	leaching
	3	201.0	300	400	1.7	0.3	leaching	271.2	300	400	1.3	0.3	leaching
B	4	332.2	300	400	1.1	0.0	no leaching	443.3	300	400	0.8	0.0	no leaching
	5	226.7	300	400	1.5	0.3	leaching	436.6	300	400	0.8	0.0	no leaching
	6	276.2	300	400	1.3	0.3	leaching	419.2	300	400	0.8	0.0	no leaching
C	7	231.4	300	400	1.5	0.3	leaching	361.0	300	400	1.0	0.3	leaching
	8	247.2	300	400	1.4	0.3	leaching	364.4	300	400	1.0	0.0	no leaching
	9	247.2	300	400	1.4	0.3	leaching	364.4	300	400	1.0	0.0	no leaching
D	10	179.2	300	400	2.0	0.3	leaching	271.2	300	400	1.3	0.3	leaching
	11	179.2	300	400	2.0	0.3	leaching	271.2	300	400	1.3	0.3	leaching
	12	179.2	300	400	2.0	0.3	leaching	271.2	300	400	1.3	0.3	leaching
E	13	412.7	300	400	0.8	0.0	no leaching	149.6	300	400	2.3	0.3	leaching
	14	412.7	300	400	0.8	0.0	no leaching	149.6	300	400	2.3	0.3	leaching
	15	412.7	300	400	0.8	0.0	no leaching	149.6	300	400	2.3	0.3	leaching
F	16	233.8	300	400	1.5	0.3	leaching	393.2	300	400	0.9	0.0	no leaching
	17	233.8	300	400	1.5	0.3	leaching	393.2	300	400	0.9	0.0	no leaching
	18	233.8	300	400	1.5	0.3	leaching	393.2	300	400	0.9	0.0	no leaching
G	19	281.4	300	400	1.2	0.0	no leaching	431.3	300	400	0.8	0.0	no leaching
	20	281.4	300	400	1.2	0.0	no leaching	431.3	300	400	0.8	0.0	no leaching
	21	281.4	300	400	1.2	0.0	no leaching	431.3	300	400	0.8	0.0	no leaching
H	22	269.4	300	400	1.3	0.3	leaching	449.0	300	400	0.8	0.0	no leaching
	23	269.4	400	500	1.7	0.3	leaching	449.0	400	500	1.0	0.0	no leaching
	24	269.4	300	400	1.3	0.3	leaching	449.0	300	400	0.8	0.0	no leaching

Appendix F.13. Climatic Variables – annual rainfall figures for 2010 (BOM, 2014)

MONTHLY RAINFALL FIGURES FOR 2010 (mm)														
	BOM weather station	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total for 2010
1	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
2	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
3	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
4	8061	19.3	43.0	43.2	42.5	0.8	1.7	31.5	32.4	38.0	11.0	5.4	53.4	322.2
5	8087	19.1	42.2	36.0	24.0	0.0	0.0	0.0	12.5	17.7	21.0	3.1	51.1	226.7
6	8039	18.0	44.7	38.1	38.3	0.4	0.6	36.6	27.7	12.3	9.0	4.3	46.2	276.2
7	10141	15.8	41.4	34.6	31.4	0.8	4.0	14.4	41.0	13.0	0.8	1.4	32.8	231.4
8	10070	16.4	33.8	30.8	20.3	0.1	8.6	16.0	36.6	36.6	5.0	1.4	41.6	247.2
9	10070	16.4	33.8	30.8	20.3	0.1	8.6	16.0	36.6	36.6	5.0	1.4	41.6	247.2
10	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
11	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
12	8230	13.8	45.4	28.6	44.2	0.0	0.0	5.2	0.0	15.0	0.0	0.0	48.8	201.0
13	7091	31.3	16.6	31.9	0.0	0.0	0.0	97.5	69.0	127.4	0.0	3.1	35.9	412.7
14	7091	31.3	16.6	31.9	0.0	0.0	0.0	97.5	69.0	127.4	0.0	3.1	35.9	412.7
15	7091	31.3	16.6	31.9	0.0	0.0	0.0	97.5	69.0	127.4	0.0	3.1	35.9	412.7
16	10023	24.6	48.0	27.8	9.6	2.0	4.6	27.6	25.0	7.4	0.0	5.0	52.2	233.8
17	10023	24.6	48.0	27.8	9.6	2.0	4.6	27.6	25.0	7.4	0.0	5.0	52.2	233.8
18	10023	24.6	48.0	27.8	9.6	2.0	4.6	27.6	25.0	7.4	0.0	5.0	52.2	233.8
19	10111	24.7	68.1	29.2	16.6	3.9	9.5	31.8	26.2	8.4	0.8	12.2	50.0	281.4
20	10111	24.7	68.1	29.2	16.6	3.9	9.5	31.8	26.2	8.4	0.8	12.2	50.0	281.4
21	10111	24.7	68.1	29.2	16.6	3.9	9.5	31.8	26.2	8.4	0.8	12.2	50.0	281.4
22	10134	26.8	57.4	35.6	16.2	2.6	6.6	13.4	14.2	6.2	35.2	5.2	50.0	269.4
23	10134	26.8	57.4	35.6	16.2	2.6	6.6	13.4	14.2	6.2	35.2	5.2	50.0	269.4
24	10134	26.8	57.4	35.6	16.2	2.6	6.6	13.4	14.2	6.2	35.2	5.2	50.0	269.4

Appendix F.14. Climatic Variables – annual rainfall figures for 2011 (BOM, 2014)

MONTHLY RAINFALL FIGURES FOR 2011 (mm)														
	BOM weather station	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total for 2011
1	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
2	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
3	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
4	8061	41.4	77.3	61.6	36.4	82.1	13.0	23.5	64.0	30.0	1.0	3.2	9.8	443.3
5	8087	46.2	69.9	62.5	30.8	64.0	18.0	31.0	12.1	13.0	20.6	21.7	46.8	436.6
6	8039	46.5	71.8	59.3	31.5	83.2	14.8	18.0	58.0	25.2	1.0	2.4	7.5	419.2
7	10141	38.2	70.4	44.6	24.6	67.6	11.6	45.8	22.6	9.4	5.0	15.6	5.6	361.0
8	10070	35.8	64.8	41.8	21.0	76.6	25.2	34.4	19.8	12.6	10.6	14.8	7.0	364.4
9	10070	35.8	64.8	41.8	21.0	76.6	25.2	34.4	19.8	12.6	10.6	14.8	7.0	364.4
10	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
11	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
12	8230	24.0	62.4	48.2	36.6	60.0	8.8	0.0	23.0	8.2	0.0	0.0	0.0	271.2
13	7091	34.0	74.4	22.8	18.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	149.6
14	7091	34.0	74.4	22.8	18.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	149.6
15	7091	34.0	74.4	22.8	18.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	149.6
16	10023	41.8	87.0	47.6	42.4	76.4	22.4	30.0	5.4	25.0	2.6	1.6	11.0	393.2
17	10023	41.8	87.0	47.6	42.4	76.4	22.4	30.0	5.4	25.0	2.6	1.6	11.0	393.2
18	10023	41.8	87.0	47.6	42.4	76.4	22.4	30.0	5.4	25.0	2.6	1.6	11.0	393.2
19	10111	68.8	93.7	62.0	50.7	60.2	16.9	15.4	1.0	37.7	0.2	6.2	17.7	430.5
20	10111	68.8	93.7	62.0	50.7	60.2	16.9	15.4	1.0	37.7	0.2	6.2	17.7	430.5
21	10111	68.8	93.7	62.0	50.7	60.2	16.9	15.4	1.0	37.7	0.2	6.2	17.7	430.5
22	10134	58.2	111.8	60.0	46.4	85.4	14.8	9.0	1.8	28.4	0.0	9.4	23.8	449.0
23	10134	58.2	111.8	60.0	46.4	85.4	14.8	9.0	1.8	28.4	0.0	9.4	23.8	449.0
24	10134	58.2	111.8	60.0	46.4	85.4	14.8	9.0	1.8	28.4	0.0	9.4	23.8	449.0

Appendix F.15. Farm A. Inventory list for chemical production per tonne of grain yield

Farm A			2010			2011		
Classification	Chemical	Paddock number	1	2	3	1	2	3
Fertilisers	Agstar Extra	kg/yr/t				2.28E+01	3.23E+01	2.97E+01
	Copper	kg/yr/t				1.39E+01		2.30E+01
	DAP Extra	kg/yr/t	2.82E+01	3.46E+01	3.03E+01			
	Flexi -N	kg/yr/t				2.79E+01		1.81E+01
	Urea	kg/yr/t				2.11E-01		2.74E-01
Fungicides and insecticides	Folicur	kg/yr/t				5.89E-02		7.67E-02
	Lorsban	kg/yr/t					3.74E-02	
	Vincit	kg/yr/t			3.73E-02			
Herbicides	Ally	kg/yr/t	3.03E-03					
	Diuron	kg/yr/t				1.03E+00	9.95E-020	
	Ester 600	kg/yr/t	4.55E-01					
	Garlon	kg/yr/t				7.66E-02		
	Gramoxone	kg/yr/t					4.46E-01	
	Jaguar	kg/yr/t				3.54E-02	8.33E-01	1.86E-01
	Logran	kg/yr/t	2.27E-02	2.48E-02	2.17E-02		1.24E-02	9.66E-02
	MCPA 242	kg/yr/t				7.66E-01	3.92E-03	7.64E-01
	Monza	kg/yr/t	1.89E-02		1.81E-02			
	Roundup	kg/yr/t	2.30E+00	9.67E-01	8.48E-01	1.67E-01	9.95E-02	5.34E-01
	Treflan	kg/yr/t	1.52E+00	1.24E+00	1.09E+00	4.11E-01	3.95E-01	3.69E-01
Adjuvants	LI 700	kg/yr/t				5.56E-03		
	Sulphate of Ammonia	kg/yr/t				3.54E-02	2.55E-02	
	BS 1000	kg/yr/t				2.31E-03	6.24E-03	7.04E-03
Lime		kg/yr/t	7.58E+01	8.26E+01	7.25E+01	3.51E+01	4.98E+01	4.57E+01

Appendix F.16. Farm A. Inventory list for for soil emissions per tonne of grain yield

Farm A		2010			2011		
Soil Emissions	Paddock number	1	2	3	1	2	3
N_2O direct	kg/yr/t	5.30E-03	6.51E-03	5.71E-03	1.86E-02	4.56E-03	7.48E-02
N_2O indirect (vol)	kg/yr/t	4.24E-04	5.21E-04	4.57E-04	1.31E-03	3.65E-04	1.64E-03
N_2O indirect (leaching)	kg/yr/t	1.59E+00	1.95E-01	1.71E+00	5.58E+00	1.37E+00	7.17E+00
CO_2 liming	kg/yr/t	9.09E+00	9.92E+00	8.70E+00	4.21E+00	5.97E+00	5.48E+00
CO_2 urea hydrolysis	kg/yr/t				2.81E+00		4.57E+00
CH_4	kg/yr/t						

Appendix F.17. Farm A. Inventory list for grazing sheep per tonne of grain yield

Farm A		2010			2011		
Emissions from grazing	Paddock number	1	2	3	1	2	3
CH_4 from Enteric Emissions	kg/ha/t	-	-	-	6.07E-02	4.75E-02	4.23E-02
CH_4 from Manure	kg/ha/t	-	-	-	1.13E-03	4.56E-04	7.72E-04

Appendix F.18. Farm A. Inventory list for stubble burning per tonne of grain yield

Farm A		2010			2011		
Emissions from stubble burning	Paddock number	1	2	3	1	2	3
CO_2	kg/ha/t	-	-	-	-	-	-
CH_4	kg/ha/t	4.36E-01	4.73E-01	2.44E-01		6.10E-01	
N_2O	kg/ha/t	9.47E-01	1.03E+00	5.30E-01		1.33E+00	

Appendix F.19. Farm A. Inventory list for production and use of farm machinery per tonne of grain yield

Farm A			2010			2011		
Emissions from production and use of farm machinery		**Paddock number**	**1**	**2**	**3**	**1**	**2**	**3**
Seeding	**Cost of seeding machinery (1998 price)**	**USD/t**	2.71E+00	2.96E+00	2.59E+00	1.26E+00	1.78E+00	1.63E+00
	Fuel Use	**l/hr/t**	3.16E+00	3.44E+00	3.02E+00	1.46E+00	2.07E+00	1.90E+00
Spraying	**Cost of spraying machinery (1998 price)**	**USD/t**	8.10E-01	2.95E-01	5.17E-01	5.00E-01	3.55E-01	4.88E-01
	Fuel Use	**l/hr/t**	8.23E-01	2.99E-01	5.25E-01	5.09E-01	3.61E-01	4.96E-01
Top-dressing - fertiliser	**Cost of top-dressing machinery (1998 price)**	**USD/t**	0.00E+00	0.00E+00	0.00E+00	2.10E+00	0.00E+00	2.74E+00
	Fuel Use	**l/hr/t**	0.00E+00	0.00E+00	0.00E+00	3.09E-01	0.00E+00	4.02E-01
Top-dressing - lime	**Cost of top-dressing machinery (1998 price)**	**USD/t**	1.49E+01	1.77E+01	1.36E+01	3.19E+00	6.41E+00	5.40E+00
	Fuel Use	**l/hr/t**	2.18E+00	2.60E+00	2.00E+00	4.68E-01	9.41E-01	7.92E-01
Harvesting	**Cost of harvesting machinery (1998 price)**	**USD/t**	1.13E+01	1.24E+01	1.09E+01	5.26E+00	7.45E+00	6.84E+00
	Fuel Use	**l/hr/t**	4.30E+00	4.70E+00	4.12E+00	1.99E+00	2.83E+00	2.59E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.20. Farm A. Inventory list for the transportation of chemicals per tonne of grain yield

Farm A			2010			2011		
Classification	Chemical Name	Paddock number	1	2	3	1	2	3
Fertilisers	Agstar Extra	tkm/t				5.78E+00	8.19E+00	7.52E+00
	Copper	tkm/t				5.33E-02		1.04E-01
	DAP extra	tkm/t	7.14E+00	8.76E+00	7.68E+00			
	Flexi -N	tkm/t				7.04E+00		8.40E+01
	Urea	tkm/t				1.45E+02		2.35E+02
Fungicides and insecticides	Folicur	tkm/t				2.74E-01		3.56E-01
	Lorsban	tkm/t					1.01E-02	
	Vincit	tkm/t			9.46E-03			
Herbicides	Ally	tkm/t	1.41E-02					
	Diuron	tkm/t				1.94E-02	3.55E-01	
	Ester 600	tkm/t	1.23E-01					
	Garlon	tkm/t				8.85E-02		
	Gramoxone	tkm/t					1.13E-01	
	Jaguar	tkm/t				7.19E-02	1.13E-01	9.35E-02
	Logran	tkm/t	8.10E-02	8.84E-02	7.75E-02		3.99E-01	3.42E-01
	MCPA 242	tkm/t				8.71E-02	3.43E-02	5.04E-02
	Monza	tkm/t	6.81E-02		6.51E-02	3.64E-01		
	Roundup	tkm/t	5.84E-01	2.45E-01	2.15E-01	3.64E-01	1.77E-01	1.35E-01
	Treflan	tkm/t	5.61E+00	4.59E+00	4.02E+00	2.17E+00	6.17E+00	2.83E+00
Adjuvants	LI 700	tkm/t				1.50E-03		
	Sulphate of Ammonia	tkm/t				8.97E-03	6.47E-03	5.53E-03
	Wetter BS 1000	tkm/t				3.35E-02	1.59E-03	1.13E-01
Lime		tkm/t	2.12E+01	2.32E+01	2.03E+01	9.84E+00	1.40E+01	1.28E+01

Appendix F.21. Farm B. Inventory list for chemical production per tonne of grain yield

Farm B			2010			2011		
Classification	**Chemical Name**	**Paddock number**	**4**	**5**	**6**	**4**	**5**	**6**
Fertilisers	**Agyield Extra**	**kg/yr/t**			2.70E+01			2.52E+01
	K Till Extra	**kg/yr/t**	4.37E+01	4.69E+01			3.83E+01	
	Urea	**kg/yr/t**	6.31E+01	5.73E+01	1.66E+01		3.83E+01	1.94E+01
Fungicides and insecticides	**Alpha Cypermethrin**	**kg/yr/t**						3.61E-02
	Alpha Duo	**kg/yr/t**		4.84E-02	3.86E-02			
	Alphasip Duo	**kg/yr/t**	4.51E-02					
	Dividend	**kg/yr/t**					6.04E-02	
	Lemat L	**kg/yr/t**	6.12E-01					4.07E-02
	Premis	**kg/yr/t**	9.71E-03					
Herbicides	**Amine 625**	**kg/yr/t**					4.25E-01	
	Bromicide	**kg/yr/t**				1.25E-01		
	Ester 800	**kg/yr/t**	2.37E-01		1.52E-01			
	Garlon	**kg/yr/t**			3.98E-01		3.38E-02	
	Gladiator	**kg/yr/t**	5.83E-01	9.38E-01				
	Lexone	**kg/yr/t**					5.31E-02	
	Logran	**kg/yr/t**		1.30E-02				5.82E+00
	Roundup	**kg/yr/t**	5.70E-01				8.71E-01	4.99E-01
	Select	**kg/yr/t**				1.69E-01		
	Sprayseed	**kg/yr/t**			1.94E-01	4.16E-02		
	Tigrex	**kg/yr/t**				7.08E-03		
	Treflan	**kg/yr/t**						6.06E-01
	Trifluralin	**kg/yr/t**		7.81E-01	4.15E-02			
	Triflurx	**kg/yr/t**	6.34E-01				7.12E-01	
	Velocity	**kg/yr/t**	2.43E-01	2.60E-01				
Adjuvants	**Ammoniun Sulphate**	**kg/yr/t**	4.47E-01		2.07E-01			1.94E-01
	LI700	**kg/yr/t**						8.73E-05
Lime		**kg/yr/t**	4.85E+01	5.21E+01	4.15E+01	3.56E+01	4.25E+01	3.88E+01

Appendix F.22. Farm B. Inventory list for soil emissions per tonne of grain yield

Farm B		2010			2011		
Soil Emissions	**Paddock number**	**4**	**5**	**6**	**4**	**5**	**6**
N_2O direct	**kg/yr/t**	3.34E-02	3.10E-02	1.23E-02	-	2.14E-02	1.33E-02
N_2O indirect (vol)	**kg/yr/t**	2.67E-03	2.48E-03	9.82E-04	-	1.71E-03	1.06E-03
N_2O indirect (leaching)	**kg/yr/t**	-	-	-	-	-	-
CO_2 liming	**kg/yr/t**	5.83E+00	6.25E+00	4.98E+00	4.27E+00	5.10E+00	4.66E+00
CO_2 urea hydrolysis	**kg/yr/t**	1.26E+01	1.15E+01	3.32E+00	-	7.65E+00	3.88E+00
CH_4	**kg/yr/t**	-	-	-	-	-	-

Appendix F.23. Farm B. Inventory list for production and use of farm machinery (1998 price) per tonne of grain yield

Farm B			2010			2011		
Emissions from production and use of farm machinery		**Paddock number**	**4**	**5**	**6**	**4**	**5**	**6**
Seeding	**Cost of seeding machinery (1998 price)**	**USD/t**	1.74E+00	1.86E+00	1.48E+00	1.27E+00	1.52E+00	1.39E+00
	Fuel Use	**l/hr/t**	2.02E+00	2.17E+00	1.73E+00	1.48E+00	1.77E+00	1.62E+00
Spraying	**Cost of spraying machinery (1998 price)**	**USD/t**	7.96E-01	3.42E-01	2.72E-01	2.33E-01	6.97E-01	2.55E-01
	Fuel Use	**l/hr/t**	8.09E-01	3.47E-01	2.77E-01	2.37E-01	7.09E-01	2.59E-01
Top-dressing -fertiliser	**Cost of top-dressing machinery (1998 price)**	**USD/t**	1.45E+00	1.56E+00	1.24E+00	1.07E+00	1.27E+00	1.16E+00
	Fuel Use	**l/hr/t**	2.14E-01	2.29E-01	1.82E-01	1.57E-01	1.87E-01	1.71E-01
Top-dressing -lime	**Cost of top-dressing machinery (1998 price)**	**USD/t**	5.24E-01	5.62E-01	4.48E-01	3.84E-01	4.59E-01	4.19E-01
	Fuel Use	**l/hr/t**	7.69E-02	8.25E-02	6.57E-02	5.63E-02	6.73E-02	6.14E-02
Harvesting	**Cost of harvesting machinery (1998 price)**	**USD/t**	7.27E+00	7.80E+00	6.22E+00	5.33E+00	6.37E+00	5.81E+00
	Fuel Use	**l/hr/t**	2.76E+00	2.96E+00	2.36E+00	2.02E+00	2.42E+00	2.20E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.24. Farm B. Inventory list for the transportation of chemicals per tonne of grain yield

Farm B			2010			2011		
Classification	Chemical Name	Paddock number	4	5	6	4	5	6
Fertilisers	Agyield Extra	tkm/t			6.62E+00			6.01E-02
	K Till Extra	tkm/t	1.07E+01	1.15E+01			9.39E+00	
	Urea	tkm/t	6.50E+02	5.90E+02	1.71E+02		3.94E+02	4.76E+00
Fungicides and insecticides	Alpha Cypermethrin	tkm/t						9.47E-03
	Alpha Duo	tkm/t		1.27E-02	1.01E-02			
	Alphasip Duo	tkm/t	1.18E-02					
	Dividend	tkm/t					1.48E-02	
	Lemat L	tkm/t	2.57E+00					1.71E-01
	Premis	tkm/t	4.50E-02					
Herbicides	Amine 625	tkm/t					1.12E-01	
	Bromicide	tkm/t				3.07E-02		
	Ester 800	tkm/t	5.83E-02		3.73E-02			
	Garlon	tkm/t					1.09E-01	
	Gladiator	tkm/t	1.43E-01	2.30E-01	9.78E-02			
	Lexone	tkm/t					1.96E-01	
	Logran	tkm/t		4.63E-02				2.07E+01
	Roundup	tkm/t	1.40E-01				2.14E-01	1.23E-01
	Select	tkm/t				4.15E-02		
	Sprayseed	tkm/t			4.77E-02	1.02E-02		
	Tigrex	tkm/t				1.74E-03		
	Treflan	tkm/t						2.24E+00
	Trifluralin	tkm/t		1.92E-01	1.02E-02			
	Triflurx	tkm/t	1.56E-01				1.75E-01	
	Velocity	tkm/t	1.13E+00	1.21E+00				
Adjuvants	Ammoniun Sulphate	tkm/t	1.10E-01		5.09E-02			4.76E-02
	LI700	tkm/t						2.29E-05
Lime		tkm/t	1.32E+01	1.42E+01	1.13E+01	9.69E+00	1.16E+01	1.06E+01

Appendix F.25. Farm C. Inventory list for chemical production per tonne of grain yield

Farm C			2010			2011		
Classification	**Chemical Name**	**Units**	**7**	**8**	**9**	**7**	**8**	**9**
Fertilisers	**DAP SZC**	**kg/yr/t**	1.56E+01	2.78E+01	2.27E+01			
	Flexi-N	**kg/yr/t**				1.50E+01		
	MAP SZC	**kg/yr/t**	1.56E+01	2.78E+01	2.27E+01			
	MaxAamRite	**kg/yr/t**				2.27E+01		
	MOP	**kg/yr/t**			1.82E+01			1.88E+01
	NPS range-Cereal	**kg/yr/t**					1.29E+01	6.88E+01
	Urea	**kg/yr/t**	1.56E+01	2.78E+01	2.27E+01	1.14E+01		
Fungicides and insecticides	**Alpha-cypermethrin**	**kg/yr/t**						1.16E-01
Herbicides	**Brodal**	**kg/yr/t**						1.47E-01
	Ester 680	**kg/yr/t**			2.18E-01			
	Gramoxone	**kg/yr/t**					3.20E-01	
	Lexone	**kg/yr/t**						1.25E-01
	Logran	**kg/yr/t**	1.25E-03	2.22E-02	2.73E-02			
	Roundup	**kg/yr/t**	5.85E-01	1.04E00	8.51E-01	5.32E-01		
	Select	**kg/yr/t**						2.97E-01
	Simazine 500	**kg/yr/t**						1.58E+00
	Sprayseed	**kg/yr/t**						1.46E+00
	Tigrex	**kg/yr/t**				2.71E-01		
	Treflan	**kg/yr/t**	7.50E-01	1.33E+00		5.45E-01		
	Trifluralin	**kg/yr/t**			1.09E+00			
	Verdict	**kg/yr/t**						5.75E-01
Adjuvant	**Ammonium Sulphate**	**kg/yr/t**						1.33E-02
Lime		**kg/yr/t**	6.25E+01	1.11E+02	1.36E+02	4.55E+01	2.86E+01	1.88E+02

Appendix F.26. Farm C. Inventory list for soil emissions per tonne of grain yield

Farm C		2010			2011		
Soil Emissions	**Paddock number**	**7**	**8**	**9**	**7**	**8**	**9**
N_2O direct	kg/year/t	1.16E-02	2.08E-02	1.70E-02	1.29E-02	1.61E-03	8.59E-03
N_2O indirect (vol)	kg/year/t	9.35E-04	1.66E-03	1.36E-03	1.03E-03	1.29E-04	6.88E-04
N_2O indirect (leaching)	kg/year/t	3.51E+00	6.23E-01	5.43E-01	3.88E+00	-	-
CO_2 liming	kg/year/t	7.50E+00	1.33E+01	1.64E+01	5.45E+00	3.43E+00	2.25E+01
CO_2 urea hydrolysis	kg/year/t	3.13E+00	5.56E+00	4.55E+00	2.27E+00	-	-
CH_4	kg/year/t	-	-	-	-	-	-

Appendix F.27. Farm C. Inventory list for grazing sheep per tonne of grain yield

Farm C		2010			2011		
Emissions from grazing	**Paddock number**	**7**	**8**	**9**	**7**	**8**	**9**
CH_4 from Enteric Emissions	kg/ha/t	1.46E+00	-	-	1.59E+00	4.38E+00	1.71E+00
CH_4 from Manure	kg/ha/t	6.75E-04	-	-	7.36E-04	2.03E-03	1.06E-03

Appendix F.28. Farm C. Inventory list for production and use of farm machinery per tonne of grain yield

Farm C			2010			2011		
Emissions from production and use of farm machinery		**Paddock number**	**7**	**8**	**9**	**7**	**8**	**9**
Seeding	Cost of seeding machinery (1998 price)	USD/t	2.24E+00	3.98E+00	3.25E+00	1.63E+00	1.02E+00	4.47E+00
	Fuel Use	l/hr/t	2.60E+00	4.63E+00	3.79E+00	1.89E+00	1.19E+00	5.21E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t	9.23E-01	5.47E-01	8.95E-01	9.72E-01	6.11E-01	2.67E+00
	Fuel Use	l/hr/t	6.25E-01	3.70E-01	6.06E-01	6.59E-01	4.14E-01	1.81E+00
Top-dressing -fertiliser	Cost of top-dressing machinery (1998 price)	USD/t				1.36E+00		
	Fuel Use	l/hr/t				2.00E-01		
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t	1.12E-01	2.00E-01	1.63E-01	8.17E-02	5.14E-02	2.25E-01
	Fuel Use	l/hr/t	2.75E-02	4.89E-02	4.00E-02	2.00E-02	1.26E-02	5.50E-02
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	9.36E+00	1.66E+01	1.36E+01	6.81E+00	4.28E+00	1.87E+01

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.29. Farm C. Inventory list for the transportation of chemicals per tonne of grain yield

Farm C			2010			2011		
Classification	**Chemical Name**	**Paddock number**	**7**	**8**	**9**	**7**	**8**	**9**
Fertilisers	**NPS range-Cereal**	**tkm/t**					3.65E+00	1.95E+01
	DAP SZC	**tkm/t**	6.70E+01	1.19E+02	9.75E+01			
	Flexi-N	**tkm/t**				4.25E+00		
	MAP SZC	**tkm/t**	6.70E+01	1.19E+02	9.75E+01			
	MaxAmRite	**tkm/t**				6.43E+00		
	MOP	**tkm/t**			5.15E+00			5.31E+00
	Urea	**tkm/t**	1.62E+02	2.87E+02	2.35E+02	1.17E+02		
Fungicides and insecticides	**Alpha-cypermethrin**	**tkm/t**						3.49E-02
Herbicides	**Brodal**	**tkm/t**						6.87E-01
	Ester 680	**tkm/t**			2.18E-01			
	Gramoxone	**tkm/t**					9.06E-02	
	Lexone	**tkm/t**						4.67E-01
	Logran	**tkm/t**	4.49E-03	7.99E-03	9.80E-02			
	Roundup	**tkm/t**	1.66E-01	2.94E-01	2.41E-01	1.51E-01		
	Select	**tkm/t**						8.40E-02
	Simazine 500	**tkm/t**						4.47E-01
	Sprayseed	**tkm/t**						4.14E-01
	Tigrex	**tkm/t**				7.68E-02		
	Treflan	**tkm/t**	2.80E+00	4.98E+00		2.04E+00		
	Trifluralin	**tkm/t**			3.09E-01			
	Verdict	**tkm/t**						1.73E-01
Adjuvants	**Ammonium Sulphate**	**tkm/t**						3.76E-03
Lime		**tkm/t**	1.94E+01	3.44E+01	4.23E+01	1.41E+01	8.86E+00	5.81E+01

Appendix F.30. Farm D. Inventory list for chemical production per tonne of grain yield

Farmer D			2010			2011		
Classification	**Chemical Name**	**Paddock number**	**10**	**11**	**12**	**10**	**11**	**12**
Fertilisers	**Agras**	**kg/yr/t**		5.56E+01	5.50E+01		3.23E+01	3.33E+01
	Flexi N	**kg/yr/t**					2.13E+01	2.20E+01
Fungicides and insecticides	**Prosaro 420**	**kg/yr/t**					5.40E-02	
Herbicides	**Avadex**	**kg/yr/t**			7.50E-01			1.29E+00
	Diuron	**kg/yr/t**			2.18E-01			5.33E-01
	Jaguar	**kg/yr/t**		5.56E-01				
	Lexone	**kg/yr/t**					3.77E-01	
	Logran	**kg/yr/t**		1.94E-02				
	Roundup	**kg/yr/t**		6.50E-01			4.52E-01	3.90E-01
	Treflan	**kg/yr/t**		4.19E-01	5.00E-01		8.06E-02	3.61E-02
Lime		**kg/yr/t**		5.56E+01	5.00E+01		3.23E+01	3.33E+01

Appendix F.31. Farm D. Inventory list for soil emissions per tonne of grain yield

Farmer D		2010			2011		
Soil Emissions	**Paddock number**	**10**	**11**	**12**	**10**	**11**	**12**
N_2O direct	**kg/yr/t**		8.94E-03	7.25E-03		1.20E-02	1.24E-02
N_2O indirect (vol)	**kg/yr/t**		7.16E-04	5.80E-04		9.61E-04	8.56E-04
N_2O indirect (leaching)	**kg/yr/t**		2.68E+00	2.17E+00		3.11E+00	3.72E+00
CO_2 liming	**kg/yr/t**		6.67E+00	6.00E+00		3.87E+00	4.00E+00
CO_2 urea hydrolysis	**kg/yr/t**		-	-		-	-
CH_4	**kg/yr/t**		-	-		-	-

Appendix F.32. Farm D. Inventory list for grazing sheep per tonne of grain yield

Farmer D		2010			2011		
Emissions from grazing	Paddock number	10	11	12	10	11	12
CH_4 from Enteric Emissions	kg/ha/t		1.42E+00	1.42E+00		-	-
CH_4 from Manure	kg/ha/t		6.56E-04	6.56E-04		-	-

Appendix F.33. Farm D. Inventory list for stubble burning per tonne of grain yield

Farmer D		2010			2011		
Emissions from stubble burning	Paddock number	10	11	12	10	11	12
CO_2	kg/ha/t		-	-	-	-	-
CH_4	kg/ha/t		1.15E+02	2.90E+01	-	-	-
N_2O	kg/ha/t		2.49E+02	6.30E+01	-	-	-

Appendix F.34. Farm D. Emissions from production and use of farm machinery per tonne of grain yield

Farmer D			2010			2011		
Emissions from production and use of farm machinery		Paddock number	10	11	12	10	11	12
Seeding	Cost of seeding machinery (1998 price)	USD/t		1.99E+00	1.79E+00		1.15E+00	1.19E+00
	Fuel Use	l/hr/t		2.31E+00	2.08E+00		1.34E+00	1.39E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t		2.46E-01	4.43E-01		5.71E-01	5.90E-01
	Fuel Use	l/hr/t		1.85E-01	3.33E-01		4.30E-01	4.44E-01
Top-dressing - fertiliser	Cost of top-dressing machinery (1998 price)	USD/t					9.67E-01	9.99E-01
	Fuel Use	l/hr/t					1.42E-01	1.47E-01
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t		5.99E-01	5.39E-01		3.48E-01	3.60E-01
	Fuel Use	l/hr/t		8.80E-02	7.92E-02		5.11E-02	5.28E-02
Harvesting	Cost of harvesting machinery (1998 price)	USD/t		8.32E+00	7.49E+00		4.83E+00	4.99E+00
	Fuel Use	l/hr/t		3.16E+00	2.84E+00		1.83E+00	1.89E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.35. Farm D. Inventory list for the transportation of chemicals per tonne of grain yield

Farmer D			2010			2011		
Classification	**Chemical Name**	**Paddock number**	**10**	**11**	**12**	**10**	**11**	**12**
Fertilisers	**Agras**	**tkm/t**		1.38E+01	1.36E+01		8.00E+00	8.26E+00
	Flexi N	**tkm/t**					5.28E+00	5.45E+00
Fungicides and insecticides	**Prosaro 420**	**tkm/t**					2.50E-01	
Herbicides	**Avadex**	**tkm/t**			1.99E-01			1.41E-01
	Diuron	**tkm/t**			5.41E-02			3.61E-02
	Jaguar	**tkm/t**		1.04E-01				
	Lexone	**tkm/t**					1.17E+00	
	Logran	**tkm/t**		6.92E-02				
	Roundup	**tkm/t**		1.61E-01			9.36E-02	9.67E-02
	Treflan	**tkm/t**		2.05E+00	1.85E+00		1.67E+00	1.48E+00
Lime		**tkm/t**		1.53E+01	1.37E+01		8.87E+00	9.16E+00

Appendix F.36. Farm E. Inventory list for chemical production per tonne of grain yield

Farm E			2010			2011		
Classification	**Chemical Name**	**Paddock number**	**13**	**14**	**15**	**13**	**14**	**15**
Fertilisers	**DAP**	**kg/yr/t**	5.13E+01	4.62E+01	5.45E+01	9.56E+00	1.91E+01	
	MAP	**kg/yr/t**						3.34E+01
	Sodium molybdate	**kg/yr/t**				8.82E-04		
	Urea	**kg/yr/t**				9.56E+00	1.91E+01	
Herbicides	**Diuron**	**kg/yr/t**			2.27E-02	9.64E-02	9.64E-02	
	Ester 600	**kg/yr/t**						2.47E-01
	Logran	**kg/yr/t**	2.39E-02	1.15E-02	5.91E-02	2.65E-02	4.41E-03	
	MCPA LVE	**kg/yr/t**	2.18E-01		2.32E-01	2.21E-02		
	Roundup	**kg/yr/t**	1.00E+00	7.69E-01	1.06E+00	3.44E-01	3.44E-01	6.52E-01
	Tigrex	**kg/yr/t**	4.25E-01		3.62E-01	1.35E-01		
	Treflan	**kg/yr/t**	2.56E-03	1.29E+00	2.98E-02	2.60E-01	2.60E-01	
	Triasulfuron	**kg/yr/t**		1.92E-02				
Adjuvants	**Ammonium Sulphate**	**kg/yr/t**				2.08E-01	2.60E-01	4.93E-01
	BS 1000	**kg/yr/t**				1.77E-03	1.77E-03	3.35E-03
	Hasten	**kg/yr/t**				1.99E-01		
Lime		**kg/yr/t**	1.07E+02	9.62E+01	1.14E+02	3.68E+01	3.68E+01	6.96E+01

Appendix F.37. Farm E. Inventory list for soil emissions per tonne of grain yield

Farm E		2010			2011		
Soil Emissions	**Paddock number**	**13**	**14**	**15**	**13**	**14**	**15**
N_2O direct	**kg/yr/t**	8.97E-03	2.42E-02	9.55E-03	6.07E-03	1.21E-02	3.68E-03
N_2O indirect (vol)	**kg/yr/t**	7.18E-04	6.46E-04	7.64E-04	4.86E-04	9.71E-04	2.94E-04
N_2O indirect (leaching)	**kg/yr/t**	-	-	-	1.82E-01	3.64E+00	1.10E+00
CO_2 liming	**kg/yr/t**	1.28E+01	1.15E+01	1.36E+01	4.41E+00	4.41E+00	8.36E+00
CO_2 urea hydrolysis	**kg/yr/t**	-	-	-	-	-	-
CH_4	**kg/yr/t**	-	-	-	-	-	-

Appendix F.38. Farm E. Inventory list for grazing sheep per tonne of grain yield

Farm E		2010			2011		
Emissions from grazing	Paddock number	13	14	15	13	14	15
CH_4 from Enteric Emissions	kg/ha/t	1.15E+00	1.04E+00	9.84E-01	5.72E-01	6.30E-01	8.91E-01
CH_4 from Manure	kg/ha/t	1.19E-03	1.07E-03	1.01E-03	5.89E-04	5.07E-04	9.18E-04

Appendix F.39. Farm E. Inventory list for production and use of farm machinery per tonne of grain yield

Farm E			2010			2011		
Emissions from production and use of farm machinery		Paddock number	13	14	15	13	14	15
Seeding	Cost of seeding machinery (1998 price)	USD/t	3.67E+00	3.30E+00	3.90E+00	1.26E+00	1.26E+00	2.39E+00
	Fuel Use	l/hr/t	3.56E+00	3.21E+00	3.79E+00	1.23E+00	1.23E+00	2.32E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t	5.61E-01	2.52E-01	5.96E-01	1.93E-01	9.65E-02	1.83E-01
	Fuel Use	l/hr/t	5.70E-01	2.56E-01	6.06E-01	1.96E-01	9.80E-02	1.86E-01
Top-dressing -fertiliser	Cost of top-dressing machinery (1998 price)	USD/t	-	-	2.72E+00	2.64E+00	1.76E+00	1.67E+00
	Fuel Use	l/hr/t	-	-	4.00E-01	3.88E-01	2.59E-01	2.45E-01
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t	1.84E+00	1.66E+00	1.96E+00	6.35E-01	6.35E-01	1.20E+00
	Fuel Use	l/hr/t	2.71E-01	2.44E-01	2.88E-01	9.31E-02	9.31E-02	1.76E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	1.28E+01	1.15E+01	1.36E+01	4.41E+00	4.41E+00	8.35E+00
	Fuel Use	l/hr/t	4.86E+00	4.37E+00	5.17E+00	1.67E+00	1.67E+00	3.17E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.40. Farm E. Inventory list for from the transportation of chemicals per tonne of grain yield

Farm E			2010			2011		
Emissions from transportation of chemicals		**Paddock number**	**13**	**14**	**15**	**13**	**14**	**15**
Fertilisers	**DAP**	**tkm/t**	2.21E+02	1.99E+02	2.35E+02	4.12E+01	8.24E+01	
	MAP	**tkm/t**						1.44E+02
	Sodium molybdate	**tkm/t**				2.65E-04		
	Urea	**tkm/t**				9.90E+01	1.98E+02	
Herbicides	**Ester 600**	**tkm/t**						7.84E-02
	Diuron	**tkm/t**			8.93E-03	2.89E-02	2.89E-02	
	Logran	**tkm/t**	7.86E-02	4.17E-02	2.13E-01	6.10E-02	1.59E-02	
	MCPA LVE	**tkm/t**	6.91E-02		7.35E-02	7.97E-02		
	Roundup	**tkm/t**	3.00E-01	2.31E-01	3.19E-01	1.03E-01	1.03E-01	1.96E-01
	Tigrex	**tkm/t**	1.28E-01		1.09E-01	4.28E-02		
	Treflan	**tkm/t**	9.26E-03	3.86E-01	4.98E+00	7.81E-02	1.61E+00	
	Triasulfuron	**tkm/t**		4.17E-02				
Adjuvants	**Ammonium Sulphate**	**tkm/t**				1.17E-01	7.81E-02	1.48E-01
	BS 1000	**tkm/t**				5.31E-04	5.31E-04	1.01E-03
	Hasten	**tkm/t**				7.53E-01		
Lime		**tkm/t**	3.49E+01	3.14E+01	3.72E+01	1.20E+01	1.20E+01	2.28E+01

Appendix F.41. Farm F. Inventory list for from chemical production per tonne of grain yield

Farm F			2010			2011		
Classification	Chemical Name	Paddock number	16	17	18	16	17	18
Fertilisers	MAP	kg/yr/t			4.29E+01			4.29E+01
	MAXamFLO	kg/yr/t			9.32E+01			5.00E+01
	UAN	kg/yr/t						5.19E+01
Herbicides	Atlantis	kg/yr/t			1.55E-01			
	Atraxine 500	kg/yr/t						1.73E+00
	Bifenthrin	kg/yr/t						4.65E+01
	Logran	kg/yr/t			1.50E-03			
	Roundup	kg/yr/t			7.92E-01			
	Select	kg/yr/t						3.39E-01
	Treflan	kg/yr/t			1.51E+00			
Lime		kg/yr/t			7.52E+01			7.14E+01

Appendix F.42. Farm F. Inventory list for soil emissions per tonne of grain yield

Farm F		2010			2011		
Soil Emissions	Paddock number	16	17	18	16	17	18
N_2O direct	kg/year/t			1.63E-02			3.23E-02
N_2O indirect (vol)	kg/year/t			1.30E-03			4.06E-03
N_2O indirect (leaching)	kg/year/t			4.89E+00			-
CO_2 liming	kg/year/t			9.02E+00			8.57E+00
CO_2 urea hydrolysis	kg/year/t			-			-
CH_4	kg/year/t			-			-

Appendix F.43. Farm F. Inventory list for stubble burning per tonne of grain yield

Farm F		2010			2011		
Emissions from stubble burning	Paddock number	16	17	18	16	17	18
CO_2	kg/ha/t			-			-
CH4	kg/ha/t			-			3.94E+00
N_2O	kg/ha/t			-			8.56E+00

Appendix F.44. Farm F. Inventory list for production and use of farm machinery per tonne of grain yield

Farm F			2010			2011		
Emissions from production and use of farm machinery		Paddock number	16	17	18	16	17	18
Seeding	Cost of seeding machinery (1998 price)	USD/t			2.56E+00			2.43E+00
	Fuel Use	l/hr/t			2.98E+00			2.83E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t			5.55E-01			5.27E-01
	Fuel Use	l/hr/t			7.83E-01			7.44E-01
Top-dressing -fertiliser	Cost of top-dressing machinery (1998 price)	USD/t			2.59E+00			5.18E+00
	Fuel Use	l/hr/t			5.63E-01			1.13E+00
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t			2.16E-01			2.06E-01
	Fuel Use	l/hr/t			4.70E-02			4.46E-02
Harvesting	Cost of harvesting machinery (1998 price)	USD/t			1.22E+01			1.16E+01
	Fuel Use	l/hr/t			4.64E+00			4.41E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.45. Farm F. Inventory list for the transportation of chemicals per tonne of grain yield

Farm F			2010			2011		
Classification	Chemical Name	Paddock number	16	17	18	16	17	18
Fertilisers	MAP	tkm/t			5.96E+00			5.96E+00
	MaxAmflo	tkm/t			1.29E+01			6.95E+00
	UAN	tkm/t						7.21E+00
Herbicides	Atlantis	tkm/t			1.66E-02			
	Atraxine	tkm/t						2.40E-01
	Bifenthrin	tkm/t						1.75E+02
	Logran	tkm/t			5.19E-03			
	Roundup	tkm/t			1.10E-01			
	Select	tkm/t						4.72E-02
	Treflan	tkm/t			1.62E-01			
Lime		tkm/t			3.22E+01			3.06E+01

Appendix F.46. Farm G. Inventory list for chemical production per tonne of grain yield

Farm G			2010			2011		
Classification	Chemical Name	Paddock number	19	20	21	19	20	21
Fertilisers	Ag Flow Extra	kg/yr/t				1.84E+01	1.75E+01	
	Agstar Trace	kg/yr/t	4.88E+01					
	Flexi-N	kg/yr/t	4.02E+01	5.10E+01	3.00E+01	2.11E+01	2.00E+01	1.78E+01
	Macro pro plus	kg/yr/t		5.15E+01	5.00E+01			3.85E+01
	Urea	kg/yr/t				1.22E+01	1.16E+01	3.85E+01
	Zinc/Manganese	kg/yr/t						6.92E-01
Fungicides and insecticides	Alpha-cypermethrin	kg/yr/t				6.38E-02	2.58E-02	3.58E-02
	Dividend	kg/yr/t			1.49E+00			7.56E-02
	Le-Mat	kg/yr/t			7.16E-02			
	Lorsban	kg/yr/t	4.80E-01	8.31E-02		8.49E-02	8.06E-02	1.03E-01
	Raxil	kg/yr/t	9.15E-03					
	Vincit	kg/yr/t				2.45E-02	2.33E-02	
Herbicides	Amine 720	kg/yr/t	3.00E-01					
	Avadex	kg/yr/t						7.69E-01
	Crusader	kg/yr/t				1.08E-01		
	Ester 680	kg/yr/t		1.80E-01				
	Gramaxone	kg/yr/t				9.21E-03	1.49E-01	
	Logran	kg/yr/t	2.13E-01	4.06E-01	1.62E-01	2.06E-01	8.75E-02	
	MCPA 242	kg/yr/t			1.68E-02	4.70E-01		1.37E-01
	Precept	kg/yr/t	1.16E+00	9.78E-04	3.58E-01			
	Roundup	kg/yr/t	9.27E-01	2.35E-01	6.91E-01	3.08E-01	2.93E-01	4.50E-01
	Sprayseed	kg/yr/t				1.07E-01		4.50E-01
	Tigrex	kg/yr/t					5.02E-01	1.65E-01
	Topik	kg/yr/t	5.60E-01				2.43E-02	
	Treflan	kg/yr/t	9.83E-02	7.84E-04	1.85E-01	1.37E-01	2.80E-01	8.58E-01
Adjuvants	Uptake	kg/yr/t					8.44E-02	
	Wetter 1000	kg/yr/t				6.60E-02		9.64E-02
Lime		kg/yr/t	1.22E+02	1.03E+02	9.09E+01	5.26E+01	5.00E+01	7.69E+01

Appendix F.47. Farm G. Inventory list for soil emissions per tonne of grain yield

Farm G		2010			2011		
Soil Emissions	**Paddock number**	**19**	**20**	**21**	**19**	**20**	**21**
N_2O direct	**kg/yr/t**	1.98E-02	2.15E-02	1.46E-02	1.59E-02	1.51E-02	2.71E-02
N_2O indirect (vol)	**kg/yr/t**	1.58E-03	1.72E-03	1.17E-03	1.27E-03	1.21E-03	2.17E-03
N_2O indirect (leaching)	**kg/yr/t**	5.94E+00	1.96E+01	4.38E+00	4.77E+00	4.54E+00	8.13E+00
CO_2 liming	**kg/yr/t**	1.46E+01	1.24E+01	1.09E+01	6.32E+00	6.00E+00	9.23E+00
CO_2 urea hydrolysis	**kg/yr/t**	-	-	-	4.21E+00	4.00E+00	7.69E+00
CH_4	**kg/yr/t**	-	-	-	-	-	-

Appendix F.48. Farm G. Inventory list for stubble burning per tonne of grain yield

Farm G		2010			2011		
Emissions from stubble burning	**Paddock number**	**19**	**20**	**21**	**19**	**20**	**21**
CO_2	**kg/tonne/ha**	-	-	-	-	-	-
CH_4	**kg/tonne/ha**	9.50E+01	1.80E+02	-	-	-	-
N_2O	**kg/tonne/ha**	2.06E+02	3.91E+02	-	-	-	-

Appendix F.49. Farm G. Inventory list for production and use of farm machinery per tonne of grain yield

Farm G			2010			2011		
Emissions from production and use of farm machinery		Paddock number	19	20	21	19	20	21
Seeding	Cost of seeding machinery (1998 price)	USD/t	2.08E+00	1.76E+00	1.55E+00	8.97E-01	8.52E-01	1.31E+00
	Fuel Use	l/hr/t	2.42E+00	2.05E+00	1.80E+00	1.04E+00	9.92E-01	1.53E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t	4.50E-01	1.90E-01	1.68E-01	9.71E-02	9.23E-02	1.42E-01
	Fuel Use	l/hr/t	6.35E-01	2.68E-01	2.37E-01	1.37E-01	1.30E-01	2.00E-01
Top-dressing - fertiliser	Cost of top-dressing machinery (1998 price)	USD/t	4.21E+00	3.56E+00	3.14E+00	3.63E+00	3.45E+00	7.97E+00
	Fuel Use	l/hr/t	9.15E-01	7.73E-01	6.82E-01	7.89E-01	7.50E-01	1.73E+00
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t	7.42E-03	7.35E-03	7.27E-03	7.42E-03	7.35E-03	7.27E-03
	Fuel Use	l/hr/t	9.15E-02	7.73E-02	6.82E-02	3.95E-02	3.75E-02	5.77E-02
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	9.92E+00	8.39E+00	7.40E+00	4.28E+00	4.07E+00	6.26E+00
	Fuel Use	l/hr/t	3.76E+00	3.18E+00	2.81E+00	1.62E+00	1.54E+00	2.37E+00

Appendix F.50. Farm G. Inventory list for he transportation of chemicals per tonne of grain yield

Farm G			2010			2011		
Classification	Chemical Name	Paddock number	19	20	21	19	20	21
Fertilisers	Ag Flow Extra	tkm/t				2.67E+00	2.54E+00	
	Agstar Trace	tkm/t	7.07E+00					
	Flexi-N	tkm/t	5.83E+00	7.39E+00	4.35E+00	1.76E+00	1.67E+00	2.57E+00
	Macropro plus	tkm/t		7.47E+00	7.25E+00			
	Macropro Extra	tkm/t						5.57E+00
	Urea	tkm/t				2.15E+02	2.04E+02	3.92E+02
Fungicides and insecticides	Alpha-cypermethrin	tkm/t				8.19E-03	3.11E-03	4.79E-03
	Dividend	tkm/t			2.16E-01			1.10E-02
	Le-Mat	tkm/t			2.94E-01			
	Lorsban	tkm/t	1.32E-02	1.11E-02		1.14E-02	1.08E-02	1.38E-02
	Raxil	tkm/t	4.15E-02					
	Vincit	tkm/t				3.93E-03	3.73E-03	
Herbicides	Ester 680	tkm/t		3.15E-02				
	Amine 720	tkm/t	4.02E-02					
	Avadex	tkm/t						1.03E-01
	Crusader	tkm/t				4.92E-01		
	Gramaxone	tkm/t				2.99E-02	4.06E-02	
	Logran	tkm/t	7.38E-01		5.50E-02	3.18E-02	3.02E-01	
	MCPA 242	tkm/t			4.66E-02	1.44E-02		1.84E-02
	Precept	tkm/t	2.18E+00	1.84E+00	1.62E+00			
	Roundup	tkm/t	1.34E-01	1.14E-04	1.00E-01	4.46E-02	4.24E-02	6.52E-02
	Sprayseed	tkm/t				1.56E-02		6.52E-02
	Tigrex	tkm/t					2.16E-02	2.38E-02
	Topik	tkm/t	2.11E+00				9.14E-02	
	Treflan	tkm/t	4.16E+00	3.05E-03	2.69E-03	1.69E+00	1.80E+00	3.09E+00
Adjuvants	Uptake	tkm/t					3.07E-01	
	Wetter 1000	tkm/t				9.53E-01		1.39E+00
Lime		tkm/t	5.29E+01	4.47E+01	3.94E+01	2.28E+01	2.17E+01	3.34E+01

Appendix F.51. Farm H. Inventory list for chemical production per tonne of grain yield

Farm H			2010			2011		
Classification	Chemical Name	Paddock number	22	23	24	22	23	24
Fertilisers	UAN	kg/yr/t					3.27E+01	2.78E+01
	MOP	kg/yr/t					2.55E+01	2.20E+01
	NPS range-Cereal	kg/yr/t					2.13E+01	1.83E+01
Fungicides and insecticides	Alpha-cypermethrin	kg/yr/t					4.50E-02	3.88E-02
	Tilt	kg/yr/t						9.53E-02
Herbicides	Crusader	kg/yr/t					1.13E-01	
	Logran	kg/yr/t					1.13E-02	3.52E-02
	MCPA LVE	kg/yr/t						3.29E-04
	Roundup	kg/yr/t					3.02E-01	2.60E-01
	Topik	kg/yr/t						6.20E-04
	Treflan	kg/yr/t					7.20E-04	2.78E-03
Lime		kg/yr/t		5.41E+01	6.62E+01		3.23E+01	3.23E+01

Appendix F.52. Farm H. Inventory list for soil emissions per tonne of grain yield

Farm H		2010			2011		
Soil Emissions	Paddock number	22	23	24	22	23	24
N_2O direct	kg/yr/t		-	-		1.80E-02	1.90E-02
N_2O indirect (vol)	kg/yr/t		-	-		1.44E-03	2.39E-03
N_2O indirect (leaching)	kg/yr/t		-	-			-
CO_2 liming	kg/yr/t		2.38E+01	2.91E+01		3.87E+00	3.87E+00
CO_2 urea hydrolysis	kg/yr/t		-	-		-	-
CH_4	kg/yr/t		-	-		-	-

Appendix F.53. Farm H. Inventory list for production and use of farm machinery per tonne of grain yield

Farm H			2010			2011		
Emissions from production and use of farm machinery		Paddock number	22	23	24	22	23	24
Seeding	Cost of seeding machinery (1998 price)	USD/t		1.84E+00	2.26E+00		1.10E+00	1.10E+00
	Fuel Use	l/hr/t		2.15E+00	2.63E+00		1.28E+00	1.28E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t					1.04E-01	8.91E-02
	Fuel Use	l/hr/t					1.46E-01	1.26E-01
Top-dressing -fertiliser	Cost of top-dressing machinery (1998 price)	USD/t					1.94E+00	1.67E+00
	Fuel Use	l/hr/t					4.21E-01	3.62E-01
Top-dressing -lime	Cost of top-dressing machinery (1998 price)	USD/t					1.94E+00	1.67E+00
	Fuel Use	l/hr/t					4.21E-01	3.62E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t		6.88E+00	8.43E+00		4.11E+00	3.54E+00
	Fuel Use	l/hr/t		2.61E+00	3.20E+00		1.56E+00	1.34E+00
Claying	Cost of claying machinery (1998 price)	USD/t			7.09E-01			
	Fuel Use	l/hr/t			7.55E+01			
Mouldboarding	Cost of mouldboarding machinery (1998 price)	USD/t		3.936E+01				
	Fuel Use	l/hr/t		9.01E-01				

Note: No swathing was done on these paddocks for 2010 and 2011

Appendix F.54. Farm H. Inventory list for transportation of chemicals per tonne of grain yield

Farm H			2010			2011		
Classification	**Chemical name**	**Paddock number**	**22**	**23**	**24**	**22**	**23**	**24**
Fertilisers	**NPS range-Cereal**	**tkm/t**					3.89E+00	3.28E+00
	MOP	**tkm/t**					1.33E+00	1.15E+00
	UAN	**tkm/t**					7.44E+00	8.15E+00
Fungicides and insecticides	**Alpha-Cypermethrin**	**tkm/t**					6.65E-03	5.73E-03
	Tilt	**tkm/t**						3.60E-01
Herbicides	**Crusader**	**tkm/t**					6.05E-01	
	Logran	**tkm/t**					3.92E-01	4.34E-02
	MCPA LVE	**tkm/t**						4.19E-05
	Roundup	**tkm/t**					4.79E-02	4.13E-02
	Topik	**tkm/t**						9.63E-02
	Treflan	**tkm/t**					2.60E-03	2.24E-03
Lime		**tkm/t**		2.42E+01	2.97E+01		1.44E+01	1.24E+01

APPENDIX G

LIFE CYCLE IMPACT ASSESSMENT

Table G.1. Calculated conversion factors for the identified chemicals

Fertilisers	Factor	Herbicides	Factor	Herbicides	Factor	Insecticides and pesticides	Factor
Agflow extra	3.62	Ally	150	Monza	32.0	Alphasip duo, Alpha duo, Scud, Sonic	0.56
AgNP	4.18	Amine 625	0.85	Optimax	0.66	Astral, Talstar	1.00
Agras	2.86	Amine 720	1.18	Polo, MCPA LVE 570	0.85	Dividend	1.45
Agstar extra	3.26	Atragranz, Atradex or Gesaprim	0.44	Precept	2.40	Fastac, Dominex	0.78
Agstar trace	3.24	Avadex	0.60	Roundup	0.60	Folicur	0.13
Agyield extra	2.67	Brodal	7.20	Select, Status	6.92	Lemat	0.22
Copper	3.31	Bromocide, Buctril	1.71	Simazine, Simagranz	0.44	Premis	186
DAP extra	2.63	Crusader	9.00	Sprayseed, Brown out	0.24	Prosaro 420	0.11
DAP SZC	2.63	Diurex	1.45	Terbyne	0.69	Raxil	2.08
Flexi N	1.44	Dual	1.88	Tigrex	3.14	Saboteur, Rogor	0.07
K-tTill Extra	4.60	Ester 600	0.39	Topik	13.1	Tilt, Bumper	0.15
Macropro plus	4.60	Ester 680	0.69	Treflan, TriflurX	0.80	Vincit	0.17
MAP	4.18	Ester 800	0.41	Triasulfuron 750	34.7		
MAP SZC	4.18	Garlon	2.84	Trifluralin 600	0.68		
MaxamFLO	2.09	Gladiator	1.00	Velocity	2.91		
MaxamRite	3.59	Gramoxone	1.20	Verdict, Asset	16.6		
MOP	0.69	Jaguar	2.71	**Adjuvants**	**Factor**		
NPS range-Cereal	3.68	Kamba	0.51	BS1000	0.03		
Sodium molybdate	0.70	Lexone, Sencor	4.80	Hasten	1.58		
UAN, Flexi-N	1.44	Logran	67.0	LI700	0.00		
Urea	1.00	Lorsban	0.03	Sulphate of Ammonia	1.00		
Zinc/Manganese	0.11	MCPA LVE 500	0.83	Uptake	0.31		

Table G.2. Calculated CO_2-e/t for chemical production on Farm A

Farm A			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	**Chemical Name**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**
Fertilisers	**Agstar Extra**	**kg/yr/t**				6.26E+01	8.88E+01	8.15E+01
	Copper	**kg/yr/t**				3.87E+01		6.40E+01
	DAP extra	**kg/yr/t**	6.24E+01	7.65E+01	6.71E+01			
	Flexi -N	**kg/yr/t**				3.38E+01		2.19E+01
	Urea	**kg/yr/t**				1.77E-01		2.31E-01
Fungicides and insecticides	**Folicur**	**kg/yr/t**				1.11E-04		1.44E-04
	Lorsban	**kg/yr/t**					1.32E-05	
	Vincit	**kg/yr/t**			8.76E-05			
Herbicides	**Amine**	**kg/yr/t**	1.58E+00					
	Ally	**kg/yr/t**	4.07E+00					
	Diuron	**kg/yr/t**				1.34E+01		
	Garlon	**kg/yr/t**				1.95E+00		
	Gramoxone	**kg/yr/t**	4.64E+01				4.79E+00	
	Jaguar	**kg/yr/t**				8.59E-01	2.8702E+01	4.52E+00
	Logran	**kg/yr/t**	1.36E+01	1.49E+01			7.46E+00	5.79E+01
	MCPA 242	**kg/yr/t**				5.70E+00	2.91E-02	5.69E+00
	Monza	**kg/yr/t**	5.43E+00		5.19E+00			
	Roundup	**kg/yr/t**	1.24E+01	9.67E-01		8.98E-01	5.35E-01	
	Treflan	**kg/yr/t**	1.09E+01	1.23+00		2.95E+00	2.84E+00	2.66E+00
Adjuvants	**BS 1000**	**kg/yr/t**	7.46E-02			3.02E-05	8.16E-05	9.21E-05
	LI 700	**kg/yr/t**						
	Sulphate of Ammonia	**kg/yr/t**				1.39E-02	1.00E-02	
Lime		**kg/yr/t**	1.28E+00	1.40E+00	1.22E+00	5.93E-01	8.41E-01	7.72E-01

TableG.3. Calculated CO_2-e/t for soil emissions on Farm A

Farm A		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	1	2	3	1	2	3
N_2O direct	kg/year/t	2.48E+00	3.05E+00	2.67E+00	8.71E+00	2.14E+00	3.50E+01
N_2O indirect (vol)	kg/year/t	1.99E-01	2.44E-01	2.14E-01	6.15E-01	1.71E-01	7.69E-01
N_2O indirect (leaching)	kg/year/t	7.45E+01	3.43E+01	8.02E+01	2.61E+02	6.41E+01	3.36E+02
CO_2 liming	kg/year/t	3.33E+01	2.19E+01	2.01E+01	1.54E+01	2.19E+01	2.01E+01
CO_2 urea hydrolysis	kg/year/t	-	-	-	1.03E+01	-	1.67E+01
CH_4	kg/year/t	-	-	-	-	-	-

Table G.4 Calculated CO_2-e/t for grazing emissions on Farm A

Farm A		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from grazing		Paddock number			Paddock number		
	Units	1	2	3	1	2	3
CH_4 from Enteric Emissions	kg/ha/t	-	-	-	1.52E+00	1.19E+00	1.06E+00
CH_4 from Manure	kg/ha/t	-	-	-	2.82E-02	1.14E-02	1.93E-02

Table G.5 Calculated CO_2-e/t for stubble burning on Farm A

Farm A		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from stubble burning		Paddock number			Paddock number		
	Units	1	2	3	1	2	3
CO_2	kg/ha/t	-	-	-	-	-	-
CH_4	kg/ha/t	1.09E-02	1.18E-02	6.10E-03	-	1.53E-02	-
N_2O	kg/ha/t	2.82E-01	3.06E-01	1.58E-01	-	3.95E-01	-

Table G.6 Calculated CO_2-e/t for machinery production and use on Farm A

Farm A			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	**1**	**2**	**3**	**1**	**2**	**3**
Seeding	**Cost of seeding machinery (1998 price)**	**USD/t**	2.51E+00	2.73E+00	2.40E+00	1.16E+00	1.65E+00	1.51E+00
	Fuel Use	**l/hr/t**	8.14E+00	8.88E+00	7.79E+00	3.77E+00	5.34E+00	4.91E+00
Spraying	**Cost of spraying machinery (1998 price)**	**USD/t**	7.49E-01	2.72E-01	4.77E-01	4.62E-01	3.28E-01	4.51E-01
	Fuel Use	**l/hr/t**	2.12E+00	7.72E-01	1.35E+00	1.31E+00	9.30E-01	1.28E+00
Top dressing - fertiliser	**Cost of top dressing machinery (1998 price)**	**USD/t**	-	-	-	1.94E+00	-	2.53E+00
	Fuel Use	**l/hr/t**	-	-	-	7.96E-01	-	1.04E+00
Top dressing - lime	**Cost of top dressing machinery (1998 price)**	**USD/t**	1.37E+01	1.63E+01	1.26E+01	2.95E+00	5.92E+00	4.99E+00
	Fuel Use	**l/hr/t**	5.62E+00	6.69E+00	5.14E+00	1.21E+00	2.43E+00	2.04E+00
Harvesting	**Cost of harvesting machinery (1998 price)**	**USD/t**	1.05E+01	1.14E+01	1.00E+01	4.86E+00	6.89E+00	6.32E+00
	Fuel Use	**l/hr/t**	1.11E+01	1.21E+01	1.06E+01	5.14E+00	7.29E+00	6.69E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.7 Calculated CO_2-e/t for chemical transportation on Farm A

Farm A			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals		**Paddock number**	**Paddock number**			**Paddock number**		
Classification	**Chemical Name**	**Units**	**1**	**2**	**3**	**1**	**2**	**3**
Fertilisers	**Agstar Extra**	**tkm/t**				9.80E-03	1.39E-02	1.28E-02
	Copper	**tkm/t**				4.59E-01		8.96E-01
	DAP Extra	**tkm/t**	1.92E+02	2.35E+02	2.06E+02			
	Flexi -N	**tkm/t**				2.02E-02		2.41E-01
	Urea	**tkm/t**				2.26E+03		3.67E+03
Fungicides and insecticides	**Folicur**	**tkm/t**				3.74E-03		4.87E-03
	Lorsban	**tkm/t**					2.59E-05	
	Vincit	**tkm/t**			1.61E-04			
Herbicides	**Ally**	**tkm/t**	2.15E+01					
	Ester 600	**tkm/t**	4.86E-01					
	Diuron	**tkm/t**				2.89E-03		
	Garlon	**tkm/t**				2.57E+00		
	Gramoxone	**tkm/t**					1.38E-02	
	Jaguar	**tkm/t**				1.99E-02	3.13E-02	2.59E-02
	Logran	**tkm/t**	5.54E-01	6.05E-01	5.30E-01		2.73E+02	2.34E+02
	MCPA 242	**tkm/t**				7.39E-03	2.91E-03	4.28E-03
	Monza	**tkm/t**	2.23E+01		2.13E+01	1.19E+02		
	Roundup	**tkm/t**	3.58E-02	3.77+01		2.23E-02	1.08E-02	8.30E-03
	Treflan	**tkm/t**	4.61E+01	3.77E+01	3.30E+01	1.79E+01	5.06E+01	2.32E+01
Adjuvants	**BS 1000**	**tkm/t**				5.09E-03	2.24E-02	2.25E-02
	LI 700	**tkm/t**				1.55E-05		
	Sulphate of Ammonia	**tkm/t**				9.16E-04	6.61E-04	5.65E-04
Lime		**tkm/t**	2.17E+00	2.37E+00	2.08E+00	1.66E-01	2.36E-01	2.16E-01

Table G.8. Calculated CO_2-e/t for chemical production on Farm B

Farm B			Calculated equivalent for 2010			Calculated equivalent for 2011		
Chemical Inputs			CO_2-e/t			CO_2-e/t		
			Paddock number			Paddock number		
Classification	Chemical Name	Units	4	5	6	4	5	6
Fertilisers	Agyield Extra	kg/yr/t			6.07E+01			5.68E+01
	K Till Extra	kg/yr/t	1.69E+02	1.82E+02			1.48E+02	
	Urea	kg/yr/t	5.31E+01	4.82E+01	1.40E+01		3.22E+01	1.63E+01
Fungicides and insecticides	Alpha Duo	kg/yr/t		3.79E-04	3.02E-04			
	Alpha Cypermethrin	kg/yr/t						3.97E-04
	Alphasip Duo	kg/yr/t	3.53E-04					
	Dividend	kg/yr/t					1.24E-03	
	Lemat L	kg/yr/t	1.86E-03					1.24E-04
	Premis	kg/yr/t	2.70E+01					
Herbicides	Amine 625	kg/yr/t					3.22E+00	
	Bromicide	kg/yr/t				1.92E+00		
	Ester 800	kg/yr/t	8.70E-01		5.56E-01			
	Garlon	kg/yr/t			1.01E+01		8.60E-01	
	Gladiator	kg/yr/t	5.22E+00	8.39E+00				
	Lexone	kg/yr/t					2.28E+00	
	Logran	kg/yr/t		7.81E+00				3.49E+03
	Roundup	kg/yr/t	3.06E+00				4.68E+00	2.68E+00
	Select	kg/yr/t				1.05E+01		
	Sprayseed	kg/yr/t			4.23E-01	9.06E-02		
	Tigrex	kg/yr/t				1.99E-01		
	Treflan	kg/yr/t						4.36E+00
	Trifluralin	kg/yr/t		5.62E+00	2.99E-01			
	Triflurx	kg/yr/t	4.56E+00				5.12E+00	
	Velocity	kg/yr/t	6.32E+00	6.78E+00				
Adjuvants	Ammoniun Sulphate	kg/yr/t	1.75E-01		8.13E-02			7.61E-02
	LI700	kg/yr/t						1.36E-07
Lime		tonne/yr/t	8.20E-01	8.80E-01	7.01E-01	6.01E-01	7.19E-01	6.56E-01

Table G.9. Calculated CO_2-e/t for soil emissions on Farm B

Farm B		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	4	5	6	4	5	6
N_2O direct	kg/yr/t	1.56E+01	1.45E+01	5.75E+00	-	1.00E+01	6.21E+00
N_2O indirect (vol)	kg/yr/t	1.25E+00	1.16E+00	4.60E-01	-	8.03E-01	4.97E-01
N_2O indirect (leaching)	kg/yr/t	-	-	-	-	-	-
CO_2 liming	kg/yr/t	2.14E+01	2.29E+01	1.83E+01	1.57E+01	1.87E+01	1.71E+01
CO_2 urea hydrolysis	kg/yr/t	4.63E+01	4.20E+01	1.22E+01	-	2.81E+01	1.42E+01
CH_4	kg/yr/t	-	-	-	-	-	-

Table G.10 Calculated CO_2-e/t for machinery production and use on Farm B

Farm B			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	4	5	6	4	5	6
Seeding	Cost of seeding machinery (1998 price)	USD/t	1.61E+00	1.72E+00	1.37E+00	1.18E+00	1.41E+00	1.28E+00
	Fuel Use	l/hr/t	5.22E+00	5.60E+00	4.46E+00	3.82E+00	4.57E+00	4.17E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t	7.36E-01	3.16E-01	2.52E-01	2.16E-01	6.44E-01	2.35E-01
	Fuel Use	l/hr/t	2.09E+00	8.95E-01	7.13E-01	6.12E-01	1.83E+00	6.67E-01
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t	1.34E+00	1.44E+00	1.15E+00	9.86E-01	1.18E+00	1.07E+00
	Fuel Use	l/hr/t	5.50E-01	5.91E-01	4.71E-01	4.04E-01	4.82E-01	4.40E-01
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t	4.84E-01	5.19E-01	4.14E-01	3.55E-01	4.24E-01	3.87E-01
	Fuel Use	l/hr/t	1.98E-01	2.13E-01	1.69E-01	1.45E-01	1.74E-01	1.58E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	6.72E+00	7.21E+00	5.74E+00	4.93E+00	5.89E+00	5.37E+00
	Fuel Use	l/hr/t	7.11E+00	7.63E+00	6.08E+00	5.21E+00	6.23E+00	5.69E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.11 Calculated CO_2-e/t for chemical transportation on Farm B

Farm B			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			Paddock number			Paddock number		
Classification	Chemical Name	Units	4	5	6	4	5	6
Fertilisers	Agyield Extra	tkm/t			1.81E+00			1.64E-02
	K Till Extra	tkm/t	5.04E+00	5.41E+00	0.00E+00		4.41E+00	
	Urea	tkm/t	1.58E+00	1.44E+00	4.16E-01		9.59E-01	1.16E-02
Fungicides and insecticides	Alpha Cypermethrin	tkm/t						7.56E-04
	Alpha Duo	tkm/t		7.21E-04	5.75E-04			
	Alphasip Duo	tkm/t	6.72E-04					
	Dividend	tkm/t					2.20E-03	
	Lemat L	tkm/t	5.67E-02					3.77E-03
	Premis	tkm/t	1.43E+00					
Herbicides	Amine 625	tkm/t					9.65E-03	
	Bromicide	tkm/t				5.37E-03		
	Ester 800	tkm/t	2.44E-03		1.56E-03			
	Garlon	tkm/t					3.62E-02	
	Gladiator	tkm/t	1.46E-02	2.35E-02	9.99E-03			
	Lexone	tkm/t					5.99E-02	
	Logran	tkm/t						1.27E+00
	Roundup	tkm/t	8.57E-03	2.84E-03			6.55E-02	7.51E-03
	Select	tkm/t				2.93E-02		
	Sprayseed	tkm/t			1.18E-03	2.54E-04		
	Tigrex	tkm/t				5.58E-04		
	Treflan	tkm/t						1.84E-01
	Trifluralin	tkm/t		1.57E-02	8.36E-04			
	Triflurx	tkm/t	1.28E-02				1.43E-02	
	Velocity	tkm/t	3.35E-01	3.59E-01				
Adjuvants	LI700	tkm/t						2.34E-06
	Ammoniun Sulphate	tkm/t	1.12E-02		5.20E-03			4.86E-03
Lime		tkm/t	1.35E+00	1.45E+00	1.15E+00	9.90E-01	1.18E+00	1.08E+00

Table G.12. Calculated CO_2-e/t for chemical production on Farm C

Farm C			Calculated equivalent for 2010			Calculated equivalent for 2011		
Chemical Inputs			CO_2-e/t			CO_2-e/t		
			Paddock number			Paddock number		
Classification	Chemical Name	Units	7	8	9	7	8	9
Fertilisers	DAP SZC	kg/yr/t	3.46E+01	6.15E+01	5.03E+01			
	Flexi-N	kg/yr/t				1.82E+01		
	MAP SZC	kg/yr/t	5.50E+01	9.78E+01	8.00E+01			
	MAXamRite	kg/yr/t				6.88E+01		
	MOP	kg/yr/t			1.06E+01			1.09E+01
	NPS range-Cereal	kg/yr/t					3.98E+01	2.13E+02
	Urea	kg/yr/t	1.32E+01	2.34E+01	1.91E+01			
Fungicides and insecticides	Alpha-cypermethrin	kg/yr/t						1.28E-03
Herbicides	Brodal	kg/yr/t						9.47E+00
	Ester 680	kg/yr/t			1.35E+00		1.98E+00	
	Gramoxone	kg/yr/t					3.44E+00	
	Lexone	kg/yr/t						5.37E+00
	Logran	kg/yr/t	7.50E-01	1.33E+01	1.64E+01			
	Roundup	kg/yr/t	3.14E+00	5.59E00	4.57E+00	2.86E+00		
	Select	kg/yr/t						1.84E+01
	Simazine 500	kg/yr/t						6.18E+00
	Sprayseed	kg/yr/t						3.18E+00
	Tigrex	kg/yr/t				7.63E+00		
	Treflan	kg/yr/t	5.40E+00	9.59E+00		3.92E+00		
	Trifluralin	kg/yr/t			7.85E+00			
	Verdict	kg/yr/t						8.56E+01
Adjuvants	Ammonium Sulphate	kg/yr/t						5.20E-03
Lime		kg/yr/t	1.06E+00	1.88E+00	2.30E+00	7.68E-01	4.83E-01	3.17E+00

TableG.13. Calculated CO_2-e/t for soil emissions on Farm C

Farm C		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	7	8	9	7	8	9
N_2O direct	kg/yr/t	5.43E+00	9.73E+00	7.96E+00	6.06E+00	7.53E-01	4.02E+00
N_2O indirect (vol)	kg/yr/t	4.38E-01	7.78E-01	6.37E-01	4.85E-01	6.02E-02	3.22E-01
N_2O indirect (leaching)	kg/yr/t	1.64E+02	2.92E+02	2.54E+02	1.82E+02	-	-
CO_2 liming	kg/yr/t	2.75E+01	4.89E+01	6.00E+01	2.00E+01	1.26E+01	8.25E+01
CO_2 urea hydrolysis	kg/yr/t	1.15E+01	2.04E+01	1.67E+01	8.33E+00	-	-
CH_4	kg/yr/t	-	-	-	-	-	-

Table G.14. Calculated CO_2-e/t for grazing emissions on Farm C

Farm C		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from grazing		Paddock number			Paddock number		
	Units	7	8	9	7	8	9
CH_4 from Enteric Emissions	kg/ha/t	3.64E+01	-	-	3.97E+01	1.09E+02	4.28E+01
CH_4 from Manure	kg/ha/t	1.69E-02	-	-	1.84E-02	5.08E-02	2.64E-02

Table G.15. Calculated CO_2-e/t for machinery production and use on Farm C

Farm C			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	7	8	9	7	8	9
Seeding	Cost of seeding machinery (1998 price)	USD/t	2.07E+00	3.67E+00	3.01E+00	1.50E+00	9.45E-01	4.13E+00
	Fuel Use	l/hr/t	6.71E+00	1.19E+01	9.77E+00	4.88E+00	3.07E+00	1.34E+01
Spraying	Cost of spraying machinery (1998 price)	USD/t	8.52E-01	5.05E-01	8.27E-01	8.99E-01	5.65E-01	2.47E+00
	Fuel Use	l/hr/t	1.61E+00	9.55E-01	1.56E+00	1.70E+00	1.07E+00	4.67E+00
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t	-	-	-	-	-	-
	Fuel Use	l/hr/t	-	-	-	-	-	-
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t	1.04E-01	1.85E-01	1.51E-01	7.55E-02	4.75E-02	2.08E-01
	Fuel Use	l/hr/t	7.09E-02	1.26E-01	1.03E-01	5.15E-02	3.24E-02	1.42E-01
Harvesting	Cost of harvesting machinery (1998 price)	l/hr/t	8.65E+00	1.54E+01	1.26E+01	6.29E+00	3.96E+00	1.73E+01
	Fuel Use	USD/t	9.16E+00	1.63E+01	1.33E+01	6.66E+00	4.19E+00	1.83E+01

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.16 Calculated CO_2-e/t for chemical transportation on Farm C

Farmer C			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			Paddock number			Paddock number		
Classification	Chemical Name	Units	7	8	9	7	8	9
Fertilisers	NPS range-Cereal	tkm/t					1.37E+00	7.34E+00
	DAP SZC	tkm/t	1.80E+01	3.20E+01	2.62E+01			
	Flexi-N	tkm/t				6.23E-01		
	MAP SZC	tkm/t	2.86E+01	5.09E+01	4.17E+01			
	MaxamRite	tkm/t				2.36E+00		
	MOP	tkm/t			3.63E-01			3.74E-01
	Urea (national)	tkm/t	4.52E-01	8.03E-01	6.57E-01	3.29E-01		
	Urea (international)	tkm/t	1.47E+00	2.61E+00	2.14E+00	1.07E+00		
Fungicides and insecticides	Alpha-cypermethrin	tkm/t						2.78E-03
Herbicides	Brodal	tkm/t						5.05E-01
	Ester 680	tkm/t			1.54E-02			
	Gramoxone	tkm/t						1.11E-02
	Lexone	tkm/t						2.29E-01
	Logran	tkm/t	3.07E-02	5.46E-02	6.71E-01			
	Roundup	tkm/t	1.01E-02	1.80E-02	1.48E-02	9.23E-03		
	Select	tkm/t						5.94E-02
	Simazine 500	tkm/t						1.99E-02
	Sprayseed	tkm/t						1.03E-02
	Tigrex	tkm/t				2.46E-02		
	Treflan	tkm/t	2.30E-01	4.09E-01		1.67E-01		
	Trifluralin	tkm/t			2.53E-02			
	Verdict	tkm/t						2.93E-01
Adjuvants	Ammonium Sulphate	tkm/t						3.84E-04
Lime		tkm/t	1.98E+00	3.52E+00	4.32E+00	1.44E+00	9.05E-01	5.94E+00

Table G.17. Calculated CO_2-e/t for chemical production on Farm D

Farm D			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	Chemical Name	Units	10	11	12	10	11	12
Fertilisers	Agras	kg/yr/t		1.34E+02	1.32E+02		7.76E+01	8.02E+01
	Flexi N	kg/yr/t					2.58E+01	2.66E+01
Fungicides and insecticides	Prosaro 420	kg/yr/t					8.61E-05	
Herbicides	Avadex	kg/yr/t			4.03E+00			7.95E+00
	Diuron	kg/yr/t			2.84E+00			6.95E+00
	Jaguar	kg/yr/t		1.35E+01				
	Lexone	kg/yr/t					1.62E+01	
	Logran	kg/yr/t		1.17E+01				
	Roundup	kg/yr/t		3.49E+00			2.43E+00	2.10E+00
	Treflan	kg/yr/t		3.02E+00	3.60E+00		5.80E-01	2.60E-01
Lime		tonne/yr/t		9.39E-01	8.45E-01		5.45E-01	5.63E-01

TableG.18. Calculated CO_2-e/t for soil emissions on Farm D

Farm D		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	10	11	12	10	11	12
N_2O direct	kg/yr/t		4.19E+00	3.39E+00		5.62E+00	5.81E+00
N_2O indirect (vol)	kg/yr/t		3.35E-01	2.71E-01		4.50E-01	4.01E-01
N_2O indirect (leaching)	kg/yr/t		1.26E+02	1.02E+02		1.45E+02	1.74E+02
CO_2 liming	kg/yr/t		2.44E+01	2.20E+01		1.42E+01	1.47E+01
CO_2 urea hydrolysis	kg/yr/t		-	-		-	-
CH_4	kg/yr/t		-	-		-	-

Table G.19 Calculated CO_2-e/t for grazing emissions on Farm D

Farm D		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from grazing		Paddock number			Paddock number		
	Units	**10**	**11**	**12**	**10**	**11**	**12**
CH_4 from Enteric Emissions	**kg/ha/t**		3.54E+01	3.54E+01		-	-
CH_4 from Manure	**kg/ha/t**		1.64E-02	1.64E-02		-	-

Table G.20 Calculated CO_2-e/t for stubble burning on Farm D

Farm D		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from stubble burning		Paddock number			Paddock number		
	Units	**10**	**11**	**12**	**10**	**11**	**12**
CO_2	**kg/ha/t**		-	-		-	-
CH_4	**kg/ha/t**		2.87E+00	7.25E-01		-	-
N_2O	**kg/ha/t**		7.43E+01	1.88E+01		-	-

Table G.21 Calculated CO_2-e/t for machinery production and use on Farm D

Farm D			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	10	11	12	10	11	12
Seeding	Cost of seeding machinery (1998 price)	USD/t		1.84E+00	1.65E+00		1.07E+00	1.10E+00
	Fuel Use	l/hr/t		5.97E+00	5.37E+00		3.47E+00	3.58E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t		2.27E-01	4.09E-01		5.28E-01	5.46E-01
	Fuel Use	l/hr/t		4.77E-01	8.59E-01		1.11E+00	1.15E+00
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t					8.93E-01	9.23E-01
	Fuel Use	l/hr/t					3.66E-01	3.78E-01
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t		5.54E-01	4.99E-01		3.22E-01	3.32E-01
	Fuel Use	l/hr/t		2.27E-01	2.04E-01		1.32E-01	1.36E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t		7.69E+00	6.92E+00		4.47E+00	4.61E+00
	Fuel Use	l/hr/t		8.14E+00	7.33E+00		4.73E+00	4.88E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.22 Calculated CO_2-e/t for chemical transportation on Farm D

Farm D			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			Paddock number			Paddock number		
Classification	Chemical Name	Units	10	11	12	10	11	12
Fertilisers	Agras	tkm/t		4.02E+00	3.98E+00		2.33E+00	2.41E+00
	Flexi N	tkm/t					7.75E-01	8.01E-01
Fungicides and insecticides	Prosaro 420	tkm/t					2.90E-03	
Herbicides	Avadex	tkm/t			1.22E-02			8.66E-03
	Diuron	tkm/t			8.05E-03			5.36E-03
	Jaguar	tkm/t		2.88E-02				
	Lexone	tkm/t					1.46E-01	
	Logran	tkm/t		4.74E-01				
	Roundup	tkm/t		1.61E-01			5.74E-03	5.93E-03
	Treflan	tkm/t		1.69E-01	1.52E-01		1.37E-01	
Lime		tkm/t		9.06E-01	9.36E-01		1.56E+00	1.40E+00

Table G.23. Calculated CO_2-e/t for chemical production on Farm E

Farm E			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	Chemical Name	Units	13	14	15	13	14	15
Fertilisers	DAP	kg/yr/t	1.14E+02	1.02E+02	1.21E+02	2.12E+01	4.23E+01	
	MAP	kg/yr/t						1.18E+02
	Sodium molybdate	kg/yr/t				5.17E-04		
	Urea	kg/yr/t				8.05E+00	1.61E+01	
Herbicides	Diuron	kg/yr/t			2.96E-01	1.25E+00	1.25E+00	
	Ester 600	kg/yr/t						8.57E-01
	Logran	kg/yr/t	1.44E+01	6.92E+00	3.54E+01	1.59E+01	2.65E+00	
	MCPA LVE	kg/yr/t	1.62E+00		1.72E+00	1.64E-01		
	Roundup	kg/yr/t	5.37E+00	4.13E+00	5.71E+00	1.85E+00	1.85E+00	3.50E+00
	Tigrex	kg/yr/t	1.20E+01		1.02E+01	3.80E+00		
	Treflan	kg/yr/t	1.85E-02	9.27E+00	2.14E-01	1.87E+00	1.87E+00	
	Triasulfuron	kg/yr/t		5.98E+00				
Adjuvants	Ammonium Sulphate	kg/yr/t				8.16E-02	1.02E-01	1.93E-01
	Hasten	kg/yr/t				1.23E-01		
	BS 1000	kg/yr/t				2.32E-05	2.32E-05	4.39E-05
Lime		tonne/yr/t	1.81E+00	1.63E+00	1.92E+00	6.21E-01	6.21E-01	1.18E+00

TableG.24. Calculated CO_2-e/t for soil emissions on Farm E

Farm E		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	13	14	15	13	14	15
N_2O direct	kg/yr/t	4.20E+00	1.13E+01	4.47E+00	2.84E+00	5.68E+00	1.72E+00
N_2O indirect (vol)	kg/yr/t	3.36E-01	3.03E-01	3.58E-01	2.27E-01	4.55E-01	1.38E-01
N_2O indirect (leaching)	kg/yr/t	-	-	-	8.53E+01	1.71E+02	5.17E+01
CO_2 liming	kg/yr/t	4.70E+01	4.23E+01	5.00E+01	1.62E+01	1.62E+01	3.06E+01
CO_2 urea hydrolysis	kg/yr/t	-	-	-	7.01E+00	1.40E+01	-
CH_4	kg/yr/t	-	-	-	-	-	-

Table G.25. Calculated CO_2-e/t for grazing emissions on Farm E

Farm E		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from grazing		Paddock number			Paddock number		
	Units	13	14	15	13	14	15
CH_4 from Enteric Emissions	kg/ha/t	2.88E+01	2.59E+01	2.46E+01	1.43E+01	1.58E+01	2.23E+01
CH_4 from Manure	kg/ha/t	2.97E-02	2.67E-02	2.53E-02	1.47E-02	1.27E-02	2.30E-02

Table G.26 Calculated CO_2-e/t for machinery production and use on Farm E

Farm E			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	13	14	15	13	14	15
Seeding	Cost of seeding machinery (1998 price)	USD/t	3.39E+00	3.05E+00	3.61E+00	1.17E+00	1.17E+00	2.21E+00
	Fuel Use	l/hr/t	9.18E+00	8.26E+00	9.77E+00	3.16E+00	3.16E+00	5.99E+00
Swathing	Cost of swathing machinery (1998 price)	USD/t				1.67E+00	1.67E+00	3.17E+00
	Fuel Use	l/hr/t				6.32E+00	6.32E+00	1.20E+01
Spraying	Cost of spraying machinery (1998 price)	USD/t	5.18E-01	2.33E-01	5.51E-01	1.78E-01	8.91E-02	1.69E-01
	Fuel Use	l/hr/t	1.47E+00	6.61E-01	1.56E+00	5.06E-01	2.53E-01	4.79E-01
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t			2.52E+00	2.44E+00	1.63E+00	1.54E+00
	Fuel Use	l/hr/t			1.03E+00	1.00E+00	6.67E-01	6.32E-01
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t	1.70E+00	1.53E+00	1.81E+00	5.86E-01	5.86E-01	1.11E+00
	Fuel Use	l/hr/t	6.98E-01	6.28E-01	7.42E-01	2.58E-01	2.58E-01	4.88E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	1.18E+01	1.06E+01	1.26E+01	4.07E+00	4.07E+00	7.71E+00
	Fuel Use	l/hr/t	1.25E+01	1.13E+01	1.33E+01	4.31E+00	4.31E+00	8.16E+00

Table G.27 Calculated CO_2-e/t for chemical transportation on Farm E

Farm E			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			Paddock number			Paddock number		
Classification	Chemical Name	Units	13	14	15	13	14	15
Fertilisers	DAP	tkm/t	5.93E+01	5.34E+01	6.31E+01	1.11E+01	2.21E+01	
	MAP	tkm/t						6.15E+01
	Sodium molybdate	tkm/t				1.88E-05		
	Urea	tkm/t				2.93E-01	5.86E-01	
Herbicides	Diuron	tkm/t			1.33E-03	4.30E-03	4.30E-03	
	Ester 600	tkm/t						7.84E-02
	Logran	tkm/t	5.35E-01	2.84E-01	1.45E+00	4.17E-01	1.09E-01	
	MCPA LVE	tkm/t	2.81E-05		2.98E-05	6.76E-03		
	Roundup	tkm/t	1.84E-02	1.41E-02	1.96E-02	6.33E-03	6.33E-03	1.20E-02
	Tigrex	tkm/t	4.07E-02		3.47E-02	1.37E-02		
	Treflan	tkm/t	8.01E-04	3.34E-02	4.93E-01	6.41E-03	1.52E-01	
	Triasulfuron	tkm/t		4.26E-03				
Adjuvants	Ammonium Sulphate	tkm/t				1.20E-02	7.98E-03	1.51E-02
	BS 1000	tkm/t				1.81E-06	1.81E-06	3.43E-06
	Hasten	tkm/t				1.22E-01		
Lime		tkm/t	3.55E+00	3.20E+00	3.78E+00	1.23E+00	1.23E+00	2.33E+00

Table G.28. Calculated CO_2-e/t for chemical production on Farm F

Farm F			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	Chemical Name	Units	16	17	18	16	17	18
Fertilisers	MAP	kg/yr/t			1.51E+02			1.51E+02
	MaxamFLO	kg/yr/t			1.64E+02			8.80E+01
	MOP	kg/yr/t						0.00E+00
	UAN	kg/yr/t						6.28E+01
Fungicides and insecticides	Talstar	kg/yr/t						6.55E-01
Herbicides	Atlantis	kg/yr/t			1.89E+01			
	Atraxine 500	kg/yr/t						6.75E+00
	Logran	kg/yr/t			9.02E-01			
	Roundup	kg/yr/t			4.25E+00			
	Select	kg/yr/t						2.10E+01
	Treflan	kg/yr/t			1.09E+01			
Lime		kg/yr/t			1.27E+00			1.21E+00

TableG.29. Calculated CO_2-e/t for soil emissions on Farm F

Farm F		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	16	17	18	16	17	18
N_2O direct	kg/yr/t			7.63E+00			1.51E+01
N_2O indirect (vol)	kg/yr/t			6.10E-01			1.90E+00
N_2O indirect (leaching)	kg/yr/t			2.29E+02			
CO_2 liming	kg/yr/t			3.31E+01			3.14E+01
CO_2 urea hydrolysis	kg/yr/t			-			-
CH_4	kg/yr/t			-			-

Table G.30 Calculated CO_2-e/t for stubble burning on Farm F

Farm F		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from stubble burning		Paddock number			Paddock number		
	Units	16	17	18	16	17	18
CO_2	kg/ha/t	-	-	-	-	-	-
CH_4	kg/ha/t	-	-	-	-	-	9.86E-02
N_2O	kg/ha/t	-	-	-	-	-	2.55E+00

Table G.31 Calculated CO_2-e/t for machinery production and use on Farm F

Farm F			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	16	17	18	16	17	18
Seeding	Cost of seeding machinery (1998 price)	USD/t			2.37E+00			2.42E+00
	Fuel Use	l/hr/t			7.69E+00			7.45E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t			5.13E-01			5.25E-01
	Fuel Use	l/hr/t			2.02E+00			1.96E+00
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t			5.18E+00			5.15E+00
	Fuel Use	l/hr/t			1.13E+00			2.96E+00
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t			2.00E-01			2.05E-01
	Fuel Use	l/hr/t			1.21E-01			1.17E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t			1.13E+01			1.16E+01
	Fuel Use	l/hr/t			1.20E+01			1.16E+01

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.32 Calculated CO_2-e/t for chemical transportation on Farm F

Farm F			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			Paddock number			Paddock number		
Classification	Chemical Name	Units	16	17	18	16	17	18
Fertilisers	MAP	tkm/t			2.55E+00			2.55E-02
	MaxamFLO	tkm/t			1.32E+00			1.48E+00
	UAN	tkm/t						1.06E+00
Fungicides and insecticides	Talstar	tkm/t						1.78E+01
Herbicides	Atlantis	tkm/t			2.31E-02			
	Atraxine	tkm/t						1.07E-02
	Logran	tkm/t			3.55E-02			
	Roundup	tkm/t			6.75E-03			
	Select	tkm/t						3.34E-02
	Treflan	tkm/t			1.33E-02			
Lime		tkm/t			3.29E+00			3.12E+00

Table G.33. Calculated CO_2-e/t for chemical production on Farm G

Farm G			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	Chemical Name	Units	19	20	21	19	20	21
Fertilisers	Ag Flow extra	kg/yr/t				5.62E+01	5.34E+01	
	Agstar trace	kg/yr/t	1.33E+02					
	Flexi-N	kg/yr/t	4.87E+01	6.18E+01	3.63E+01	2.55E+01	2.42E+01	2.15E+01
	Macro pro plus	kg/yr/t		2.00E+02	1.94E+02			1.49E+02
	Urea	kg/yr/t				1.02E+01	9.73E+00	3.24E+01
	Zinc/Manganese	kg/yr/t						6.38E-02
Fungicides and insecticides	Alpha-cypermethrin	kg/yr/t				7.02E-04	2.83E-04	3.94E-04
	Dividend	kg/yr/t			3.05E-02			1.55E-03
	Le-Mat	kg/yr/t			2.17E-04			
	Lorsban	kg/yr/t	1.69E-04	2.93E-05		2.99E-05	2.84E-05	3.64E-05
	Raxil	kg/yr/t	2.68E-04					
	Vincit	kg/yr/t				5.74E-05	5.46E-05	
Herbicides	Amine 720	kg/yr/t	3.17E+00					
	Avadex	kg/yr/t						4.13E+00
	Crusader	kg/yr/t				8.68E+00		
	Ester 680	kg/yr/t		1.12E+00				
	Gramaxone	kg/yr/t				9.90E-02	1.60E+00	
	Logran	kg/yr/t	1.28E+02	2.43E+02		1.24E+02	5.25E+01	
	Lorsban	kg/yr/t	3.36E-05	2.84E-05				
	MCPA 242	kg/yr/t			1.25E-01	3.50E+00		1.02E+00
	Precept	kg/yr/t	2.49E+02	2.10E-01	7.69E+00			
	Roundup	kg/yr/t	4.98E+00	1.266E+00	3.71E+00	1.65E+00	1.57E+00	2.42E+00
	Sprayseed	kg/yr/t				2.34E-01		9.79E-01
	Tigrex	kg/yr/t					1.41E+01	4.63E+00
	Topik	kg/yr/t	6.56E+01				2.85E+00	
	Treflan	kg/yr/t	7.08E-01	5.64E-03	1.33+00	9.85E-01	2.01E+00	6.18E+00
Adjuvants	Uptake	kg/yr/t					1.01E-02	
	Wetter 1000	kg/yr/t				8.63E-04		1.26E-03
Lime		tonne/yr/t	2.06E+00	1.74E+00	1.54E+00	8.89E-01	8.45E-01	1.30E+00

TableG.34. Calculated CO_2-e/t for soil emissions on Farm G

Farm G		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	19	20	21	19	20	21
N_2O direct	kg/yr/t	9.27E+00	1.01E+01	6.84E+00	7.45E+00	7.08E+00	1.27E+01
N_2O indirect (vol)	kg/yr/t	7.42E-01	8.05E-01	5.47E-01	5.96E-01	5.66E-01	1.02E+00
N_2O indirect (leaching)	kg/yr/t	2.78E+02	9.18E+02	2.05E+02	2.24E+02	2.12E+02	3.81E+02
CO_2 liming	kg/yr/t	5.37E+01	4.54E+01	4.00E+01	2.32E+01	2.20E+01	3.38E+01
CO_2 urea hydrolysis	kg/yr/t	-	-	-	1.54E+01	1.47E+01	2.82E+01
CH_4	kg/yr/t	-	-	-	-	-	-

Table G.35 Calculated CO_2-e/t for stubble burning on Farm G

Farm G		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Emissions from stubble burning		Paddock number			Paddock number		
	Units	19	20	21	19	20	21
CO_2	kg/ha/t	-	-	-	-	-	-
CH_4	kg/ha/t	2.37E+00	4.50E+00	-	-	-	-
N_2O	kg/ha/t	6.15E+01	1.17E+02	-	-	-	-

Table G.36 Calculated CO_2-e/t for machinery production and use on Farm G

Farm G			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	19	20	21	19	20	21
Seeding	Cost of seeding machinery (1998 price)	USD/t	1.92E+00	1.62E+00	1.43E+00	8.29E-01	7.87E-01	1.21E+00
	Fuel Use	l/hr/t	6.24E+00	5.27E+00	4.65E+00	2.69E+00	2.56E+00	3.94E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t	4.16E-01	1.76E-01	1.55E-01	8.97E-02	8.52E-02	1.31E-01
	Fuel Use	l/hr/t	1.64E+00	6.92E-01	6.10E-01	3.53E-01	3.36E-01	5.17E-01
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t	3.89E+00	3.29E+00	2.90E+00	3.36E+00	3.19E+00	7.36E+00
	Fuel Use	l/hr/t	2.36E+00	1.99E+00	1.76E+00	2.04E+00	1.93E+00	4.46E+00
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t	6.86E-03	6.79E-03	6.72E-03	6.86E-03	6.79E-03	6.72E-03
	Fuel Use	l/hr/t	2.36E-01	1.99E-01	1.76E-01	1.02E-01	9.67E-02	1.49E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t	9.17E+00	7.75E+00	6.84E+00	3.96E+00	3.76E+00	5.78E+00
	Fuel Use	l/hr/t	9.71E+00	8.20E+00	7.23E+00	4.19E+00	3.98E+00	6.12E+00

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.37 Calculated CO_2-e/t for chemical transportation on Farm G

Farm G			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals		**Paddock number**	**Paddock number**			**Paddock number**		
Classification	**Chemical Name**	**Units**	**19**	**20**	**21**	**19**	**20**	**21**
Fertilisers	**Ag Flow xtra**	**tkm/t**				9.88E-01	9.38E-01	
	Agstar Trace	**tkm/t**	4.33E-01					
	Flexi-N	**tkm/t**	8.56E-01	1.09E+00	6.38E-01	2.59E-01	2.46E-01	3.78E-01
	Macro pro plus	**tkm/t**		3.51E+00	3.40E+00			1.49E+02
	Urea (national)	**tkm/t**				3.12E-01	2.96E-01	5.69E-01
	Urea (international)	**tkm/t**				1.98E+00	1.88E+00	3.62E+00
Fungicides and insecticides	**Alpha-cypermethrin**	**tkm/t**				6.54E-04	2.48E-04	3.82E-04
	Dividend	**tkm/t**			3.21E-02			1.63E-03
	Le-Mat	**tkm/t**			6.47E-03			
	Lorsban	**tkm/t**	3.36E-05	2.84E-05		2.90E-05	2.76E-05	3.54E-05
	Raxil	**tkm/t**	8.83E-03					
	Vincit	**tkm/t**				6.69E-05	6.35E-05	
Herbicides	**Amine 720**	**tkm/t**	4.85E-03					
	Avadex	**tkm/t**						6.31E-03
	Crusader	**tkm/t**				4.52E-01		
	Ester 680	**tkm/t**		2.22E-03				
	Gramaxone	**tkm/t**				3.67E-03	4.97E-03	
	Logran	**tkm/t**	5.05E+00		3.76E-01	2.18E-01	2.07E+00	
	Lorsban	**tkm/t**	3.36E-05	2.84E-05				
	MCPA 242	**tkm/t**			3.95E-03	1.22E-03		1.56E-03
	Precept	**tkm/t**	5.34E-01	4.52E-01	3.98E-01			
	Roundup	**tkm/t**	8.24E-03	6.96E-06	6.14E-03	2.73E-03	2.60E-03	4.00E-03
	Sprayseed	**tkm/t**				3.88E-04		1.62E-03
	Tigrex	**tkm/t**					6.94E-03	7.65E-03
	Topik	**tkm/t**	2.82E+00				1.22E-01	
	Treflan	**tkm/t**	3.41E-01	2.89E-04	2.54E-04	1.39E-01	1.48E-01	2.53E-01
Adjuvants	**Uptake**	**tkm/t**					9.56E-03	
	Wetter 1000	**tkm/t**				3.26E-05		4.76E-05
Lime		**tkm/t**	5.41E+00	4.57E+00	4.03E+00	2.33E+00	2.22E+00	3.41E+00

Table G.38. Calculated CO_2-e/t for chemical production on Farm H

Farm H			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Chemical Inputs			Paddock number			Paddock number		
Classification	**Chemical Name**	**Units**	**22**	**23**	**24**	**22**	**23**	**24**
Fertilisers	**NPS range-Cereal**	**kg/yr/t**					6.60E+01	5.68E+01
	UAN	**kg/yr/t**					3.96E+01	3.36E+01
	Mop	**kg/yr/t**					1.48E+01	1.28E+01
Fungicides and insecticides	**Alpha-cypermethrin**	**kg/yr/t**					4.95E-04	4.26E-04
	Tilt	**kg/yr/t**						2.06E-04
Herbicides	**Crusader**	**kg/yr/t**					1.35E+01	
	Logran	**kg/yr/t**					6.77E+00	2.11E+01
	MCPA LVE	**kg/yr/t**						2.11E-03
	Roundup	**kg/yr/t**					1.62E+00	1.40E+00
	Topik	**kg/yr/t**						7.27E-02
	Treflan	**kg/yr/t**					8.12E-01	2.00E-02
Lime		**tonne/year/tonne**		9.14E-01	1.12E+00		5.45E-01	4.69E-01

TableG.39. Calculated CO_2-e/t for soil emissions on Farm H

Farm H		Calculated equivalent for 2010			Calculated equivalent for 2011		
		CO_2-e/t			CO_2-e/t		
Soil Emissions		Paddock number			Paddock number		
	Units	**22**	**23**	**24**	**22**	**23**	**24**
N_2O direct	**kg/year/t**		-	-		8.44E+00	8.92E+00
N_2O indirect (vol)	**kg/year/t**		-	-		6.76E-01	1.12E+00
N_2O indirect (leaching)	**kg/year/t**		-	-			
CO_2 liming	**kg/year/t**		8.72E+01	1.07E+02		1.42E+01	1.22E+01
CO_2 urea hydrolysis	**kg/year/t**		-	-		-	-
CH_4	**kg/year/t**		-	-		-	-

Table G.40 Calculated CO_2-e/t for machinery production and use on Farm H

Farm H			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from production and use of farm machinery			Paddock number			Paddock number		
		Units	22	23	24	22	23	24
Seeding	Cost of seeding machinery (1998 price)	USD/t		1.70E+00	2.09E+00		1.02E+00	8.75E-01
	Fuel Use	l/hr/t		5.53E+00	6.78E+00		3.30E+00	2.84E+00
Spraying	Cost of spraying machinery (1998 price)	USD/t					9.57E-02	8.24E-02
	Fuel Use	l/hr/t					3.77E-01	3.24E-01
Top dressing -fertiliser	Cost of top dressing machinery (1998 price)	USD/t					1.79E+00	1.54E+00
	Fuel Use	l/hr/t					1.08E+00	9.34E-01
Top dressing -lime	Cost of top dressing machinery (1998 price)	USD/t					1.79E+00	1.54E+00
	Fuel Use	l/hr/t					1.08E+00	9.34E-01
Harvesting	Cost of harvesting machinery (1998 price)	USD/t		6.36E+00	7.79E+00		3.80E+00	3.27E+00
	Fuel Use	l/hr/t		6.73E+00	8.25E+00		4.02E+00	3.46E+00
Claying	Cost of claying machinery (1998 price)	USD/t			6.55E-01			
	Fuel Use	l/hr/t			1.95E+02			
Mouldboarding	Cost of mouldboarding machinery (1998 price)	USD/t		6.43E+02				
	Fuel Use	l/hr/t		2.32E+00				

Note: No swathing was done on these paddocks for 2010 and 2011

Table G.41 Calculated CO_2-e/t for chemical transportation on Farm H

Farm H			Calculated equivalent for 2010			Calculated equivalent for 2011		
			CO_2-e/t			CO_2-e/t		
Emissions from transportation of chemicals			**Paddock number**			**Paddock number**		
Classification	**Chemical Name**	**Units**	**22**	**23**	**24**	**22**	**23**	**24**
Fertilisers	**UAN**	**tkm/t**					1.09E+00	1.20E+00
	Cereal	**tkm/t**					1.46E+00	1.23E+00
	Mop	**tkm/t**					9.39E-02	8.08E-02
Fungicides and insecticides	**Alpha-cypermethrin**	**tkm/t**					5.31E-04	4.57E-04
	Tilt	**tkm/t**						5.65E-03
Herbicides	**Crusader**	**tkm/t**					5.56E-01	
	Logran	**tkm/t**					2.68E+00	2.97E-01
	MCPA LVE	**tkm/t**						3.55E-06
	Roundup	**tkm/t**					2.94E-03	2.53E-03
	Topik	**tkm/t**						1.29E-01
	Treflan	**tkm/t**					2.13E-04	1.84E-04
Lime		**tkm/t**		2.47E+00	3.03E+00		1.48E+00	1.27E+00

APPENDIX H

CARBON FOOTPRINT

Table H.1 Carbon footprint for Farm A, pre-farm and on-farm stages

Farm A			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	**Paddock number**	**Units**	**Fertilisers**	**Fungicides and pesticides**	**Herbicides**	**Adjuvants**	**Lime**				
2010	**1**	**kg CO_2**-e/t	6.24E+01	-	9.44E+01	7.46E-02	1.28E+00	2.75E+01	1.92E+02	9.31E+01	4.70E+02
	2	**kg CO_2**-e/t	7.65E+01	-	2.90E+01	-	1.40E+00	3.08E+01	2.35E+02	4.07E+01	4.14E+02
	3	**kg CO_2**-e/t	6.71E+01	8.76E-05	3.06E+01	-	1.22E+00	2.55E+01	2.06E+02	5.70E+01	3.88E+02
2011	**1**	**kg CO_2**-e/t	1.35E+02	1.11E-04	2.57E+01	1.39E-02	5.93E-01	1.14E+01	2.26E+03	1.40E+02	2.57E+03
	2	**kg CO_2**-e/t	8.88E+01	1.32E-05	3.72E+01	1.01E-02	8.41E-01	1.48E+01	1.39E-02	8.13E+01	2.23E+02
	3	**kg CO_2**-e/t	1.68E+02	1.44E-04	7.37E+01	9.21E-05	7.72E-01	1.58E+01	3.67E+03	2.57E+02	4.19E+03

Farm A			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	**Paddock number**	**Units**		**Stubble burning**	**Enteric Emissions**	**Excreta emissions**	**CO_2 urea hydrolysis**	**CO_2 liming**	**N_2O from fertiliser**	**CH_4 from soil**	**N_2O from leaching**	**N_2O from NH_3 volatilisation**		
2010	**1**	**kg CO_2**-e/t	2.70E+01	2.93E-01	-	-	-	3.33E+01	2.48E+00	-	7.45E+01	1.99E-01	1.38E+02	6.08E+02
	2	**kg CO_2**-e/t	2.85E+01	3.18E-01	-	-	-	2.19E+01	3.05E+00	-	9.14E+00	2.44E-01	6.31E+01	4.77E+02
	3	**kg CO_2**-e/t	2.49E+01	1.64E-01	-	-	-	2.01E+01	2.67E+00	-	8.02E+01	2.14E-01	1.28E+02	5.16E+02
2011	**1**	**kg CO_2**-e/t	1.22E+01	-	1.52E+00	2.82E-02	1.03E+01	1.54E+01	8.71E+00	-	2.61E+02	6.15E-01	3.10E+02	2.88E+03
	2	**kg CO_2**-e/t	1.60E+01	4.10E-01	1.19E+00	1.14E-02	-	2.19E+01	2.14E+00	-	6.41E+01	1.71E-01	1.06E+02	3.29E+02
	3	**kg CO_2**-e/t	1.60E+01	0.00E+00	1.06E+00	1.93E-02	1.67E+01	2.01E+01	3.50E+01	-	3.36E+02	7.69E-01	4.25E+02	4.61E+03

Table H.2 Carbon footprint for Farm B, pre-farm and on-farm stages

Farm B			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvant	Lime				
2010	4	kg CO_2-e/t	2.22E+02	2.21E-03	4.70E+01	1.75E-01	8.20E-01	1.09E+01	1.26E+01	3.22E+00	2.97E+02
	5	kg CO_2-e/t	2.30E+02	3.79E-04	2.86E+01	-	8.80E-01	1.12E+01	1.22E+01	1.85E+00	2.85E+02
	6	kg CO_2-e/t	7.47E+01	3.02E-04	1.14E+01	8.13E-02	7.01E-01	8.93E+00	3.79E+00	1.17E+00	1.01E+02
2011	4	kg CO_2-e/t	-	-	1.27E+01	-	6.01E-01	7.66E+00	-	1.03E+00	2.20E+01
	5	kg CO_2-e/t	1.80E+02	1.24E-03	1.62E+01	-	7.19E-01	9.54E+00	8.97E+00	1.37E+00	2.17E+02
	6	kg CO_2-e/t	7.31E+01	5.21E-04	3.50E+03	7.61E-02	6.56E-01	8.35E+00	7.15E-02	2.55E+00	3.58E+03

Farm B			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	4	kg CO_2-e/t	1.52E+01	-	-	-	4.63E+01	2.14E+01	1.56E+01	-	-	1.25E+00	9.97E+01	3.97E+02
	5	kg CO_2-e/t	1.49E+01	-	-	-	4.20E+01	2.29E+01	1.45E+01	-	-	1.16E+00	9.56E+01	3.80E+02
	6	kg CO_2-e/t	1.19E+01	-	-	-	1.22E+01	1.83E+01	5.75E+00	-	-	4.60E-01	4.85E+01	1.49E+02
2011	4	kg CO_2-e/t	1.02E+01	-	-	-	-	1.57E+01	0.00E+00	-	-	-	2.59E+01	4.78E+01
	5	kg CO_2-e/t	1.33E+01	-	-	-	2.81E+01	1.87E+01	1.00E+01	-	-	8.03E-01	7.09E+01	2.88E+02
	6	kg CO_2-e/t	1.11E+01	-	-	-	1.42E+01	1.71E+01	6.21E+00	-	-	4.97E-01	4.91E+01	3.63E+03

Table H.3 Carbon footprint for Farm C, pre-farm and on-farm stages

Farm C			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvant	Lime				
2010	7	kg CO_2-e/t	1.03E+02	-	9.29E+00	-	1.06E+00	1.17E+01	4.86E+01	2.25E+00	1.76E+02
	8	kg CO_2-e/t	1.83E+02	-	2.85E+01	-	1.88E+00	1.97E+01	8.64E+01	4.49E+00	3.24E+02
	9	kg CO_2-e/t	1.60E+02	-	3.01E+01	-	2.30E+00	1.66E+01	7.10E+01	5.04E+00	2.85E+02
2011	7	kg CO_2-e/t	9.65E+01	-	1.44E+01	-	7.68E-01	1.00E+01	4.38E+00	1.64E+00	1.28E+02
	8	kg CO_2-e/t	3.98E+01	-	5.42E+00	-	4.83E-01	5.51E+00	1.37E+00	9.16E-01	5.35E+01
	9	kg CO_2-e/t	2.24E+02	1.28E-03	1.28E+02	5.20E-03	3.17E+00	2.41E+01	7.71E+00	7.06E+00	3.94E+02

Farm C			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	7	kg CO_2-e/t	1.76E+01	-	3.64E+01	1.69E-02	1.15E+01	2.75E+01	5.43E+00	-	1.64E+02	4.38E-01	2.63E+02	4.39E+02
	8	kg CO_2-e/t	2.93E+01	-	-	-	2.04E+01	4.89E+01	9.73E+00	-	2.92E+02	7.78E-01	4.01E+02	7.25E+02
	9	kg CO_2-e/t	2.48E+01	-	-	-	1.67E+01	6.00E+01	7.96E+00	-	2.54E+02	6.37E-01	3.64E+02	6.49E+02
2011	7	kg CO_2-e/t	1.38E+01	-	3.97E+01	1.84E-02	8.33E+00	2.00E+01	6.06E+00	-	1.82E+02	4.85E-01	2.70E+02	3.98E+02
	8	kg CO_2-e/t	8.36E+00	-	1.09E+02	5.08E-02	-	1.26E+01	7.53E-01	-	-	6.02E-02	1.31E+02	1.85E+02
	9	kg CO_2-e/t	3.66E+01	-	4.28E+01	2.64E-02	-	8.25E+01	4.02E+00	-	-	3.22E-01	1.66E+02	5.603E+02

Table H.4 Carbon footprint for Farm D, pre-farm and on-farm stages

Farm D			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvant	Lime				
2010	10	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	11	kg CO_2-e/t	1.34E+02	-	3.16E+01	-	9.39E-01	1.03E+01	4.02E+00	2.25E+01	2.03E+02
	12	kg CO_2-e/t	1.32E+02	-	1.05E+01	-	8.45E-01	9.48E+00	3.98E+00	2.02E+01	1.77E+02
2011	10	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	11	kg CO_2-e/t	1.03E+02	8.61E-05	1.92E+01	-	5.45E-01	7.28E+00	3.11E+00	1.85E+00	1.35E+02
	12	kg CO_2-e/t	1.07E+02	-	1.72E+01	-	5.63E-01	7.52E+00	3.21E+00	1.55E+00	1.37E+02

Farm D			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	10	kg CO_2-e/t	-	-	-	-	-	-	-	-	-	-	-	-
	11	kg CO_2-e/t	1.48E+01	7.72E+01	3.54E+01	1.64E-02	0.00E+00	2.44E+01	4.19E+00	-	1.26E+02	3.35E-01	2.82E+02	4.85E+02
	12	kg CO_2-e/t	1.38E+01	1.95E+01	3.54E+01	1.64E-02	0.00E+00	2.20E+01	3.39E+00	-	1.02E+02	2.71E-01	1.96E+02	3.73E+02
2011	10	kg CO_2-e/t	-	-	-	-	-	-	-	-	-	-	-	-
	11	kg CO_2-e/t	9.80E+00	-	-	-	-	1.42E+01	5.62E+00	-	1.45E+02	4.50E-01	1.76E+02	3.11E+02
	12	kg CO_2-e/t	1.01E+01	-	-	-	-	1.47E+01	5.81E+00	-	1.74E+02	4.01E-01	2.05E+02	3.42E+02

Table H.5 Carbon footprint for Farm E, pre-farm and on-farm stages

Farm E			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvant	Lime				
2010	13	kg CO_2-e/t	1.14E+02	-	3.33E+01	-	1.81E+00	1.74E+01	5.93E+01	4.15E+00	2.30E+02
	14	kg CO_2-e/t	1.02E+02	-	2.63E+01	-	1.63E+00	1.55E+01	5.34E+01	3.53E+00	2.02E+02
	15	kg CO_2-e/t	1.21E+02	-	5.36E+01	-	1.92E+00	2.11E+01	6.31E+01	5.78E+00	2.66E+02
2011	13	kg CO_2-e/t	2.92E+01	-	2.48E+01	2.05E-01	6.21E-01	1.01E+01	1.23E+01	1.82E+00	7.90E+01
	14	kg CO_2-e/t	5.84E+01	-	7.62E+00	1.02E-01	6.21E-01	9.21E+00	2.45E+01	1.51E+00	1.02E+02
	15	kg CO_2-e/t	1.18E+02	-	4.36E+00	1.93E-01	1.18E+00	1.59E+01	6.15E+01	2.36E+00	2.03E+02

Farm E			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	13	kg CO_2-e/t	2.39E+01	-	2.88E+01	2.97E-02	-	4.70E+01	4.20E+00	-	0.00E+00	3.36E-01	1.04E+02	3.34E+02
	14	kg CO_2-e/t	2.08E+01	-	2.59E+01	2.67E-02	-	4.23E+01	1.13E+01	-	0.00E+00	3.03E-01	1.01E+02	3.03E+02
	15	kg CO_2-e/t	2.64E+01	-	2.46E+01	2.53E-02	-	5.00E+01	4.47E+00	-	0.00E+00	3.58E-01	1.06E+02	3.72E+02
2011	13	kg CO_2-e/t	1.63E+01	-	1.43E+01	1.47E-02	7.01E+00	1.62E+01	2.84E+00	-	8.527E+01	2.27E-01	1.42E+02	2.21E+02
	14	kg CO_2-e/t	1.54E+01	-	1.58E+01	1.27E-02	1.40E+01	1.62E+01	5.68E+00	-	1.71E+02	4.55E-01	2.38E+02	3.40E+02
	15	kg CO_2-e/t	2.82E+01	-	2.23E+01	2.30E-02	0.00E+00	3.06E+01	1.72E+00	-	5.17E+01	1.38E-01	1.35E+02	3.38E+02

Table H.6 Carbon footprint for Farm F, pre-farm and on-farm stages

Farm F			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvants	Lime				
2010	16	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	18	kg CO_2-e/t	3.15E+02	-	3.49E+01	-	1.27E+00	1.96E+01	3.87E+00	3.40E+00	3.78E+02
2011	16	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	18	kg CO_2-e/t	3.02E+02	6.55E-01	2.78E+01	-	1.21E+00	1.99E+01	2.57E+00	2.10E+01	3.75E+02

Farm F			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	16	kg CO_2-e/t	-	-	-	-	-	-	-	-	-	-	-	-
	17	kg CO_2-e/t	-	-	-	-	-	-	-	-	-	-	-	-
	18	kg CO_2-e/t	1.96E+01	-	-	-	-	3.31E+01	7.63E+00	-	2.29E+02	6.10E-01	2.90E+02	6.68E+02
2011	16	kg CO_2-e/t	-	-	-	-	-	-	-	-	-	-	-	-
	17	kg CO_2-e/t												
	18	kg CO_2-e/t	2.41E+01	2.65E+00	-	-	-	3.14E+01	1.51E+01	-	0.00E+00	1.90E+00	7.52E+01	4.50E+02

Table H.7 Carbon footprint for Farm G, pre-farm and on-farm stages

Farm G			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvants	Lime				
2010	19	kg CO_2-e/t	1.82E+02	4.37E-04	2.27E+02	-	2.06E+00	1.54E+01	1.29E+00	1.42E+01	4.42E+02
	20	kg CO_2-e/t	2.61E+02	2.93E-05	2.46E+02	-	1.74E+00	1.28E+01	4.60E+00	5.02E+00	5.31E+02
	21	kg CO_2-e/t	2.30E+02	3.07E-02	1.10E+02	-	1.54E+00	1.13E+01	4.04E+00	4.85E+00	3.62E+02
2011	19	kg CO_2-e/t	9.19E+01	7.89E-04	1.39E+02	8.63E-04	8.89E-01	8.24E+00	3.54E+00	3.15E+00	2.47E+02
	20	kg CO_2-e/t	8.73E+01	3.66E-04	7.46E+01	1.01E-02	8.45E-01	7.83E+00	3.36E+00	4.58E+00	1.79E+02
	21	kg CO_2-e/t	2.03E+02	1.98E-03	1.94E+01	1.26E-03	1.30E+00	1.45E+01	7.19E+00	3.69E+00	2.49E+02

Farm G			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	19	kg CO_2-e/t	2.09E+01	6.38E+01	-	-	-	5.37E+01	9.27E+00	-	2.78E+02	7.42E-01	4.27E+02	8.69E+02
	20	kg CO_2-e/t	1.70E+01	1.21E+02	-	-	-	4.54E+01	1.01E+01	-	9.18E+02	8.05E-01	1.11E+03	1.64E+03
	21	kg CO_2-e/t	1.50E+01	-	-	-	-	4.00E+01	6.84E+00	-	2.05E+02	5.47E-01	2.67E+02	6.29E+02
2011	19	kg CO_2-e/t	9.37E+00	-	-	-	1.54E+01	2.32E+01	7.45E+00	-	2.24E+02	5.96E-01	2.80E+02	5.26E+02
	20	kg CO_2-e/t	8.90E+00	-	-	-	1.47E+01	2.20E+01	7.08E+00	-	2.12E+02	5.66E-01	2.66E+02	4.44E+02
	21	kg CO_2-e/t	1.52E+01	-	-	-	2.82E+01	3.38E+01	1.27E+01	-	3.81E+02	1.02E+00	4.72E+02	7.21E+02

Table H.8 Carbon footprint for Farm H, pre-farm and on-farm stages

Farm H			Pre-farm (kg CO_2-e)								
			Chemical production					Farm machinery production	Transportation of Fertilisers	Transportation of Chemicals	Sub-Total
Description	Paddock number	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvants	Lime				
2010	22	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	23	kg CO_2-e/t	-	-	-	-	9.14E-01	4.44E+01	-	2.47E+00	4.78E+01
	24	kg CO_2-e/t	-	-	-	-	1.12E+00	1.05E+01	-	3.03E+00	1.47E+01
2011	22	kg CO_2-e/t	-	-	-	-	-	-	-	-	-
	23	kg CO_2-e/t	1.20E+02	4.95E-04	2.19E+01	-	5.45E-01	8.49E+00	2.65E+00	2.30E+00	1.56E+02
	24	kg CO_2-e/t	1.03E+02	6.33E-04	2.26E+01	-	4.69E-01	7.31E+00	2.51E+00	1.71E+00	1.38E+02

Farm H			On-farm (kg CO_2-e)											Total
			Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	Paddock number	Units		Stubble burning	Enteric emissions	Excreta emissions	CO_2 urea hydrolysis	CO_2 liming	N_2O from fertiliser	CH_4 from soil	N_2O from leaching	N_2O from NH_3 volatilisation		
2010	22	**kg CO_2**-e/t	-	-	-	-	-		-	-	-	-		
	23	**kg CO_2**-e/t	1.46E+01	-	-	-	-	8.72E+01	-	-	-	-	1.02E+02	1.50E+02
	24	**kg CO_2**-e/t	2.10E+02	-	-	-	-	1.07E+02	-	-	-	-	3.17E+02	3.31E+02
2011	22	**kg CO_2**-e/t	-	-	-	-	-	-	-	-	-	-		
	23	**kg CO_2**-e/t	9.87E+00	-	-	-	-	1.42E+01	8.44E+00	-	-	6.76E-01	3.32E+01	1.90E+02
	24	**kg CO_2**-e/t	8.50E+00	-	-	-	-	1.22E+01	8.92E+00	-	-	1.12E+00	3.08E+01	1.69E+02

APPENDIX I

MITIGATION

Fertiliser mitigation calculation

The following calculation was used to calculate the equivalent amount of a fertiliser (fertiliser B), required to replace the original fertiliser (fertiliser A), based on the nitrogen content of the original fertiliser.

The following variables will be used to illustrate the calculation:

The actual dosage of 50 kg of urea (fertiliser A), should be replaced with Flexi-N (fertiliser B). The nitrogen applied to the soil should remain the same. The nitrogen content of solid urea is 46%. Flexi-N has a nitrogen content of 32% and a density of 1.32.

Fertiliser A:

Thus to calculate the amount of N in 50 kg of urea Equation I.1 is used.

$$\boldsymbol{Mass\ N_{fertA} = density_{fertA} \times Content\ N_{fertA} \times Dosage_{fertA}}$$ **Equation I.1**

Where, 'Mass N_{fertA}' is the mass of N in fertiliser A (kg), '$density_{fertA}$' is the density of the fertiliser if a liquid (kg/l) otherwise the density is 1, 'Content N_{fertA}' is the N that is in fertiliser A (%) and '$Dosage_{fertA}$' is the actual dosage rate of the fertiliser used (kg or l). When Fertiliser A is a solid the mass is reported in g or kg, alternatively if it is a liquid it is reported in ml or l

For example: Mass N_{fertA} = 1 kg/l x 46% x 50 kg = 23 kg N per kg of fertiliser A

Thereafter the mass for fertiliser B required is calculated using equation I.2.

$$\boldsymbol{Dosage_{fertB} = \frac{Mass\ N_{fertA}}{Content\ N_{\ fertB} \times density_{fertB}}}$$ **Equation I.2**

Where,’Dosage $_{fertB}$’ is the required dosage of fertiliser B to replace fertiliser A (kg or l), ‘Mass N $_{fertA}$’is the is the mass of N in fertiliser A (kg), ‘Content N_{fertB}’is the N content in fertiliser B (%) and ‘density $_{fertB}$’ is the density of fertiliser B (kg/l) when a liquid. When Fertiliser B is a solid the mass is reported in g or kg, alternatively if it is a liquid it is reported in ml or l

For example: Dosage $_{fertB}$=23 kg N per kg of fertiliser A / (32% N x 1.32 kg/l) = 54.5 kg

Colwell soil tests

Table I.1 presents the results obtained from DAFWA for the soil tests. The soil was sampled in the 0-10 cm horizon and in the 20-40 cm horizon. Planting is usually done in the top 10 cm to as nutrients should be available to the plant in this horizon. The sampling is done in the 20-40 cm horizon to ascertain whether any leaching may have occurred (Croppro.com, 2015).

Table I.1. Soil nutrient test results (Colwell)

Paddock	2010						2011					
Element	P	K	S	P	K	S	P	K	S	P	K	S
Soil horizon	0-10 mm	0-10 mm	0-10 mm	20-40 mm	0-10 mm	20-40 mm	0-10 mm	0-10 mm	0-10 mm	20-40 mm	20-40 mm	20-40 mm
Unit	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
1	35	788	8.52	719	92.2	0.16	35	236	6.9	9	719	92.2
2	33	131	10.6	377	3.6	0.36	33	788	8.52	4	377	3.6
3	41	88	9.5	65	41.1	0.32	41	131	10.6	32	65	41.1
4	61	104	54	34	33	0.2	61	104	28	3	34	33
5	30	43	8.77	25	23.6	0.2	30	43	54	4	25	23.6
6	36	926	7.09	295	17.7	0.47	36	926	8.77	4	295	17.7
7	27	378	7.09	3	222	7.4	27	378	0.63	3	222	7.4
8	25	136	9.04	2	63	20.9	25	136	1.03	2	63	20.9
9	-	-	-	3	23	17.6	-	-	-	3	23	17.6
11	38	61	105	6	47	31.7	38	61	105	4	47	31.7
12	56	693	5.81	3	210	39.4	56	693	5.81	3	210	39.4
13	37	118	9.59	2	60	14.3	37	118	9.59	2	60	9.1
14	30	161	8.3	4	72	9.1	30	161	8.3	4	72	21.5
15	38	885	9.46	5	40	21.5	38	85	9.46	5	40	16.3
18	35	145	7.12	10	114	13.2	16	71	3.42	10	114	13.2
19	56	265	7.36	15	29	7	56	265	7.36	15	29	7
20	64	314	6.64	13	178	6.9	64	314	6.64	13	178	6.9
21	45	66	6.75	10	69	8.2	45	66	6.75	10	69	8.2
23	20	38	7.44	13	19	4.4	20	38	7.44	13	19	4.4
24	19	43	44.6	11	20	6.7	19	43	44.6	11	20	6.7

P=phosphorus, K=potassium, S=sulphur [results obtained from DAFWA)