Amount of words: 6919

INTEGRATED SPATIAL TECHNOLOGY TO MITIGATE GREENHOUSE GAS EMISSIONS IN GRAIN PRODUCTION

Deborah Engelbrecht[a], Wahidul Biswas[b], Deborah Pritchard[c], Waqar Ahmad[d]

[a]*Sustainable Engineering Department, Curtin University, GPO Box U1987, Perth 6845, Western Australia, Australia, Deborah.engelbrecht@postgrad.curtin.edu.au*[*]

[b]*Sustainable Engineering Department, Curtin University, GPO Box U1987, Perth 6845, Western Australia, Australia,* W.Biswas@curtin.edu.au

[c]*Department of Environment and Agriculture, Curtin University, GPO Box U1987, Perth 6845, Western Australia, Australia, D.Pritchard@curtin.edu.au*

[d]*CSIRO , Animal, Food and Nutritional Sciences, Perth, Australia,* Waqar.Ahmad@csiro.au

[*]Corresponding author Email address:

Deborah.engelbrecht@postgrad.curtin.edu.au (D. Engelbrecht)

Abstract

The causes and implications of climate change are currently at the forefront of many researching agendas. Countries that have ratified the Kyoto Protocol are bound by agreements to focus on and reduce greenhouse gas emissions which impact on the natural and anthropogenic environment. Internationally agriculture contributes to environmental impacts such as land use change, loss of biodiversity, greenhouse gas emissions, increased soil salinity, soil acidity and soil erosion. To combat and control the greenhouse gas emissions generated during agricultural production, methodologies are being developed and investigated worldwide. Agriculture is the second largest emitter of greenhouse gases in Australia and consequently the integrated spatial technology was developed using data from a crop rotation project conducted by the Department of Agriculture and Food, Western Australia. The aim of the integrated spatial technology was to combine remote sensing, geographical information systems and life cycle assessment, to ascertain the component or system within the agricultural production cycle, generating the most greenhouse gases. Cleaner production strategies were then used to develop mitigation measures for the reduction of greenhouse gases within the integrated spatial technology.

Keywords: Remote sensing; geographical information systems; life cycle assessment; integrated spatial technology; agriculture; carbon footprint

Abbreviations:

ACCU	Australian carbon credit units
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
DSE	Direct soil emissions
ERF	Emissions Reduction Fund
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GIS	Geographical Information Systems
IPCC	Intergovernmental Panel on Climate Change
ISE	Indirect soil emissions
IST	Integrated Spatial Technology
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NGGI	National greenhouse gas inventory
N_2O	nitrous oxide
RS	Remote Sensing

1. Introduction

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).

To reduce poverty and feed the projected world population of nine billion people by 2050 agricultural productivity needs to increase by 60%−70% compared to 2006 levels. For increases in productivity to remain sustainable, agriculture should focus on minimal environmental degradation and its associated greenhouse gas (GHG) emissions (FAO, WFP & IFAD), 2015). However, Darwin, (2004) and Huang & Wang (2014) state that in the face of climate change, agricultural productivity has fallen, with greater fluctuations in crop yields and local food supplies expected. Furthermore it is widely accepted 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; FAO, 2012; FAO, WFP & IFAD, 2012; Huang & Wang; 2014). The fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC) notes that climate change is having a negative impact on agriculture (IPCC, 2014). Lee et al. (2014) and Vermeulen et al. (2012) also confirm that climate change can further destabilise current farming systems by a rise of 2°C in global temperatures, and in turn this can transform the agricultural sector and place productivity under pressure.

In 2010 agriculture contributed to approximately 14.5% of global climate altering GHG emissions (Engelbrecht et al., 2013; FAO, 2014). These GHG emissions were mainly comprised of emissions from soil N_2O, CH_4 from animal husbandry and CO_2 from fertiliser products and the hydrolysis of urea (Biswas et al., 2010). In 2005, agricultural emissions of N_2O and CH_4 accounted for approximately 60% and 50% of the total global N_2O and CH_4 emissions, respectively (Smith et al., 2007). Generating 1.5% of the global total of 37,928 Mt carbon dioxide equivalents (CO_2-e), Australia was ranked 12th in the world in 2010 with the agricultural sector emitting 18% of the national GHG emissions, of which 61% was CH_4 and 39% was N_2O (TSP, 2015).

Changes in water availability, water quality and rising temperatures in Australia arising from climate change is expected to impact highly on agricultural productivity due to high levels of exposure and sensitivity (Garnaut, 2008). In order to sustain and evaluate the environmental impact of agricultural productivity and increase the efficiency of the agriculture and livestock sectors, the entire Australian agricultural sector requires different options for production to be investigated (Biswas et al., 2010; NGGI, 2010). The FAO (2014) recommends that farmers respond to local and regional needs and vulnerabilities by developing and implementing mitigation and adaptation strategies, hence methodologies are being developed and trialled worldwide to combat and control the emissions generated during agricultural production. Farmers in Australia should focus on reducing N_2O and CH_4 as agriculture is the highest emitter of these two GHGs (NGGI, 2013) and the second largest emitter of total GHGs.

In Australia the Emissions Reduction Fund (ERF) 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 (CER, 2014; ERF, 2014). It provides an incentive for the adoption of new practices and technologies that will enable businesses, land owners, state and local governments, community organisations and individuals to sell their CO_2 abatement back to the Government (CER, 2014; ERF, 2014). Included in the ERF is the Carbon Farming Initiative (CFI), which enables individuals and entities to be issued with Australian carbon credit units (ACCUs), each ACCU represents one tonne of CO_2-e (CFI, 2012; Engelbrecht et al., 2013). The attainment of these ACCU's is achieved by implementing projects that fall into one of two categories – emissions avoidance, where GHG emissions are prevented from entering the atmosphere, and sequestration, where carbon is stored on the land (CER, 2014). Methodologies such as manure management in piggeries, the establishment of environmental plantings, the capture and combustion of landfill gas and the management of savannah fires have been integrated in order to address these two categories (CFI, 2012; Engelbrecht et al., 2013).

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. Ideally no one system, whether mitigation or adaptation, exists that will work for all farms given that 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).

A user-friendly and comprehensive decision support tool, identifying the areas within the agricultural cycle generating the most GHGs for farmers, was not available in the literature reviewed to date. In contrast there are established methods wherein the industry and academic institutions are able to identify the concerning areas within the agricultural cycle. To track stages in the farming system most responsible for GHG emissions, a comprehensive environmental management tool known as the integrated spatial technology (IST) was thus developed using data from a crop rotation project conducted by the Department of Agriculture and Food, Western Australia (DAFWA) (Engelbrecht et al., 2013; 2015). Prior to this, the IST was pre-tested using the published data of Biswas et al. (2008) (Engelbrecht et al., 2013; 2015).

As a newly developed tool, the IST was applied for the first time in this current study by utilizing real world data from a Western Australian farm that met the requirements of the IST and identified hotspots for both the paddock and farm scales. Furthermore, it facilitates the selection of mitigation measures that are then remodelled within the IST to allow the user to make visual comparisons with the original results. As a simple, quick and easy to use tool, the purpose of the IST is to focus on farmers, government policy makers and agricultural researchers who have limited time at their disposal. Whilst it is beyond the scope of the current study, 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).

This article introduces the use of IST as a methodological approach, as previously presented and tested using a hypothetical example (Article title - 'An evaluation of Integrated Spatial Technology framework for Greenhouse Gas mitigation in Western Australia' (Engelbrecht et al., 2013)). The IST applies the concept of cleaner production (CP) for the formulation and application of cost-effective GHG mitigation options from grain production in Western Australia. Additionally it allows for visual identification of the impact from the farm management systems used and is able to identify areas where mitigation measures may be applied. Finally it could be used to suggest appropriate CP strategies.

2. Materials

The IST is a tool designed by integrating RS, GIS and LCA (Figure 1) to calculate the carbon footprint on grain farms in south-western Australia. The IST highlights the area in which the GHGs are the highest and most concerning (the hotspot) and can subsequently be used to select different mitigation scenarios based on CP strategies.

2.1 Remote Sensing, GIS and LCA

RS 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 (Lillesand et al., 2004; NASA, 2014). Although the availability and cost of RS images has limited its use in agriculture it 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 et al., 2011), crop nutrient detection (Goel et al., 2003; Nigon, et al., 2015), water stress (Nigon et al., 2015; Tilling et al., 2007), weed infestations (Cavalli et al., 2009; Goel et al., 2003) and soil properties (Mulder et al., 2011), amongst others.

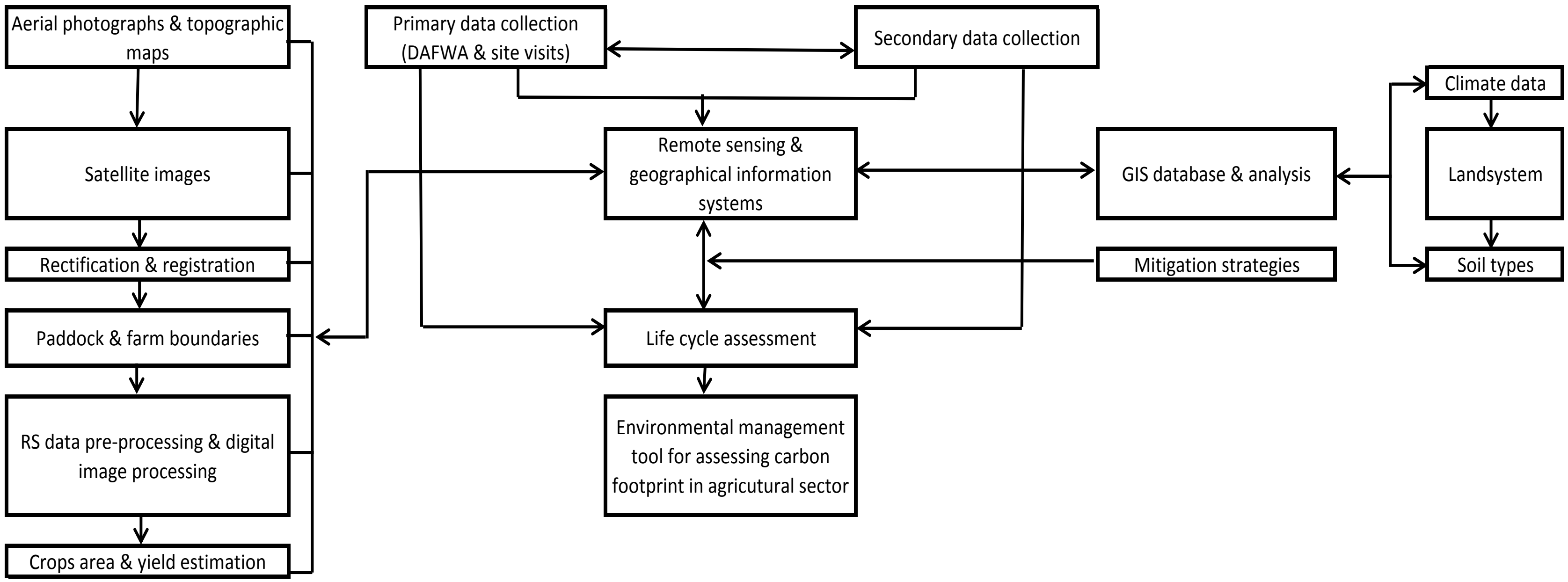


Figure 1. Integrated spatial technology (IST) (Engelbrecht et al., 2013).

GIS is used to capture, edit and analyse multi-layered environmental and ancillary data layers along with its geographic location and temporal variation (Lillesand et al., 2004) and enables the user to visualise, question, analyse and interpret data to understand relationships, patterns and trends (ESRI, 2014). GIS and RS has been used successfully in agricultural applications such as the mapping of GHGs and energy requirements for agricultural fertiliser and pesticide production in Australia (Navarro et al., 2013), the integration of GIS and RS to map crop suitability and crop production in India (Bharathkumar & Mohammed-Aslam; 2015) and the mapping of hydrology and groundwater potentiality (Oikonomidis et al., 2015).

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). A LCA consists of four stages, the goal and scope definition, the development of a life cycle inventory (LCI), the development of the life cycle impact assessment (LCIA) and the interpretation (Curran, 2006; ISO 2006; UNEP, 2014). When the scope of the LCA is limited to exclude impacts that are not relevant to the study, the LCA is coined a limited focus LCA. The limited focus is not an alternative LCA methodology as it uses the four steps as outlined previously and limits the scope analyses by defining the boundaries more specifically (Finkbeiner, Tan, Raimbult, 2011). LCA has been used extensively in the agricultural sector in Australia and internationally (Biswas et al., 2010; Grant & Beer, 2008) and internationally (Meisterling et al., 2009; Thomassen et al., 2008).

2.2 Cleaner production

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). Five CP strategies that focus on agriculture (internationally), as documented by van Berkel (2007) and Biswas et al. (2011) include are listed below:

- *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 promoting 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 associated GHG emissions.
- *Product modification* is used to change features of product development 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 waste-water for irrigation purposes.

2.3 The stages of the IST

The IST (Figure 1) primarily consists of two stages. In the first stage the RS data from the satellite imagery is used as an input into a GIS. In the GIS data layers pertaining to paddock[1], farm[2] and shire[3] boundaries, corresponding rainfall, temperature, soil types and administrative[4] boundaries are stored. The second stage applies a LCA-based approach to calculate the carbon footprint of the paddock. Currently the IST only focuses on the pre-farm and on-farm stages of the agricultural system, excluding all processes occurring from and after the farm-gate.

In the pre-farm stage the IST includes the GHG emissions generated through farm machinery production, farm inputs and transportation. Figure 2 illustrates the variables included in the system boundary considered in this LCA, for the pre-

[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 (Dictionary.com, 2014).
[2] A farm is an area of land (within the shire) and its buildings, used for growing crops and rearing animals (Dictionary.com, 2014).
[3] A shire is a rural district having its own local council (Dictionary.com, 2014). 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 (Australian Government, 2013).

farm stage. The variables include energy and raw material requirements for the production and transportation of chemicals and the production of machinery.

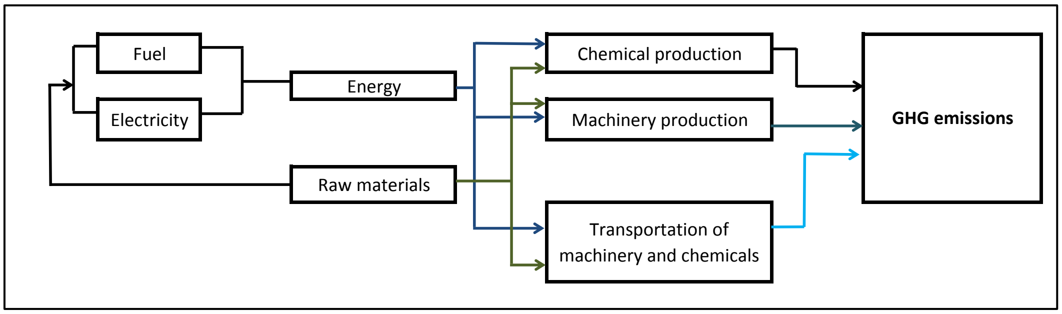


Figure 2. System boundary for the pre-farm stage of the IST

The on-farm stage makes provision for the quantification of GHG emissions from farm machinery operation, stubble burning, enteric and excreta emissions from animal husbandry, direct soil emissions (DSE) and indirect soil emissions (ISE) (Figure 3). DSE include CO_2 from urea hydrolysis, CO_2 from liming, N_2O from fertiliser and CH_4 from the soil. ISE include the N-emissions from leaching and runoff that are quantised as N_2O (N_2O-N), and emissions from NH_3 volatilisation, quantised as N_2O (N_2O-N) (IPCC, 2007).

3. Methods and results

In the following section each of the components of the methodology are outlined separately, however it should be remembered throughout that these components should not be considered separate from each other as the process is an interactive process.

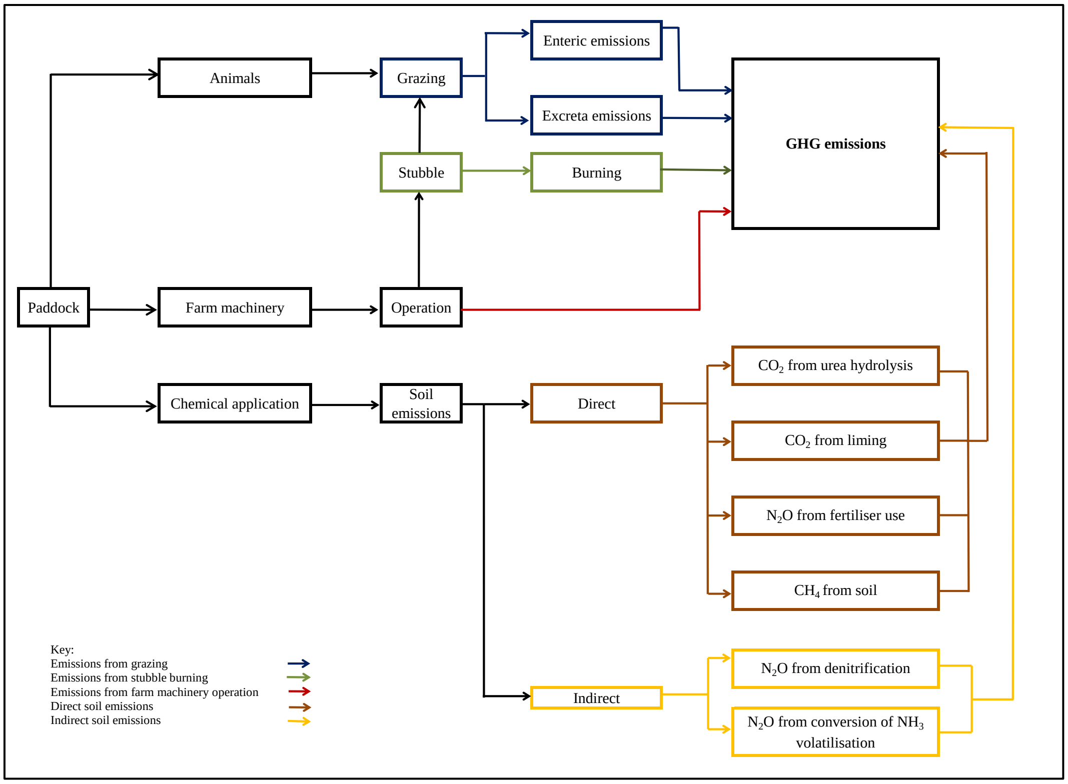


Figure 3. System boundary for the on-farm stage of the IST

3.1 Data Collection

Data collected by DAFWA using questionnaires were supplied from a current crop sequencing project which comprised of 188 paddocks throughout the wheatbelt area of south-western Australia (pers. comm., Harries, DAFWA, Geraldton, Western Australia), from which 24 paddocks were selected for this project. For ground-truthing purposes and to gather additional data (not covered by the DAFWA questionnaire) a site visit to the paddocks was conducted with each farmer. A questionnaire was used to collect additional data, such as the farming practices used, the soil types and climatic conditions. The paddock selected for this article was located in the Liebe Grower Group area close to Dalwallinu, Western Australia. The grain grown in 2010 was wheat and in 2011 it was barley.

3.2 Life cycle assessment

The functional unit was selected as the production of one tonne of grain and the scope was limited to only include the pre-farm and on-farm stages. Thereafter all data collected were uploaded into Microsoft Excel spreadsheets for the development of the LCI (Tables 1−3). The LCI emissions factors were extracted from the Australian LCA database, where available (RMIT, 2007). Emissions factors for chemicals were not always available and thus all chemicals were converted to a generic chemical within the same classification unit (e.g. herbicide, fungicide, adjuvant) to enable calculation of the GHGs from the production of chemicals. The Australian LCA database was used to calculate the transportation of inputs, based on 30 t articulated trucks, ships and 1 t utility vehicles (RMIT, 2004). The manufacture of farm machinery was estimated using the USA input/output database and the price of current farm machinery deflated to the 1998 price (Barton et al., 2014; Suh, 2004). Soil emissions were quantified using recommended emissions factors and calculations from the National Greenhouse Gas Inventory (NGGI, 2006) and the Intergovernmental Panel on Climate Change (IPCC, 2006).

Table 1. Inventory list for the production and transportation of chemicals of the selected paddock for 2010−2011.

Farm B- Paddock number 4			2010	2011	2010	2011
Chemical Inputs						
Classification	Chemical Name	Units	Chemical production		Chemical transportation	
Fertilisers	K Till Extra	kg/yr/t	4.37E+01		1.07E+01	
	Urea	kg/yr/t	6.31E+01		6.50E+02	
Fungicides and insecticides	Alpha Duo	kg/yr/t				
	Alphasip Duo	kg/yr/t	4.51E-02		1.18E-02	
	Lemat L	kg/yr/t	6.12E-01		8.90E+00	
	Premis	kg/yr/t	9.71E-03		4.50E-02	
Herbicides	Bromicide	kg/yr/t		1.25E-01		3.07E-02
	Ester 800	kg/yr/t	2.37E-01		5.83E-02	
	Gladiator	kg/yr/t	5.83E-01		1.43E-01	
	Roundup	kg/yr/t	5.70E-01		1.40E-01	
	Select	kg/yr/t		1.69E-01		4.15E-02
	Sprayseed	kg/yr/t		4.16E-02		1.02E-02
	Tigrex	kg/yr/t		7.08E-03		1.74E-03
	Triflurx	kg/yr/t	6.34E-01		1.56E-01	
	Velocity	kg/yr/t	2.43E-01		1.13E+00	
Lime		kg/yr/t	4.85E+01	3.56E+01	1.32E+01	9.69E+00

Table 2. Inventory list for the production and use of farm machineryof the selected paddock for 2010−2011.

Farm B-Paddock 4			2010	2011
Emissions from production and use of farm machinery based on 1998 prices				
		Units		
Seeding	Cost of seeding machinery	USD/t	1.74E+00	1.27E+00
	Fuel Use	l/hr/t	2.02E+00	1.48E+00
Spraying	Cost of spraying machinery	USD/t	7.96E-01	2.33E-01
	Fuel Use	l/hr/t	8.09E-01	2.37E-01
Top dressing -fertiliser	Cost of top dressing machinery	USD/t	1.45E+00	1.07E+00
	Fuel Use	l/hr/t	2.14E-01	1.57E-01
Top dressing -lime	Cost of top dressing machinery	USD/t	5.24E-01	3.84E-01
	Fuel Use	l/hr/t	7.69E-02	5.63E-02
Harvesting	Cost of harvesting machinery	USD/t	7.27E+00	5.33E+00
	Fuel Use	l/hr/t	2.76E+00	2.02E+00

Table 3. Inventory list for direct and indirect soil emissions of the selected paddock for 2010−2011.

Farm B		2010	2011
Soil Emissions	Paddock number	4	4
N_2O direct from fertiliser use	kg/yr/t	3.34E-02	-
N_2O indirect (NH_3 from volatilisation converted to N_2O)	kg/yr/t	2.67E-03	-
N_2O indirect (from denitrification)	kg/yr/t	-	-
CO_2 liming	kg/yr/t	5.83E+00	4.27E+00
CO_2 urea hydrolysis	kg/yr/t	1.26E+01	-

Following the LCI the carbon footprint was calculated as carbon dioxide equivalents (CO_2-e) as presented in Tables 4−5. In calculating the carbon footprint the GHGs were converted from individual gases (CO_2, N_2O and CH_4) to CO_2-e by multiplying with the respective global warming potential (1, 298 and 25 for CO_2, N_2O and CH4, respectively) (IPCC, 2007). The final carbon footprint was the sum of these individual results.

Tables 4 and 5 specify the total GHG emissions as kg CO_2-e/t for each of the pre-farm and on-farm stages for each year as well as the overall total for the year. It is clear from these tables that the pre-farm stage of 2010 was the highest GHG emitter and subsequently the total GHG emissions for 2010 were the highest. The 'hotspot' analysis shows that the production of fertilisers in 2010 was the hotspot, followed by DSE, due mainly to the hydrolysis of urea.

Table 4. Carbon footprint for the pre-farm stage of the selected paddock, 2010-2011

Farm B – Paddock 4		Pre-farm (kg CO_2-e)								
		Chemical production					Farm machinery production	Transportation of fertilisers	Transportation of chemicals	Sub-total
Description	Units	Fertilisers	Fungicides and pesticides	Herbicides	Adjuvant	Lime				
2010	kg CO_2-e/t	2.22E+02	2.21E-03	4.70E+01	-	8.20E-01	1.09E+01	1.26E+01	3.22E+00	2.97E+02
2011	kg CO_2-e/t	-	-	1.27E+01	-	6.01E-01	7.66E+00	-	1.03E+00	2.20E+01

Table 5. Carbon footprint for the on-farm stage of the selected paddock, 2010-2011

Farm B –Paddock 4		On-farm (kg CO_2-e)											Total
		Farm machinery operation	Stubble	Grazing		Direct soil emissions				Indirect soil emissions		Sub-total	
Description	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	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
2011	kg CO_2-e/t	1.02E+01	-	-	-	-	1.57E+01	0.00E+00	-	-	-	2.59E+01	4.78E+01

3.3 Remote sensing and geographical information systems

During the pre-processing of the RS imagery, radiometric and geometric errors were removed to enable the digital processing and integration of the RS image with GIS (Lillesand et al., 2004; Mather, 2006). The RS stage of the IST was initiated after the pre-processing of the image using the outline in Figure 4. In this case, the data were pre-processed in ERDAS Imagine software for atmospheric path correction (radiometric correction), stretching or colour enhancement and image rectification and registration, and thereafter classified.

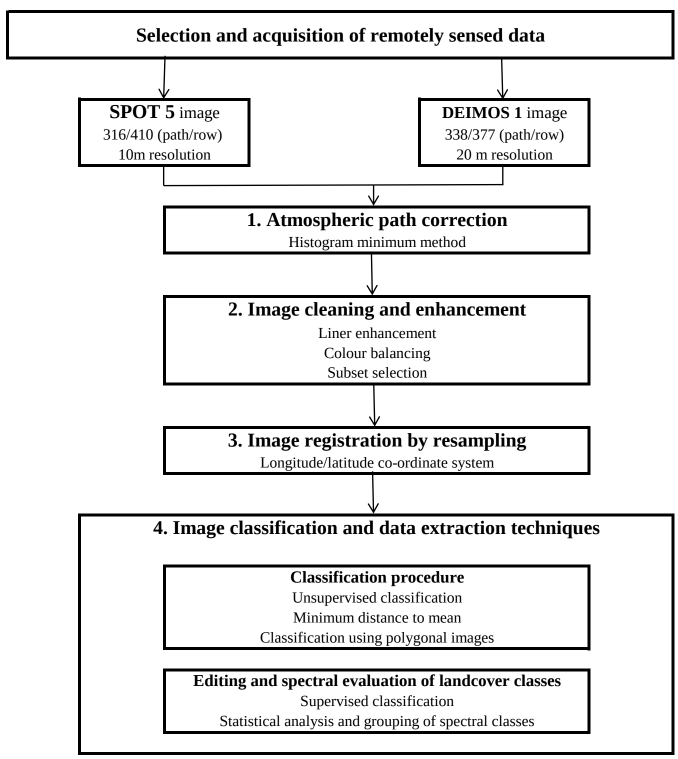


Figure 4. Pre-processing of satellite imagery

After the pre-processing of the satellite image (Figure 5) it was uploaded into the GIS. The co-ordinates of the paddocks were registered on the satellite image (black dots), the paddocks numbered (yellow) and then outlined in the GIS (black polygon). The IST used farming system data of paddock 4 as shown in Figure 5. This image may be used to identify the shape of the paddock, analyse underlying soil health, identify drainage areas and investigate crop yield, crop density and crop type. The red colour in the satellite imagery represents vegetation, with the changes in intensity due to variations in the infrared light reflected by each plant species, or from one plant specimen in different stages of growth. 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).

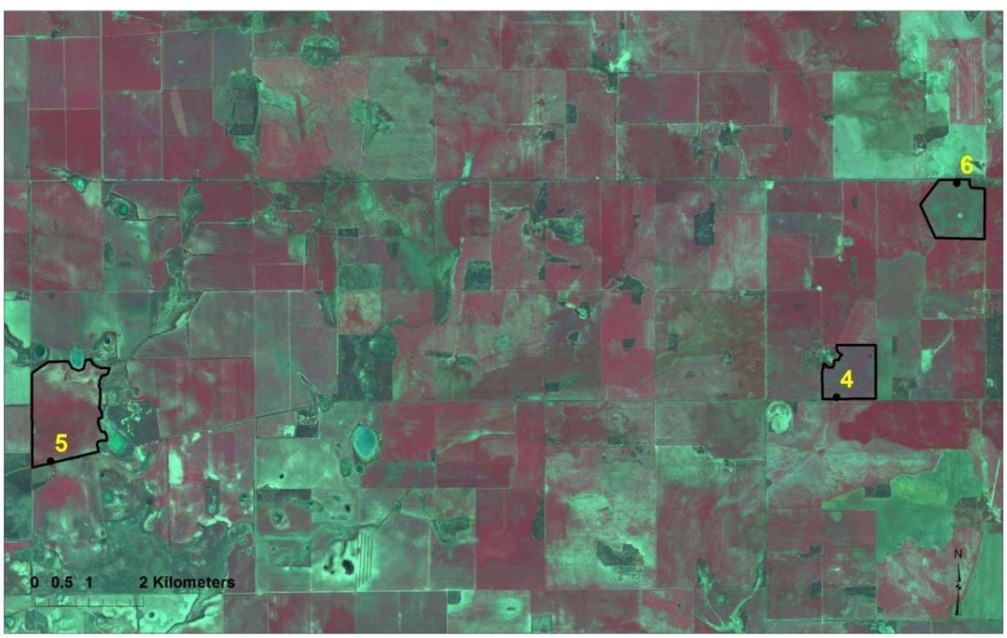
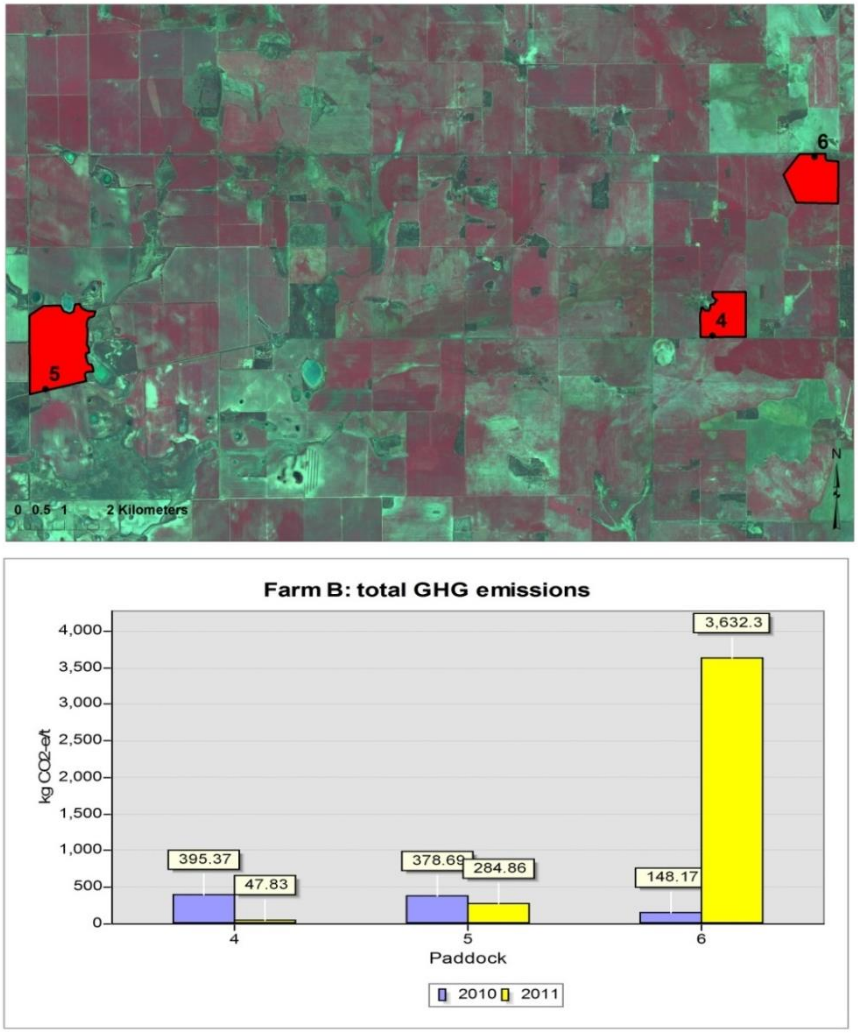


Figure 5. Satellite image (September 2012) of the area in which paddock 4 is found

3.4 Image generation using the integrated spatial technology

Following the registration and paddock identification using RS in GIS, the carbon footprint results were uploaded from Microsoft Excel into the GIS application (ArcGIS/ArcMap). The variables required were then selected and an image incorporating the LCA results and the RS images was generated in the GIS. An example of an image that may be generated using the IST is illustrated in Figure 6. This image however, includes the results of all the paddocks on this farm. It can be seen from Figure 6 that the GHG emissions on paddock 4 totalled 395.4 kg CO_2-e in 2010 and 47.8 kg CO_2-e in 2011.



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. Example of image that may be generated using the IST

Using the IST, two more images were generated (Figure 7 and Figure 8). Figure 7 is a comparative analysis of the GHGs from both the pre-farm and on-farm stages for 2010 and 2011 and shows that the pre-farm stage of 2010 emitted the most GHGs (295.7 kg CO2-e) over the period investigated.

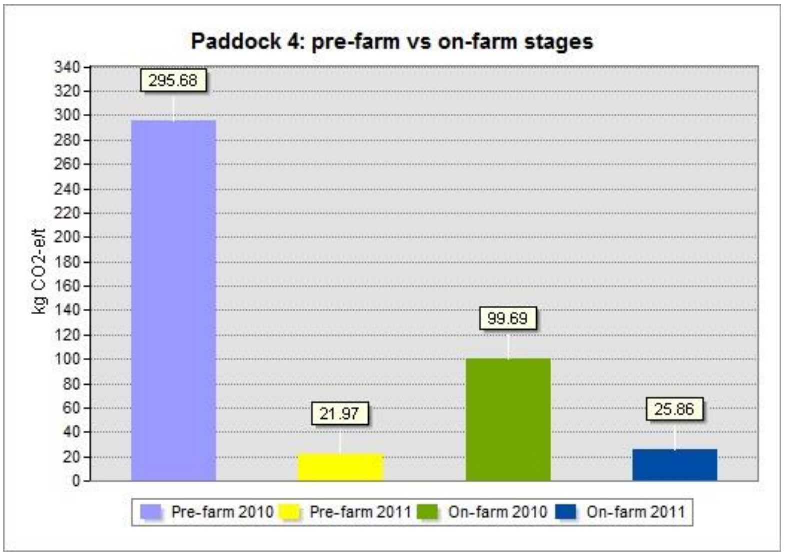


Figure 7. Extraction from IST imagery showing the pre-farm and on-farm stages for 2010 and 2011.

To ascertain the exact input category generating the most emissions in the pre-farm stage of 2010, Figure 8 was created. Figure 8 shows that the production of fertiliser (of the fertilisers applied to the paddock) in 2010, generating 56.2% of the paddock emissions for 2010 and 75.2 % of the pre-farm stage emissions, was the hotspot. In defining the hotspot further the LCI tables were considered and it was determined that two fertilisers were used in 2010, namely K-Till Extra (10% N) and urea (46% N) (Table 1), emitting a total 2.22 x 10^2 kg CO_2-e/t.

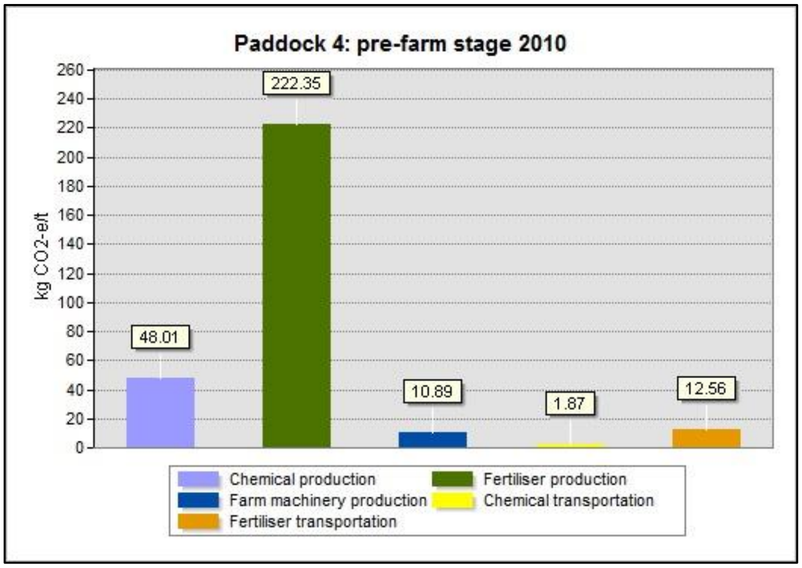


Figure 8. Extraction from IST showing the hotspot for paddock 4 in 2010 during the pre-farm stage.

3.5 Mitigation using cleaner production strategies

The final step of the IST is the identification of CP strategies that could be employed to mitigate the GHGs from the hotspot. The CP strategies considered for mitigation purposes on this paddock were input substitution and good housekeeping, focusing on reducing GHG emissions from fertiliser production (Table 4) and subsequently DSE (Table 5), the second highest hotspot.

3.5.1 Input substitution

In the first instance K-Till Extra (9% N, 11% P) was replaced with MaxamRite (12.8% N, 17.7% P), a fertiliser with a similar nitrogen (N) content. The replacement of one fertiliser with another 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. As K-Till Extra has a potassium (K) content of 11.2% and MaxamRite contains no K, the soil test results were consulted. The test results measured104 mg K/kg, and thus substitution with MaxamRite is not expected to cause K deficiency. For cereal crops, soil available K levels should not fall below 45-50 mg K/kg soil and 70 mg K/kg is considered optimal (Department of Agriculture, 2015) and for legumes 50−80 mg K/kg soil (Quinlan & Wherrett, 2015). After replacing K-Till Extra with MaxamRite the paddock showed a reduction in GHG emissions. MaxamRite produced 1.09 x 10^2 kg CO_2-e/t compared to 1.69 x 10^2 kg CO_2-e/t from K-Till Extra using the calculated 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%.

3.5.2 Good housekeeping

In the next instance the focus was on reducing the DSE using a good housekeeping CP strategy. As urea generated the most GHGs an alternative was sought focusing on this fertiliser. An alternative that was identified was to use a legume in a crop rotation sequence, in which legumes were grown prior to the year under investigation (Barton et al., 2014; Khakbazan et al., 2009). As no data were available for the 2009 growing season an assumption was made that legumes were grown in paddock 4 in 2009, followed by wheat in 2010. On average it has been found that legumes fix about 100 kg N/ha/yr, thereby reducing the N-fertiliser application requirement by 40–80 kg N/ha/yr (GRDC, 2014c). In 2010 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 assumed to be fixed in the soil through legume growth. The paddock emissions were thus reduced by 21.5% and the DSE output category reduced by 49.8%.

To calculate the residual N allocation 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).

$$Allocation\ factor = \frac{Nfert_{saved}}{Lupin\ N_{AG} + Lupin\ N_{BG}} \qquad \textbf{Equation 7.1}$$

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 Barton et al. (2014) as this study was conducted in south-western Australia.

4 Application of the IST in real world situations

As stated by Towie (2013) various options exist for the use of the IST in the agricultural cycle and this article highlighted the use and acquisition of chemicals (including fertilisers) and how these contribute to GHG emissions through production, dosage control, the substitution of one chemical with another and the transportation of the chemicals. Further factors highlighted in this study were the GHG emissions from the use of farm machinery due to production costs and the combustion of fuel, the GHG emissions from animal husbandry and stubble burning and how these could be reduced or eliminated by altering or adapting other farm management practices (Engelbrecht, 2015).

Relevant organisations, such as DAFWA in this case, could use this IST to maintain up-to-date records of the carbon footprints of selected cropping practices on farms in the agricultural region of south-western Australia. Research organisations could calculate carbon footprints for various agricultural systems and applications and national organisations could integrate the IST into policy-making strategies. Finally, the IST could encourage the user to develop more informed, robust and region-specific decision-making mitigation strategies (Towie, 2013).

5 Limitations and recommendations

As the acquisition of high quality satellite imagery is costly and problematic, and the pre-processing limited to the availability of RS applications, the identification of the study area could be problematic and thus alternative means of obtaining satellite imagery, such as Google Earth, needs to be explored

The development of an LCI is a time-consuming task, especially if data records are incomplete. To reduce the time for data collection the farmers should be encouraged to maintain comprehensive records. This will eliminate the need for assumptions.

Currently in Australia the emissions factor database for chemical production is incomplete. To calculate more accurate results for each chemical, a local emissions factor database needs to be developed based on actual fieldwork research.

The IST was developed for Western Australian grain growers, it should however, be extended for use in other farming regions, cropping systems, pasture and grazing systems and horticultural enterprises.

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 usage 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 further enhanced 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 establishing to allocate GHG emissions to co-products.

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 conditions and future farm planning. It is therefore recommended that the IST be used to calculate the GHG emissions on, for example, a five year future based scenario taking the previous years into consideration and then plan accordingly.

Automation of the transferral of data from the LCA to the GIS, although conceptually sound, has not been completed. Development of algorithms and an interface allowing for this transferral should be developed.

6 Conclusions

Different methodologies have been developed and have been included in the CFI which mostly focus on mitigating GHGs in a few farming systems. No methodology was available for the farmer to quickly and easily establish the level of GHGs or test alternative strategies. Based on this shortcoming the IST was researched and developed to enable the farmer to ascertain the GHG emissions per farm or paddock, prior to, during or after the questioned farming cycle.

This article presented the concept the IST which can be successfully applied to calculate GHG emissions for grain growers in Western Australia. However further development is required for the IST to be automated in the transferral of the LCA data tables into the GIS. Finally, it is envisaged that the IST 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.

Acknowledgements

I would like to thank all the staff concerned at DAFWA, the WANTFA and Liebe grower groups, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the provision of the satellite imagery and to the Australian Government for the Australian Postgraduate Award (APA) and Curtin University for the top-up award.

References

Anderson, G. (2009). *The impact of tillage practices and crop residue (stubble) retention in the cropping system of Western Australia*. (Bulletin 4786). The Department of Agriculture and Food of Western Australia.

Australian Government. (2013). About Australia. Retrieved from. http://australia.gov.au/about-australia/our-government/state-and-territory-government

Barton, L., Thamo, T., Engelbrecht, D., & Biswas, W.K. (2014). Does growing grain legumes or applying lime cost effectively lower greenhouse gas emissions from wheat production in a semi-arid climate? *Journal of Cleaner Production, 83*, 194-203.

Bharathkumar, L., & Mohammed-Aslam, M.A. (2015). Crop Pattern Mapping of Tumkur Taluk using NDVI Technique: A Remote Sensing and GIS Approach. *Aquatic Procedia, 4*, 1397-1404.

Biswas, W.K., Graham, J., Kelly, K., & John, M.B. (2010). Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia. A Life Cycle Assessment. *Journal of Cleaner Production, 18*, 1386-1392.

Biswas, W.K., John, M.B., Batt, P.J., & Noonan, J.B. (2011). Chapter 6: Environmental supply chain management in Australian grain industries: A life cycle assessment approach. In M.A. Quaddas & M.A.B. Siddique (Eds.), *Handbook of corporate sustainability: Frameworks, strategies and tools* (pp. 93-112). United Kingdom: Edgar Elgar Publishers Ltd.

Carbon Farming Initiative (CFI). (2012). The carbon farming initiative handbook. Department of Climate Change and Energy Efficiency, Commonwealth of Australia. Retrieved from www.cleanenergyfuture.gov.au

Cavalli, R.M., Laneve, G., Fusilli, L., Pignatti, S., & Santini, F. (2009). Lake Victoria weed management. *Journal of Environmental Management, 90*, 2199-2211.

Clean Energy Regulator (CER). (2014). Clean energy regulator. Retrieved from www.cleanenergyregulator.gov.au/About-

Curran, M.A. (2006). *Life cycle assessment: Principles and practice*. EPA/600/R-06/060. Reston, VA: Scientific Applications International Corporations.

Dictionary.com (2014). Paddock. Retrieved from http://dictionary.reference.com/browse/paddock

Darwin, R. (2004). Effects of greenhouse gas emissions on world agriculture, food consumption, and economic welfare. *Climatic Change, 66*, 191-238.

Emissions Reduction Fund (ERF). (2014). Emissions reduction fund. Retrieved from www.environment.gov.au/climate-change/emissions-reduction-fund

Environmental Systems Research Institute (ESRI). (2014). What is GIS? Retrieved from www.esri.com/what-is-gis

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.

Engelbrecht, D. (2015). Integrated Spatial Technology Framework for Greenhouse Gas Mitigation in Grain Production in Western Australia. Unpublished PhD thesis. School of Civil and Mechanical Engineering, Curtin University, Perth, Australia.

Engelbrecht, D., Biswas, W., Pritchard, D. & Ahmad, W. (2015). A new tool for calculating the carbon footprint of WA farms. 2015 Agribusiness crop updates. CROWN, Perth. 24th - 25th February, 2015.

Finkbeiner, M., Tan, R., Raimbault, M., (2011). Life cycle assessment (ISO 14040/44) as basis for environmental declarations and carbon footprint of products, ISO Technical Committee 207 Workshop, Oslo.

Food and Agriculture Organization of the United Nations (FAO). (2014). *Agri-environmental statistics*. Retrieved from www.fao.org/statistics/en/

Food and Agriculture Organization of the United Nations (FAO), International Fund for Agriculture Development (IFAD), & United Nations World Food Programme (WFP). (2015). *The state of food insecurity in the world 2015. Meeting the 2015 international hunger targets: Taking stock of uneven progress*. Rome: FAO.

Garnaut, R. (2008). *The Garnaut climate change review*. Retrieved from http://www.garnautreview.org.au/2008-review.html.

Goel, P.K., Prasher, S.O., Landry, J.A., Patel, R.M., Bonnell, R.B., Viau, A.A., & Miller, J.R. (2003). Potential of airborne hyperspectral remote sensing to detect nitrogen deficiency and weed infestation in corn. *Computers and Electronics in Agriculture, 38,* 99-124.

Grant T., & Beer, T. (2008). Life cycle assessment of greenhouse gas emissions from irrigated maize and their significance in the value chain. *Australian Journal of Experimental Agriculture, 48*, 375-381.

Grains Research and Development Corporation (GRDC). (2011). *Stubble management fact sheet*. Retrieved from www.grdc.com.au/uploads/.../GRDC_FS_StubbleManagement.pdf.

Huang, H., von Lampe, M., & van Tongeren, F. (2011). Climate change and trade in agriculture. *Food, Policy 36*, S9-S13.

Huang, J., & Wang, Y. (2014) Financing sustainable agriculture under climate change. *Journal of Integrative Agriculture, 13*(4), 698-712.

Intergovernmental Panel on Climate Change (IPCC). (2006). Emission factor database. Retrieved from http://www.ipcc-nggip.iges.or.jp/EFDB/main.php

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: Working Group I: The physical science basis. Concept of radiative forcing. Retrieved from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-2.html

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. Geneva, Switzerland: IPCC.

International Organization of Standardization (ISO). (2006). Environmental management. life cycle assessment. Requirements and guidelines. *ISO 14044:2006*. Geneva, Switzerland: International Organization of Standardization.

Lee, D.R., Edmeades, S., De Nys, E., McDonald, A., & Janssen, W. (2014). Developing local adaptation strategies for climate change in agriculture: A priority-setting approach with application to Latin America. *Global Environmental Change, 29,* 78-91.

Lillesand, M., Kiefer, R., & Chipman, J. (2004). *Remote sensing and image interpretation* (5th ed.). USA: John Wiley and Sons.

Mather, P.L. (2006). *Computer processing of remotely-sensed images, An introduction.* England: John Wiley and Sons.

Meisterling, K., Samaras, C., & Schweizer, V. (2009). Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. *Journal of Cleaner Production, 17*, 222-230.

Mo, X., Liu, S., Lin, Z., Xu, Y., Xiang, Y., & McVicar, T.R. 2005. Prediction of crop yield, water consumption and water use efficiency with a SVAT-crop growth model using remotely sensed data on the North China Plain. *Ecological Modelling, 183*, 301-322.

Mulder, V.L., de Bruin, S., Schaepman, M.E., & Mayr, T.R. (2011). The use of remote sensing in soil and terrain mapping – A review. *Geoderma, 162,* 1-19.

Mulla, D.J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Systems Engineering, 114*, 358-371.

National Aeronautics and Space Administration (NASA). (2014a). Atmosphere layers. Retrieved from http://airs.jpl.nasa.gov/maps/satellite_feed/atmosphere_layers/

National Greenhouse Gas Inventory (NGGI) Committee. (2006). Australian methodology for the estimation of greenhouse gas emissions and sinks. Agriculture. Department of Climate Change. Retrieved from www.climatechange.gov.au/inventory

National Greenhouse Gas Inventory (NGGI). 2013. Australian national greenhouse accounts. Quarterly update of Australia's national greenhouse gas inventory, September quarter 2013. Department of Climate Change and Energy Efficiency. Retrieved from www.climatechange.gov.au

National Greenhouse Gas Inventory (NGGI). (2010). *National Greenhouse Gas Inventory accounting for the Kyoto target December quarter 2010*. Canberra: Department of Climate Change and Energy Efficiency.

Navarro, J., Bryan, B., Marinoni O., Eady, S., & Halog, A. (2013). Production of a map of greenhouse gas emissions and energy use from Australian agriculture. *20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013*. Retrieved from www.mssanz.org.au/modsim

Nigon, T.J., Mulla, D.J., Rosen, C.J., Cohen, Y., Alchanatis, V., Knight, J., & Rud, R. (2015). Hyperspectral aerial imagery for detecting nitrogen stress in two potato cultivars. *Computers and Electronics in Agriculture, 112*, 36-46.

Northern Territory Government (NTGov). 2015. What is conservation farming? Retrieved from www.nt.gov.au/d/Content/File/p/Tech_Bull/STB2_Chapters3_4.pdf

Oikonomidis, D., Dimogianni, S., Kazakis, N., & Voudouris, K. (2015). A GIS/remote sensing-based methodology for groundwater potentiality assessment in Tirnavos area, Greece. *Journal of Hydrology 525*, 197-208.

Peña-Barragán, J.M., Ngugi, M.K., Plant, R.E., & Six, J. 2011. Object-based crop identification using multiple vegetation indices, textural features and crop phenology. *Remote Sensing of Environment*, *115*, 1301-1316.

Royal Melbourne Institute of Technology (RMIT). (2007). Australian LCA Database 2007. Centre for Design, Royal Melbourne Institute of Technology, Melbourne, Australia.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., & Sirotenko, O. (2007). Agriculture. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, & L.A. Meyer (Eds.),*Climate change 2007: Mitigation. Contribution of Working Group III to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Suh, S., 2004. *Material and energy flows in industry and ecosystem network*. Centre for Environmental Science, University of Leiden, The Netherlands.

The Shift Project (TSP). (2015). *Top 20 emitters by sector*. Retrieved from www.tsp-data-portal.org/TOP-20-emitter-by-sector#tspQvChart.

Thomassen, M.A., van Calker, K.J., Smits, M.C.J., Iepema, G.L., & de Boer, I.J.M., (2008). Life cycle assessment of conventional and organic milk production in the Netherlands. *Agricultural Systems 96*, 95-107.

Tilling, A.K., O'Leary, G.J., Ferwerda, J.G., Jones, S.D., Fitzgerald, G.J., Rodriguez, D., & Belford, R. (2007). Remote sensing of nitrogen and water stress in wheat. *Field Crops Research, 104*, 77-85.

Towie, N. (2013). *Software zeros in on carbon pollution*. Retrieved from www.sciencewa.net.au/topics/agriculture/item/2296-software-zeros-in-on-carbon-pollution.html.

Vermeulen, S.J., Aggarwal, P.K., Ainslie, A., Angelone, C., Campbell, B.M., Challinor, A.J., Hansen, J.W., Ingram, J.S.I., Jarvis, A., Kristjanson, P., Lau, C., Nelson, G.C., Thornton, P.K., & Wollenberg, E. (2012). Options for support to agriculture and food security under climate change. *Environmental Science & Policy, 15*, 136-144.

Van Berkel, R. (2007). Cleaner production and eco-efficiency initiatives in Western Australia 1996–2004*, Journal of Cleaner Production 15*, 741-755.