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Mapping the stability of spatial production in integrated crop and pasture systems: towards zonal management that accounts for both yield and livestock-landscape interactions.

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Abstract. Precision farming technologies are now widely applied within Australian cropping systems. However, the use of spatial monitoring technologies to investigate livestock and pasture interactions in mixed farming systems remains largely unexplored. Spatio-temporal patterns of grain yield and pasture biomass production were monitored over a four-year period on two Australian mixed farms, one in the south-west of Western Australia and the other in south-east Australia. A production stability index was calculated for two paddocks on each farm. An example is given here for one paddock from Western Australia. The stability index described here is unique in that it combines spatial and temporal variation across both cropping and pasture phases. Co-efficient of variation in yield was used as the threshold value for determining stability. Production in each stability zone was analysed statistically for consistency and correlation between the cropping and pasture phases. Results indicate that the stability index can be used in mixed farming systems to assist in management decisions and for the paddock described, spatial and temporal variation in production between crop and pasture phases was strongly correlated.

Keywords. Mixed Farming, Precision agriculture, Stability index, Management zones, Australia.

1. INTRODUCTION:

The cereal–livestock zone in southern Australia lies approximately between the 300 and 600 mm average annual rainfall isohyets and is highly seasonal and variable. Rainfall variability within this zone presents challenges for crop production both between and within years. Additionally, soils are generally of low inherent fertility and often structurally unstable. The Australian mixed farming system has evolved as a response to these biophysical limitations. This zone has a predominantly mediterranean-type climate that allows regular cropping of wheat in conjunction with other cereals, pulses and oilseeds. Crops are sown in late autumn and harvested in late spring before the onset of the hot, dry summer. Sheep for meat and wool are grazed year-round on pastures and crop residues, supplemented with conserved fodders and/or grain in poor seasons (Kirkegaard et al., 2011). The combination of livestock and cropping enterprises provides flexibility to farm management, improving the capacity to manage risk associated with variable rainfall and commodity prices, building soil organic matter content, supplying nutrients, managing crop diseases and herbicide resistant weeds (Ewing & Flugge, 2004; Fisher et al., 2010).

Relatively little is known, currently, about the nature, extent, or temporal stability of the spatial variability of pasture production in Australian mixed farming systems and whether it is feasible to manage this variability in a site-specific way. Mixed farms where precision agriculture (PA) tools and technologies are already used during the cropping phase, have the opportunity to utilise state-of-the-art PA "crop" technologies to create high resolution data for managing pasture and livestock.

To manage spatial and temporal variations in yield, the high and low performing areas in a paddock during both the crop and pasture phases must be identified. The most common approach to managing spatial variability in crops is to define and use 'management zones' in a system of "site specific management" (SSM) (Plant, 2001; Taylor et al., 2007). However, experience has indicated that spatial variation in yield is not always consistent, but influenced by seasonal variations and often temporally unstable (McBratney et al., 1997; Wong & Asseng, 2006). Some areas within paddocks exhibit "flip-flop" behaviour, alternating between high, medium or low yielding, in different years (Cook & Bramley, 2001; Nuttall & Armstrong, 2006). Spatial variation in yield is primarily influenced by within-season rainfall and soil properties (Basso et al., 2012), whereas temporal variation is mainly influenced by climate and its interaction with soil properties, disease and management interventions (Lawes et al., 2009). The notion of productive stability is important for farm management, because if the year-to-year spatial variation in crop and pasture yields are significant and unpredictable, then site-specific management becomes impractical.

The aim of the study was to create inter-annual spatial variability maps across both pasture and crop phases. To achieve this, the methodology of Blackmore (2000) was followed which involved calculation of the standardised temporal arithmetic mean of crop and pasture yield for the same point over a given number of years. The mean yield of each point, obtained from four years of data, provided the information for the inter-annual spatial variability maps. The analysis presented is unique in that it includes both crop and pasture yield data. The results reported here form part of a larger study of spatial mapping in mixed farming properties in the south-west of Western Australia and north-eastern Victoria, Australia.

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2. MATERIALS AND METHODS:

2.1 Site description

The study site described here was a 60 ha paddock at "Milroy", a 1900 ha sheep and cropping enterprise located at Brookton (32.22°S, 116.57°E), 120 km east of Perth, Western Australia. "Milroy" has a mean daily maximum temperature of 24.1 ºC, and a mean daily minimum temperature of 9.8ºC. Rainfall is winter dominant, with a mean annual rainfall of 437 mm and growing season rainfall (April-October) of 357 mm. Wheat (*Triticum* spp. L.) and canola (*Brassica napus* L.) are the main crops grown on the property. Pastures on "Milroy" are predominantly self-sown and dominated by sub-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.).

2.2 Data description:

Wheat yield data from the 2009 and 2014 seasons from a Case 8010 harvester connected to a differentially corrected RTK GPS was provided by the farm owner. The paddock was in a pasture phase from 2011 to 2013. Crop yield data from 2010 was corrupt and unable to be used. Pasture yield data was obtained from CropCircle™ NDVI scans of pasture, conducted in September 2012 and September 2013, calibrated to pasture total green dry matter (TGDM) by paddock pasture cuts (Trotter et al., 2010). Raw crop and pasture yield data was processed using the protocol developed by Taylor et.al., (2007).

2.3 Calculating the spatial trend:

The crop yield and pasture TGDM data was kriged to a regular grid with Vesper 1.62 using an exponential variogram and a block size of 10 m x 10 m. The spatial trend of grain and pasture yields was determined by averaging the yield at each grid point over the sequence of yield maps. Crop grain and pasture TGDM yield data was standardised to remove the yield units (t/ha), replacing them with a relative percentage yield that allows comparison between crop and pasture. The standardised yield was calculated as per Blackmore (2000) as follows:

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

Where;

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

The point mean was then calculated as:

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

Where;

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

The standardised data were then classified into four yield zones, in relation to the relative percentage difference from the paddock mean (100 %); the areas for which this value was greater than the paddock mean were classified as "above average" (AA) and "relatively high yielding" (RHY), while the areas for which this value was less than 100 %, were defined as "below average" (BA) and “relatively low yielding” (RLY). The standardised crop and pasture yield data was then imported into ArcGIS 10.2 (Environmental Systems Research Institute, Redlands, California) and mapped to a standard square 5 m x 5 m grid. The data was interpolated to the grid with Vesper 1.62 using an exponential variogram and a block size of 10 m x 10 m. Interpolated data was then converted to raster surfaces in ArcGIS 10.2 to produce yield maps of standardised data for each year of crop grain yield and each year of pasture TGDM yield. Spatial trend yield maps were then created by averaging the standardised yield at each grid cell over the years being considered (effectively “combining” yield maps) and similarly processing in ArcGIS 10.2. These spatial trend maps show the spatial yield pattern in a paddock over time for both crops and pastures.

2.4 Calculating temporal stability:

To estimate how stable in time the crop and pasture TGDM yields were at “Milroy”, the co-efficient of variation (CV) was calculated at each point in the paddock for which there was a yield value for either grain yield or pasture TGDM (Equation 3), following the procedure developed by Blackmore (2000).

For multiple crops, 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 the paddock for both cropping and pasture phases.

The CV data for crop yields and pasture TGDM yields were processed in ArcGIS 10.2 to produce maps showing the range of CV values (%) across the paddock for crop grain yield and pasture TGDM yield. Paddock areas with a low CV value were considered to be areas of stable yield (less dispersed) in temporal terms while areas with high CV values were regarded as unstable in yield in temporal terms. The temporal stability maps were classified into stable yield zones and unstable yield zones using a threshold value of temporal CV value to sub-divide the two zones. Previously, a threshold value for the temporal CV of 30 % was used by Blackmore (2000) for cereal crops and two threshold values (15 and 25 %) were used by Xu et al., (2006) and Serrano et al., (2011) respectively for grassland. The mean CV value for crop yield (13 %) and pasture TGDM distribution (13 %) were calculated in JMP 12.2 (SAS Institute Inc., Cary, NC) and used as threshold values.

2.5 Creating a spatial and temporal trend map:

By combining the data behind the spatial trend and temporal stability maps, a single representation of the paddock over time and across rotation phases was obtained by classifying the paddock into four categories based on yield (high or low) and stability (stable or unstable) at a point over time. The four classes are:

1) high-yield zone - a zone in which mean yield for crop or pasture at a given point (Equation 2) is greater than inter-annual mean yield (ie > 100 %);

(2) low-yield zone - a zone in which the mean yield for crop or pasture at a given point is lesser than inter-annual mean yield (ie < 100 %);

(3) stable zone - low inter-annual spatial variance of crop or pasture production (based on a defined threshold value for CV); and

(4) unstable zone - high inter-annual spatial variance of crop or pasture production (based on a defined threshold value for CV).

There are four possible combinations for these two variables: high and stable (HS); high and unstable (HUS); low and stable (LS), and low and unstable (LUS). Initially, separate maps were created for crop and pasture phases. Crop grain and pasture TGDM yields were determined to be high if a particular point value was above the mean (> 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 a paddock, to determine if the yield at that point was stable (< mean CV) or unstable (> mean CV) (Table 1).

The stability indices for the crop and pasture phases described above were then combined to create an overall stability index for the paddock. Mapping this index shows areas of the paddock that are high and stable in both crop and pasture yield, and areas that are high and unstable, low and stable, low and unstable.

Table 1: Stability index (SI) class codes and the conditions for meeting a stability index class.

Management Class (code)	Condition 1	Condition 2
High and stable (HS)	$\bar{s}_i$ >100	$\mathrm{CV}s_i <$ mean CV
High and unstable (HUS)	$\bar{s}_i$ >100	$\mathrm{CV}s_i >$ mean CV
Low and stable (LS)	$\bar{s}_i$ <100	$\mathrm{CV}s_i <$ mean CV
Low and unstable (LUS)	$\bar{s}_i$ <100	$\mathrm{CV}s_i >$ mean CV

The percentages of the paddock that fell within a particular zone for either spatial variation in crop and pasture yield, temporal stability or stability index categories were calculated as the number of grid points that fell within a particular zone as a percentage of the total number (27,850) of grid points in the paddock.

2.6 Statistical analysis:

Randomised points were generated in ArcGIS across all four stability zones for the paddock using the standardised crop yield data. The number of points generated was proportional to the area of each zone, with the smallest zone within the paddock always having a minimum of 30 points. Crop and pasture TGDM and CV values for these points were extracted in ArcGIS. The pasture TGDM and CV values were then tested against the crop yield and CV point values at each random point. Analysis was conducted on the random data set to compare relationships across all four zones (HS, HUS, LS and LUS). Since the stability indices are categorical data, a Chi-squared analysis was used. Not all of the data sets were from normal distributions, and so a non-parametric analysis was used, in this case Spearman’s rho to test the correlation of the whole data set, using JMP 12.2 and the Kruskal-Wallis one way anova test (Kruskal & Wallis, 1952) to test for differences between stability zones in R (v3.2.4 - The R Foundation for Statistical Computing, Vienna, Austria). 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 (0.05 in this case). For the Kruskal-Wallis tests, the null hypothesis was that the medians of all zones were equal, and the alternative hypothesis was that the population median of at least one zone was different from the population median of at least one other zone. The following combinations were tested for the 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 zones as the categorical variable in each case. It was hypothesised that: (i) the medians of the standardised values for the high yielding zones (HS and HUS) would be similar as would yields in the two low yielding zones (LS and LUS), but that the yield medians between both groups (HS, HUS) and (LS, LUS) would be different. For the stability measure (co-efficient of variation) it was hypothesised that the medians of CV for the stable zones (HS and LS) would be similar as would the unstable zones (HUS and LUS) and that the CV medians between both groups (HS, HUS) and (LS, LUS) would be different.

3. RESULTS:

The maps of spatial variability of standardised yield over time for both crop and pasture are presented in Figures 1 a and b. Yields were categorised by quartile and coded as relatively low yielding, below average, above average and relatively high yielding. The maps of temporal variability of standardised yield over time for both crop and pasture are presented in Figures 1 c and d. In both cases, there are significant areas of the paddock that fall into the same categories. Figures 1 e and f show the stability index maps for the individual crop and pasture phases. Figure 2 shows the overall paddock stability map, which combines the crop and pasture spatial trend and temporal stability data into one map. In Figure 2, map (a) shows areas of the paddock where the yields for both crop and pasture, over time, responded in a similar fashion – either high yield and stable (HS), high yield and unstable (HUS), low yield and stable (LS), low yield and unstable (LUS). The areas of the map that remain uncoloured represent other combinations of yield and stability other than HS, HUS, LS or LUS zones. Figure 2, map (b) shows the stability zones from map (a), (HS, HUS, LS or LUS) plus those areas of the paddock that were always temporally stable (where CV < mean), but flip-flopped in terms of yield for crop and pasture (eg HS for crop and LS for pasture, or vice versa). These areas are designated HLS on the maps – high or low, but stable. Map (c) is map (b) with the added inclusion of all zones that are temporally unstable (where CV > mean), ie either HUS crop and LUS in pasture, or vice versa. So zones with green tones are showing stable areas of the paddock, whereas red/yellow tones are showing unstable areas.

The results from the statistical analyses are summarised at Table 2. Spearman's rho revealed a moderately strong, statistically significant relationship for the paddock between the standardised values for crop yield and pasture TGDM for the randomised points ($\rho = 0.66$, $p < 0.0001$, N=262).

The Kruskal-Wallis one way anova showed that the stability index categories (HS, HUS, LS, LUS) for the paddock had significantly different medians for most of the differences between high and low yield zones and stable and unstable zones. Where the differences in medians were not significant (e.g. crop CV unstable or pasture CV), the medians were still grouped as would be expected.

The strong correlations between crop and pasture production are shown in Table 3. For spatial variation in yield, 55 % of the paddock is high yielding (RHY + HY) for crop and 56 % for pasture. Temporal stability shows 66 % of the paddock is stable over time for the cropping phase and 69 % for the pasture phase. For the paddock stability indices, 45 % of the paddock is high yielding and stable in the cropping phase and 52 % high yielding and stable during the pasture phase.

Table 2: Results from Spearman's rho correlation and Kruskall-Wallis one-way anova test for differences between the stability zones based on standardised crop and pasture yields or CV. The table shows the four zone median values calculated by the Kruskall-Wallis test. HS = high and stable yielding zones, HUS = high and unstable, LS = low and stable LUS = low and unstable. χ^2 is the Chi-squared test statistic for each Kruskall-Wallis test, ρ is the Spearman's correlation co-efficient and P the related probability.

	HS	HUS	LS	LUS	χ^2	P	ρ	P
Spearman's rho: correlation crop yld x pasture yld							0.66	<0.001
Crop yield (%)	110.53^{a}	112.65^{a}	85.61^{b}	78.31^{b}	193.18	<0.001		
Pasture yield (%)	116.75^{a}	105.96^{a}	91.25^{b}	82.77^{b}	99.29	<0.001		
Crop CV	5.24^{a}	18.68^{b}	5.76^{a}	25.17^{c}	177.09	<0.001		
Pasture CV	4.92^{a}	7.29^{b}	10.99^{bc}	14.9^{c}	53.17	<0.001		
Crop yld – Pasture yld	9.98^{a}	7.48^{a}	15.64^{b}	17.22^{b}	25.68	<0.001		
Crop CV- Pasture CV	3.19^{a}	11.43^{bc}	6.56^{c}	14.83^{b}	54.81	<0.001		

Median values with different letters indicate that the SI zone medians are significantly different across the row.

Table 3: Numbers and percentages of total grid points (N = 27,850) for crop grain and pasture biomass yields by spatial and temporal categories based on the number of individual grid points in each category. For example, 25 % of the paddock was relatively high yielding (RHY) for grain and 22 % for pasture.

CATEGORY	CROP		PASTURE	
	No. points	Percentage	No. points	Percentage
Crop and pasture yld:				
RHY	6,864	25 %	6,079	22 %
AA	8,354	30 %	9,951	36 %
BA	5,350	19 %	4,569	16 %
RLY	7282	26 %	7,251	26 %
Temporal stability:				
Stable: CV <13	18,429	66 %	19,344	69 %
Unstable: CV >13	9,421	34 %	8,506	31 %
Stability index:				
HS	12,612	45 %	14,588	52 %
HUS	3,177	11 %	1,442	5 %
LS	5,722	21 %	4,707	17 %
LUS	6,339	23 %	7,113	26 %

RHY = relatively high yielding, AA = above average yield, BA = below average yield and RLY = relatively low yielding; HS = high and stable yielding zones, HUS = high and unstable, LS = low and stable LUS = low and unstable.

(a) (b)

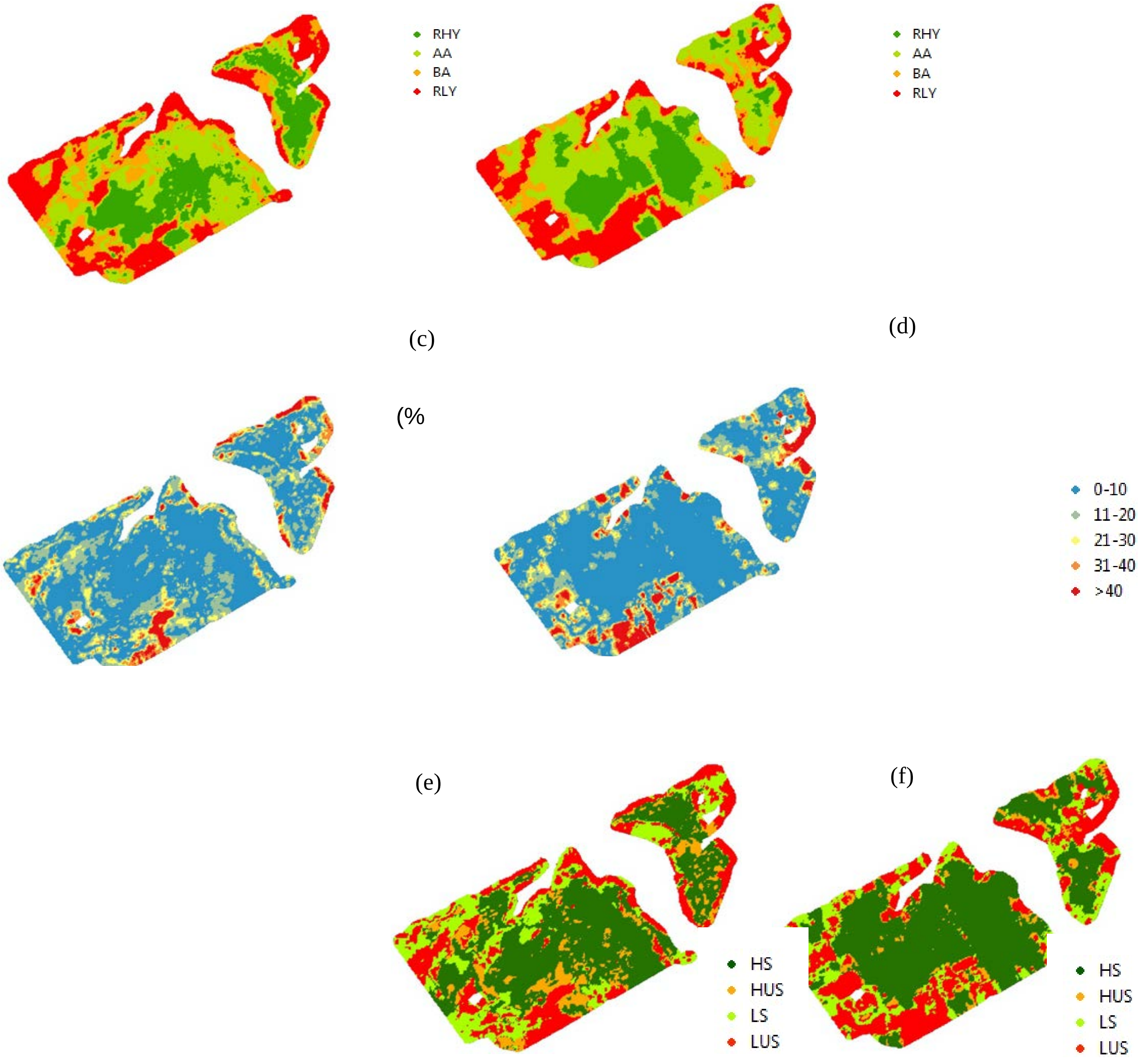

Figure 1: (a) standardised crop yield and (b) standardised pasture TGDM. RHY = relatively high yielding, AA = above average yield, BA = below average yield and RLY = relatively low yielding; (c) distribution of the CV of standardised yield over time for crop yield and (d) pasture TGDM; (e) stability index map for crop yield and (f) pasture TGDM. HS = high and stable yielding zones, HUS = high and unstable, LS = low and stable LUS = low and unstable.

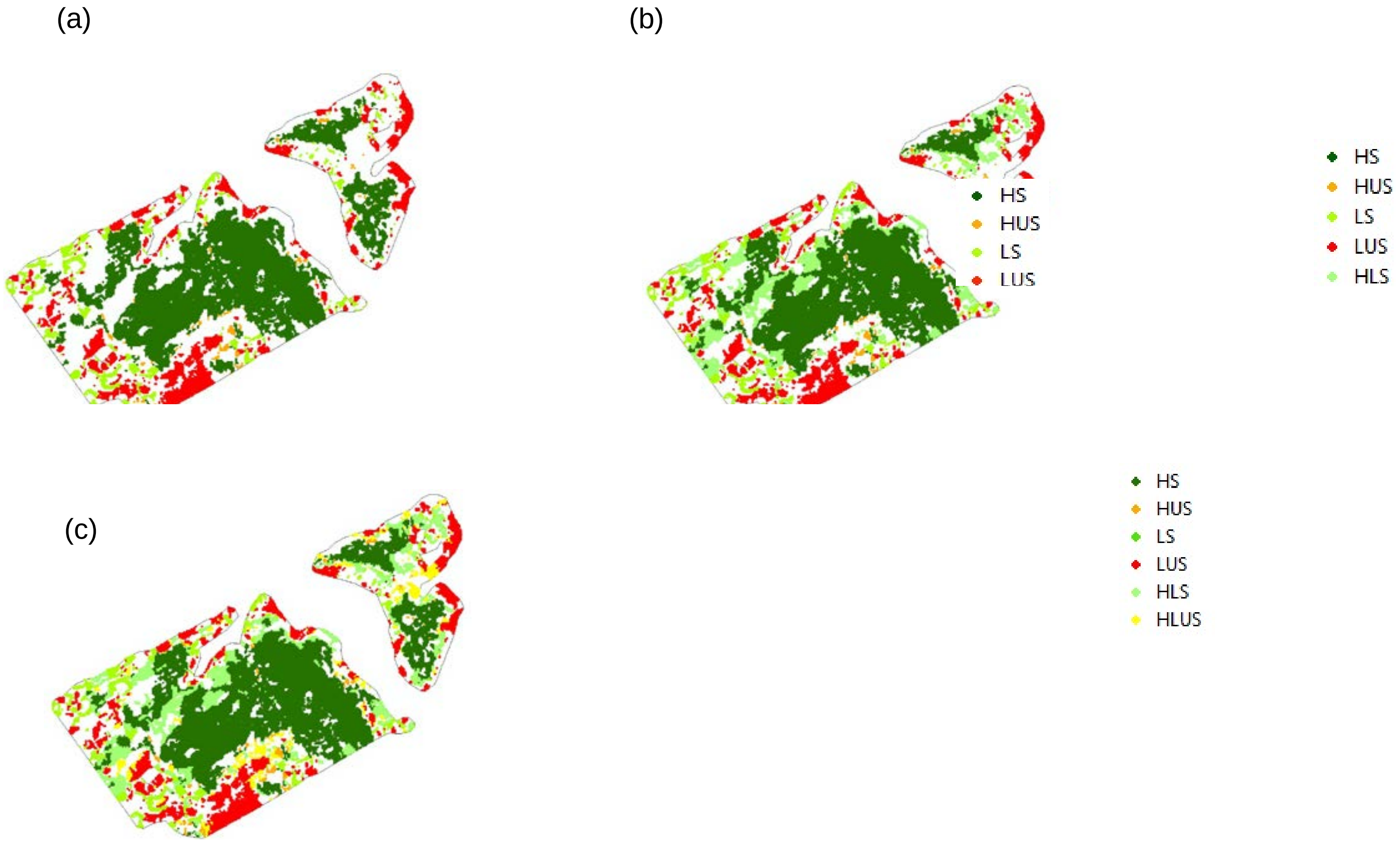

Figure 2: Combined crop and pasture stability maps. (a) all data points that are either HS, HUS, LS and LUS for both crop and pasture; (b) is map (a) including points where yields are temporally stable, but exhibit contrary yield behaviour (ie points are HS in crop but LS in pasture, or vice versa); (c) shows map (b) including all points that are temporally unstable, and exhibiting contrary yield behaviour (ie points are HUS in crop but LUS in pasture, or vice versa).

4. DISCUSSION:

The aim of the study was to create a single spatial and temporal index of production stability that combined crop yield and pasture TGDM data, reducing it to a single variable. This was successfully achieved in the form of a SI (stability index) for the paddock. Previous attempts to create paddock stability zones have been restricted to either crop or grassland paddocks, never with crop and pasture sequences simultaneously. A number of researchers have described the creation of stability zones in either crop or pasture paddocks (Blackmore, 2000; Blackmore et al., 2003; Marques da Silva, 2006; Marques Da Silva et al., 2008; Xu et al., 2006). However, all have reported difficulty in establishing a valid approach to determine a “threshold” value for temporal variability. In the work described here, the CV distribution mean was used as the threshold stability value for crop and pasture yield. Four productivity zones were identified: high and stable, high and unstable, low and stable and low and unstable. Production in each zone was analysed statistically for consistency and relevance between crop and pasture phases.

The Kruskal-Wallis one-way anova test showed that the paddock spatial variability aspects of the crop stability zones and pasture stability zones conformed with expectation. That is, the medians for high yield in crop and high yield in pasture for both the stable and unstable zones were not significantly different. This was also the case with the low yielding zones. However, there was a significant difference between the high yielding zones and the low yielding zones. This provides strong evidence in support of the hypotheses and methodology used to split the yield data among zones. The Kruskal-Wallis test for the temporal stability aspect (CV) did not always show a significant difference between the stable and unstable zones. However, examining the medians for the four zones shows that the values of the unstable zone medians were close (eg medians of 18.68 and 25.17 for crop CV for HUS and LUS) and distant from the medians in the stable zones (5.24 and 5.76), which were not significantly different.

There is also a strong similarity between the percentages of the paddock falling into the various stability zones in the cropping and the pasture phases (Table 3). For example, 45 % of the paddock is high and stable for the cropping phase and 52 % for pasture. Similarly, 23 % was low and unstable for crop and 26 % percent for pasture. So although not always establishing statistical difference in medians at $p = 0.05$ for stable and unstable zones, it is clear that the medians are falling into similar stable and unstable groupings. This reflects the difficulty in establishing the “ideal” stability threshold.

There are many factors in the pasture phase which compound variability compared to a crop. In this study, a highly managed monoculture in the cropping phase was compared to a largely unmanaged, highly diverse and complex sward of pasture species with uncontrolled animal impact. The creation of stability indices for cropping enterprises is relatively straight forward and has been documented (Basso et al., 2012; Blackmore et al., 2003; Marques da Silva, 2006). There is also usually a reasonable number of years of high resolution crop yield data available. This contrasts strongly with pasture phases where little recording of pasture production is undertaken, with the focus instead being on animal performance. For this research, two consecutive years of high resolution pasture data were obtained through crop circle NDVI scans correlated to pasture biomass cuts, to create paddock-wide data sets of pasture dry matter. It is recognised that the accuracy of NDVI data would be lower than that obtained from calibrated yield monitors on crop harvesters.

There is still a great deal of work required to refine the definition of pasture SI zones. For example, the impact of grazing on pasture TGDM estimation and decisions about productive stability is an area where there are significant knowledge gaps that were not able to be taken account of in the work described here. This is evident in the Kruskal-Wallis tests, where there were a number of non-significant results associated with the pasture CVs. 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 it was eaten off. Sward stability is affected by animal grazing and diet selection impact, stocking rate decisions by managers, pasture regrowth and often highly variable species in the swards. Nutrients enter and leave the soil and farm system via several pathways. Losses include crops, animal products, fodder, leaching and run-off and soil retention and imports include feed (hay, grain). The amounts lost through leaching are not readily or accurately known, and the distributions brought about through manure and urine deposition by grazing animals is highly variable and can influence the spatial distribution of nutrients across a paddock. While the overall spatial and temporal utilisation of this paddock by livestock is unclear, without acquiring data through GPS tracking (Trotter & Lamb, 2008), it would be reasonable to expect that the high and stable areas would require more fertiliser than the low and unstable areas, as greater nutrient removal would be expected from the high and stable areas in the form of crop and animal product exports compared to low and unstable areas. Meta-analysis of data from livestock fitted with GPS tracking collars and accelerometers could identify spatial preference and distribution of animals within a paddock at particular times of day, week, month or season and of livestock social networks. It could also identify foraging patterns, time spent grazing, resting and ruminating. This applies to the grazing of a crop in a “grain & graze” system (Price & Hacker, 2009) as well as when the paddock is in pasture. The use of tracking data combined with modelling of grazing with software packages such as “Grass Gro” (Clark et al., 2000) or “Ausfarm” (Freer et al., 2012) could further refine the accuracy of the pasture data. The levels of nutrients exported by both crops and animal products have been quantified (Price, 2006) and the use of nutrient budgets are available to make sure that the fertiliser inputs match the nutrient requirements reflected in the spatial distribution of each nutrient over the entire farm. It would be interesting to conduct further soil testing now that zones have been identified to help identify and possibly better characterise zone differences. Currently, variable rate (VR) fertiliser decisions are based solely on crop grain yield. With overall paddock stability indices, farm managers now have some data that could be integrated with crop data to enhance decisions about VR fertiliser. This would also have implications for decisions about in-season N applications and for N decisions coming out of pasture into crop.

5. CONCLUSION:

This paper has described the creation of paddock stability maps and a stability index that identifies and combines the spatial and temporal variation for both crop and pasture phases in an Australian mixed farming system. Not-withstanding the reservations described above, this work has shown the paddock stability index to be a robust methodology that is able to identify significant areas of a paddock that exhibit similar productive behaviour, whether in crop or pasture, year in year out. The methodology can be of great benefit to a farm manager, not only in terms of future expectations of production, but also in terms of decisions regarding variable rate applications of seed and fertiliser and even future land uses. The stability zones can also be used to create “gross margin” maps of each paddock to assist in optimising financial inputs and returns.

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