Title

Mapping the spatial and temporal stability of production in mixed farming systems: an index that integrates crop and pasture productivity to assist in the management of variability.

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Conflicts of Interest: The authors declare no conflict of interest

Acknowledgements

The authors wish to thank Mr. Murray Hall ("Milroy") and Mr. Adam Inchbold ("Grandview") for allowing this study to be conducted on their properties and for their technical input. We also wish to thank Mr. Simon McDonald from Charles Sturt University Thurgoona for his statistical advice and Ms. Deanna Duffy for assistance with ArcGIS.

Funding: This work was supported by the Australian Grains Research and Development Corporation through a Grains Research Scholarship (GRDC Project No 10042).

Abstract

While precision agriculture (PA) technologies are widely used in cropping systems, these technologies have received less attention in mixed farming systems. Little is known about the nature, extent, and temporal stability of spatial variability of pastures in mixed farming systems and the feasibility of managing this variability. This paper describes a technique to create a Stability Index based on both crop grain yield and pasture total green dry matter (TGDM) production over time, using high resolution spatial data in two climatic zones of Australia. Four productivity zones were used to characterise the stability index: high and stable, high and unstable, low and stable, and low and unstable. Mapping the indices shows the location and size of the spatial and temporal features of each paddock. The features of the stability zones generally corresponded with soil texture classes. Testing the Stability Indices with a Kruskal-Wallis one-way ANOVA showed significantly different medians for high and low production categories for both grain yield and pasture TGDM ($p < 0.01$). Crop grain yield stability showed significant differences between medians. In pasture TGDM, the differences between stability medians were not significant, but the technique still separated medians into stable and unstable groupings. This production Stability Index has the potential to be used by farmers to manage spatial variability in mixed farming systems by identifying homogenous areas within a paddock for investigation / amelioration and can also separate out areas of either spatial and/or temporal instability for specific management strategies.

Key words

Stability Index, Spatial and temporal variability, Mixed farming systems, Crop-livestock integration, Precision agriculture, Management zones.

Introduction

Mixed farming systems that combine grain cropping and pasture-based livestock enterprises dominate the dryland farming regions of Australia. In southern Australia, the mixed farming zone lies between the 300 and 600 mm average annual rainfall isohyets and is highly seasonal, encompassing climates with cool, wet winters and hot, dry summers. The combination of highly variable rainfall and volatile commodity prices faced by Australian farmers in these regions has favoured a diversified farming system that moderates the risks to the farm enterprise (Bell and Moore 2011). While precision agriculture (PA) technologies are widely used in Australian cropping systems, their use as a whole-of-farm management strategy in mixed farming systems has received far less attention. There are few published reports of attempts to use spatial monitoring technologies to investigate livestock and pasture interactions in the pasture phase and to follow the after-effects of different management strategies into a subsequent cropping phase. Relatively little is known about the nature, extent, or temporal stability in relation to spatial variability of pasture production in mixed farming systems, whether it is feasible to manage this variability in a site-specific way and therefore, to integrate it into a precision management system across crop and pasture sequences. For the most part paddocks tend to be managed as single units during pasture phases, ignoring the existence of productivity gradients across the landscape (Hill et al. 1999). Given that, in a typical Australian mixed farming system, somewhere between 20 and 50% of the farm area is in pasture at any time (Angus and Peoples 2013; Bell et al. 2014b; Ewing and Flugge 2004; Li et al. 2010), this is an aspect of precision farming technology that has not been previously explored to any extent. A significant amount of on-farm high-resolution data has been gathered and is available for analysis of within-paddock spatial variability of yield in cropping phases in the form of geo-referenced yield monitor data, soil analytical data (Oliver and Robertson 2009; Simeoni et al. 2009; Sudduth et al. 2010; Sudduth et al. 2009), proximal soil sensors (Pullanagari et al. 2012; Schirrmann et al. 2011; Serrano et al. 2010; Sun et al. 2012) or combinations of these (Castrignanò et al. 2012; Wong et al. 2010). The most common approach to managing spatial variability in crops is to use this data to define 'management zones' in a system known as 'site-specific management' (SSM) (Plant 2001; Taylor et al. 2007; Whelan and McBratney 2003). SSM aims to better quantify and delineate the causes of yield variability between different parts of a paddock (Buttafuoco et al. 2010; Farid et al. 2016; Moral et al. 2010). However, there is little information about the nature of spatial variability in pasture biomass production from these same paddocks when in a pasture phase. This presents a significant lost opportunity given that pasture phases can last from between one or two years (annual pastures) to between three and six years (perennial pastures) (Bell et al. 2014a; Kirkegaard et al. 2014; Nichols et al. 2007). By and large, pasture–livestock phases are 'low-input', where livestock and the pastures they graze are managed less intensively than crops (Bell et al. 2014a; Kirkegaard et al. 2011). Several approaches have been used in the past to identify regions of temporal stability in crops (Blackmore 2000, 2003; Diacono et al. 2012; Dobermann et al. 2003; Marques da Silva 2006); and in pastures (Marques da Silva et al. 2008; Serrano et al. 2014; Schmer et al. 2009; Serrano et al. 2011; Xu et al. 2006). The assessment of temporal stability is important because it affects the reliability of management zones as a strategy for differential management in crop and pasture phases.

The objectives of this research were:

1. To determine a methodology by which NDVI can be calibrated to estimate pasture biomass to characterise spatial variability of production in the pasture phase of mixed farming systems;

2. To compare within-paddock spatial variation in crop grain yield and pasture biomass production in two mixed farming systems; and
3. To create a single map of spatial variation of crop yield and pasture biomass production at a point, across a paddock, a "Stability Index", to assist decision making by farm owners and managers in implementing site-specific management strategies in a sequence of grazed pasture and cropping phases.

It was hypothesised that spatial variation of production in both the crop and pasture phases of a mixed farming system could be identified and quantified at high resolution using PA technologies and that the data so acquired could be used to create a single index of productivity that described the spatial variation in, and temporal stability of, both crop grain and pasture biomass yields within a paddock over time.

Materials and Methods

Study sites

Two properties were used for the study: "Milroy", a 1900 ha sheep and cropping enterprise located at Brookton (32.22°S, 116.57°E), 120 km east of Perth, Western Australia (WA) and "Grandview", a 2250 ha cattle and cropping enterprise located 10 km south of Yarrawonga (36.05°S, 145.60°E) in north-eastern Victoria (Fig. 1). Wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.) are the main crops grown on both properties. Pastures on "Milroy" are dominated by subterranean clover (*Trifolium subterraneum* L.) and capeweed (*Arctotheca calendula* L.) with some serradella (*Ornithopus sativus* Brot.), barley grass (*Hordeum glaucum* Steud.) and annual ryegrass (*Lolium rigidum* Gaud.). After a continuous cropping rotation of four years or more, (eg canola, wheat, wheat, barley), pastures at "Milroy" are re-sown. Where pasture phases occur in between crops (eg wheat, pasture, wheat, pasture, wheat), pastures are self-sown.

At "Grandview", the crop and pasture phases are each of six years' duration. Pastures comprise lucerne (*Medicago sativa* L.), subterranean clover and chicory (*Chicorium intybus* L.), and are established by under-sowing with the crop in the last cropping year. Crop yield and pasture biomass data was collected from three paddocks on each property between 2004 and 2014. Here data is presented for one representative paddock from each property: paddock M41 at "Milroy" (2008-2014) and paddock GV39 at "Grandview" (2007-2013). Pasture and crop rotations and paddock sizes for both study paddocks are described in Table 1. At both properties livestock were set-stocked. The paddock at "Milroy" was stocked with cross-bred lambs at 8 dry sheep equivalent (DSE) / ha in 2012 and 9 DSE / ha in 2013. At "Grandview" the paddock was stocked with Angus feeder steers at an equivalent stocking rate of 10 DSE / ha.

Fig. 1 Location of the two study sites

"Milroy" has a Mediterranean climate with a winter dominant rainfall, whereas "Grandview" has a temperate climate and rainfall pattern. The mean annual rainfall (AR) and growing season rainfall (GSR) at "Milroy" is 437 mm and 357 mm, and at "Grandview" is 539 mm and 359 mm, respectively (Table 2). GSR is defined as total rainfall received between 1 April – 31 October.

Rainfall data from 1970 to 2000 for both properties was extracted from SILO Data Drill Set (https://www.longpaddock.qld.gov.au/silo/datadrill/). The Data Drill accesses grids of data derived by interpolating Australian Bureau of Meteorology records (Jeffrey et al. 2001).

Soil landscapes at "Milroy" (Fig. 2) are highly variable, consisting of Red, Yellow and Brown Chromosols, Ferric Chromosols, Yellow/Brown Sodosols and Bleached-Orthic Tenosols (Isbell 2016), with soil surface textures ranging from sandy loams to sandy gravels. Soils at "Grandview" (Fig. 4) comprise Red-Brown Chromosols, Sodosols and patches of Vertosols (Isbell 2016).

Table 1 Crop/pasture sequences for paddocks used in the study[a]

YEAR	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
"MILROY"Brookton,WA											
M41 (70 ha)	L	B	P	P	**C**	W	P	P	**P**	**P**	**W**
"GRANDVIEW"Yarrawonga,Vic											
GV39 (60 ha)	P	C	W	**C**	**W**	**W**	B	P	**P**	**P**	P

[a] The paddock notation (e.g. M41) is the system used by the farm owners to identify individual paddocks. B = barley, C = canola, L = lupins, W = wheat, P = pasture. Crop yield and pasture TGDM data used for calculating the paddock stability indices are in bold; paddock size is given in the brackets

Table 2 Average monthly rainfall, maximum and minimum temperatures (1970-2000) for "Milroy", Brookton, WA and "Grandview" Yarrawonga, NSW[a]

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
"MILROY"												
Tmax (°C)	34	33	30	26	21	18	16	17	20	24	28	32
Tmin (°C)	16	17	15	12	8	6	5	5	6	8	11	14
Rain (mm)	16	20	16	27	52	80	81	63	42	24	19	11
"GRANDVIEW"												
Tmax (°C)	32	32	28	23	18	14	13	15	18	22	26	30
Tmin (°C)	16	16	13	9	7	4	3	4	6	8	11	14
Rain (mm)	45	32	31	42	58	48	58	59	54	53	41	37

[a] The growing season is defined as the period between 1 April and 31 October. Brookton and Yarrawonga climate data was obtained from the SILO Data Drill data base

Electromagnetic induction surveys

Electromagnetic induction (EMI) surveys were conducted across both paddocks in 2013, whilst they were in a pasture rotation. At "Milroy", EMI measurements were taken using a DUALEM 21S sensor (Dualem Inc, Milton, ON, Canada) using a commercial contractor. The unit was set to measure to a depth of 0.5 m in horizontal dipole mode (ECah) and 1 m in vertical mode (ECav). Data was gathered on 35 m transects at a sampling rate of one reading/sec and a groundspeed of between 15 and 20 km/h, resulting in a sampling density of approximately 60 readings/ha. All data was geo-referenced using a real-time kinematic (RTK) differential correction signal.

At "Grandview" EMI data was again collected by a commercial contractor, using a Geonics EM38-M2 with 0.5 m and 1 m intercoil spacings (Geonics Limited, Mississauga, ON, Canada). The instrument was used in horizontal mode (ECah), giving a conductivity of 0.38 m at 0.5 m coil separation and 0.75 m conductivity at 1 m coil separation. Transect width was 30 m. The horizontal mode was used at the recommendation of the contractor, who has many years of EMI sensing experience in the region. The instrument was calibrated on-site as per instructions outlined in the Geonics EM38-MK2 Ground Conductivity Meter Operating Manual, July 2008. Data was logged using an Allegro CX Field PC (Juniper Systems, Logan, Utah, USA) loaded with Geonics EM38-MK2 software. The data logger was set to acquire and record survey data from the EM38-MK2 system at four readings per second. Output feed and guidance was provided using a Raven 'Cruizer' GPS (Raven Industries, Sioux Falls, South Dakota, USA).

Soil sampling and testing

Soil sampling was conducted across both paddocks in 2013 in conjunction with the EMI scanning, whilst they were in a pasture rotation. This was before the spatial mapping and stability index work had been completed. At both properties, soil sample locations and number of sampling sites were determined by the soil-sensing contractors using a 50 mm hydraulic soil corer to ground-truth the data and support the interpretation of the EMI survey results. Samples were taken at 0-0.1 m, 0.1-0.3 m and 0.3-0.6 m. Additional soil testing was carried out at "Milroy" in 2014 by the farm owner at eight sites chosen by him, within paddock M41 as part of a pre-liming paddock analysis. Samples for these tests were taken between 0 m and 0.5 m, at 0.1 m intervals, using a hydraulic soil coring drill. All soil analyses (N, P, K, S, pH, OC, PBI, Cond, Cu, Fe, Mn, Zn, Ca, Mg, Al, Na, B) were conducted by the CSBP Soil and Plant Analysis Laboratories (Bibra Lake, Western Australia) (www.csbp.com.au/CSBP-Lab).

Crop harvest yield data and yield mapping

Grain yield data was acquired at both properties from harvester mounted yield monitors using differentially corrected real-time kinematic (RTK) GPS systems. Raw yield data was processed using the protocol developed by Taylor et al. (2007) to remove outliers and trim data to practical yield threshold limits. Yield data was then imported into ArcGIS 10.2 (ESRI, Redlands, California) and mapped to a standard 5 m x 5 m grid. The grid was established in ArcGIS 10.2 using the Geospatial Modelling Environment platform (Spatial Ecology, http://www.spatialecology.com) and kept constant throughout the analysis. Data was interpolated to the grid using Vesper 1.62 software (Australian Centre for Precision Agriculture, The University of Sydney, NSW) (Whelan et al. 2001). Block kriging was used with an exponential variogram and a block size of 10 m x 10 m to generate continuous surface maps. Kriging was used as there were insufficient data points to confidently interpolate yield values between sampled areas and to enable data from different times and sources to be compared. General settings were as described in the Vesper 1.62 User Manual (Australian Centre for Precision Agriculture, The University of Sydney, NSW) (Whelan et al. 2001) .

Mapping pasture green herbage mass in pastures

Red (~650 nm) and near-infrared (NIR) (~880 nm) reflectance values for the calculation of pasture vegetation indices (Holland et al. 2004) were acquired using a Crop Circle^{TM} ACS-210 active sensor (Holland Scientific Inc., Lincoln, NE, USA). To map the pasture biomass, the Crop Circle^{TM} sensor head was linked to a Trimble EZ-Guide 250 GPS Lightbar guidance system (Trimble, Sunnyvale, CA, USA) and a Holland Scientific GeoSCOUT 400 series data logger set to record geo-referenced red and NIR outputs at 1 Hz. The Crop Circle^{TM} sensor was vehicle mounted so that its height was approximately 0.9 m above the ground. All Crop Circle^{TM}

data was collected along transects spaced 40 m apart. Speed across the paddocks was approximately 10–15 km/hr. Normalised difference vegetation index (NDVI) values from the transects were trimmed to remove values <0.1 and >0.9. Remaining points were then imported into ArcGIS 10.2 and mapped to the 5 m x 5 m grid. Data was interpolated to the grid using Vesper 1.62 software as previously described. At “Milroy”, Crop Circle^{TM} scans were taken in July, August and September 2012 and in August/ September 2013. At “Grandview”, scans were conducted in August and September 2012 and September/ October 2013.

Collection of pasture samples for calibration of vegetation index

To calibrate the NDVI scans to actual pasture biomass present in the paddock, twenty-five randomly selected pasture samples were taken across each paddock. Multivariate *k*-means clustering (JMP version 12.2; SAS Institute Inc., Cary, NC, 2016), based on the NDVI values from the Crop Circle^{TM} scans, was used to randomly select twenty-five pasture sampling sites in each paddock. The NDVI point values from the pasture scans were divided into five clusters, and five points selected randomly from within each cluster, to give twenty-five sampling points for each paddock. These sites were then imported into ArcGIS 10.2 and mapped as geo-referenced points in the paddock. To locate each sampling point for the calibration cuts, the selected pasture sites were imported into ‘gpMapper’ mapping software (Fairport Farm Software, Perth WA), loaded on a laptop computer and linked to the Trimble EZ-guide 250 GPS. Pasture samples were then taken at these sites in Spring (September / October) of 2012 and 2013 at both properties, when plants were actively growing and pasture canopies were reasonably extensive. At each sample point, the Crop Circle^{TM} unit was used in ‘hand-held’ configuration to measure the NDVI value within a 0.56 m x 0.12 m quadrat. Pasture within the quadrat was harvested to ground level using battery powered shears. The cut pasture samples were subsequently sorted into green and dead herbage mass fractions and legume/grass/herb fractions and oven-dried at 80ºC for 48 hours before weighing, to provide total herbage mass (kg) of total green dry matter (TGDM) per hectare for each sample site. To test the validity of using NDVI rather than an alternative vegetation index, the averaged red and NIR reflectance values acquired from Crop Circle^{TM} scans for each pasture sample site were used to create four different spectral indices; (i) NDVI, (ii) the Soil-Adjusted Vegetation Index, SAVI (Huete 1988), (iii) the Non-Linear Vegetation Index, NLI (Goel and Qin 1994) and (iv) the Modified Non-Linear Vegetation Index, MNLI (Gong et al. 2003). Because of the small sample sizes involved (n=25), the datasets were validated using Leave One Out Cross Validation (LOOCV) in the R statistical package (v. 3.3.3) (R Core Team 2017).

Calculation of TGDM calibration equations

The NDVI value taken at each pasture sampling cut site was regressed against the corresponding TGDM site value from the pasture sample cuts to produce a calibration equation for each paddock in each year of scanning. As the two sites were more than 3000 km apart, and in different climatic zones, it was not valid to combine data into a single calibration equation. The calibration equations were then used to convert NDVI values acquired from the pasture scans to geo-referenced TGDM values. The TGDM values were imported into ArcGIS 10.2 to produce maps showing spatial variation in predicted pasture biomass yield for each paddock.

Calculating the spatial trend of yield

The spatial trend of yield for crops and pastures was determined by standardising the yield data at each grid point over a sequence of yield maps. Standardising the data replaces the units of yield with a percentage that can be used for comparison between crops and pastures, as each point is compared to the paddock average of 100%. The standardised yield was calculated as per Blackmore (2000):

$$s_i = \left(\frac{y_i}{\bar{y}}\right) \times 100 \qquad (1)$$

where s_i is the standardised crop or pasture yield (%) at point *i*; y_i is the interpolated yield at point *i*; and $\bar{y}$ is the mean yield for that year.

The point mean was then calculated over the years of interest, enabling different crops or pasture to be included and compared:

$$\bar{s}_i = \left(\sum_{t=1}^{n} s_{i,t}\right)/n \qquad (2)$$

where $\bar{s}_i$ is the average of s_i, the standardised yield at point *i*, over *n* years.

This standardised yield shows, at any point, in any one year, how the yield differs from the paddock mean (100%). The standardised data were then classified into four yield zones in relation to the relative percentage difference from the paddock mean (100%) using the yield data distribution quartiles to define the four yield classes. The areas for which this value was greater than the paddock mean were classified as ‘high yielding’ (HY, 4th quartile) and ‘above average’ (AA, 3rd quartile); while the areas for which this value was less than the paddock mean were defined as ‘below average’ (BA, 2nd quartile) and ‘low yielding’ (LY, 1st quartile). Yield maps of spatial trend for crop and pasture were then created by averaging the standardised yield at each grid cell over the years being considered (effectively ‘combining’ yield maps) and processing in ArcGIS 10.2. These spatial trend maps show the spatial yield pattern in a paddock over time for both crops and pastures.

Calculating temporal stability

To estimate how stable in time the crop and pasture yields were at “Milroy” and “Grandview”, the coefficient of variation (CV) in yield was calculated at each point in the paddock for which there was a yield value for either grain yield or pasture TGDM, following the procedure developed by Blackmore (2000). The advantage of using CV is that it is unit-less, allowing multiple crops and pastures to be compared with each other.

The CV was calculated from the standardised yield values calculated previously, using the equation from Blackmore (2000):

$$\mathrm{CV}s_i = \frac{\left(\frac{n\sum_{t=1}^{n} s_{i_t}^2 - \left(\sum_{t=1}^{n} s_{i_t}\right)^2}{n(n-1)}\right)^{0.5}}{\bar{s}_i} \times 100 \qquad (3)$$

where CVs_i is the coefficient of variation of the standardised data at point *i*, over *n* years.

Using this equation, the CVs of crop grain yield and pasture TGDM yield were calculated for “Milroy” paddock M41 and “Grandview” paddock GV39, for both cropping and pasture phases for the years with sufficient data (Table 1). Five arbitrary classes were used: 0-10%, 11-20%, 21-30%, 31-40% and >40%. The CV data for crop yields and pasture DM yields were processed in ArcGIS 10.2 to produce maps showing the range of CV values (%) across each paddock for crop grain yield and pasture TGDM yield. The temporal stability maps were then classified into stable yield zones and unstable yield zones when a given temporal CV value (threshold) was adopted to subdivide the two zones.

Mapping spatial and temporal trend

By combining the data behind the spatial trend maps and the temporal stability data, a single representation of each paddock over time and for both crop and pasture–livestock phases was developed by classifying the paddock into four categories based on yield (high or low) and stability (stable or unstable) at a point in time (Table 3). Because yield and stability are not mutually exclusive variables, there were four possible combinations for these two variables: high and stable (HS); high and unstable (HUS); low and stable (LS), and low and unstable (LUS). Crop grain and pasture TGDM yields were considered high if a particular point value was above the mean yield (>100%) and vice versa. The stability of yield at that point was compared to a threshold value - in this case, the mean of the distribution of yield CV values for the paddock - to determine if the yield at that point was stable (< mean CV) or unstable (> mean CV) (Table 4).

The spatial trend and temporal stability categories for the crop and pasture rotations were allocated a numerical code between 1 and 4 based on the class conditions (Table 3) and the concatenate function in Microsoft Excel was then used to combine crop and pasture codes at each point to create an overall stability index for each paddock. Mapping this index shows areas of the paddock that were high and stable (HS) in both crop and pasture yield (ie concatonation gives a "1,1" result), low and stable in both crop and pasture yield (LS - "3,3"), areas that were high and unstable (HUS – "2,2"), and low and unstable (LUS – "4,4"). Because the crop and pasture yields at a point will not always be both high and stable, low and unstable etc, concatenation results in areas that were neither HS, HUS, LS or LUS, in the overall stability map, leaving areas that were uncategorised (e.g. "1,3", "4,2" etc). There were areas of the paddock that remain uncategorised with the SI process, where production could be stable, but high yielding in one phase and low yielding in the other (eg, high and stable in crop, but low yielding and stable in pasture (HS/LS).

Table 3 Stability Index (SI) classes, codes and the conditions for meeting a class

	Condition 1	**Condition 2**	**Code**
High and stable - HS	$\bar{s}_i > 100$	CVs_i $<$ mean CV	1
High and unstable - HUS	$\bar{s}_i > 100$	CVs_i $>$ mean CV	2
Low and stable - LS	$\bar{s}_i < 100$	CVs_i $<$ mean CV	3
Low and unstable - LUS	$\bar{s}_i < 100$	CVs_i $>$ mean CV	4

Table 4 Stability thresholds used in the calculation of stability indices for "Milroy" and "Grandview" paddocks[a]

Property	**Paddock**	**Stability threshold**	
		Crop	**Pasture**
"MILROY"	M41	13%	13%
"GRANDVIEW"	GV39	22%	12%

[a] In each case, the mean value of the distribution of cv values for crop or pasture were used

Using such a large data set (15,000 data points - the "population") in the statistical analysis would almost certainly have led to significant differences between the medians (Meehl 1990; Waller 2004; Ziliak and McCloskey 2008), so a representative sample of the data set was used instead for hypothesis testing. The number of points generated was proportional to the area of each stability class, with the smallest class within a paddock always having a minimum of 30 points. These randomised points were generated in ArcGIS 10.2 across all four stability classes in each paddock. Crop and pasture TGDM and CV values for these points were extracted in ArcGIS. For each paddock, analyses were conducted on that paddock's random dataset to investigate the relationships between the pattern of crop and pasture production across all four classes (HS, HUS, LS and LUS). Since the stability indices were categorical data, a Chi-squared analysis was used. The Kruskal–Wallis one-way ANOVA test (Kruskal and Wallis 1952) was used to test for differences between stability classes using the R statistical package (v. 3.3.3) (R Core Team 2017). The Kruskal–Wallis test computes a test statistic and P-value (assuming a Chi-square distribution) as well as pairwise comparisons at a specified alpha level (α=0.05 in this case). For the Kruskal–Wallis tests, the null hypothesis was that the medians of all classes were equal, and the alternative hypothesis was that the population median of at least one class was different from the population median of at least one other class. The following combinations were tested for each paddock: crop yield, pasture yield, crop yield CV, pasture yield CV, crop yield minus pasture yield, and crop CV minus pasture CV, with the stability classes as the categorical variable in each case. Yield differences (crop yield minus pasture yield) at a point were tested to see if the differences between crop and pasture medians were significant. If both crop and pasture were responding in the same way at a point (highly correlated) then it would be expected that they would not be significantly different. If the crop and pasture values were highly variable then a significant difference between them would be expected.

Based on our hypothesis that the data acquired across both crop and pasture phases could be used to create a single index of productivity that described the spatial variation in, and temporal stability of yields within a paddock over time, the expectation was that: (i) the medians of the standardised values for the high-yielding classes (HS and HUS) would be similar as would yields in the two low-yielding classes (LS and LUS) but that the yield medians between both groups (HS, HUS) and (LS, LUS) would differ and (ii) for the stability measure (coefficient of variation), that the medians of CV for the stable classes (HS and LS) would be similar as would the unstable classes (HUS and LUS) and that the CV medians between both groups (HS, LS) and (HUS, LUS) would differ.

Correlation analysis of point values for crop grain yield and pasture dry matter production

To see if there was any relationship between crop and pasture yields at a point, a correlation analysis was conducted using JMP 12.2 (SAS Institute Inc, Cary, North Carolina,USA) on between-year crop yields and pasture TGDM yields for each paddock. As not all of the datasets were from normal distributions, a non-parametric Spearman’s rho analysis was used (Corder and Foreman 2014).

Results

Electromagnetic Induction Surveys

Figures 2 and 4 show soil textures as identified by the farm owners of “Milroy” and “Grandview” respectively, based on their knowledge and experience with their paddocks. Figures 3 and 5 show the spatial distributions of the ECa data for “Milroy” and “Grandview” respectively. The differences in mean ECa likely reflect the contrasting soil textures between the highly weathered, sandy soils at “Milroy” and the finer-textured clays at “Grandview”. The CVs for the data sets were much higher for “Milroy” (82% shallow; 104% deep) compared to

"Grandview" (60% shallow; 9.7% deep) (Table 5), suggesting much greater soil variability at the "Milroy" sites, although there also appears to be considerable variability in the shallow (0-0.38 m) region at "Grandview". At "Grandview", the 0-0.38 m and 0-0.75 m ECa maps (Fig. 5a, b resp.) showed similar patterns of spatial distribution. At "Milroy" the percentage sand was negatively correlated with ECa, ECa 0-0.5 m showed a stronger correlation with sand content than ECa (0-1 m) (data not shown). There was also a reasonable similarity between the soil texture zones identified by the "Milroy" farm owner (Fig. 2), particularly with the ECa 0-1 m map (Fig. 3b). At "Grandview" there was a strong positive correlation between ECa 0-0.38 m values and clay content at 0-0.1 m and 0.1-0.5 m at "Grandview" (data not shown). The soil texture properties in lower-lying areas with the highest conductivity at "Grandview" corresponded with sodosols, with pockets of vertosols (Isbell 2016). There was a strong resemblance between the soil texture zones identified by the owner of "Grandview" for paddock GV39 (Fig. 4) and the ECa 0-0.5 and 0-1 m maps (Fig. 5a, b).

Soil sampling and testing

A summary of results from the soil analysis from CSBP is provided in Table 5. The results indicate that the majority of soils in the "Milroy" paddock had more than 70% sand and less than 20% clay throughout the profile (0-0.6 m depth), and were described as either sandy, sandy loam or duplex (sand over clay) soils. These high sand percentages are typical of soils in the south-west of Western Australia. Clay content increased marginally with depth to 0.6 m; average clay content ranged from 13 to 20%. The range of soil test phosphorus concentrations (0-0.1m) across the "Milroy" paddock was 25 to 55 mg/kg, with an average Colwell P-value of 45.6 mg/kg (Table 5). The lowest P-value in M41 was in the lowest part of the paddock, in deep sand. These values were above the critical range of 18-22 mg/kg for wheat/canola (Peverill et al. 1999; Reuter and Robinson 1997) and generally above the 30 mg/kg for pastures (Gourley et al. 2007; Reuter and Robinson 1997). The variation in Colwell P values reflects the variability in soils at "Milroy", from deep sands to sandy loams/gravels (Fig. 2).

At "Grandview", subsoils were 50–60% clay. In the more elevated sections of the paddock, the "Grandview" soils (0-0.1 m) had more than 35% clay. Soils in the lower-lying areas had up to 60% clay (0-0.1 m). There were differences in soil texture between the tops of hills, mid-slopes and points of lowest elevation (Fig. 4). For "Grandview" Colwell P concentrations (0-0.1 m) ranged between 29 and 72 mg/kg (Table 5). The highest soil test P-value in GV39 was associated with a cattle camp and feed trough, indicating that there may have been some nutrient transfer occurring. Lower phosphorus levels in GV39 were associated with increased elevation. The mean soil P-value for GV39 was 45 mg/kg, well above the critical P-values for both crops and pastures.

Crop yield mapping

Crop yield maps for “Milroy” and “Grandview” paddocks are shown at Fig. 6. The patterns of spatial variation in “Milroy” paddock M41 for 2008 (Fig. 6a) and 2014 (Fig. 6b) were similar. During the 2014 season 233 mm of rain fell between July and November, resulting in higher average yields across the paddock than in 2008. At “Grandview”, the period under crop 2006-2009 was impacted by the Millennium Drought (Heberger 2011; van Dijk et al. 2013), with GSR in 2006 being 41% of mean GSR, 53% in 2007, 43% in 2008 and 68% in 2009.

Table 5 Summary of soil texture and selected soil chemistry data for “Milroy” and “Grandview” paddocks. The table shows the range of values obtained, from lowest to highest in each case, from CSBP soil tests

Paddock	**Depth (m)**	**Sand (%)**	**Clay (%)**	**Gravel (%)**	**pH ($CaCl_2$)**	**Colwell P (mg/kg)**	**Mean ECa mS/m**	**CV ECa %**
M41 (n=11)	0-0.1	76	18	0	4.7-5.1	25-55	0-0.5 m	
	0.1-0.3	80	13	0-5	4.4-4.9	6-12	7.6	82
	0.3-0.6	73	20	0-5	4.5-5.9	24	0-1 m	
							12.7	104
GV39 (n=6)	0-0.1	30-53	35-60	< 5	5.2-6.3	29-72	0-0.38 m	
	0.1-0.5	28-35	50-60	< 5	4.8-6.4	7-20	16.4	60
							0-0.75 m	
							79.5	9.7

n = the number of soil sampling sites in each paddock

Total annual rainfall at “Grandview” in 2006 was 217 mm, so little residual moisture was available for the 2007 season, which was reflected in the very poor crop yield in 2007 (Fig. 6e) compared to the 2008 and 2009 seasons (Fig. 6f, g).

A higher proportion of the paddock yielded poorly, although some areas still recorded reasonable yields of around 4 t/ha. Yield variation within the paddock was apparent, even during the drought years. When GSR was closer to the mean (2009), the lower-lying parts of the paddock also yielded well (Fig. 6g).

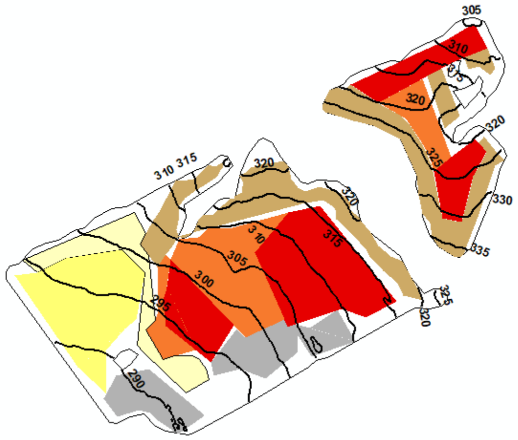

Fig. 2 Soil map created from farmer knowledge (Murray Hall, pers. comm.) for "Milroy" paddock M41. 🟥 sandy loam, 🟧 friable sand, 🟫 gravels, ◼ sandy duplex (sodic), ⬜ sand on clay loam, 🟨 deep sand. Elevations are in metres at 5 m intervals

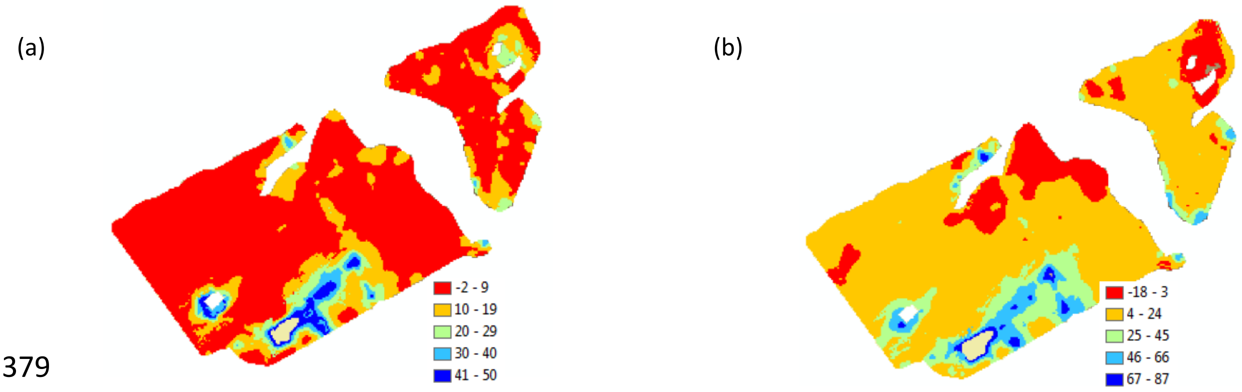

Fig. 3 Maps of soil EC_a (mS/m) from EMI scans of "Milroy" paddock M41 conducted in October 2013. (a) 0-0.5 m and (b) 0-1 m

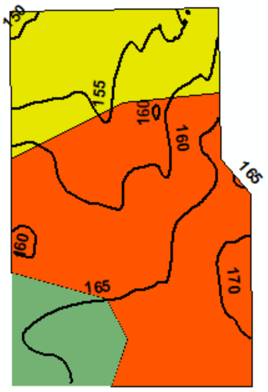

Fig. 4 Soil map created from farmer knowledge for "Grandview" paddock GV39 (Adam Inchbold, pers. comm.). 🟩 sandy clay loam over medium clay, 🟥 sandy clay loam over sodic fine clay, 🟨 clay loam over fine clay. Elevations are in metres at 5 m intervals

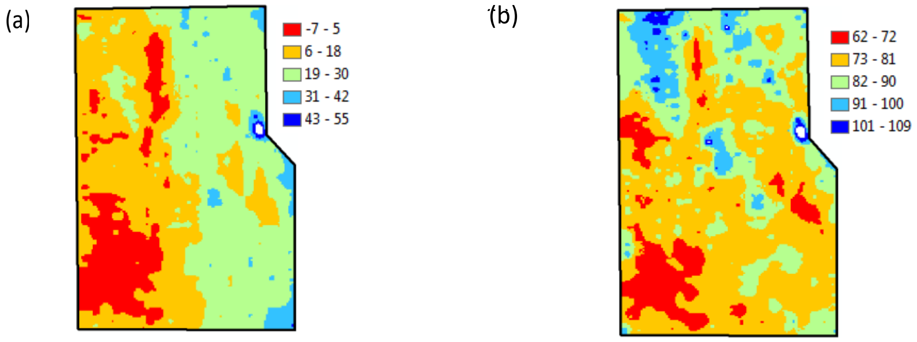

Fig. 5 Maps of soil ECa (mS/m) from EM38 scans of “Grandview” paddock GV39 conducted in October 2013. (a) 0-0.38 m and (b) 0-0.75 m. Scans were conducted with the EM38 in horizontal mode (ECa*h*)

Mapping pasture green herbage mass in pastures

Pasture biomass maps are shown for “Milroy” (Fig. 6c, d), and “Grandview” (Fig. 6h, i). “Milroy” paddock M41 had a similar pattern in spatial variation of TGDM distribution in both September 2012 and 2013 (Fig. 6c, d). The difference in overall biomass between the two years was due to the paddock being destocked at the time of scanning in 2013, resulting in more standing pasture than in 2012. The south-eastern area of the paddock shows low TGDM. The pasture here was dominated by capeweed (*Arctotheca calendula* L.). There were also salt affected areas on the south-eastern edge of the paddock, with sparse vegetation giving a very low TGDM. The remainder of the paddock was dominated by subterranean clover (*Trifolium subterraneum* L.), with some annual ryegrass (*Lolium rigidum* L.) and capeweed. At “Grandview” in 2012 (Fig. 6h), the better TGDM yields occurred in areas of higher elevation e.g. the southern part of paddock GV39. High rainfall preceded the 2012 growing season, with nearly 350 mm recorded from late February to early March. However, “Grandview” then received only 218 mm GSR, which was below average. GSR in 2013 was a little closer to the long-term mean at 254 mm, but the June–September cumulative rainfall was also higher in 2013 (184 mm) than 2012 (122 mm), leading to higher pasture biomass and NDVI values at the time of sampling (Fig. 6i).

Correlation between Crop Circle^{TM} NDVI and pasture biomass (TGDM)

The NDVI was considered the appropriate vegetation index to use to develop the pasture calibration equations for total green dry matter (TGDM) as it generated the lowest root mean square error values compared to the other indices tested (data not shown). The NDVI is the most widely used vegetation index (Ollinger 2011; Tucker 1979), as it is strongly correlated with vegetation biophysical properties. Regression of the Crop Circle^{TM} NDVI scan values at each of the 25 pasture harvesting sites in each paddock against the actual TGDM harvested at each site in 2013 and derived calibration equations are shown for “Milroy” M41 (Fig. 7a) and “Grandview” GV39 (Fig. 7b). In both cases, a non-linear relationship best represented the capacity of NDVI to predict TGDM, with R^2 values of 0.88 at “Milroy” and 0.81 at “Grandview”. Saturation of the NDVI signal at high biomass levels can be seen at both “Milroy” (Fig. 7a) and “Grandview” (Fig. 7b) where increasing TGDM values above around 3000kg/ha does not result in an increase in NDVI. This effect has been widely documented in the literature, especially for agricultural landscapes (Glenn et al. 2008; Mutanga and Skidmore 2004; Thenkabail et al. 2000), resulting in non-linear relationships between NDVI and biomass (Edirisinghe et al. 2011; Huete et al. 2002; Mutanga and Skidmore 2004; Viña et al. 2011).

Spatial trend maps

The standardised yield shows, at any point, in any one year, how the yield differs from the paddock mean (100%). The standardised data across years has been averaged and classified into four yield zones in relation to the relative percentage difference from the paddock mean (100%) using the yield data distribution quartiles to define the four yield classes. The process used to combine crop yield maps (Fig. 8a, b) and pasture TGDM maps (Fig. 8f, g) to create spatial trend maps over time for crop phases (Fig. 8c) and pasture phases (Fig. 8h) is illustrated using data from “Milroy”. The same process was used to create spatial trend maps for “Grandview”.

Temporal variability maps

Whilst the spatial variability maps show the consistently high and low yielding areas of the paddocks over time at “Milroy” and “Grandview”, the temporal variability maps show how stable in time these crop and pasture yields were. The maps for temporal variability of standardised yield for crop and pasture are presented for “Milroy” paddock M41 (Fig. 8d, i) respectively (“Grandview” not shown). The CV shows a low value if a particular area of the paddock has a yield value that was always close to the mean. These areas can be considered to have stable yield over time. If the yield in other areas of the paddock sometimes approaches the mean and sometimes deviates from it, then these can be regarded as areas of temporally unstable yield. The percentage of the paddock area across both sites in the most stable class (CV 0-10%) was >58%, with the exception of “Grandview” in crop (21%) (Table 6). The area of the paddock in the highly unstable category (CV >40%) in pasture phases ranged between 1% (“Grandview”) and 6% (“Milroy”) and in crop between 3% (“Milroy”) and 7% (“Grandview”).

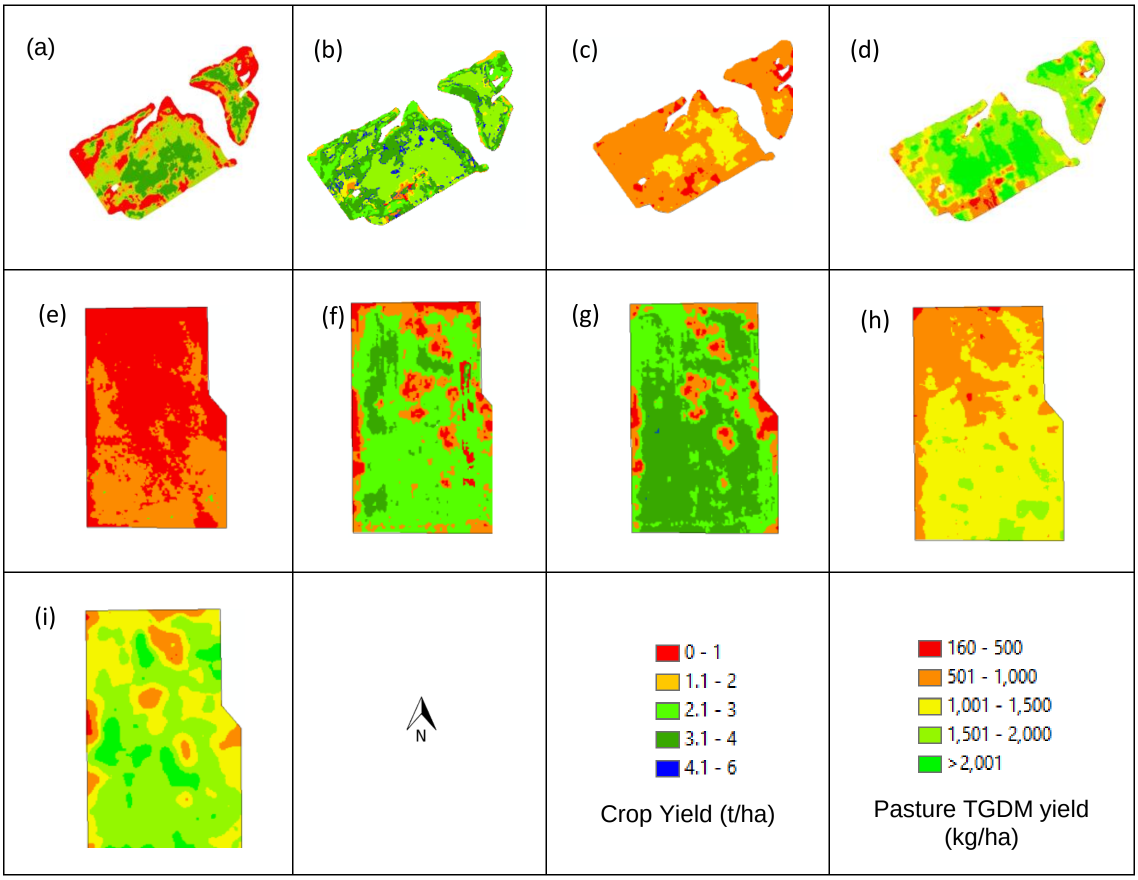

Fig. 6 Crop yield maps and pasture biomass maps for research paddocks. "Milroy" paddock M41: (a) crop 2008 and (b) 2014; (c) pasture Sept 2012 and (d) Sept 2013, "Grandview" paddock GV39: (e) crop 2007, (f) 2008 and (g) 2009; (h) pasture Sept 2012 and (i) Sept 2013

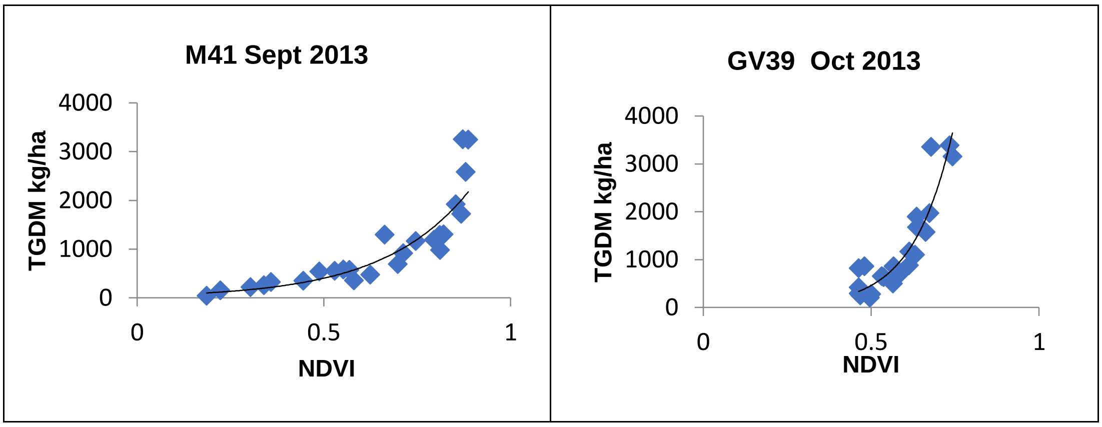

Fig. 7 Regression of Crop Circle normalised difference vegetation index (NDVI) values against total green dry matter (TGDM) determined by direct harvesting for "Milroy" paddock M41 ($y=45.927e^{4.3528x}$; $R^2 = 0.884$) and "Grandview" paddock GV39 ($y=6.416e^{548x}$; $R^2 = 0.807$) in September 2013

Stability Index maps (spatial and temporal trend maps)

The Stability Index maps for crop and pasture phases are shown in Fig. 9a (crop) and 9b (pasture) for "Milroy" and Fig. 10a (crop) and 10b (pasture) for "Grandview". In these maps, the data from the spatial trend classes (low yielding, LY; below average, BA; above average, AA; and high yielding, HY) and temporal stability maps

(CV ranges) have been combined and categorised into four new classes—high or low yielding depending on whether the data value was above or below the spatial mean, and stable or unstable depending on whether the data value was above or below the stability threshold (Table 3). Fig. 9c shows the overall paddock stability map for “Milroy” M41 which combines the crop (Fig. 9a) and pasture (Fig. 9b) spatial trend and temporal stability data into one map. Fig. 10a-c shows the same process for “Grandview”. The maps show areas of the paddock where the yields for both crop and pasture, over time, responded in a similar fashion—either high yielding and stable (HS), high yielding and unstable (HUS), low yielding and stable (LS) or low yielding and unstable (LUS). The areas of the map that remain uncoloured represent other possible combinations of yield and stability other than the four defined zones. For each paddock, the “high and stable” class ranged from 68% of total grid points analysed at “Milroy” to 54% at “Grandview (Table 7). The “low and unstable” class accounted for 21% of grid points analysed at “Milroy” to 19% at “Grandview” (Table 7). Data points for each paddock that didn’t fall into one of the four Stability Index categories (for example, points that were temporally stable - CVs_i < mean CV, but high yielding in one phase and low in another, or temporally unstable - CVs_i > mean CV, but high yielding in one phase and low in another), were combined to form maps for “Milroy” (Fig. 11a) and “Grandview” (Fig. 11b) respectively, clarifying the nature of uncategorised areas.

Correlation of crop and pasture values at a point

At “Milroy”, the Spearman’s rho correlation revealed a moderately strong, statistically significant relationship in paddock M41 between the standardised values for crop yield and pasture TGDM for the randomised points (ρ=0.66, P<0.01, N=262, Table 8). At “Grandview” paddock GV39, there was also a statistically significant relationship for Spearman’s rho correlation between the standardised values for crop yield and pasture TGDM for the randomised points (ρ=0.66, P<0.01, N=192, Table 8). These significant results confirm the validity of the method used to develop the combined crop and pasture stability maps.

Kruskal-Wallis analysis

The results of the Kruskal–Wallis one-way ANOVA (Table 8) showed that at both sites the Stability Index categories for yield (high and low) partitioned the yield medians into high yielding categories (HS & HUS) and low yielding categories (LS & LUS) and these differences were significant (p< 0.01). This was also the case when yield differences (crop yield minus pasture yield) were tested. For temporal stability, crop and pasture stability medians did not always show significant differences between stable and unstable areas, but the median values were grouped correctly. For example, crop CV median values at “Grandview” for stable were close to each other (12.0 and 16.7) and distant from the unstable category (29.4 and 30.5). The same occurred with crop-pasture yield differences at “Grandview”, with yield medians falling into high (10.1 and 13.8) and low (14.9 and 17.3) and stability medians grouped stable (6.3 and 12.3) and unstable (19.1 and 17.2). The results for the pasture phase temporal stability analysis were much less consistent. There were no paddocks where the pasture CV category medians differed significantly and “Grandview” GV39 was the only paddock where the values of the medians were grouped into stable and unstable categories. The impact of livestock grazing as a possible cause of these pasture effects is discussed further in the discussion. Although the Kruskal–Wallis test for the temporal stability aspect (CV) of the Stability Index did not always show a significant difference between the medians of the stable and unstable categories, the results provide strong evidence to support the validity of the methodology used to define and allocate yield spatial variability data among the Stability Index categories.

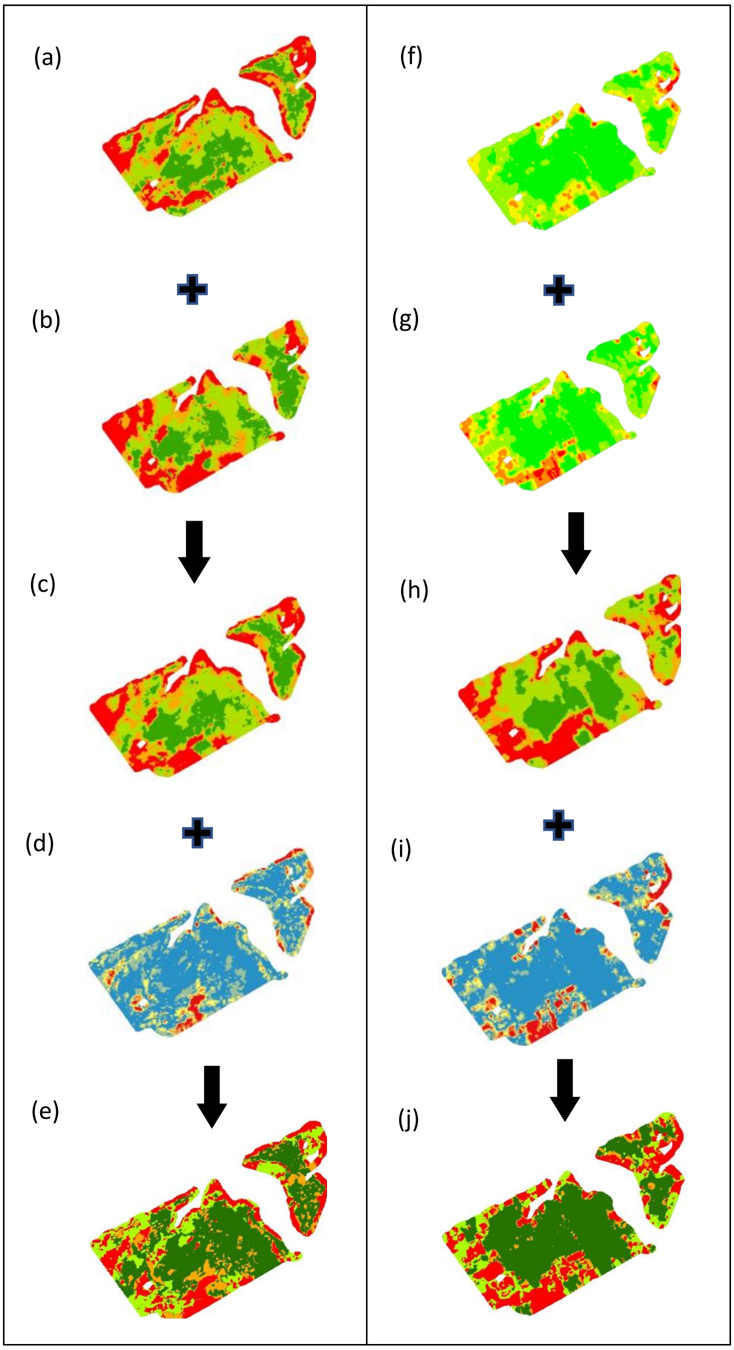

Fig. 8 Diagram illustrating the creation of Stability Index maps for crop and pasture phases for “Milroy” paddock M41. Standardised yield maps (a) and (b) for crop, (f) and (g) for pasture total green dry matter (TGDM), are combined to create spatial trend maps (c) and (h), which show the standardised yields (crop and pasture TGDM) over time 🟥 = low yielding; 🟫 = below average; 🟩 = above average; 🟩= high yielding. Combining the features found in the spatial trend maps with the temporal stability maps (d) and (i) for crop yield and pasture TGDM respectively 🟦= 0-10%, 🟩 = 11-20%, 🟨= 21-30%, 🟫 = 31-40%, 🟥 = >40%, produces the Stability Index maps for crop (e) and pasture (j) 🟩= HS, 🟫= HUS, 🟩= LS, 🟥= LUS

Table 6 Temporal variability of production (based on CV) for “Milroy” and “Grandview” paddocks by percentage of paddock affected[a]

			CV categories (%)		
Paddock	**0-10**	**11-20**	**21-30**	**31-40**	**>40**
“Milroy”					
M41 crop	59	25	9	4	3
M41 pasture	65	17	8	4	6
“Grandview”					
GV39 crop	21	34	25	14	7
GV39 pasture	58	29	9	3	1

[a] 0-10% is the most stable category and >40% the least stable

Fig. 9 Combining the Stability Index maps in "Milroy" paddock M41 for crop (a) and pasture (b) phases provides the overall paddock Stability Index map (c), with four zones: 🟩 high yielding and stable (HS); 🟧high yielding and unstable(HUS);🟩 low yielding and stable (LS); 🟥 low yielding and unstable (LUS). The areas of the map that remain uncoloured represent other possible combinations of yield and stability other than the four defined stability zones

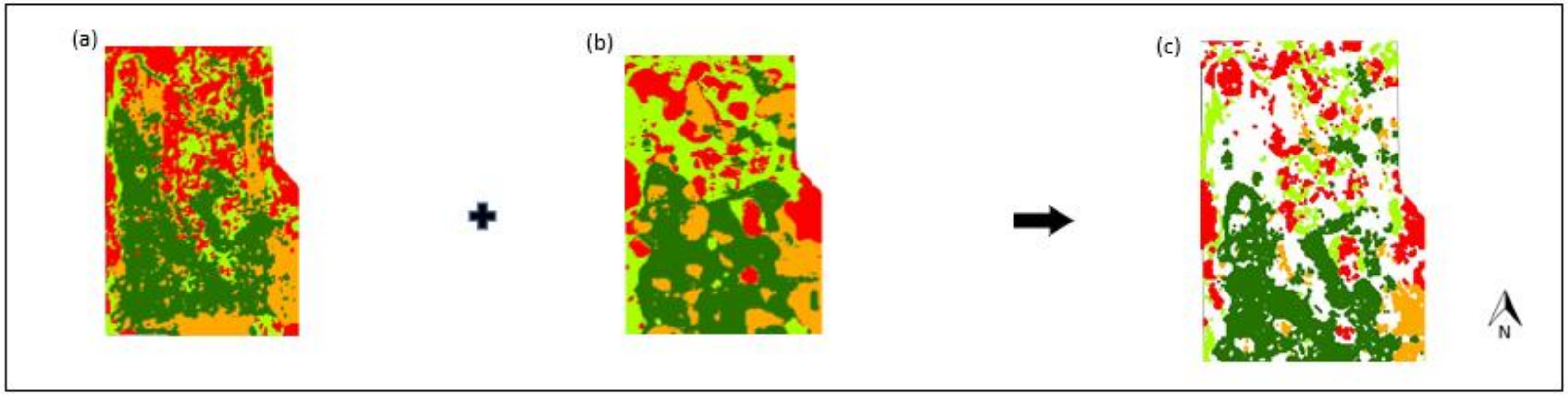

Fig. 10 Combining the Stability Index maps in "Grandview" paddock GV39 for crop (a) and pasture (b) phases provides the overall paddock Stability Index map (c), with four zones: 🟩 high yielding and stable (HS); 🟧high yielding and unstable (HUS); 🟩low yielding and stable (LS); 🟥low yielding and unstable (LUS). The areas of the map that remain uncoloured represent other possible combinations of yield and stability other than the four defined stability zones

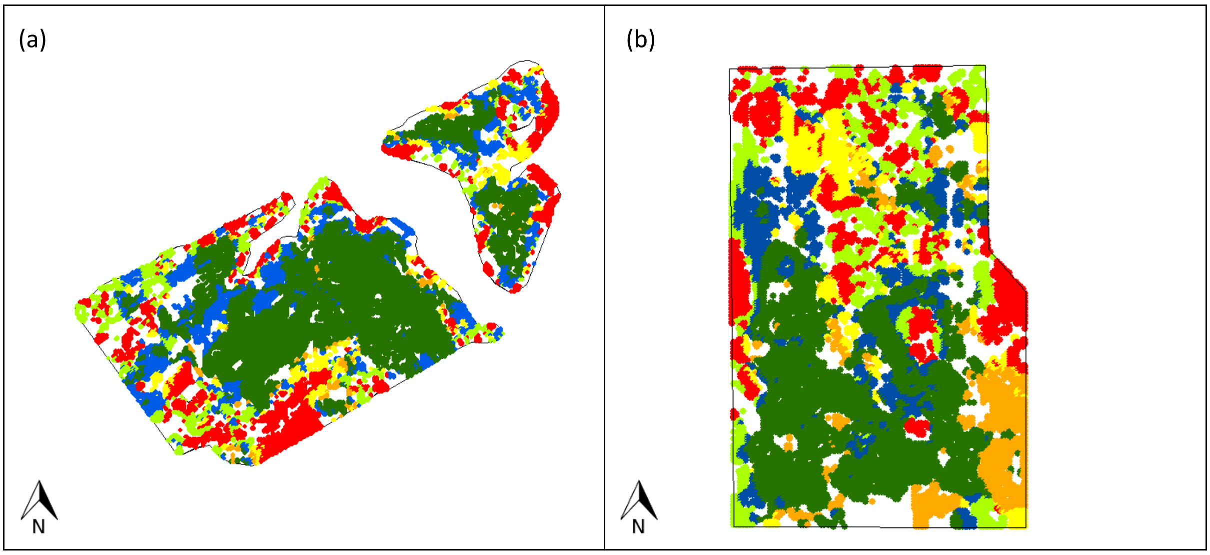

Fig. 11 Stability Index maps for “Milroy” paddock M41 (a) and “Grandview” paddock GV39 (b) showing all data points that are either: high yielding and stable (🟩), high yielding and unstable (🟧), low yielding and stable (🟩), low yielding and unstable (🟥), high/low yielding and stable (🟦), high/low yielding and unstable (🟨), for both crop and pasture.

Table 7 Stability Index categories as a percentage of paddock area by crop, pasture and crop and pasture combined, for “Milroy” and “Grandview” [a]

	Stability Category			
Paddock	**HS**	**HUS**	**LS**	**LUS**
“Milroy”				
M41 crop	45	11	21	23
M41 past	52	5	17	26
M41 combined	68	2	9	21
“Grandview”				
GV39 crop	38	21	13	28
GV39 past	31	24	22	23
GV39 combined	54	13	14	19

[a] The combined values are the percentages of the paddock classified as either HS, HUS, LS, or LUS, not of total paddock area

Table 8 Results from the Kruskal–Wallis one-way ANOVA test for differences between the stability zones based on crop and pasture yield or CV for "Milroy" and "Grandview" paddocks. Values show the zone medians calculated by the Kruskal–Wallis test and indicate where a significant difference occurred between at least one median[a,b]

PADDOCK	HS	HUS	LS	LUS	χ^2	P	ρ	P
"MILROY" M41	(N=262)							
Correlation: crop yld x pasture yld							0.66	**<0.01**
Crop yield	110.5^{a}	112.7^{a}	85.6^{b}	78.3^{b}	193.18	**<0.01**		
Pasture yield	116.8^{a}	105.9^{a}	91.3^{b}	82.8^{b}	99.29	**<0.01**		
Crop CV	5.2^{a}	18.7^{b}	5.8^{a}	25.2^{c}	177.09	**<0.01**		
Pasture CV	4.9^{a}	7.3^{b}	11.0^{bc}	14.9^{c}	53.17	**<0.01**		
Crop yld–Pasture yld	10.0^{a}	7.5^{a}	15.6^{b}	17.2^{b}	25.68	**<0.01**		
Crop CV–Pasture CV	3.2^{a}	11.4^{bc}	6.6^{c}	14.8^{b}	54.81	**<0.01**		
"GRANDVIEW" GV39	(N=192)							
Correlation:crop yld x pasture yld							0.66	**<0.01**
Crop yield	114.8^{a}	119.2^{a}	77.2^{b}	74.3^{b}	138.9	**<0.01**		**<0.01**
Pasture yield	112.1^{a}	105.9^{a}	88.4^{b}	86.4^{b}	57.84	**<0.01**		**<0.01**
Crop CV	12.0^{a}	29.4^{b}	16.7^{c}	30.5^{b}	143.09	**<0.01**		**<0.01**
Pasture CV	7.8^{ns}	12.2^{ns}	7.6^{ns}	10.4^{ns}	7.34	0.06		**<0.01**
Crop yld–Pasture yld	10.1^{a}	13.8^{ab}	14.9^{b}	17.3^{b}	11.36	**0.01**		**<0.01**
Crop CV–Pasture CV	6.3^{a}	19.1^{b}	12.3^{c}	17.2^{bd}	54.45	**<0.01**		**<0.01**

[a] Median values with different letters indicate that the SI zone medians are significantly different. ns = not significant

[b] The correlation between crop yield and pasture TGDM was also tested with Spearman's rho. HS = high and stable yielding zones, HUS = high and unstable, LS = low and stable and LUS = low and unstable. χ^2 is the Chi-squared test statistic for each Kruskal–Wallis test, ρ is the Spearman's correlation coefficient and P is the related probability. N is the number of points in the sample

Discussion

Spatial and temporal variability and the Stability Index – strategic versus tactical decisions

Being able to identify areas of a paddock that exhibit consistent behaviour across all rotations means that a farm manager is in a better position to make longer-term strategic decisions regarding appropriate cropping and grazing management strategies, targeted amelioration of soil/subsoil constraints or variable nutrient management. It is physically difficult and expensive to accurately map the extent of within-paddock soil variability at the spatial resolution required by precision agriculture methodologies using conventional laboratory-based soil testing techniques alone. The objectives of this research were to (1) use a proximal NDVI sensor to characterise spatial variability of production in the pasture phase of mixed farming systems; (2) to compare within-paddock spatial variation in crop grain yield and pasture biomass production and (3) to develop a methodology to create a single map of spatial variation of crop yield and pasture biomass production at a point, across a paddock, ("Stability Index"). It was hypothesised that the use of high resolution data could identify spatial variation in production across crop and pasture rotations and that the data could be used to create a single index of productivity that described the spatial variation in, and temporal stability of, both crop grain and pasture biomass yields within a paddock over time – the "Stability Index". All three objectives were met. The Kruskal-Wallis analysis provided strong evidence to support both the hypothesis and the validity of the methodology used to split the yield spatial variability data among zones. That is, the methodology partitioned both crop and pasture yields in the same areas in each paddock, although the impacts of livestock grazing during the pasture phase tend to confound temporal stability in comparison to the cropping phase. At both properties, the majority of the paddock, by area, was classified as stable in production over time. At "Milroy", the stable area (HS + LS) was 77% of the paddock and at "Grandview" 68%.

While proximal soil sensing technologies alone, (such as EMI), cannot replace the detail provided by manual soil sampling in the field, both techniques could be used together to identify spatial and temporal variability and its potential causes, to inform strategic planning for soil management at a given site. Although highly mobile nutrients like nitrogen need to be managed in-season during cropping phases in response to in-season soil moisture and rainfall (Basso et al. 2012), less mobile nutrients such as P, K and S can be managed with a longer-term view, based on the temporal variance reflected in stability zones In this way, the different outcomes required from a crop (maximising grain yield) and pasture (maximising digestible biomass) phase can be managed together and monitored at the sub-paddock scale. In this context, it was anticipated that the stability zones might be useful for identifying potential nutrient variations across a paddock and provide the opportunity to better manage decisions around fertiliser application. Areas of a paddock that have different soil textures and nutrient levels can have differing maintenance fertiliser requirements and might benefit from differential fertiliser treatment. Conventional wisdom suggests that high and stable zones could have higher soil fertility, but there is evidence (Price 2006) that high and stable zones could show lower nutrient levels than the low and stable areas, as greater nutrient removal would occur from the high and stable areas in the form of crop and animal product exports. When the paddock Stability Index maps were overlain on the soil test results no definitive trends were apparent. Unfortunately, the limited number of soil tests precluded detailed analyses of the impacts of soil chemical / textural factors. A better understanding of how the spatial patterns in soil properties may have impacted on yield variations could have been achieved with better targeted soil sampling. However, the soil testing was undertaken for earlier research, prior to the definition of the SI zones and did not specifically target SI zones which probably contributed to the low correlation between soil chemistry and SI zones.

At “Milroy” paddock M41, the areas identified as high and stable (HS Stability Index - dark green; Fig. 8) are mainly in the central section of the paddock, associated with finer-textured loamy soils. This section of the paddock is sloped, rising from south to north, with an elevation variation of around 10 metres (Fig. 2). The pastures in this zone are dominated by subterranean clover. It was likely that the areas dominated by subterranean clover in the pasture phase may have contributed to improved fertility through biologically fixed nitrogen. The small areas categorised as “low and stable” (LS – light green; Fig. 9c) at “Milroy” comprise sand over clay soils (Fig. 2). These are areas of low but stable production. The “low and unstable” areas (LUS – red; Fig. 9c) largely comprise “problem” soils - non-wetting gravels and sodic sandy duplex soils occurring around the edges of the paddock. The sodic soils border a saline drainage line on the southern boundary. Crop yields here are low, but in the pasture phase, there can be a reasonable amount of weedy biomass growing, resulting in an unstable production pattern between crop and pasture phases. The LUS areas comprise 21% of the paddock area that was classified (Table 7), which could be considered significant in management terms, requiring further investigation.

At “Grandview, there were differences in soil texture between the tops of hills, mid-slopes and points of lowest elevation in GV39. On the tops of the hills, the topsoil tended to be stonier sandy clay loams, transforming down the slope to sandy clay loam over clay (Fig. 4). The southern half of the paddock, which includes the HS zone (dark green; Fig 8c), has higher elevation and sandy-loam over clay soils. The LUS areas (red; Fig. 10c) are on the margins (fence-lines) of the paddock, where existence of trees could be affecting production, and in the lower-lying (northern) parts of the paddock dominated by fine textured soils with scattered large trees. The farm owner also reported that the elevated areas of the paddock, although of lower inherent fertility, would yield well with sufficient fertiliser application (Adam Inchbold, pers. comm.). Previous research at "Grandview" (Inchbold et al. 2009) reported that sodosols on the lower slopes always had surplus soil water, leading to the conclusion that rooting depth in these soils was limited by factors other than moisture (e.g. salinity or elevated exchangeable sodium percentage (ESP) in subsoils) (Kirkegaard and Lilley 2007; Lilley and Kirkegaard 2016), which corresponds with the SI results. The farm owner reported little water extraction below 0.6 m on these soils (Adam Inchbold, pers. comm.).

Influence of livestock grazing on biomass

Grazing livestock create specific spatial patterns of pasture biomass utilisation which affect the spatial heterogeneity of the paddock and bring about significant nutrient redistribution (Laca 2009; Murray et al. 2007; Rook et al. 2004; Schellberg et al. 2008; Schnyder et al. 2009; Trotter et al. 2010a). For example, as noted in the results section, the highest soil test P value in "Grandview" paddock GV39 was associated with a stock camp and feed trough. These effects are compounded from year to year by stocking rate decisions of managers, pasture regrowth, and often highly variable species composition within complex swards over time (Bailey and Provenza 2008; Chapman et al. 2007; Soder et al. 2009). These factors combine to affect the spatial heterogeneity of a paddock during the pasture–livestock phase compared to grain yield when the paddock is in crop. As a result, it is not always going to be clear if a particular part of a paddock happened to be low in pasture TGDM production because nothing much grew there, or because the vegetation was grazed off, or there was a change in species dominance affecting the NDVI reflectance values. This was evident in the Kruskal–Wallis tests (Table 8), where there were a number of statistically non-significant results associated with the pasture CVs. The overall spatial and temporal utilisation of a paddock by livestock is going to remain unclear without acquiring data through GPS tracking (Trotter et al. 2010a, 2010b). Meta-analysis of data from livestock fitted with GPS tracking collars and accelerometers could identify spatial preference, grazing behaviour and distribution of animals within a paddock and help to identify animal impacts from soil texture / chemistry effects. This also applies to the grazing of a crop in a 'grain & graze' system (Price and Hacker 2009) as well as when the paddock is in pasture.

Uncategorised areas of the paddocks

There are areas of the paddock that remain uncategorised with the SI process, where production can be stable, but high yielding in one phase and low yielding in the other. For example, an area of a paddock can be temporally stable (ie CVs_i < mean CV; Table 3), but high yielding in crop and low yielding in pasture. This could result from highly productive areas of the paddock when in pasture being heavily grazed by stock, and thereby giving a low TGDM yield when the paddock was measured. At "Milroy", these areas – "high-low stable" (HLS - blue areas in Fig. 11a) are mostly on the margins of the darker green HS zones and a section on the south-western boundary. The area on the southwest boundary comprises deep sands of low fertility, dominated by broadleaf weeds (capeweed and *Erodium* spp.). This area also comprised a significant proportion of the paddock that remains uncategorised. Pasture quality and livestock residence times on capeweed can be highly variable, and can impact estimates of TGDM in these areas, particularly if plants are flowering, as the yellow flowers can impact NDVI values (Behrens et al. 2006; Shen et al. 2009; Shen et al. 2010). The other possibility in the uncategorised zones was high yielding in one phase and low yielding in the other while unstable in yield (distant from the mean) and unstable in time (ie CVs_i > mean CV; Table 3). These "high-low unstable" areas (HLUS - yellow in Fig. 11a) tend to be on the margins of the LUS (red) zones. The soil textures in these areas are coarse and variations in yield between crop and pasture may be driven by variations in rainfall amount and timing as they will run out of water first in dry years.

As with "Milroy" when the uncategorised parts of the "Grandview" paddock were included (Fig. 11b), the high or low but stable areas (HLS-blue; Fig. 11b) tended to be associated with, and on the margins of, the high and stable areas (HS-dark green; Fig. 11b) areas. The high or low but unstable areas (HLUS-yellow; Fig. 11b) were in the lowest-lying part of the paddock and tended to be associated with the low and unstable (LUS) zones. There was a band of very high ECa that extended from the north-west corner of the paddock to the LUS area at the middle of the eastern boundary, where soil ESP (0.1-0.5 m) was very high (10%) (data not presented). This may account for the wide variation in Stability Indices in this part of the paddock, encompassing LS, LUS, HLS, HLUS and some uncategorised areas. The HLS areas described above for both paddocks that adjoin the HS zones could also be affected by livestock grazing.

Practical benefits of the Stability Index classifications

The results of this research show that it is possible, using readily available precision technologies, to correlate and map the responses of both crop and pasture yields over time within the same paddock at the sub-paddock scale. The analysis addresses a number of factors that impact on the objectives and forward planning decisions of the managers of mixed-farming systems. Spatial variation in yield is not always consistent, but influenced by seasonal variations and often temporally unstable (McBratney et al. 1997; Wong and Asseng 2006), opening 'a Pandora's box of uncertainty' for the agronomic interpretation of yield maps (Cook and Bramley 2001). By identifying commonality in spatial and temporal variability across both crop and pasture phases through the Stability Index, some of this uncertainty is reduced. If farm managers can be confident about what is happening at the whole of system scale in both crop and pasture phases in a paddock, it enables them to make management decisions with greater confidence. Using the stability zones to create 'gross margin' maps of each paddock (Blackmore 2000; Whelan and Taylor 2013) can assist in optimising financial inputs and returns, although this was not explored here. If the spatial trend indicates that lower yielding areas are sufficiently significant in size to warrant attention, then these areas can be investigated and the cause(s) ameliorated. If the cause cannot be addressed (e.g. salinity), reducing inputs to match average yields can be explored. For example, variable rate fertiliser P decisions in all paddocks at "Grandview" are currently based solely on P removal in grain during the cropping phase. The pastures receive a blanket rate of P. The farm owner at "Grandview" has indicated that based on the results of this research, he would be interested in implementing a variable rate fertiliser strategy during pasture phases also, to complement his cropping strategy. Either way, the stability zone maps provide the property manager with an indication on whether focussing on spatial or temporal management is the best strategy, especially if informed with gross margin maps.

Conclusions

The analysis presented here is unique in that it includes both crop and pasture yield data from within the same paddock. The Stability Index has the potential to fill significant knowledge gaps for the farm manager, who currently only has crop yield data to make decisions about paddock management. Previous attempts to create paddock stability zones (Blackmore (2000), Blackmore et al. (2003), Marques da Silva (2006), Marques da Silva et al. (2008) and Xu et al. (2006)) have been restricted to either single crop or grassland paddocks, but never for paddocks that include a sequence of both crop and pasture rotations in a mixed farming system. With the benefit of hindsight, additional soil test data based on the SI zones would have been invaluable to help identify and possibly better characterise some of the differences between zones outside of the "HS" areas and possibly reduce the extent of un-categorised parts of the paddocks. The research identified that there were some exceptions and uncertainties around the measurement of spatial variation and temporal stability in pasture phases. In the short term, it can be difficult to differentiate between variations in temporal stability of pasture growth brought about by rainfall, soil moisture and soil nutrient supply from those caused by grazing. As the size of Australian farm holdings increases (Australian Bureau of Agricultural and Resource Economics 2017, http://apps.daff.gov.au/AGSURF/), not all paddocks can be sown at the optimal time. Being aware of how different parts of a paddock are responding and the extent of those areas in both crop and pasture phases through the use of the paddock stability indices can inform decisions about the order and timing of paddock sowing when faced with a time-constrained sowing window. The methodology and concepts described and demonstrated here open the way for further research to identify a new field of "whole of system" precision management in mixed farming systems. For example, further research into the effects of livestock grazing impacts on spatial variability of pasture production through the use of tracking collar data would help to clarify issues around overall spatial and temporal utilisation of a paddock by livestock. A longer term on-farm trial of the stability index to inform decisions about the mix of crop and pasture rotations on a paddock by paddock basis, optimal crop and pasture sequences, which paddocks are better suited to either cropping or pasture and pasture species selection would also be of great value. There is significant potential for the Stability Index methodology described here to be of benefit to a farm manager, as a guide to enhancing and improving mixed farming system management practices.

Availability of supporting data

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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