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1 **Title**

2 2 Mapping the spatial and temporal stability of production in mixed farming systems: an index that integrates crop
3
4 3 and pasture productivity to assist in the management of variability.

5
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40
41 21

22 **Abstract**

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

38 **Key words**

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

41 **Introduction**

42 Mixed farming systems that combine grain cropping and pasture-based livestock enterprises dominate the
43 dryland farming regions of Australia. In southern Australia, the mixed farming zone lies between the 300 and
44 600 mm average annual rainfall isohyets and is highly seasonal, encompassing climates with cool, wet winters
45 and hot, dry summers. The combination of highly variable rainfall and volatile commodity prices faced by
46 Australian farmers in these regions has favoured a diversified farming system that moderates the risks to the
47 farm enterprise (Bell and Moore 2011). While precision agriculture (PA) technologies are widely used in
48 Australian cropping systems, their use as a whole-of-farm management strategy in mixed farming systems has
49 received far less attention. There are few published reports of attempts to use spatial monitoring technologies to
50 investigate livestock and pasture interactions in the pasture phase and to follow the after-effects of different
51 management strategies into a subsequent cropping phase. Relatively little is known about the nature, extent, or

52 temporal stability in relation to spatial variability of pasture production in mixed farming systems, whether it is
53 feasible to manage this variability in a site-specific way and therefore, to integrate it into a precision
54 management system across crop and pasture sequences. For the most part paddocks tend to be managed as
55 single units during pasture phases, ignoring the existence of productivity gradients across the landscape (Hill et
56 al. 1999). Given that, in a typical Australian mixed farming system, somewhere between 20 and 50% of the
57 farm area is in pasture at any time (Angus and Peoples 2013; Bell et al. 2014b; Ewing and Flugge 2004; Li et al.
58 2010), this is an aspect of precision farming technology that has not been previously explored to any extent. A
59 significant amount of on-farm high-resolution data has been gathered and is available for analysis of within-
60 paddock spatial variability of yield in cropping phases in the form of geo-referenced yield monitor data, soil
61 analytical data (Oliver and Robertson 2009; Simeoni et al. 2009; Sudduth et al. 2010; Sudduth et al. 2009),
62 proximal soil sensors (Pullanagari et al. 2012; Schirrmann et al. 2011; Serrano et al. 2010; Sun et al. 2012) or
63 combinations of these (Castrignanò et al. 2012; Wong et al. 2010). The most common approach to managing
64 spatial variability in crops is to use this data to define ‘management zones’ in a system known as ‘site-specific
65 management’ (SSM) (Plant 2001; Taylor et al. 2007; Whelan and McBratney 2003). SSM aims to better
66 quantify and delineate the causes of yield variability between different parts of a paddock (Buttafuoco et al.
67 2010; Farid et al. 2016; Moral et al. 2010). However, there is little information about the nature of spatial
68 variability in pasture biomass production from these same paddocks when in a pasture phase. This presents a
69 significant lost opportunity given that pasture phases can last from between one or two years (annual pastures)
70 to between three and six years (perennial pastures) (Bell et al. 2014a; Kirkegaard et al. 2014; Nichols et al.
71 2007). By and large, pasture–livestock phases are ‘low-input’, where livestock and the pastures they graze are
72 managed less intensively than crops (Bell et al. 2014a; Kirkegaard et al. 2011). Several approaches have been
73 used in the past to identify regions of temporal stability in crops (Blackmore 2000, 2003; Diacono et al. 2012;
74 Dobermann et al. 2003; Marques da Silva 2006); and in pastures (Marques da Silva et al. 2008; Serrano et al.
75 2014; Schmer et al. 2009; Serrano et al. 2011; Xu et al. 2006). The assessment of temporal stability is important
76 because it affects the reliability of management zones as a strategy for differential management in crop and
77 pasture phases.

78 The objectives of this research were:

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

- 81 2. To compare within-paddock spatial variation in crop grain yield and pasture biomass production in two
1 2 82 mixed farming systems; and
3
4 83 3. To create a single map of spatial variation of crop yield and pasture biomass production at a point,
5
6 84 across a paddock, a “Stability Index”, to assist decision making by farm owners and managers in
7
8 85 implementing site-specific management strategies in a sequence of grazed pasture and cropping phases.
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10 86 It was hypothesised that spatial variation of production in both the crop and pasture phases of a mixed farming
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12 87 system could be identified and quantified at high resolution using PA technologies and that the data so acquired
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14 88 could be used to create a single index of productivity that described the spatial variation in, and temporal
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16 89 stability of, both crop grain and pasture biomass yields within a paddock over time.
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18 90 **Materials and Methods**

19 20 91 **Study sites**

21
22 92 Two properties were used for the study: “Milroy”, a 1900 ha sheep and cropping enterprise located at Brookton
23
24 93 (32.22°S, 116.57°E), 120 km east of Perth, Western Australia (WA) and “Grandview”, a 2250 ha cattle and
25
26 94 cropping enterprise located 10 km south of Yarrawonga (36.05°S, 145.60°E) in north-eastern Victoria (Fig. 1).
27
28 95 Wheat (*Triticum aestivum* L.) and canola (*Brassica napus* L.) are the main crops grown on both properties.
29
30 96 Pastures on “Milroy” are dominated by subterranean clover (*Trifolium subterraneum* L.) and capeweed
31
32 97 (*Arctotheca calendula* L.) with some serradella (*Ornithopus sativus* Brot.), barley grass (*Hordeum glaucum*
33
34 98 Steud.) and annual ryegrass (*Lolium rigidum* Gaud.). After a continuous cropping rotation of four years or more,
35
36 99 (eg canola, wheat, wheat, barley), pastures at “Milroy” are re-sown. Where pasture phases occur in between
37
38 100 crops (eg wheat, pasture, wheat, pasture, wheat), pastures are self-sown.
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40 101 At “Grandview”, the crop and pasture phases are each of six years’ duration. Pastures comprise lucerne
41
42 102 (*Medicago sativa* L.), subterranean clover and chicory (*Chicorium intybus* L.), and are established by under-
43
44 103 sowing with the crop in the last cropping year. Crop yield and pasture biomass data was collected from three
45
46 104 paddocks on each property between 2004 and 2014. Here data is presented for one representative paddock from
47
48 105 each property: paddock M41 at “Milroy” (2008-2014) and paddock GV39 at “Grandview” (2007-2013). Pasture
49
50 106 and crop rotations and paddock sizes for both study paddocks are described in Table 1. At both properties
51
52 107 livestock were set-stocked. The paddock at “Milroy” was stocked with cross-bred lambs at 8 dry sheep
53
54 108 equivalent (DSE) / ha in 2012 and 9 DSE / ha in 2013. At “Grandview” the paddock was stocked with Angus
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56 109 feeder steers at an equivalent stocking rate of 10 DSE / ha.
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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” Yarrowonga, Vic											
GV39 (60 ha)	P	C	W	C	W	W	B	P	P	P	P

^aThe 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

135 **Table 2** Average monthly rainfall, maximum and minimum temperatures (1970-2000) for “Milroy”, Brookton,
 136 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

137 ^aThe growing season is defined as the period between 1 April and 31 October. Brookton and Yarrawonga
 138 climate data was obtained from the SILO Data Drill data base

139 **Electromagnetic induction surveys**

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

147 At “Grandview” EMI data was again collected by a commercial contractor, using a Geonics EM38-M2 with 0.5
 148 m and 1 m intercoil spacings (Geonics Limited, Mississauga, ON, Canada). The instrument was used in
 149 horizontal mode (ECah), giving a conductivity of 0.38 m at 0.5 m coil separation and 0.75 m conductivity at 1 m
 150 coil separation. Transect width was 30 m. The horizontal mode was used at the recommendation of the
 151 contractor, who has many years of EMI sensing experience in the region. The instrument was calibrated on-site
 152 as per instructions outlined in the Geonics EM38-MK2 Ground Conductivity Meter Operating Manual, July
 153 2008. Data was logged using an Allegro CX Field PC (Juniper Systems, Logan, Utah, USA) loaded with
 154 Geonics EM38-MK2 software. The data logger was set to acquire and record survey data from the EM38-MK2
 155 system at four readings per second. Output feed and guidance was provided using a Raven ‘Cruizer’ GPS
 156 (Raven Industries, Sioux Falls, South Dakota, USA).

157 **Soil sampling and testing**

158 Soil sampling was conducted across both paddocks in 2013 in conjunction with the EMI scanning, whilst they
1 were in a pasture rotation. This was before the spatial mapping and stability index work had been completed. At
2 159 both properties, soil sample locations and number of sampling sites were determined by the soil-sensing
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4 160 contractors using a 50 mm hydraulic soil corer to ground-truth the data and support the interpretation of the EMI
5
6 161 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
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8 162 at “Milroy” in 2014 by the farm owner at eight sites chosen by him, within paddock M41 as part of a pre-liming
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10 163 paddock analysis. Samples for these tests were taken between 0 m and 0.5 m, at 0.1 m intervals, using a
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12 164 hydraulic soil coring drill. All soil analyses (N, P, K, S, pH, OC, PBI, Cond, Cu, Fe, Mn, Zn, Ca, Mg, Al, Na, B)
13
14 165 were conducted by the CSBP Soil and Plant Analysis Laboratories (Bibra Lake, Western Australia)
15
16 166 (www.csbp.com.au/CSBP-Lab).
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168 **Crop harvest yield data and yield mapping**

169 Grain yield data was acquired at both properties from harvester mounted yield monitors using differentially
20
21 170 corrected real-time kinematic (RTK) GPS systems. Raw yield data was processed using the protocol developed
22
23 171 by Taylor et al. (2007) to remove outliers and trim data to practical yield threshold limits. Yield data was then
24
25 172 imported into ArcGIS 10.2 (ESRI, Redlands, California) and mapped to a standard 5 m x 5 m grid. The grid was
26
27 173 established in ArcGIS 10.2 using the Geospatial Modelling Environment platform (Spatial Ecology,
28
29 174 <http://www.spatial ecology.com>) and kept constant throughout the analysis. Data was interpolated to the grid
30
31 175 using Vesper 1.62 software (Australian Centre for Precision Agriculture, The University of Sydney, NSW)
32
33 176 (Whelan et al. 2001). Block kriging was used with an exponential variogram and a block size of 10 m x 10 m to
34
35 177 generate continuous surface maps. Kriging was used as there were insufficient data points to confidently
36
37 178 interpolate yield values between sampled areas and to enable data from different times and sources to be
38
39 179 compared. General settings were as described in the Vesper 1.62 User Manual (Australian Centre for Precision
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41 180 Agriculture, The University of Sydney, NSW) (Whelan et al. 2001) .
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181 **Mapping pasture green herbage mass in pastures**

182 Red (~650 nm) and near-infrared (NIR) (~880 nm) reflectance values for the calculation of pasture vegetation
46
47 183 indices (Holland et al. 2004) were acquired using a Crop Circle™ ACS-210 active sensor (Holland Scientific
48
49 184 Inc., Lincoln, NE, USA). To map the pasture biomass, the Crop Circle™ sensor head was linked to a Trimble
50
51 185 EZ-Guide 250 GPS Lightbar guidance system (Trimble, Sunnyvale, CA, USA) and a Holland Scientific
52
53 186 GeoSCOUT 400 series data logger set to record geo-referenced red and NIR outputs at 1 Hz. The Crop Circle™
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55 187 sensor was vehicle mounted so that its height was approximately 0.9 m above the ground. All Crop Circle™
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188 data was collected along transects spaced 40 m apart. Speed across the paddocks was approximately 10–15
1 km/hr. Normalised difference vegetation index (NDVI) values from the transects were trimmed to remove
2 189 values <0.1 and >0.9. Remaining points were then imported into ArcGIS 10.2 and mapped to the 5 m x 5 m
3
4 190 grid. Data was interpolated to the grid using Vesper 1.62 software as previously described. At “Milroy”, Crop
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6 191 Circle™ scans were taken in July, August and September 2012 and in August/ September 2013. At
7
8 192 “Grandview”, scans were conducted in August and September 2012 and September/ October 2013.
9

10 193 11 194 **Collection of pasture samples for calibration of vegetation index**

12 195 To calibrate the NDVI scans to actual pasture biomass present in the paddock, twenty-five randomly selected
13
14 196 pasture samples were taken across each paddock. Multivariate *k*-means clustering (JMP version 12.2; SAS
15
16 197 Institute Inc., Cary, NC, 2016), based on the NDVI values from the Crop Circle™ scans, was used to randomly
17
18 198 select twenty-five pasture sampling sites in each paddock. The NDVI point values from the pasture scans were
19
20 199 divided into five clusters, and five points selected randomly from within each cluster, to give twenty-five
21
22 200 sampling points for each paddock. These sites were then imported into ArcGIS 10.2 and mapped as geo-
23
24 201 referenced points in the paddock. To locate each sampling point for the calibration cuts, the selected pasture
25
26 202 sites were imported into ‘gpMapper’ mapping software (Fairport Farm Software, Perth WA), loaded on a laptop
27
28 203 computer and linked to the Trimble EZ-guide 250 GPS. Pasture samples were then taken at these sites in Spring
29
30 204 (September / October) of 2012 and 2013 at both properties, when plants were actively growing and pasture
31
32 205 canopies were reasonably extensive. At each sample point, the Crop Circle™ unit was used in ‘hand-held’
33
34 206 configuration to measure the NDVI value within a 0.56 m x 0.12 m quadrat. Pasture within the quadrat was
35
36 207 harvested to ground level using battery powered shears. The cut pasture samples were subsequently sorted into
37
38 208 green and dead herbage mass fractions and legume/grass/herb fractions and oven-dried at 80°C for 48 hours
39
40 209 before weighing, to provide total herbage mass (kg) of total green dry matter (TGDM) per hectare for each
41
42 210 sample site. To test the validity of using NDVI rather than an alternative vegetation index, the averaged red and
43
44 211 NIR reflectance values acquired from Crop Circle™ scans for each pasture sample site were used to create four
45
46 212 different spectral indices; (i) NDVI, (ii) the Soil-Adjusted Vegetation Index, SAVI (Huete 1988), (iii) the Non-
47
48 213 Linear Vegetation Index, NLI (Goel and Qin 1994) and (iv) the Modified Non-Linear Vegetation Index, MNLI
49
50 214 (Gong et al. 2003). Because of the small sample sizes involved (n=25), the datasets were validated using Leave
51
52 215 One Out Cross Validation (LOOCV) in the R statistical package (v. 3.3.3) (R Core Team 2017).
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216 Calculation of TGDM calibration equations

1
2 217 The NDVI value taken at each pasture sampling cut site was regressed against the corresponding TGDM site
3
4 218 value from the pasture sample cuts to produce a calibration equation for each paddock in each year of scanning.

5
6 219 As the two sites were more than 3000 km apart, and in different climatic zones, it was not valid to combine data
7
8 220 into a single calibration equation. The calibration equations were then used to convert NDVI values acquired
9
10 221 from the pasture scans to geo-referenced TGDM values. The TGDM values were imported into ArcGIS 10.2 to
11
12 222 produce maps showing spatial variation in predicted pasture biomass yield for each paddock.

14 223 Calculating the spatial trend of yield

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16 224 The spatial trend of yield for crops and pastures was determined by standardising the yield data at each grid
17
18 225 point over a sequence of yield maps. Standardising the data replaces the units of yield with a percentage that can
19
20 226 be used for comparison between crops and pastures, as each point is compared to the paddock average of 100%.

21
22 227 The standardised yield was calculated as per Blackmore (2000):

$$24 \quad 228 \quad s_i = \left(\frac{y_i}{\bar{y}} \right) \times 100 \quad (1)$$

25
26
27 229 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
28
29 230 mean yield for that year.

30
31 231 The point mean was then calculated over the years of interest, enabling different crops or pasture to be included
32
33 232 and compared:

$$35 \quad 233 \quad \bar{s}_i = (\sum_{t=1}^n s_{i,t})/n \quad (2)$$

36
37 234 where \bar{s}_i is the average of s_i , the standardised yield at point i , over n years.

38
39 235 This standardised yield shows, at any point, in any one year, how the yield differs from the paddock mean
40
41 236 (100%). The standardised data were then classified into four yield zones in relation to the relative percentage
42
43 237 difference from the paddock mean (100%) using the yield data distribution quartiles to define the four yield
44
45 238 classes. The areas for which this value was greater than the paddock mean were classified as 'high yielding'
46
47 239 (HY, 4th quartile) and 'above average' (AA, 3rd quartile); while the areas for which this value was less than the
48
49 240 paddock mean were defined as 'below average' (BA, 2nd quartile) and 'low yielding' (LY, 1st quartile). Yield
50
51 241 maps of spatial trend for crop and pasture were then created by averaging the standardised yield at each grid cell
52
53 242 over the years being considered (effectively 'combining' yield maps) and processing in ArcGIS 10.2. These
54
55 243 spatial trend maps show the spatial yield pattern in a paddock over time for both crops and pastures.
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244 **Calculating temporal stability**

1
2 245 To estimate how stable in time the crop and pasture yields were at “Milroy” and “Grandview”, the coefficient of
3
4 246 variation (CV) in yield was calculated at each point in the paddock for which there was a yield value for either
5
6 247 grain yield or pasture TGDM, following the procedure developed by Blackmore (2000). The advantage of using
7
8 248 CV is that it is unit-less, allowing multiple crops and pastures to be compared with each other.

9
10 249 The CV was calculated from the standardised yield values calculated previously, using the equation from
11
12 250 Blackmore (2000):

$$13$$
$$14$$
$$15$$
$$16 \text{CV}_{s_i} = \frac{\left(\frac{n \sum_{t=1}^n s_{it}^2 - (\sum_{t=1}^n s_{it})^2}{n(n-1)} \right)^{0.5}}{\bar{s}_i} \times 100 \quad (3)$$
$$17$$

18 252 where CV_{s_i} is the coefficient of variation of the standardised data at point i , over n years.

19 253 Using this equation, the CVs of crop grain yield and pasture TGDM yield were calculated for “Milroy” paddock
20
21 254 M41 and “Grandview” paddock GV39, for both cropping and pasture phases for the years with sufficient data
22
23 255 (Table 1). Five arbitrary classes were used: 0-10%, 11-20%, 21-30%, 31-40% and >40%. The CV data for crop
24
25 256 yields and pasture DM yields were processed in ArcGIS 10.2 to produce maps showing the range of CV values
26
27 257 (%) across each paddock for crop grain yield and pasture TGDM yield. The temporal stability maps were then
28
29 258 classified into stable yield zones and unstable yield zones when a given temporal CV value (threshold) was
30
31 259 adopted to subdivide the two zones.

32 260 **Mapping spatial and temporal trend**

33
34
35 261 By combining the data behind the spatial trend maps and the temporal stability data, a single representation of
36
37 262 each paddock over time and for both crop and pasture–livestock phases was developed by classifying the
38
39 263 paddock into four categories based on yield (high or low) and stability (stable or unstable) at a point in time
40
41 264 (Table 3). Because yield and stability are not mutually exclusive variables, there were four possible
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43 265 combinations for these two variables: high and stable (HS); high and unstable (HUS); low and stable (LS), and
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45 266 low and unstable (LUS). Crop grain and pasture TGDM yields were considered high if a particular point value
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47 267 was above the mean yield (>100%) and vice versa. The stability of yield at that point was compared to a
48
49 268 threshold value - in this case, the mean of the distribution of yield CV values for the paddock - to determine if
50
51 269 the yield at that point was stable (< mean CV) or unstable (> mean CV) (Table 4).

52
53 270 The spatial trend and temporal stability categories for the crop and pasture rotations were allocated a numerical
54
55 271 code between 1 and 4 based on the class conditions (Table 3) and the concatenate function in Microsoft Excel
56
57 272 was then used to combine crop and pasture codes at each point to create an overall stability index for each
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273 paddock. Mapping this index shows areas of the paddock that were high and stable (HS) in both crop and
 274 pasture yield (ie concatenation gives a “1,1” result), low and stable in both crop and pasture yield (LS - “3,3”),
 275 areas that were high and unstable (HUS – “2,2”), and low and unstable (LUS – “4,4”). Because the crop and
 276 pasture yields at a point will not always be both high and stable, low and unstable etc, concatenation results in
 277 areas that were neither HS, HUS, LS or LUS, in the overall stability map, leaving areas that were uncategorised
 278 (e.g. “1,3”, “4,2” etc). There were areas of the paddock that remain uncategorised with the SI process, where
 279 production could be stable, but high yielding in one phase and low yielding in the other (eg, high and stable in
 280 crop, but low yielding and stable in pasture (HS/LS).

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

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

282
 283 **Table 4** Stability thresholds used in the calculation of stability indices for “Milroy” and “Grandview”
 284 paddocks^a

Property	Paddock	Stability threshold	
		Crop	Pasture
“MILROY”	M41	13%	13%
“GRANDVIEW”	GV39	22%	12%

285 ^aIn each case, the mean value of the distribution of cv values for crop or pasture were used

286 Using such a large data set (15,000 data points - the “population”) in the statistical analysis would almost
 287 certainly have led to significant differences between the medians (Meehl 1990; Waller 2004; Ziliak and
 288 McCloskey 2008), so a representative sample of the data set was used instead for hypothesis testing. The
 289 number of points generated was proportional to the area of each stability class, with the smallest class within a
 290 paddock always having a minimum of 30 points. These randomised points were generated in ArcGIS 10.2
 291 across all four stability classes in each paddock. Crop and pasture TGDM and CV values for these points were
 292 extracted in ArcGIS. For each paddock, analyses were conducted on that paddock’s random dataset to
 293 investigate the relationships between the pattern of crop and pasture production across all four classes (HS,
 294 HUS, LS and LUS). Since the stability indices were categorical data, a Chi-squared analysis was used. The
 295 Kruskal–Wallis one-way ANOVA test (Kruskal and Wallis 1952) was used to test for differences between
 296 stability classes using the R statistical package (v. 3.3.3) (R Core Team 2017). The Kruskal–Wallis test

297 computes a test statistic and P-value (assuming a Chi-square distribution) as well as pairwise comparisons at a
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2 298 specified alpha level ($\alpha=0.05$ in this case). For the Kruskal–Wallis tests, the null hypothesis was that the
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4 299 medians of all classes were equal, and the alternative hypothesis was that the population median of at least one
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6 300 class was different from the population median of at least one other class. The following combinations were
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8 301 tested for each paddock: crop yield, pasture yield, crop yield CV, pasture yield CV, crop yield minus pasture
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10 302 yield, and crop CV minus pasture CV, with the stability classes as the categorical variable in each case. Yield
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12 303 differences (crop yield minus pasture yield) at a point were tested to see if the differences between crop and
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14 304 pasture medians were significant. If both crop and pasture were responding in the same way at a point (highly
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16 305 correlated) then it would be expected that they would not be significantly different. If the crop and pasture
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18 306 values were highly variable then a significant difference between them would be expected.

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20 307 Based on our hypothesis that the data acquired across both crop and pasture phases could be used to create a
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22 308 single index of productivity that described the spatial variation in, and temporal stability of yields within a
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24 309 paddock over time, the expectation was that: (i) the medians of the standardised values for the high-yielding
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26 310 classes (HS and HUS) would be similar as would yields in the two low-yielding classes (LS and LUS) but that
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28 311 the yield medians between both groups (HS, HUS) and (LS, LUS) would differ and (ii) for the stability measure
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30 312 (coefficient of variation), that the medians of CV for the stable classes (HS and LS) would be similar as would
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32 313 the unstable classes (HUS and LUS) and that the CV medians between both groups (HS, LS) and (HUS, LUS)
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34 314 would differ.

35 36 315 **Correlation analysis of point values for crop grain yield and pasture dry matter production**

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38 316 To see if there was any relationship between crop and pasture yields at a point, a correlation analysis was
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40 317 conducted using JMP 12.2 (SAS Institute Inc, Cary, North Carolina, USA) on between-year crop yields and
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42 318 pasture TGDM yields for each paddock. As not all of the datasets were from normal distributions, a non-
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44 319 parametric Spearman's rho analysis was used (Corder and Foreman 2014).

45 46 320 **Results**

47 48 321 **Electromagnetic Induction Surveys**

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50 322 Figures 2 and 4 show soil textures as identified by the farm owners of “Milroy” and “Grandview” respectively,
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52 323 based on their knowledge and experience with their paddocks. Figures 3 and 5 show the spatial distributions of
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54 324 the ECa data for “Milroy” and “Grandview” respectively. The differences in mean ECa likely reflect the
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56 325 contrasting soil textures between the highly weathered, sandy soils at “Milroy” and the finer-textured clays at
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58 326 “Grandview”. The CVs for the data sets were much higher for “Milroy” (82% shallow; 104% deep) compared to
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327 “Grandview” (60% shallow; 9.7% deep) (Table 5), suggesting much greater soil variability at the “Milroy” sites,
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2 328 although there also appears to be considerable variability in the shallow (0-0.38 m) region at “Grandview”. At
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4 329 “Grandview”, the 0-0.38 m and 0-0.75 m ECa maps (Fig. 5a, b resp.) showed similar patterns of spatial
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6 330 distribution. At “Milroy” the percentage sand was negatively correlated with ECa, ECa 0-0.5 m showed a
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8 331 stronger correlation with sand content than ECa (0-1 m) (data not shown). There was also a reasonable
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10 332 similarity between the soil texture zones identified by the “Milroy” farm owner (Fig. 2), particularly with the
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12 333 ECa 0-1 m map (Fig. 3b). At “Grandview” there was a strong positive correlation between ECa 0-0.38 m values
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14 334 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-
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16 335 lying areas with the highest conductivity at “Grandview” corresponded with sodosols, with pockets of vertosols
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18 336 (Isbell 2016). There was a strong resemblance between the soil texture zones identified by the owner of
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20 337 “Grandview” for paddock GV39 (Fig. 4) and the ECa 0-0.5 and 0-1 m maps (Fig. 5a, b).

22 338 **Soil sampling and testing**

24 339 A summary of results from the soil analysis from CSBP is provided in Table 5. The results indicate that the
25
26 340 majority of soils in the “Milroy” paddock had more than 70% sand and less than 20% clay throughout the
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28 341 profile (0-0.6 m depth), and were described as either sandy, sandy loam or duplex (sand over clay) soils. These
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30 342 high sand percentages are typical of soils in the south-west of Western Australia. Clay content increased
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32 343 marginally with depth to 0.6 m; average clay content ranged from 13 to 20%. The range of soil test phosphorus
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34 344 concentrations (0-0.1m) across the “Milroy” paddock was 25 to 55 mg/kg, with an average Colwell P-value of
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36 345 45.6 mg/kg (Table 5). The lowest P-value in M41 was in the lowest part of the paddock, in deep sand. These
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38 346 values were above the critical range of 18-22 mg/kg for wheat/canola (Peverill et al. 1999; Reuter and Robinson
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40 347 1997) and generally above the 30 mg/kg for pastures (Gourley et al. 2007; Reuter and Robinson 1997). The
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42 348 variation in Colwell P values reflects the variability in soils at “Milroy”, from deep sands to sandy loams/gravels
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44 349 (Fig. 2).

46 350 At “Grandview”, subsoils were 50–60% clay. In the more elevated sections of the paddock, the “Grandview”
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48 351 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
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50 352 differences in soil texture between the tops of hills, mid-slopes and points of lowest elevation (Fig. 4). For
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52 353 “Grandview” Colwell P concentrations (0-0.1 m) ranged between 29 and 72 mg/kg (Table 5). The highest soil
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54 354 test P-value in GV39 was associated with a cattle camp and feed trough, indicating that there may have been
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56 355 some nutrient transfer occurring. Lower phosphorus levels in GV39 were associated with increased elevation.
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58 356 The mean soil P-value for GV39 was 45 mg/kg, well above the critical P-values for both crops and pastures.
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357 **Crop yield mapping**

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

363 **Table 5** Summary of soil texture and selected soil chemistry data for “Milroy” and “Grandview” paddocks. The
 364 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

365 n = the number of soil sampling sites in each paddock

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

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

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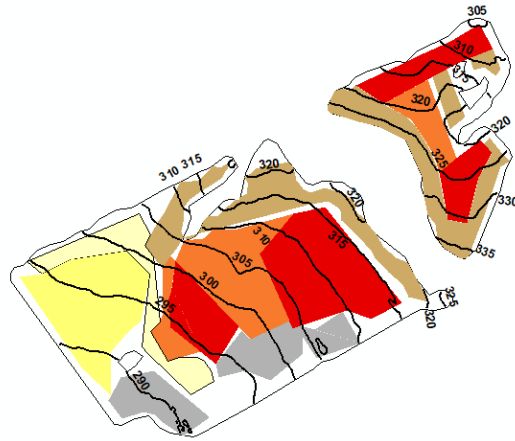


Fig. 2 Soil map created from farmer knowledge (Murray Hall, pers. comm.) for “Milroy” paddock M41. ■ sandy loam, ■ friable sand, ■ gravels, ■ sandy duplex (sodic), ■ sand on clay loam, ■ deep sand. Elevations are in metres at 5 m intervals

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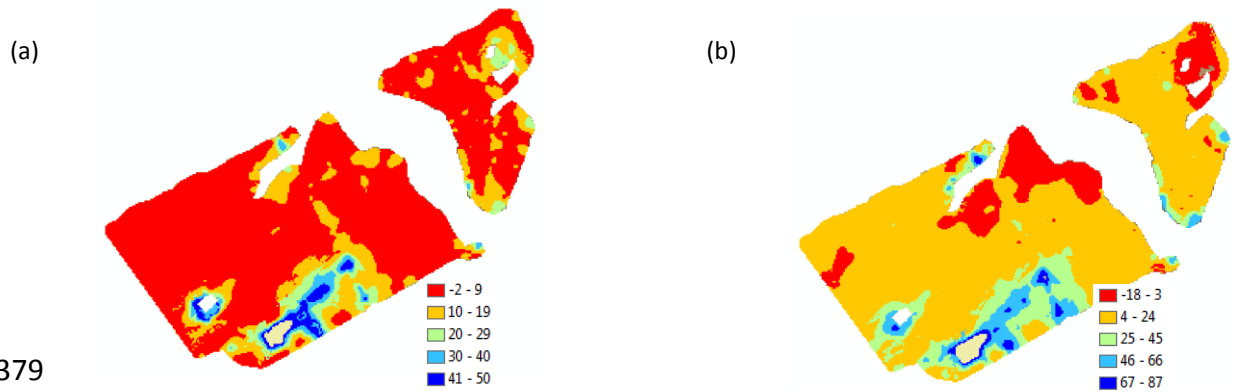


Fig. 3 Maps of soil EC_a (mS/m) from EMI scans of “Milroy” paddock M41 conducted in October 2013. (a) 0-0.5 m and (b) 0-1 m

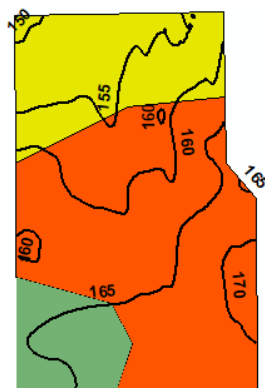


Fig. 4 Soil map created from farmer knowledge for “Grandview” paddock GV39 (Adam Inchbold, pers. comm.). ■ sandy clay loam over medium clay, ■ sandy clay loam over sodic fine clay, ■ clay loam over fine clay. Elevations are in metres at 5 m intervals

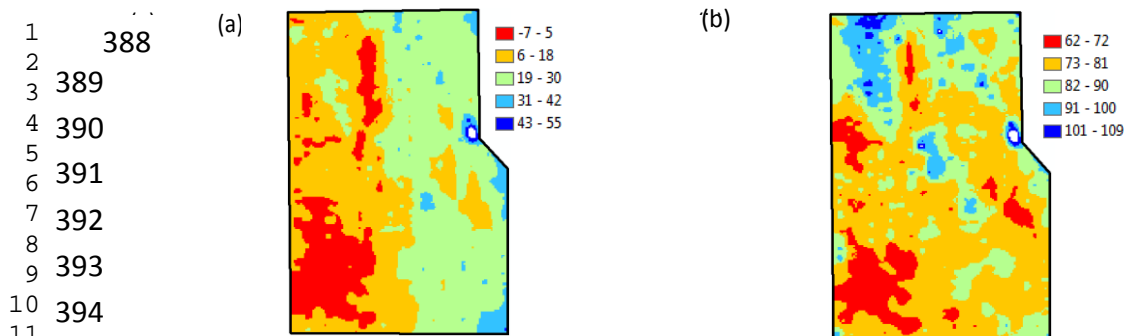


Fig. 5 Maps of soil ECa (mS/m) from EM38 scans of “Grandview” paddock GV39 conducted in October 2013. (a) 0-0.38 m and (b) 0-0.75 m. Scans were conducted with the EM38 in horizontal mode (ECa_h)

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™ 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™ 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

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419 predict TGDM, with R^2 values of 0.88 at “Milroy” and 0.81 at “Grandview”. Saturation of the NDVI signal at
420 high biomass levels can be seen at both “Milroy” (Fig. 7a) and “Grandview” (Fig. 7b) where increasing TGDM
421 values above around 3000kg/ha does not result in an increase in NDVI. This effect has been widely documented
422 in the literature, especially for agricultural landscapes (Glenn et al. 2008; Mutanga and Skidmore 2004;
423 Thenkabail et al. 2000), resulting in non-linear relationships between NDVI and biomass (Edirisinghe et al.
424 2011; Huete et al. 2002; Mutanga and Skidmore 2004; Viña et al. 2011).

425 **Spatial trend maps**

426 The standardised yield shows, at any point, in any one year, how the yield differs from the paddock mean
427 (100%). The standardised data across years has been averaged and classified into four yield zones in relation to
428 the relative percentage difference from the paddock mean (100%) using the yield data distribution quartiles to
429 define the four yield classes. The process used to combine crop yield maps (Fig. 8a, b) and pasture TGDM
430 maps (Fig. 8f, g) to create spatial trend maps over time for crop phases (Fig. 8c) and pasture phases (Fig. 8h) is
431 illustrated using data from “Milroy”. The same process was used to create spatial trend maps for “Grandview”.

432 **Temporal variability maps**

433 Whilst the spatial variability maps show the consistently high and low yielding areas of the paddocks over time
434 at “Milroy” and “Grandview”, the temporal variability maps show how stable in time these crop and pasture
435 yields were. The maps for temporal variability of standardised yield for crop and pasture are presented for
436 “Milroy” paddock M41 (Fig. 8d, i) respectively (“Grandview” not shown). The CV shows a low value if a
437 particular area of the paddock has a yield value that was always close to the mean. These areas can be
438 considered to have stable yield over time. If the yield in other areas of the paddock sometimes approaches the
439 mean and sometimes deviates from it, then these can be regarded as areas of temporally unstable yield. The
440 percentage of the paddock area across both sites in the most stable class (CV 0-10%) was >58%, with the
441 exception of “Grandview” in crop (21%) (Table 6). The area of the paddock in the highly unstable category (CV
442 >40%) in pasture phases ranged between 1% (“Grandview”) and 6% (“Milroy”) and in crop between 3%
443 (“Milroy”) and 7% (“Grandview”).

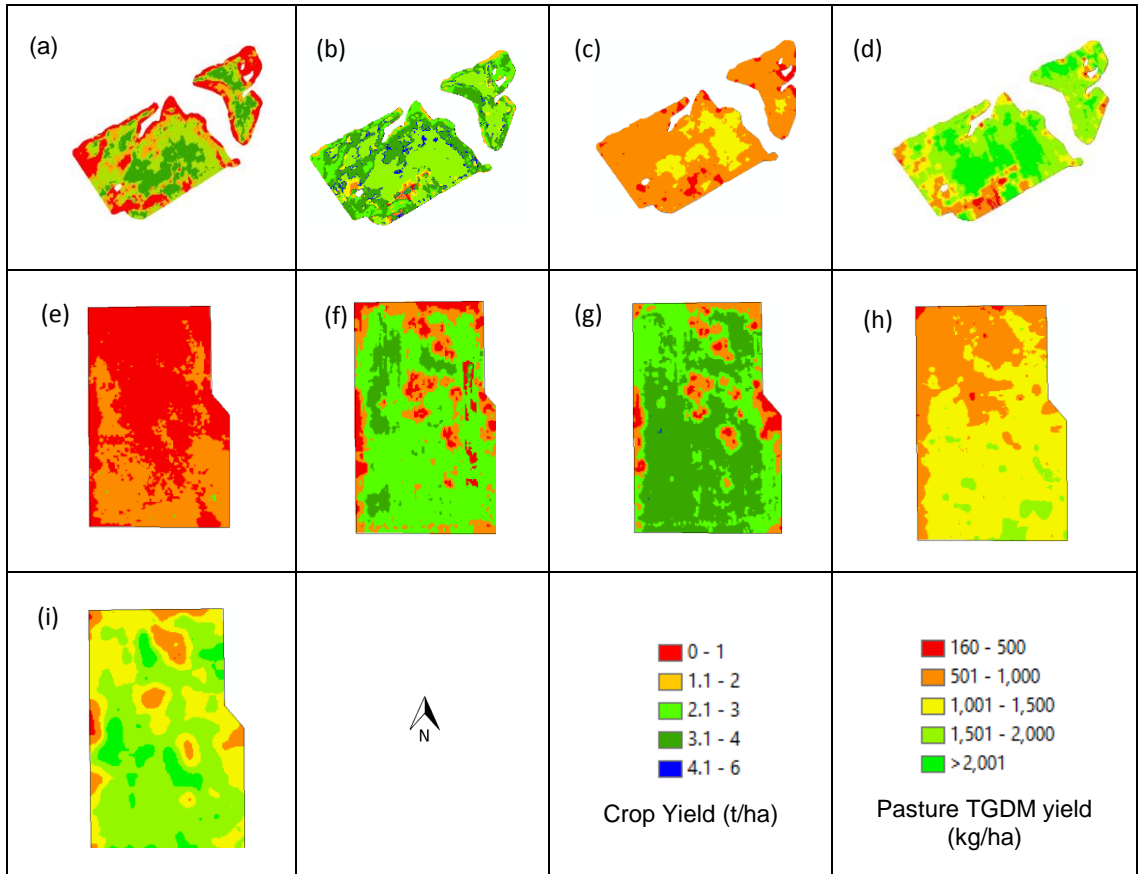


Fig. 6 Crop yield maps and pasture biomass maps for research paddocks. “Milroy” paddock M41: (a) crop 2008 and (b) 2014; (c) pasture Sept 2012 and (d) Sept 2013, “Grandview” paddock GV39: (e) crop 2007, (f) 2008 and (g) 2009; (h) pasture Sept 2012 and (i) Sept 2013

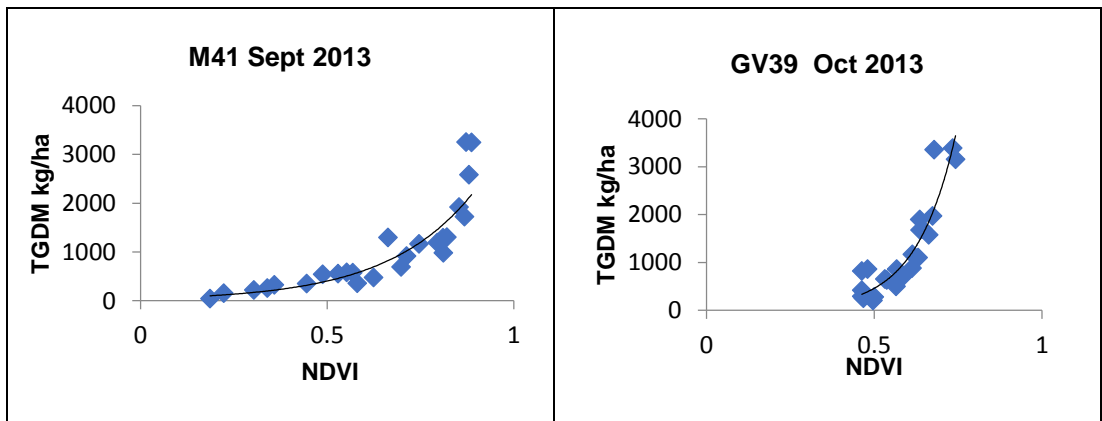


Fig. 7 Regression of Crop Circle normalised difference vegetation index (NDVI) values against total green dry matter (TGDM) determined by direct harvesting for “Milroy” paddock M41 ($y=45.927e^{4.3528x}$; $R^2 = 0.884$) and “Grandview” paddock GV39 ($y=6.416e^{5.48x}$; $R^2 = 0.807$) in September 2013

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

457 (CV ranges) have been combined and categorised into four new classes—high or low yielding depending on
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2 458 whether the data value was above or below the spatial mean, and stable or unstable depending on whether the
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4 459 data value was above or below the stability threshold (Table 3). Fig. 9c shows the overall paddock stability map
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6 460 for “Milroy” M41 which combines the crop (Fig. 9a) and pasture (Fig. 9b) spatial trend and temporal stability
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8 461 data into one map. Fig. 10a-c shows the same process for “Grandview”. The maps show areas of the paddock
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10 462 where the yields for both crop and pasture, over time, responded in a similar fashion—either high yielding and
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12 463 stable (HS), high yielding and unstable (HUS), low yielding and stable (LS) or low yielding and unstable (LUS).
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14 464 The areas of the map that remain uncoloured represent other possible combinations of yield and stability other
15
16 465 than the four defined zones. For each paddock, the “high and stable” class ranged from 68% of total grid points
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18 466 analysed at “Milroy” to 54% at “Grandview (Table 7). The “low and unstable” class accounted for 21% of grid
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20 467 points analysed at “Milroy” to 19% at “Grandview” (Table 7). Data points for each paddock that didn’t fall into
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22 468 one of the four Stability Index categories (for example, points that were temporally stable - $CV_{s_i} < \text{mean CV}$,
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24 469 but high yielding in one phase and low in another, or temporally unstable - $CV_{s_i} > \text{mean CV}$, but high yielding
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26 470 in one phase and low in another), were combined to form maps for “Milroy” (Fig. 11a) and “Grandview” (Fig.
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28 471 11b) respectively, clarifying the nature of uncategorised areas.

472 **Correlation of crop and pasture values at a point**

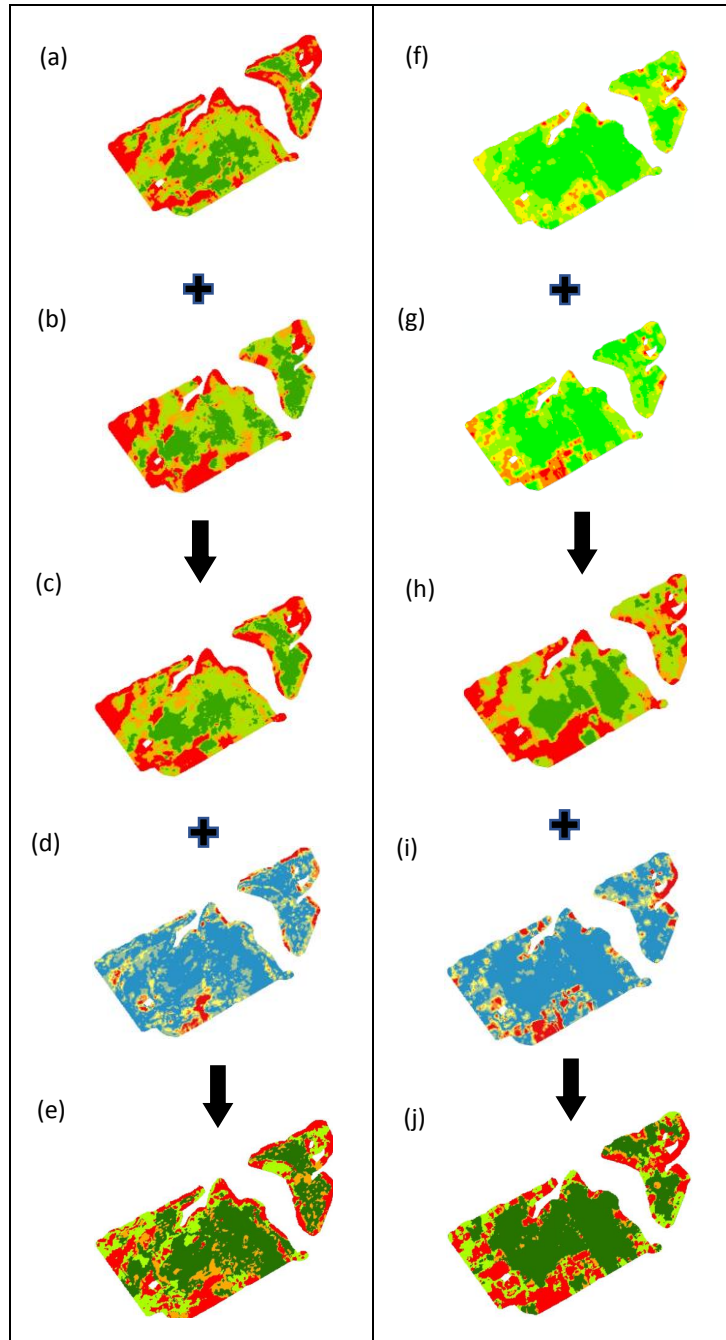
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32 473 At “Milroy”, the Spearman’s rho correlation revealed a moderately strong, statistically significant relationship in
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34 474 paddock M41 between the standardised values for crop yield and pasture TGDM for the randomised points
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36 475 ($\rho=0.66$, $P<0.01$, $N=262$, Table 8). At “Grandview” paddock GV39, there was also a statistically significant
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38 476 relationship for Spearman’s rho correlation between the standardised values for crop yield and pasture TGDM
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40 477 for the randomised points ($\rho=0.66$, $P<0.01$, $N=192$, Table 8). These significant results confirm the validity of the
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42 478 method used to develop the combined crop and pasture stability maps.

479 **Kruskal-Wallis analysis**

46
47 480 The results of the Kruskal–Wallis one-way ANOVA (Table 8) showed that at both sites the Stability Index
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49 481 categories for yield (high and low) partitioned the yield medians into high yielding categories (HS & HUS) and
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51 482 low yielding categories (LS & LUS) and these differences were significant ($p < 0.01$). This was also the case
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53 483 when yield differences (crop yield minus pasture yield) were tested. For temporal stability, crop and pasture
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55 484 stability medians did not always show significant differences between stable and unstable areas, but the median
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57 485 values were grouped correctly. For example, crop CV median values at “Grandview” for stable were close to
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59 486 each other (12.0 and 16.7) and distant from the unstable category (29.4 and 30.5). The same occurred with crop-

487 pasture yield differences at “Grandview”, with yield medians falling into high (10.1 and 13.8) and low (14.9 and
1 488 17.3) and stability medians grouped stable (6.3 and 12.3) and unstable (19.1 and 17.2). The results for the
2 489 pasture phase temporal stability analysis were much less consistent. There were no paddocks where the pasture
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4 490 CV category medians differed significantly and “Grandview” GV39 was the only paddock where the values of
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6 491 the medians were grouped into stable and unstable categories. The impact of livestock grazing as a possible
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8 492 cause of these pasture effects is discussed further in the discussion. Although the Kruskal–Wallis test for the
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10 493 temporal stability aspect (CV) of the Stability Index did not always show a significant difference between the
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12 494 medians of the stable and unstable categories, the results provide strong evidence to support the validity of the
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14 495 methodology used to define and allocate yield spatial variability data among the Stability Index categories.
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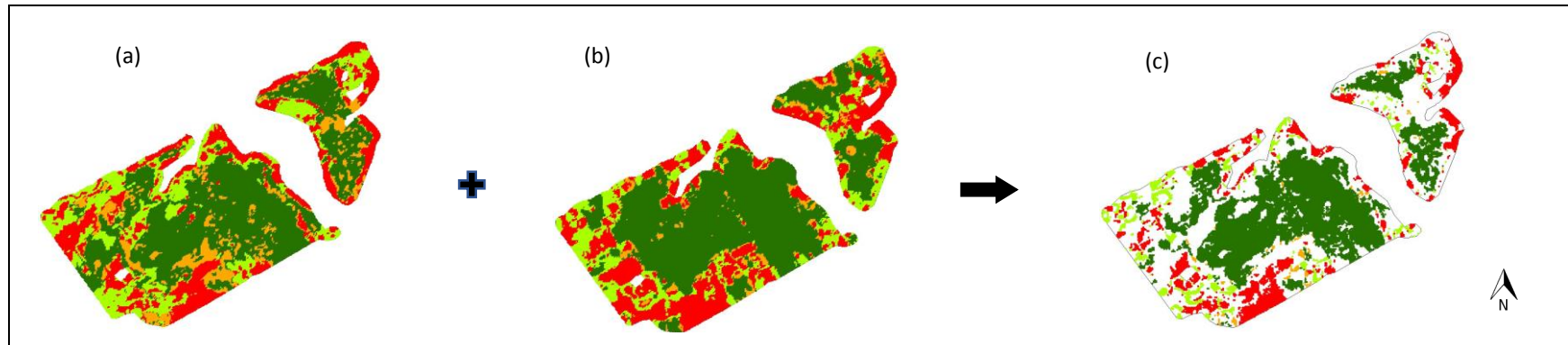
Fig. 8 Diagram illustrating the creation of Stability Index maps for crop and pasture phases for “Milroy” paddock M41. Standardised yield maps (a) and (b) for crop, (f) and (g) for pasture total green dry matter (TGDM), are combined to create spatial trend maps (c) and (h), which show the standardised 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

548 **Table 6** Temporal variability of production (based on CV) for “Milroy” and “Grandview” paddocks by
 549 percentage of paddock affected^a

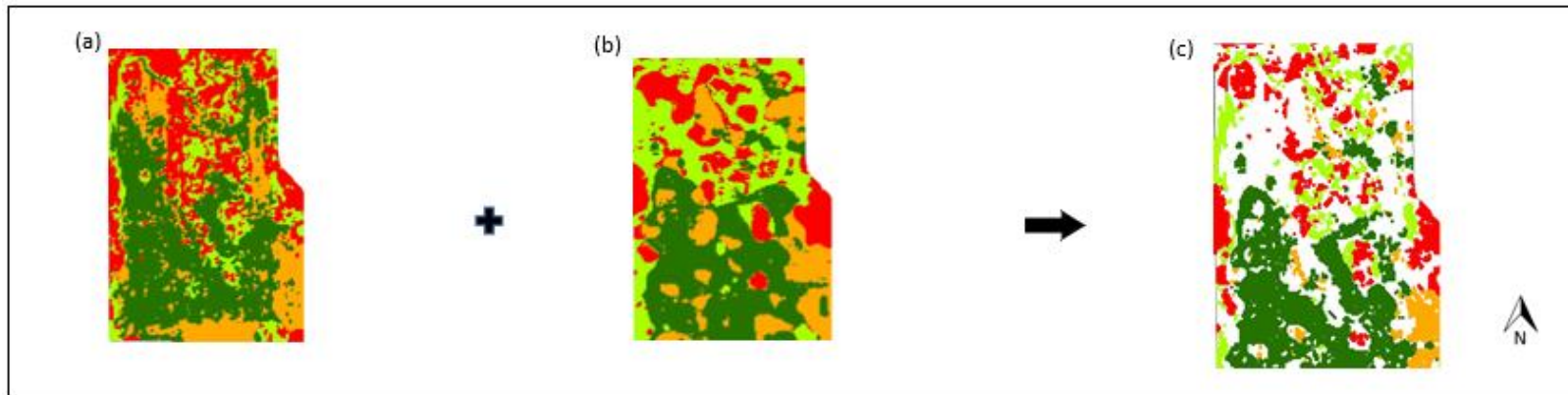
		CV categories (%)				
Paddock		0-10	11-20	21-30	31-40	>40
“Milroy”						
M41 crop		59	25	9	4	3
M41 pasture		65	17	8	4	6
“Grandview”						
GV39 crop		21	34	25	14	7
GV39 pasture		58	29	9	3	1

550 ^a0-10% is the most stable category and >40% the least stable

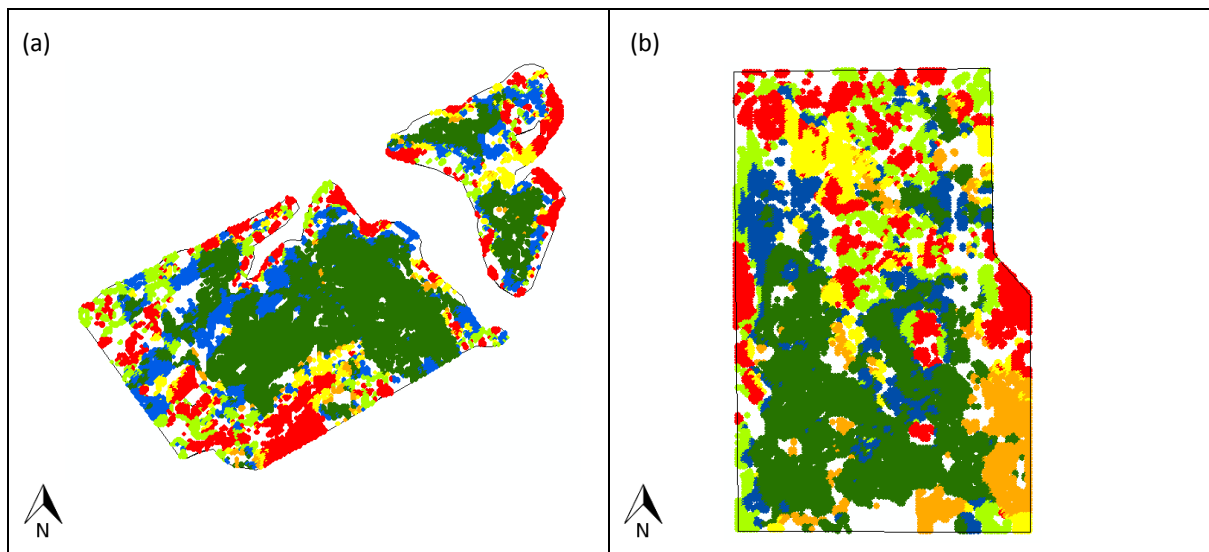
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551 **Fig. 9** Combining the Stability Index maps in “Milroy” paddock M41 for crop (a) and pasture (b) phases provides the overall paddock Stability Index map (c), with four
 552 zones: ■ high yielding and stable (HS); ■ high yielding and unstable(HUS);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



554
 555 **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
 556 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
 557 that remain uncoloured represent other possible combinations of yield and stability other than the four defined stability zones



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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.

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

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Paddock	Stability Category			
	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

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

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570 **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
571 “Grandview” paddocks. Values show the zone medians calculated by the Kruskal–Wallis test and indicate where a significant difference occurred between at least one
572 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

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

574 ^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
575 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.

576 N is the number of points in the sample

577 **Discussion**

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

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

598 While proximal soil sensing technologies alone, (such as EMI), cannot replace the detail provided by manual
599 soil sampling in the field, both techniques could be used together to identify spatial and temporal variability and
600 its potential causes, to inform strategic planning for soil management at a given site. Although highly mobile
601 nutrients like nitrogen need to be managed in-season during cropping phases in response to in-season soil
602 moisture and rainfall (Basso et al. 2012), less mobile nutrients such as P, K and S can be managed with a longer-
603 term view, based on the temporal variance reflected in stability zones. In this way, the different outcomes
604 required from a crop (maximising grain yield) and pasture (maximising digestible biomass) phase can be
605 managed together and monitored at the sub-paddock scale. In this context, it was anticipated that the stability
606 zones might be useful for identifying potential nutrient variations across a paddock and provide the opportunity

607 to better manage decisions around fertiliser application. Areas of a paddock that have different soil textures and
1 608 nutrient levels can have differing maintenance fertiliser requirements and might benefit from differential
2 609 fertiliser treatment. Conventional wisdom suggests that high and stable zones could have higher soil fertility, but
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4 610 there is evidence (Price 2006) that high and stable zones could show lower nutrient levels than the low and
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6 611 stable areas, as greater nutrient removal would occur from the high and stable areas in the form of crop and
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8 612 animal product exports. When the paddock Stability Index maps were overlain on the soil test results no
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10 613 definitive trends were apparent. Unfortunately, the limited number of soil tests precluded detailed analyses of
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12 614 the impacts of soil chemical / textural factors. A better understanding of how the spatial patterns in soil
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14 615 properties may have impacted on yield variations could have been achieved with better targeted soil sampling.
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16 616 However, the soil testing was undertaken for earlier research, prior to the definition of the SI zones and did not
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18 617 specifically target SI zones which probably contributed to the low correlation between soil chemistry and SI
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20 618 zones.

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24 619 At “Milroy” paddock M41, the areas identified as high and stable (HS Stability Index - dark green; Fig. 8) are
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26 620 mainly in the central section of the paddock, associated with finer-textured loamy soils. This section of the
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28 621 paddock is sloped, rising from south to north, with an elevation variation of around 10 metres (Fig. 2). The
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30 622 pastures in this zone are dominated by subterranean clover. It was likely that the areas dominated by
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32 623 subterranean clover in the pasture phase may have contributed to improved fertility through biologically fixed
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34 624 nitrogen. The small areas categorised as “low and stable” (LS – light green; Fig. 9c) at “Milroy” comprise sand
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36 625 over clay soils (Fig. 2). These are areas of low but stable production. The “low and unstable” areas (LUS – red;
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38 626 Fig. 9c) largely comprise “problem” soils - non-wetting gravels and sodic sandy duplex soils occurring around
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40 627 the edges of the paddock. The sodic soils border a saline drainage line on the southern boundary. Crop yields
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42 628 here are low, but in the pasture phase, there can be a reasonable amount of weedy biomass growing, resulting in
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44 629 an unstable production pattern between crop and pasture phases. The LUS areas comprise 21% of the paddock
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46 630 area that was classified (Table 7), which could be considered significant in management terms, requiring further
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48 631 investigation.

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50 632 At “Grandview, there were differences in soil texture between the tops of hills, mid-slopes and points of lowest
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52 633 elevation in GV39. On the tops of the hills, the topsoil tended to be stonier sandy clay loams, transforming down
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54 634 the slope to sandy clay loam over clay (Fig. 4). The southern half of the paddock, which includes the HS zone
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56 635 (dark green; Fig 8c), has higher elevation and sandy-loam over clay soils. The LUS areas (red; Fig. 10c) are on
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58 636 the margins (fence-lines) of the paddock, where existence of trees could be affecting production, and in the
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637 lower-lying (northern) parts of the paddock dominated by fine textured soils with scattered large trees. The farm
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2 638 owner also reported that the elevated areas of the paddock, although of lower inherent fertility, would yield well
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4 639 with sufficient fertiliser application (Adam Inchbold, pers. comm.). Previous research at “Grandview” (Inchbold
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6 640 et al. 2009) reported that sodosols on the lower slopes always had surplus soil water, leading to the conclusion
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8 641 that rooting depth in these soils was limited by factors other than moisture (e.g. salinity or elevated
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10 642 exchangeable sodium percentage (ESP) in subsoils) (Kirkegaard and Lilley 2007; Lilley and Kirkegaard 2016),
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12 643 which corresponds with the SI results. The farm owner reported little water extraction below 0.6 m on these
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14 644 soils (Adam Inchbold, pers. comm.).

16 645 **Influence of livestock grazing on biomass**

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18 646 Grazing livestock create specific spatial patterns of pasture biomass utilisation which affect the spatial
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20 647 heterogeneity of the paddock and bring about significant nutrient redistribution (Laca 2009; Murray et al. 2007;
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22 648 Rook et al. 2004; Schellberg et al. 2008; Schnyder et al. 2009; Trotter et al. 2010a). For example, as noted in the
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24 649 results section, the highest soil test P value in “Grandview” paddock GV39 was associated with a stock camp
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26 650 and feed trough. These effects are compounded from year to year by stocking rate decisions of managers,
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28 651 pasture regrowth, and often highly variable species composition within complex swards over time (Bailey and
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30 652 Provenza 2008; Chapman et al. 2007; Soder et al. 2009). These factors combine to affect the spatial
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32 653 heterogeneity of a paddock during the pasture–livestock phase compared to grain yield when the paddock is in
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34 654 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
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36 655 TGDM production because nothing much grew there, or because the vegetation was grazed off, or there was a
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38 656 change in species dominance affecting the NDVI reflectance values. This was evident in the Kruskal–Wallis
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40 657 tests (Table 8), where there were a number of statistically non-significant results associated with the pasture
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42 658 CVs. The overall spatial and temporal utilisation of a paddock by livestock is going to remain unclear without
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44 659 acquiring data through GPS tracking (Trotter et al. 2010a, 2010b). Meta-analysis of data from livestock fitted
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46 660 with GPS tracking collars and accelerometers could identify spatial preference, grazing behaviour and
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48 661 distribution of animals within a paddock and help to identify animal impacts from soil texture / chemistry
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50 662 effects. This also applies to the grazing of a crop in a ‘grain & graze’ system (Price and Hacker 2009) as well as
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52 663 when the paddock is in pasture.

54 664 **Uncategorised areas of the paddocks**

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56 665 There are areas of the paddock that remain uncategorised with the SI process, where production can be stable,
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58 666 but high yielding in one phase and low yielding in the other. For example, an area of a paddock can be
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667 temporally stable (ie $CV_{St} < \text{mean CV}$; Table 3), but high yielding in crop and low yielding in pasture. This
668 could result from highly productive areas of the paddock when in pasture being heavily grazed by stock, and
669 thereby giving a low TGDM yield when the paddock was measured. At “Milroy”, these areas – “high-low
670 stable” (HLS - blue areas in Fig. 11a) are mostly on the margins of the darker green HS zones and a section on
671 the south-western boundary. The area on the southwest boundary comprises deep sands of low fertility,
672 dominated by broadleaf weeds (capeweed and *Erodium* spp.). This area also comprised a significant proportion
673 of the paddock that remains uncategorised. Pasture quality and livestock residence times on capeweed can be
674 highly variable, and can impact estimates of TGDM in these areas, particularly if plants are flowering, as the
675 yellow flowers can impact NDVI values (Behrens et al. 2006; Shen et al. 2009; Shen et al. 2010). The other
676 possibility in the uncategorised zones was high yielding in one phase and low yielding in the other while
677 unstable in yield (distant from the mean) and unstable in time (ie $CV_{St} > \text{mean CV}$; Table 3). These “high-low
678 unstable” areas (HLUS - yellow in Fig. 11a) tend to be on the margins of the LUS (red) zones. The soil textures
679 in these areas are coarse and variations in yield between crop and pasture may be driven by variations in rainfall
680 amount and timing as they will run out of water first in dry years.

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

690 **Practical benefits of the Stability Index classifications**

691 The results of this research show that it is possible, using readily available precision technologies, to correlate
692 and map the responses of both crop and pasture yields over time within the same paddock at the sub-paddock
693 scale. The analysis addresses a number of factors that impact on the objectives and forward planning decisions
694 of the managers of mixed-farming systems. Spatial variation in yield is not always consistent, but influenced by
695 seasonal variations and often temporally unstable (McBratney et al. 1997; Wong and Asseng 2006), opening ‘a
696 Pandora’s box of uncertainty’ for the agronomic interpretation of yield maps (Cook and Bramley 2001). By

697 identifying commonality in spatial and temporal variability across both crop and pasture phases through the
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2 698 Stability Index, some of this uncertainty is reduced. If farm managers can be confident about what is happening
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4 699 at the whole of system scale in both crop and pasture phases in a paddock, it enables them to make management
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6 700 decisions with greater confidence. Using the stability zones to create ‘gross margin’ maps of each paddock
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8 701 (Blackmore 2000; Whelan and Taylor 2013) can assist in optimising financial inputs and returns, although this
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10 702 was not explored here. If the spatial trend indicates that lower yielding areas are sufficiently significant in size to
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12 703 warrant attention, then these areas can be investigated and the cause(s) ameliorated. If the cause cannot be
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14 704 addressed (e.g. salinity), reducing inputs to match average yields can be explored. For example, variable rate
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16 705 fertiliser P decisions in all paddocks at “Grandview” are currently based solely on P removal in grain during the
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18 706 cropping phase. The pastures receive a blanket rate of P. The farm owner at “Grandview” has indicated that
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20 707 based on the results of this research, he would be interested in implementing a variable rate fertiliser strategy
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22 708 during pasture phases also, to complement his cropping strategy. Either way, the stability zone maps provide the
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24 709 property manager with an indication on whether focussing on spatial or temporal management is the best
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26 710 strategy, especially if informed with gross margin maps.

28 711 **Conclusions**

30 712 The analysis presented here is unique in that it includes both crop and pasture yield data from within the same
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32 713 paddock. The Stability Index has the potential to fill significant knowledge gaps for the farm manager, who
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34 714 currently only has crop yield data to make decisions about paddock management. Previous attempts to create
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36 715 paddock stability zones (Blackmore (2000), Blackmore et al. (2003), Marques da Silva (2006), Marques da
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38 716 Silva et al. (2008) and Xu et al. (2006)) have been restricted to either single crop or grassland paddocks, but
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40 717 never for paddocks that include a sequence of both crop and pasture rotations in a mixed farming system. With
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42 718 the benefit of hindsight, additional soil test data based on the SI zones would have been invaluable to help
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44 719 identify and possibly better characterise some of the differences between zones outside of the “HS” areas and
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46 720 possibly reduce the extent of un-categorised parts of the paddocks. The research identified that there were some
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48 721 exceptions and uncertainties around the measurement of spatial variation and temporal stability in pasture
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50 722 phases. In the short term, it can be difficult to differentiate between variations in temporal stability of pasture
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52 723 growth brought about by rainfall, soil moisture and soil nutrient supply from those caused by grazing. As the
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54 724 size of Australian farm holdings increases (Australian Bureau of Agricultural and Resource Economics 2017,
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56 725 <http://apps.daff.gov.au/AGSURE/>), not all paddocks can be sown at the optimal time. Being aware of how
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58 726 different parts of a paddock are responding and the extent of those areas in both crop and pasture phases through
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727 the use of the paddock stability indices can inform decisions about the order and timing of paddock sowing
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2 728 when faced with a time-constrained sowing window. The methodology and concepts described and
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4 729 demonstrated here open the way for further research to identify a new field of “whole of system” precision
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6 730 management in mixed farming systems. For example, further research into the effects of livestock grazing
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8 731 impacts on spatial variability of pasture production through the use of tracking collar data would help to clarify
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10 732 issues around overall spatial and temporal utilisation of a paddock by livestock. A longer term on-farm trial of
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12 733 the stability index to inform decisions about the mix of crop and pasture rotations on a paddock by paddock
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14 734 basis, optimal crop and pasture sequences, which paddocks are better suited to either cropping or pasture and
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16 735 pasture species selection would also be of great value. There is significant potential for the Stability Index
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18 736 methodology described here to be of benefit to a farm manager, as a guide to enhancing and improving mixed
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20 737 farming system management practices.

22 738 **Availability of supporting data**

24 739 The datasets generated during and/or analysed during the current study are available from the corresponding
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26 740 author on reasonable request.

28 741 **References**

- 31 742 Angus, J. F., & Peoples, M. B. (2013). Nitrogen from Australian dryland pastures. *Crop and Pasture Science*,
32 743 63(9), 746-758, doi:<https://doi.org/10.1071/CP12161>.
- 33 744 Bailey, D. W., & Provenza, F. D. (2008). Mechanisms determining large-herbivore distribution. In H. H. T.
34 745 Prins, & F. Van Langevelde (Eds.), *Resource Ecology* (pp. 7-28, Wageningen UR Frontis Series, Vol.
35 746 23). Dordrecht, Netherlands: Springer.
- 37 747 Basso, B., Fiorentino, C., Cammarano, D., Cafiero, G., & Dardanelli, J. (2012). Analysis of rainfall distribution
38 748 on spatial and temporal patterns of wheat yield in mediterranean environment. *European Journal of*
39 749 *Agronomy*, 41, 52-65, doi:<https://doi.org/10.1016/j.eja.2012.03.007>.
- 40 750 Behrens, T., Müller, J., & Diepenbrock, W. (2006). Utilization of canopy reflectance to predict properties of
41 751 oilseed rape (*Brassica napus* L.) and barley (*Hordeum vulgare* L.) during ontogenesis. *European*
42 752 *Journal of Agronomy*, 25(4), 345-355, doi:<https://doi.org/10.1016/j.eja.2006.06.010>.
- 44 753 Bell, L. W., Hayes, R. C., Pembleton, K. G., & Waters, C. M. (2014a). Opportunities and challenges in
45 754 Australian grasslands: pathways to achieve future sustainability and productivity imperatives. *Crop and*
46 755 *Pasture Science*, 65(6), 489-507, doi:<https://doi.org/10.1071/CP13420>.
- 47 756 Bell, L. W., & Moore, A. D. (2011). *Mixed crop-livestock businesses reduce price and climate-induced*
48 757 *variability in farm returns: a model-derived case study*. Paper presented at the 5th World Congress of
49 758 Conservation Agriculture incorporating 3rd Farming Systems Design Conference Brisbane, Australia,
50 759 26-29 September 2011
- 52 760 Bell, L. W., Moore, A. D., & Kirkegaard, J. A. (2014b). Evolution in crop–livestock integration systems that
53 761 improve farm productivity and environmental performance in Australia. *European Journal of*
54 762 *Agronomy*, 57, 10-20, doi:<http://dx.doi.org/10.1016/j.eja.2013.04.007>.
- 56 763 Blackmore, S. (2000). The interpretation of trends from multiple yield maps. *Computers and Electronics in*
57 764 *Agriculture*, 26(1), 37-51, doi:[https://doi.org/10.1016/S0168-1699\(99\)00075-7](https://doi.org/10.1016/S0168-1699(99)00075-7).
- 58 765 Blackmore, S. (2003). *The role of yield maps in Precision Farming*. Cranfield University, Silsoe UK.

- 766 Blackmore, S., Godwin, R. J., & Fountas, S. (2003). The analysis of spatial and temporal trends in yield map
1 767 data over six years. *Biosystems Engineering*, 84(4), 455-466, doi:[https://doi.org/10.1016/S1537-
2 768 5110\(03\)00038-2](https://doi.org/10.1016/S1537-5110(03)00038-2).
- 3 769 Buttafuoco, G., Castrignanò, A., Colecchia, A. S., & Ricca, N. (2010). Delineation of management zones using
4 770 soil properties and a multivariate geostatistical approach. *Italian Journal of Agronomy*, 5(4), 323-332,
5 771 doi:<https://doi.org/10.4081/ija.2010.323>.
- 6
7 772 Castrignanò, A., Wong, M. T. F., Stelluti, M., De Benedetto, D., & Sollitto, D. (2012). Use of EMI, gamma-ray
8 773 emission and GPS height as multi-sensor data for soil characterisation. *Geoderma*, 175-176, 78-89,
9 774 doi:<https://doi.org/10.1016/j.geoderma.2012.01.013>.
- 10 775 Chapman, D., Parsons, A., Cosgrove, G., Barker, D. J., Marotti, D., Venning, K., et al. (2007). Impacts of
11 776 spatial patterns in pasture on animal grazing behavior, intake, and performance. *Crop Science*, 47(1),
12 777 399-415, doi:<https://doi.org/10.2135/cropsci2006.01.0036>.
- 13
14 778 Cook, S., & Bramley, R. G. V. (2001). *Is agronomy being left behind by precision agriculture?* Paper presented
15 779 at the Proceedings of the 10th Australian agronomy conference Hobart, Tasmania, Australia, 29
16 780 January - 1 February 2001
- 17 781 Corder, G. W., & Foreman, D. I. (2014). *Nonparametric statistics: A step-by-step approach* (2nd ed.). Hoboken,
18 782 New Jersey, USA: John Wiley & Sons.
- 19
20 783 Diacono, M., Castrignanò, A., Troccoli, A., De Benedetto, D., Basso, B., & Rubino, P. (2012). Spatial and
21 784 temporal variability of wheat grain yield and quality in a Mediterranean environment: A multivariate
22 785 geostatistical approach. *Field Crops Research*, 131, 49-62,
23 786 doi:<https://doi.org/10.1016/j.fcr.2012.03.004>.
- 24
25 787 Dobermann, A., Ping, J. L., Adamchuk, V. I., Simbahan, G. C., & Ferguson, R. B. (2003). Classification of crop
26 788 yield variability in irrigated production fields. *Agronomy Journal*, 95(5), 1105-1120,
27 789 doi:<https://doi.org/10.2134/agronj2003.1105>.
- 28 790 Edirisinghe, A., Hill, M. J., Donald, G. E., & Hyder, M. (2011). Quantitative mapping of pasture biomass using
29 791 satellite imagery. *International Journal of Remote Sensing*, 32(10), 2699-2724,
30 792 doi:<https://doi.org/10.1080/01431161003743181>.
- 31
32 793 Ewing, M. A., & Flugge, F. (2004). *The benefits and challenges of crop-livestock integration in Australian
33 794 agriculture*. Paper presented at the 4th International Crop Science Congress 26 September-1 October
34 795 2004, Brisbane Australia,
- 35 796 Farid, H. U., Bakhsh, A., Ahmad, N., Ahmad, A., & Mahmood-Khan, Z. (2016). Delineating site-specific
36 797 management zones for precision agriculture. *The Journal of Agricultural Science*, 154(02), 273-286,
37 798 doi:<https://doi.org/10.1017/S0021859615000143>.
- 38
39 799 Glenn, E. P., Huete, A. R., Nagler, P. L., & Nelson, S. G. (2008). Relationship between remotely-sensed
40 800 vegetation indices, canopy attributes and plant physiological processes: what vegetation indices can
41 801 and cannot tell us about the landscape. *Sensors*, 8(4), 2136-2160, doi:<https://doi.org/10.3390/s8042136>.
- 42
43 802 Goel, N. S., & Qin, W. (1994). Influences of canopy architecture on relationships between various vegetation
44 803 indices and LAI and FPAR: a computer simulation. *Remote sensing reviews*, 10(4), 309-347,
45 804 doi:<https://doi.org/10.1080/02757259409532252>.
- 46 805 Gong, P., Pu, R., Biging, G. S., & Larrieu, M. R. (2003). Estimation of forest leaf area index using vegetation
47 806 indices derived from Hyperion hyperspectral data. *IEEE Transactions on Geoscience and Remote
48 807 Sensing*, 41(6), 1355-1362, doi:<https://doi.org/10.1109/TGRS.2003.812910>.
- 49
50 808 Gourley, C. J. P., Peverill, K. I., & Dougherty, W. J. (2007). *Making better fertiliser decisions for grazed
51 809 pastures in Australia, accounting for nutrients and fertcare*. Paper presented at the Australian Fertilizer
52 810 Industry Conference Hamilton Island, Queensland, Australia, 6-10 August 2007
- 53 811 Heberger, M. (2011). Australia's Millennium Drought: Impacts and Responses. In P. H. Gleick (Ed.), *The
54 812 World's Water: The Biennial Report on Freshwater Resources* (pp. 97-125). Washington DC, USA:
55 813 Island Press/Center for Resource Economics.
- 56
57 814 Hill, M. J., Donald, G. E., Vickery, P. J., Moore, A. D., & Donnelly, J. R. (1999). Combining satellite data with
58 815 a simulation model to describe spatial variability in pasture growth at a farm scale. *Australian Journal
59 816 of Experimental Agriculture*, 39(3), 285-300, doi:<https://doi.org/10.1071/EA98109>.
- 60
61
62
63
64
65

- 1 817 Holland, K. H., Schepers, J. S., Shanahan, J. F., Horst, G. L., & Mulla, D. J. (2004). *Plant canopy sensor with*
2 818 *modulated polychromatic light source*. Paper presented at the 7th International Conference on precision
3 819 agriculture and other precision resources management, Minneapolis, USA, 25-28 July 2004,
- 4 820 Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, 25(3), 295-309,
5 821 doi:[https://doi.org/10.1016/0034-4257\(88\)90106-X](https://doi.org/10.1016/0034-4257(88)90106-X).
- 6 822 Huete, A. R., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the
7 823 radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of*
8 824 *Environment*, 83(1-2), 195-213, doi:[https://doi.org/10.1016/s0034-4257\(02\)00096-2](https://doi.org/10.1016/s0034-4257(02)00096-2).
- 9 825 Inchbold, A., Whelan, B., & Baines, P. (2009). Making money out of precision agriculture. *Improving winter*
10 826 *cropping systems in the Riverine Plains*. Yarrowonga, Victoria, Australia: Riverine Plains Inc.
- 11 827 Isbell, R. (2016). *The Australian soil classification*: CSIRO Publishing Collingwood, Victoria, Australia.
- 12 828 Jeffrey, S. J., Carter, J. O., Moodie, K. B., & Beswick, A. R. (2001). Using spatial interpolation to construct a
13 829 comprehensive archive of Australian climate data. *Environmental Modelling & Software*, 16(4), 309-
14 830 330, doi:[https://doi.org/10.1016/S1364-8152\(01\)00008-1](https://doi.org/10.1016/S1364-8152(01)00008-1).
- 15 831 Kirkegaard, J. A., Conyers, M. K., Hunt, J. R., Kirkby, C. A., Watt, M., & Rebetzke, G. J. (2014). Sense and
16 832 nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed
17 833 farming systems. *Agriculture, Ecosystems & Environment*, 187(0), 133-145,
18 834 doi:<http://dx.doi.org/10.1016/j.agee.2013.08.011>.
- 19 835 Kirkegaard, J. A., & Lilley, J. M. (2007). Root penetration rate—a benchmark to identify soil and plant
20 836 limitations to rooting depth in wheat. *Australian Journal of Experimental Agriculture*, 47(5), 590-602,
21 837 doi:<https://doi.org/10.1071/EA06071>.
- 22 838 Kirkegaard, J. A., Peoples, M. B., Angus, J. F., & Unkovich, M. J. (2011). Diversity and evolution of rainfed
23 839 farming systems in southern Australia. In P. Tow, I. Cooper, I. Partridge, & C. Birch (Eds.), *Rainfed*
24 840 *Farming Systems* (pp. 715-754). Dordrecht: Springer Netherlands.
- 25 841 Kruskal, W. H., & Wallis, W. A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the*
26 842 *American statistical Association*, 47(260), 583-621, doi:<https://doi.org/10.2307/2280779>.
- 27 843 Laca, E. A. (2009). New approaches and tools for grazing management. *Rangeland Ecology & Management*,
28 844 62(5), 407-417, doi:<https://doi.org/10.2111/08-104.1>.
- 29 845 Li, G. D., Dear, B., Casburn, G., Walker, J., Bowden, P., & Hayes, R. (2010). *A survey of the current and future*
30 846 *use of lucerne, chicory and perennial grasses in pasture-crop rotations in southern New South Wales*.
31 847 Paper presented at the Food Security from Sustainable Agriculture: 15th Australian Agronomy
32 848 Conference Lincoln, New Zealand, 15-18 November 2010
- 33 849 Lilley, J. M., & Kirkegaard, J. A. (2016). Farming system context drives the value of deep wheat roots in semi-
34 850 arid environments. *Journal of Experimental Botany*, 67(12), 3665-3681,
35 851 doi:<https://doi.org/10.1093/jxb/erw093>.
- 36 852 Marques da Silva, J. R. (2006). Analysis of the spatial and temporal variability of irrigated maize yield.
37 853 *Biosystems Engineering*, 94(3), 337-349, doi:<https://doi.org/10.1016/j.biosystemseng.2006.03.006>.
- 38 854 Marques da Silva, J. R., Peça, J. O., Serrano, J. M., de Carvalho, M. J., & Palma, P. M. (2008). Evaluation of
39 855 spatial and temporal variability of pasture based on topography and the quality of the rainy season.
40 856 *Precision Agriculture*, 9(4), 209-229, doi:<https://doi.org/10.1007/s11119-008-9066-0>.
- 41 857 McBratney, A. B., Whelan, B. M., & Shatar, T. M. (1997). *Variability and uncertainty in spatial, temporal and*
42 858 *spatiotemporal crop- yield and related data*. Paper presented at the Precision Agriculture: Spatial and
43 859 Temporal Variability of Environmental Quality Conference, Wageningen, The Netherlands., 21-23
44 860 January 1997.
- 45 861 Meehl, P. E. (1990). Why summaries of research on psychological theories are often uninterpretable.
46 862 *Psychological reports*, 66(1), 195-244, doi:<https://doi.org/10.2466/pr0.1990.66.1.195>.
- 47 863 Moral, F. J., Terrón, J. M., & Marques da Silva, J. R. (2010). Delineation of management zones using mobile
48 864 measurements of soil apparent electrical conductivity and multivariate geostatistical techniques. *Soil*
49 865 *and Tillage Research*, 106(2), 335-343, doi:<https://doi.org/10.1016/j.still.2009.12.002>.
- 50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 866 Murray, R. I., Yule, I. J., & Gillingham, A. G. (2007). Developing variable rate application technology:
1 867 modelling annual pasture production on hill country. *New Zealand Journal of Agricultural Research*,
2 868 50(1), 41-52, doi:https://doi.org/10.1007/978-1-4020-6850-8_2.
- 3 869 Mutanga, O., & Skidmore, A. K. (2004). Narrow band vegetation indices overcome the saturation problem in
4 870 biomass estimation. *International Journal of Remote Sensing*, 25(19), 3999-4014,
5 871 doi:<https://doi.org/10.1080/01431160310001654923>.
- 6
7 872 Nichols, P. G. H., Loi, A., Nutt, B. J., Evans, P. M., Craig, A. D., Pengelly, B. C., et al. (2007). New annual and
8 873 short-lived perennial pasture legumes for Australian agriculture -15 years of revolution. *Field Crops*
9 874 *Research*, 104(1-3), 10-23, doi:<https://doi.org/10.1016/j.fcr.2007.03.016>.
- 10 875 Oliver, Y. M., & Robertson, M. J. (2009). Quantifying the benefits of accounting for yield potential in spatially
11 876 and seasonally responsive nutrient management in a mediterranean climate. *Australian Journal of Soil*
12 877 *Research*, 47(1), 114-126, doi:<https://doi.org/doi:10.1071/SR08099>.
- 13
14 878 Ollinger, S. V. (2011). Sources of variability in canopy reflectance and the convergent properties of plants. *New*
15 879 *Phytologist*, 189(2), 375-394, doi:<https://doi.org/10.1111/j.1469-8137.2010.03536.x>.
- 16
17 880 Peverill, K., Sparrow, L., & Reuter, D. (Eds.). (1999). *Soil Analysis: An Interpretation Manual*. Collingwood,
18 881 Australia: CSIRO Publishing.
- 19 882 Plant, R. (2001). Site-specific management: the application of information technology to crop production.
20 883 *Computers and Electronics in Agriculture*, 30(1), 9-29, doi:[https://doi.org/10.1016/S0168-](https://doi.org/10.1016/S0168-1699(00)00152-6)
21 884 [1699\(00\)00152-6](https://doi.org/10.1016/S0168-1699(00)00152-6).
- 22
23 885 Price, G. H. H. (2006). *Australian Soil Fertility Manual* (3rd ed.). Collingwood, Victoria, Australia: CSIRO
24 886 Publishing.
- 25 887 Price, R. J., & Hacker, R. B. (2009). Grain and Graze: an innovative triple bottom line approach to collaborative
26 888 and multidisciplinary mixed-farming systems research, development and extension. *Animal Production*
27 889 *Science*, 49(10), 729-735, doi:<https://doi.org/10.1071/EA08306>.
- 28
29 890 Pullanagari, R. R., Yule, I. J., Tuohy, M. P., Hedley, M. J., Dynes, R. A., & King, W. M. (2012). Proximal
30 891 sensing of the seasonal variability of pasture nutritive value using multispectral radiometry. *Grass and*
31 892 *Forage Science*, doi:<https://doi.org/10.1111/j.1365-2494.2012.00877.x>.
- 32
33 893 R Core Team (2017). R: A Language and Environment for Statistical Computing. (Vol. 3.3.3): R Foundation for
34 894 Statistical Computing, Vienna, Austria.
- 35 895 Reuter, D., & Robinson, J. B. (1997). *Plant analysis: an interpretation manual*. Collingwood, Victoria,
36 896 Australia: CSIRO publishing.
- 37
38 897 Rook, A. J., Dumont, B., Isselstein, J., Osoro, K., WallisDeVries, M. F., Parente, G., et al. (2004). Matching
39 898 type of livestock to desired biodiversity outcomes in pastures - a review. *Biological Conservation*,
40 899 119(2), 137-150, doi:<https://doi.org/10.1016/j.biocon.2003.11.010>.
- 41 900 Schellberg, J., Hill, M. J., Gerhards, R., Rothmund, M., & Braun, M. (2008). Precision agriculture on grassland:
42 901 applications, perspectives and constraints. *European Journal of Agronomy*, 29(2-3), 59-71,
43 902 doi:<https://doi.org/10.1016/j.eja.2008.05.005>.
- 44
45 903 Schirrmann, M., Gebbers, R., Kramer, E., & Seidel, J. (2011). Soil pH Mapping with an On-The-Go Sensor.
46 904 *Sensors*, 11(1), 573-598, doi:<https://doi.org/10.3390/s110100573>.
- 47 905 Schmer, M. R., Mitchell, R. B., Vogel, K. P., Schacht, W. H., & Marx, D. B. (2009). Spatial and Temporal
48 906 Effects on Switchgrass Stands and Yield in the Great Plains. *BioEnergy Research*, 3(2), 159-171,
49 907 doi:<https://doi.org/10.1007/s12155-009-9045-y>.
- 50
51 908 Schnyder, H., Locher, F., & Auerswald, K. (2009). Nutrient redistribution by grazing cattle drives patterns of
52 909 topsoil N and P stocks in a low-input pasture ecosystem. *Nutrient Cycling in Agroecosystems*, 88(2),
53 910 183-195, doi:<https://doi.org/10.1007/s10705-009-9334-z>.
- 54 911 Serrano, J., Marques da Silva, J., & Shahidian, S. (2014). Spatial and temporal patterns of potassium on grazed
55 912 permanent pastures - management challenges. *Agriculture, Ecosystems & Environment*, 188, 29-39,
56 913 doi:<https://doi.org/10.1016/j.agee.2014.02.012>.
- 57
58 914 Serrano, J. M., Peça, J. O., Marques da Silva, J. R., & Shahidian, S. (2011). Spatial and temporal stability of soil
59 915 phosphate concentration and pasture dry matter yield. *Precision Agriculture*, 12(2), 214-232,
60 916 doi:<https://doi.org/10.1007/s11119-010-9170-9>.
- 61
62
63
64
65

- 917 Serrano, J. M., Peça, J. O., Marques da Silva, J. R., & Shaidian, S. (2010). Mapping soil and pasture variability
1 918 with an electromagnetic induction sensor. *Computers and Electronics in Agriculture*, 73(1), 7-16,
2 919 doi:<https://doi.org/10.1016/j.compag.2010.03.008>.
- 3 920 Shen, M., Chen, J., Zhu, X., & Tang, Y. (2009). Yellow flowers can decrease NDVI and EVI values: Evidence
4 921 from a field experiment in an alpine meadow. *Canadian Journal of Remote Sensing*, 35(2), 99-106,
5 922 doi:<https://doi.org/10.5589/m09-003>.
- 6
7 923 Shen, M., Chen, J., Zhu, X., Tang, Y., & Chen, X. (2010). Do flowers affect biomass estimate accuracy from
8 924 NDVI and EVI? *International Journal of Remote Sensing*, 31(8), 2139-2149,
9 925 doi:<https://doi.org/10.1080/01431160903578812>.
- 10 926 Simeoni, M. A., Galloway, P. D., O'Neil, A. J., & Gilkes, R. J. (2009). A procedure for mapping the depth to the
11 927 texture contrast horizon of duplex soils in south-western Australia using ground penetrating radar, GPS
12 928 and kriging. *Soil Research*, 47(6), 613-621, doi:<https://doi.org/doi:10.1071/SR08241>.
- 13
14 929 Soder, K. J., Gregorini, P., Scaglia, G., & Rook, A. J. (2009). Dietary selection by domestic grazing ruminants
15 930 in temperate pastures: current state of knowledge, methodologies, and future direction. *Rangeland
16 931 Ecology & Management*, 62(5), 389-398, doi:<https://doi.org/10.2111/08-068.1>.
- 17
18 932 Sudduth, K. A., Kitchen, N., & Drummond, S. (2010). *Comparison of three canopy reflectance sensors for
19 933 variable-rate nitrogen application in corn*. Paper presented at the 10th International Conference on
20 934 Precision Agriculture Denver, Colorado, USA, 18-21 July, 2010
- 21 935 Sudduth, K. A., Kitchen, N. R., & Kremer, R. J. (2009). *VNIR spectroscopy estimation of soil quality indicators*.
22 936 Paper presented at the American Society of Agricultural and Biological Engineers Annual International
23 937 Meeting, Reno, Nevada, USA, 21-24 June, 2009
- 24
25 938 Sun, W., Whelan, B. M., Minasny, B., & McBratney, A. B. (2012). Evaluation of a local regression kriging
26 939 approach for mapping apparent electrical conductivity of soil (ECa) at high resolution. *Journal of Plant
27 940 Nutrition and Soil Science*, 175(2), 212-220, doi:<https://doi.org/10.1002/jpln.201100005>.
- 28 941 Taylor, J. A., McBratney, A. B., & Whelan, B. M. (2007). Establishing management classes for broadacre
29 942 agricultural production. *Agronomy Journal*, 99(5), 1366-1376,
30 943 doi:<https://doi.org/10.2134/agronj2007.0070>.
- 31
32 944 Thenkabail, P. S., Smith, R. B., & De Pauw, E. (2000). Hyperspectral vegetation indices and their relationships
33 945 with agricultural crop characteristics. *Remote Sensing of Environment*, 71(2), 158-182,
34 946 doi:[https://doi.org/10.1016/S0034-4257\(99\)00067-X](https://doi.org/10.1016/S0034-4257(99)00067-X).
- 35
36 947 Trotter, M. G., Lamb, D. W., Hinch, G. N., & Guppy, C. N. (2010a). Global navigation satellite system
37 948 livestock tracking: system development and data interpretation. *Animal Production Science*, 50(6),
38 949 616-623, doi:<https://doi.org/10.1071/AN09203>.
- 39 950 Trotter, M. G., Lamb, D. W., Hinch, G. N., & Guppy, C. N. (2010b). *GNSS tracking of livestock: towards
40 951 variable fertilizer strategies for the grazing industry*. Paper presented at the 10th International
41 952 Conference on Precision Agriculture, Denver, Colorado, USA, 18-21 July 2010
- 42
43 953 Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote
44 954 Sensing of Environment*, 8(2), 127-150, doi:[https://doi.org/10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0).
- 45 955 van Dijk, A. I. J. M., Beck, H. E., Crosbie, R. S., de Jeu, R. A. M., Liu, Y. Y., Podger, G. M., et al. (2013). The
46 956 Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications
47 957 for water resources, ecosystems, economy, and society. *Water Resources Research*, 49(2), 1040-1057,
48 958 doi:<https://doi.org/10.1002/wrcr.20123>.
- 49
50 959 Viña, A., Gitelson, A. A., Nguy-Robertson, A. L., & Peng, Y. (2011). Comparison of different vegetation
51 960 indices for the remote assessment of green leaf area index of crops. *Remote Sensing of Environment*,
52 961 115(12), 3468-3478, doi:<https://doi.org/10.1016/j.rse.2011.08.010>.
- 53
54 962 Waller, N. G. (2004). The fallacy of the null hypothesis in soft psychology. *Applied and Preventive Psychology*,
55 963 11(1), 83-86, doi:<https://doi.org/10.1016/j.appsy.2004.02.015>.
- 56 964 Whelan, B. M., & McBratney, A. B. (2003). *Definition and interpretation of potential management zones in
57 965 Australia*. Paper presented at the 11th Australian Agronomy Conference: "Solutions for a better
58 966 environment" Geelong, Victoria, 2-5 February 2003
- 59
60
61
62
63
64
65

967 Whelan, B. M., McBratney, A. B., & Minasny, B. (2001). *Vesper 1.5 - spatial prediction software for precision*
1 968 *agriculture*. Paper presented at the 3rd European Conference on Precision Agriculture Montpellier,
2 969 France., 18-20 June 2001

3 970 Whelan, B. M., & Taylor, J. A. (2013). *Precision Agriculture for Grain Production Systems*: CSIRO Publishing,
4 971 Australia.

5
6 972 Wong, M. T. F., & Asseng, S. (2006). Determining the causes of spatial and temporal variability of wheat yields
7 973 at sub-field scale using a new method of upscaling a crop model. *Plant and Soil*, 283(1-2), 203-215,
8 974 doi:<https://doi.org/10.1007/s11104-006-0012-5>.

9
10 975 Wong, M. T. F., Wittwer, K., Oliver, Y. M., & Robertson, M. J. (2010). Use of EM38 and gamma ray
11 976 spectrometry as complementary sensors for high-resolution soil property mapping. In R. Viscarra-
12 977 Rossel (Ed.), *Proximal soil sensing* (pp. 343-349): Springer Science.

13 978 Xu, H. W., Wang, K., Bailey, J. S., Jordan, C., & Withers, A. (2006). Temporal stability of sward dry matter and
14 979 nitrogen yield patterns in a temperate grassland. *Pedosphere*, 16(6), 735-744,
15 980 doi:[https://doi.org/10.1016/S1002-0160\(06\)60109-4](https://doi.org/10.1016/S1002-0160(06)60109-4).

16
17 981 Ziliak, S., & McCloskey, D. N. (2008). *The cult of statistical significance: How the standard error costs us jobs,*
18 982 *justice, and lives* (4ed.). Ann Arbor: University of Michigan Press.

19 983

20
21
22
23
24
25
26
27
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