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Shifting fertilizer response zones in a four year, whole-field cereal cropping experiment.

[1]Ben Jones, [2]Therese McBeath, [3]Nigel Wilhelm

[1]GrainGrowers Limited, Barton, Australian Capital Territory, Email: ben.jones@graingrowers.com.au

[2]CSIRO Agriculture, Waite Campus, Adelaide, South Australia, Email: therese.mcbeath@csiro.au

[3]PIRSA-SARDI, Adelaide, South Australia, Email: nigel.wilhelm@sa.gov.au

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Abstract. *Precision agriculture in cropping areas of dryland Australia has focused on managing within production zones. These are ideally stable, possibly soil- and topography-based areas within fields. There are many different ideas on how to delimit and implement zones, and a four year whole-field experiment, with low, medium and high treatment philosophies applied per 9m seeder/harvester width across the entire field, was established to explore how zones might best be established and used. The treatment philosophies combined wheat/barley seed rate, starter (N/P) and in-season fertilizer, varying according to season, but applied to the same seeder widths over the four years. The boundaries of treatment responses, determined using geographically weighted regression on yield data in each season, were compared to apparent electrical conductivity (ECa) and elevation surveys, and also zones created from clustering prior yield data. There were significant responses to the medium or high treatments over 23-66% of the field area in three out of four seasons. The zones created from yield data were good at predicting the pattern of yield variation, but not treatment responses. Responses were most likely to the fertilizer component of the treatments, and related to field history, and nutrient use in previous seasons. The pattern of ECa and elevation was similar to the yield zones, and not well related to treatment responses. The results support the role of fixed zones related to yield as a way of estimating overall input requirements and limits of likely responses, but imply that in-season crop sensing will be required to predict the responsive parts of fields, which will change from season to season.*

Keywords. *Fertilizer, yield zones, ECa, EM38.*

Introduction

Practitioners of precision agriculture use a wide range of methods for deciding on management zones, and then deciding on treatments to apply to zones. The range of approaches reflects the range of opinions on how zoning ought to be done in the farmer, adviser and research communities, as well as the available data, and the cost of data relative to cost of production. The main research community idea has been to create stable zones based on clustering areas with like ranges of soil properties, with key soil properties depending on the correlation with yield (Rab *et al.* 2009). Farmer approaches may be subjective (a recollection of which areas grow well, or the extent of soil types visually evident in the field), or objectively based on yield maps (Oliver *et al.* 2010). Adviser approaches range between the two extremes, and include freely 'mixing' sources of inexpensive data such as satellite NDVI, elevation, and apparent EC and gamma radiometric surveys to create zone patterns that 'make sense'.

In broadacre, dryland cropping, the low cost of inputs and uncertainty in responses puts a limit on the possible investment in data (Monjardino *et al.* 2013), which in turn adds uncertainty to the location and likelihood of possible responses. Zones are often established with the aim of zone-based soil or tissue testing (ie. several deep soil cores in a representative part of the zone), and using crop simulation modeling to guide production decisions during the year, but in practice the soil testing may only be carried out in a few fields on a farm, and the modeling may be the use of simple water use/nitrogen efficiency rules of thumb (Carberry *et al.* 2002). Other approaches use previous year yield maps to estimate 'replacement' input amounts, also often without soil testing to validate the use of the strategy.

Over all of the zoning methods, and methods for using zones, in broadacre, dryland cropping there is a question of whether the zones chosen by any method actually predict the location of treatment responses in any given year. Field- and landscape-scale experiments offer the prospect of allowing actual treatment responses to show where zones should have been created optimally in particular years, how stable the zones are, and how they might have been selected a priori according to known data layers; or whether in fact sensible zones in any year may be unpredictable with the information we have to hand.

This analysis used a field-scale experiment at Minnipa, South Australia. The experiment had treatments repeated regularly across the field (61 ha) for four years, with yield monitor data. Supporting data included two years of preceding yield maps, and elevation and apparent EC surveys. The aim was to show:

1. where appropriate zones would have been made on a field scale experiment according to treatment responses, and
2. understand how zones may have been predicted a priori according to covariates, if appropriate.

Methods

In-field treatments 2008-2011

Three treatments representing low, medium, and high input levels were repeated in 9m wide strips across a field at Minnipa Agriculture Center, South Australia (32.81S, 135.17E). The treatments varied each year in seed rate and fertilizer, with the 'medium' treatment intended to be district practice (Table 1). Wheat (*cv. Wyalkatchem*) was grown in 2008-2010 and barley (*cv. Hindmarsh*) was grown in 2011.

Table 1. Seed and fertilizer inputs for low, medium and high input treatments in each year of the experiment where DAP is di-ammonium phosphate fertilizer and UAN is urea ammonium nitrate fertilizer.

Year	Low Input			Medium Input			High Input		
	Seed (kg/ha)	DAP (kg/ha)	UAN (L/ha)	Seed (kg/ha)	DAP (kg/ha)	UAN (L/ha)	Seed (kg/ha)	DAP (kg/ha)	UAN (L/ha)
2008	35	0	0	50	50	0	50	60	0
2009	40	0	0	55	40	25	55	60	50
2010	50	0	0	65	40	0	65	60	50
2011	40	0	0	50	40	30	50	60	50+30

Spatial data treatment

A coordinate system in meters was developed parallel to the 9m seeder widths. Survey (elevation and ECa from vertical dipole EM38) and yield data was cleaned, lag corrected, and transformed to the coordinate system after reprojection to the local UTM zone. Transformed data was local variogram kriged using Vesper 1.62 (Minasny *et al.* 2011) onto a regular grid with cells 9 x 10m.

Yield data from both 2006 and 2007 was incomplete (reason unrecorded). The overlapping area of both datasets had yield data from 2006 to 2011 and was used for long-term average yield analysis (‘contiguous’). Where average yield excludes 2006 and 2007, this is referred to as ‘whole field’.

Geographically Weighted Regression

Geographically Weighted Regression (Fotheringham *et al.* 1998), as implemented in R package spgwr, was used to estimate local treatment effects, after accounting for local gradients in elevation and ECa. GWR fits a linear regression (in this case) to each point on a surface. A weighting function is applied to the data so that the regression coefficients represent the relationship close to each point, but are not completely biased by noise in the points immediately surrounding each point. The weighting function used is typically an exponential function of distance from the point being fitted, characterised by a ‘bandwidth’ (at which the weight is equal to exp (-0.5), or 0.6065).

There is an automated bandwidth selection process (gwr.sel in R) which iterates towards an optimal bandwidth based on cross-validation, by minimising a ‘cross validation’ score. Running this for yield data in each year gave an optimum bandwidth around 7m (range 6.67-7.09m). A 7m bandwidth optimally selected by cross-validation seemed too narrow. With this bandwidth, the regression had little weight for more than the adjacent treatments, and grid squares either side within the same treatment. It is likely that the repeating treatment pattern created local gradients in yield, which in turn biased the automated selection process toward excluding the nearest identical treatment. Including the treatment factor in the bandwidth selection model (ie. yield = elevation + ECa + trt) resulted in slightly lower bandwidth again. We considered several bandwidths greater than 7.5m, and opted for 30m, which weights the adjacent identical treatments (ie. 27m away) to at least 0.6, effectively regressing over three replicates of the treatments but with a bias toward the local one, and giving cross-validation scores not much higher than the optimum (data not shown).

The model fitted at each point was:

Yield = Elevation + ECa + Treatment + Error

Given the bandwidth chosen, this gave local estimates for linear variation of yield with elevation, ECa, and the treatment factor (low, medium or high) simultaneously. This paper reports only the medium and high treatment effects (compared to low).

Spatial association

Lee’s measure of spatial association, ‘L’ (Lee 2001), as implemented in R package spdep, was used to measure the degree to which potential predictors of yield and treatment effects (elevation, ECa, average and coefficient of variation of previous yields) had a similar pattern and were correlated. L has a higher absolute value when there is a high degree of spatial grouping in both data sets. If positive, they are grouped in the same pattern (positively correlated), if negative, grouped in the opposite pattern (negatively correlated). L is intermediate where spatial grouping is not as strong, or correlation between values is weaker.

Results

Yield and landscape covariate (ECa and elevation) results

The Minnipa field is a central swale with rises to local granite outcrops to the north east (south-facing) and south west (north-facing) (Figure 1a). The soil types on the rises are sandy loam, less eroded (deeper) to the north than to the south, and with more clay in the swale. The field drains to the north west, and receives concentrated flows from the east and south. The ECa map shows features consistent with differential drainage: the soil has lower ECa (more leached) where water flows, and there is a distinctive higher-ECa feature at the break of slope which suggests lateral flow. Soils higher in this landscape have higher ECa (Figure 1b).

The years before the experiment commenced (2006, 2007) were both dry, with 97.6 and 91.4mm April-October (growing season) rainfall following wet summer fallow periods (94.6 and 79mm January-March). The four years of the Minnipa experiment contained one dry (2008) and three wet (2009-2011) growing seasons. The 2010 growing season was preceded by a dry summer fallow period, but the 2009 and 2011 seasons similarly had a wet March on top of earlier summer rainfall.

Yields in 2008 were low and variation was driven by the propensity of the soil and crop to store and efficiently use small rainfall events. Yield along the break of slope/high ECa feature was very low, whereas the adjacent valley floor, which had low ECa, had yields similar to the rest of the southwest part of the field (Figure 2a). Highest yields were in the north, in the west corner, and along the ridge in the southeast corner of the field. Yields in 2009 were high and presumably driven by nutrition. Yields in the low ECa (drained) parts of the field were low, as was the north corner. Yields on the north-facing slope were generally higher than yields on the south-facing slope. There was a distinctive high yield strip running from the north corner south south-east along the 163-165m contour (a former contour bank; Figure 2b). Yields in 2010 followed a similar pattern to 2009, but the north half had the higher yields (similar to 2008 but in different areas) and the high yield strip from 2009 no longer stood out. High yields were generally in the same places. There were small patches (80-100m x 5-6 seeder widths) south of each of the rectangular cutouts to the north and south that had low yields in 2009 and were followed by high yields in 2010 (Figure 2c). Yields in 2011 followed the 2010 pattern, but were generally 0.5-1.0t/ha lower (Figure 2d).

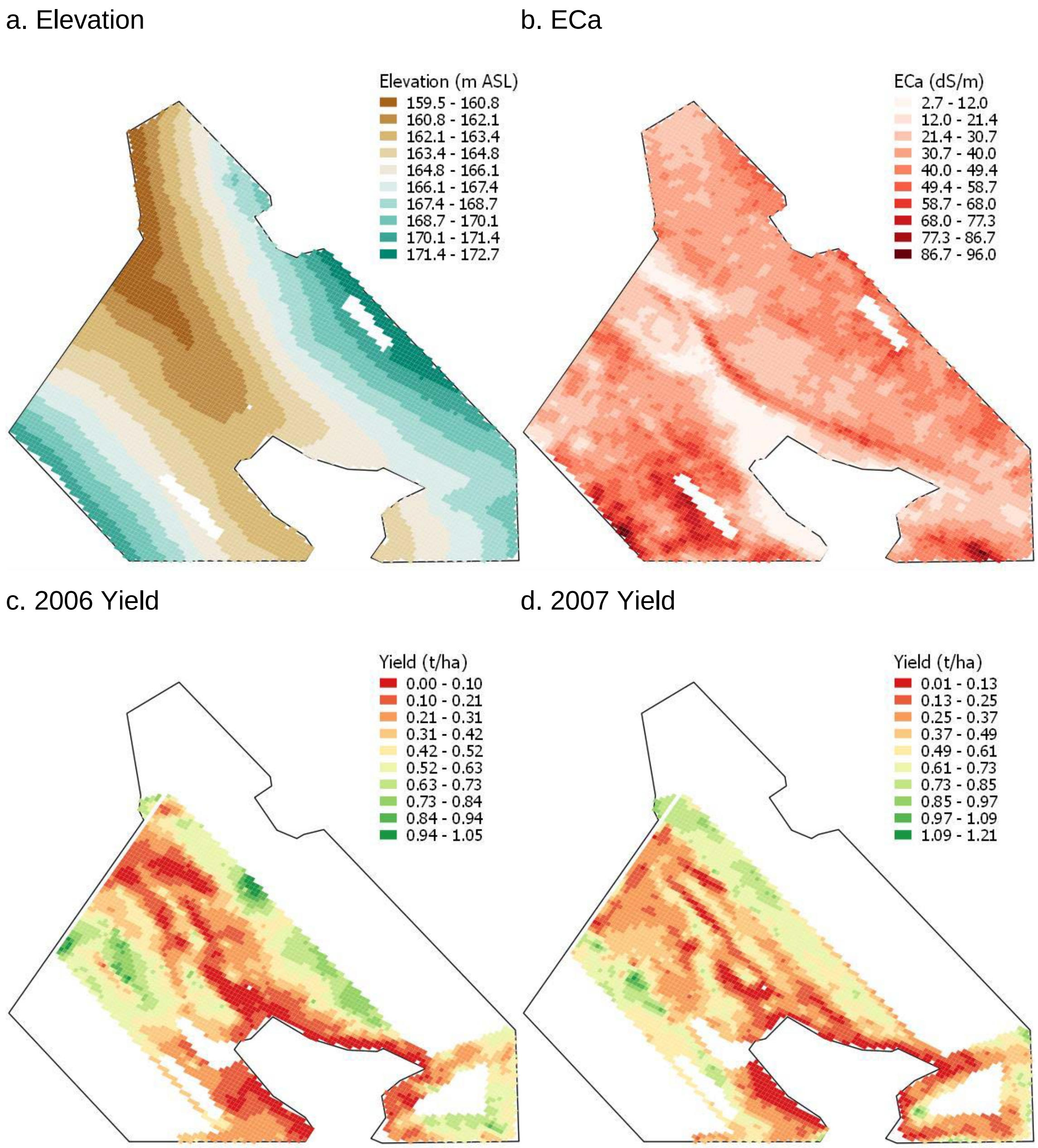

Figure 1. Field elevation (a), ECa (b) and crop yield in 2006 (c) and 2007 (d).

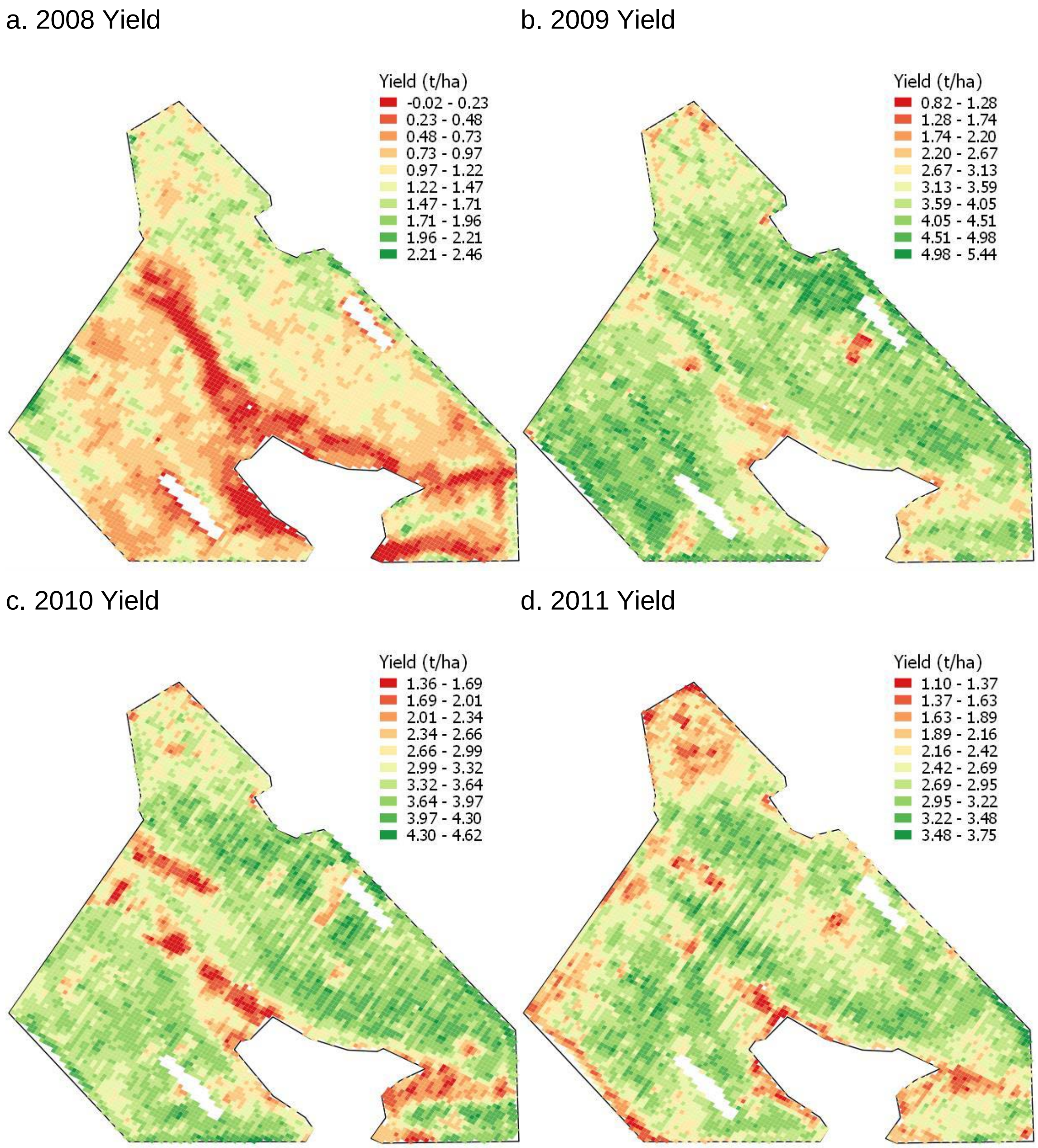

Figure 2. Crop yield in 2008 (a), 2009 (b), 2010 (c) and 2011 (d).

Spatial association

The area where yield was recorded in every year from 2006 to 2011 was about half of the field (33.2 ha 'contiguous' of 63.2 ha 'whole field'; see 'Methods, Spatial data treatment') and tended to be biased towards lower elevation and ECa (Table 2). Between 2008 and 2011 the average, minimum and maximum of yields were similar between the contiguous area and the whole field. The effects of the Medium and High treatments were also similar, but tended to have greater range than on the contiguous part of the field (data not shown).

Table 2. Summary measures of elevation and apparent EC measured over the part of the site where yields were contiguous from 2006 through 2011, and over the whole site.

	Elevation (m ASL)		ECa (dS/m)	
Summary	Contiguous	Whole	Contiguous	Whole
Min	159.59	159.52	2.73	2.73
Av	163.84	165.57	31.66	35.69
Max	169.54	172.67	85.87	95.99

Average yield and coefficient of variation

In the first year, 2006, yield was equally spatially associated with both elevation and ECa (Table 3). As additional years of data were added to the average (visualized in Appendix 3 and 4), the spatial association with ECa in the contiguous area strengthened, and the spatial association with elevation weakened. Across the whole field, the spatial association of average yield with elevation was relatively stronger than with ECa, and spatial associations with coefficient of variation negative or relatively small. Coefficient of variation was negatively associated with average yield, more so in the contiguous part than in the whole field.

Table 3. Spatial association (Lee's L) between yield average for medium treatments (Av), coefficient of variation (Cv), and elevation (El) and soil ECa as additional years of data are added. Values are given for the area where yield data was available 2006-2011 ('Contiguous', 33.2Ha), and where yield was available for the whole field (2008-2011, 63.2 Ha).

		Lee's L (p)					
Predictor	Variate	2006	2007	2008	2009	2010	2011
		Contiguous part of field (years from 2006)					
El	Av	+0.341 ***	+0.258 ***	+0.115 ***	+0.146 ***	+0.206 ***	+0.182 ***
	Cv		-0.188 ***	-0.279 ***	-0.103 ***	-0.091 ***	-0.076 ***
ECa	Av	+0.275 ***	+0.279 ***	+0.208 ***	+0.300 ***	+0.333 ***	+0.326 ***
	Cv		-0.062 ***	-0.167 ***	-0.133 ***	-0.127 ***	-0.118 ***
Av	Cv		-0.282 ***	-0.171 ***	-0.403 ***	-0.342 ***	-0.303 ***
		Whole field (years from 2008)					
El	Av			+0.179 ***	+0.342 ***	+0.378 ***	+0.329 ***
	Cv				-0.060 ***	-0.036 ***	+0.039 ***
ECa	Av			+0.087 ***	+0.254 ***	+0.308 ***	+0.293 ***
	Cv				-0.002	+0.014 **	+0.052 ***
Av	Cv				-0.207 ***	-0.163 ***	-0.090 ***

Seasonal relationship between yield and inputs

In 2008 the medium level input treatment produced some modest, significant yield increases in a small area in the north part of the field (Appendix 1). This was the area that produced the highest responses in 2009, but the significantly responsive area was more widespread, covering the whole southwest-facing slope. In 2010 the most responsive area was further southeast along the slope, and in 2011 the positively responsive area was the lower part of the field, an area that had not been responsive before, and was typically lower yielding (Appendix 1c and d). The pattern of response to the high input treatment was similar to medium level inputs, but less widespread in the lower-yielding 2008 season (Appendix 2), and more widespread in the wetter seasons (Appendix 2 b-d). The response was also more uniform on the north half of the field than to the medium level input treatment in 2009/2010.

Seasonal relationship between yield and landscape covariates

Yield in 2006 was positively associated with both elevation and ECa (Table 4). In following years, the positive association was more consistent with ECa than with elevation. Out of ECa, elevation and the average of preceding yields, yield in the 'contiguous' part of the field was most positively associated with the average of preceding yields, in nearly all years. Similar patterns were present in the whole field data, but the association with the average of preceding yields was less.

Treatment effects in the contiguous part of the field had a similar pattern of associations to those in the whole field (Table 4). Spatial associations of treatment effects with elevation and ECa were either small (2009, 2010), or larger and negative (2008, 2011). Treatment effects were positively associated with average yield in 2009 and 2010. The association between yields, treatment effects and coefficient of variation were smaller or negligible (Table 4).

Table 4. Spatial association (Lee's L) between yield of the medium treatment (Yld), medium- and high- treatment effects (eMedium, eHi) in each year, and elevation (El), soil ECa, average of yields up to that year (Av), and coefficient of variation for yields up to that year (Cv). Values are given for the area where yield data was available 2006-2011 ('Contiguous', 33.2Ha), and where yield was available for the whole field (2008-2011, 63.2 Ha).

		Lee's L (p)					
Predictor	Variate	2006	2007	2008	2009	2010	2011
		Contiguous part of field					
El	Yld	+0.341 ***	+0.112 ***	-0.037 ***	+0.138 ***	+0.274 ***	+0.037 ***
	eMedium			-0.150 ***	-0.064 ***	+0.033 ***	-0.346 ***
	eHi			-0.167 ***	+0.007	+0.036 ***	-0.431 ***
ECa	Yld	+0.275 ***	+0.220 ***	+0.100 ***	+0.312 ***	+0.327 ***	+0.211 ***
	eMedium			-0.042 ***	+0.063 ***	+0.025 ***	-0.298 ***
	eHi			-0.057 ***	+0.077 ***	+0.015 *	-0.270 ***
Av	Yld		+0.383 ***	+0.352 ***	+0.293 ***	+0.389 ***	+0.323 ***
	eMedium			+0.039 ***	+0.204 ***	+0.145 ***	-0.239 ***
	eHi			+0.004	+0.189 ***	+0.204 ***	-0.192 ***
Cv	Yld			-0.158 ***	-0.173 ***	-0.175 ***	-0.106 ***
	eMedium			-0.026 ***	-0.008	-0.142 ***	+0.015 **
	eHi			-0.005	-0.069 ***	-0.197 ***	-0.036 ***
		Whole field					
El	Yld			+0.179 ***	+0.340 ***	+0.347 ***	+0.065 ***
	eMedium			-0.155 ***	-0.024 ***	+0.065 ***	-0.361 ***
	eHi			-0.125 ***	+0.067 ***	+0.095 ***	-0.435 ***
ECa	Yld			+0.087 ***	+0.281 ***	+0.318 ***	+0.141 ***
	eMedium			-0.078 ***	+0.001	+0.030 ***	-0.326 ***
	eHi			-0.076 ***	+0.055 ***	+0.014 ***	-0.262 ***
Av	Yld				+0.175 ***	+0.355 ***	+0.278 ***
	eMedium				+0.170 ***	+0.103 ***	-0.249 ***
	eHi				+0.195 ***	+0.183 ***	-0.220 ***
Cv	Yld					-0.028 ***	+0.111 ***
	eMedium					-0.103 ***	-0.030 ***
	eHi					-0.186 ***	-0.014 **

Discussion

In general the pattern of yield variation was consistent from year to year, and consistent with the overall pattern in ECa, despite the varying seasons experienced over the six years of available data. There were some areas which had an opposite yield pattern in dry years (eg. Nuttall and Armstrong 2006), but they were relatively small. This was evident in the first wetter season yield map (2009) having a lower spatial association with the average of the dry years before it (2006-2008). Apart from this, the pattern in any year's yield map would be a fair predictor of the pattern of yield in any other year. Composites of dry- and wet-season yield maps might add to the understanding of minimum yield and yield potential, providing they were not biased by agronomic quirks such as weed patches in the period collected.

The pattern of treatment response, however, was quite different from the pattern of yield, and not consistently spatially associated with either of the layers that might be used as a non-yield input for zoning (ECa and elevation). There was a better spatial association of treatment response with the pattern of average yield in the wetter years, but the association was only partial. The response was strongly biased towards the north half of the field in 2009 and 2010, where the pattern of average yield was not, and only approximately the inverse of the pattern of average yield in 2011. Future work should also test historical satellite NDVI.

The lack of association between input response pattern and yield pattern in a low-input environment seems unsurprising, but the contrary assumption is often made in practice. The nutrient balance in any part of a paddock is a complex balance between paddock history, inputs applied and removed, and the dynamics of mineralization, immobilization and fixation. There is still more complexity when the spatial histories of biotic factors such as weeds, pests and disease are considered. The studied field was an amalgamation of smaller fields (common throughout the Australian cropping area), and this adds another spatial dimension. In future, the history of zone patterns and differential treatments will form its own complex overlay in an economic environment where the cost of high-intensity soil sampling to integrate the effects of paddock history will always be prohibitive.

Conclusion

A sensible recommendation for precision agriculture in this and other environments where exhaustive (grid) soil sampling is ruled out because of cost, is to assume that responses to inputs will not follow the pattern of zones based on yield, or any other fixed factor. Zoning on yield (or a predictor of yield eg. ECa in this environment) is good for estimating starter nutrient requirements, and the potential for yield in different seasonal conditions. Soil sampling within zones should consider the history of paddock layout, and sample representatively across it if sampling within ancestor paddocks x zone combinations is cost-prohibitive. Zoning for in-season treatment responses should rely on scouting, proximal or remote sensing of the crop itself.

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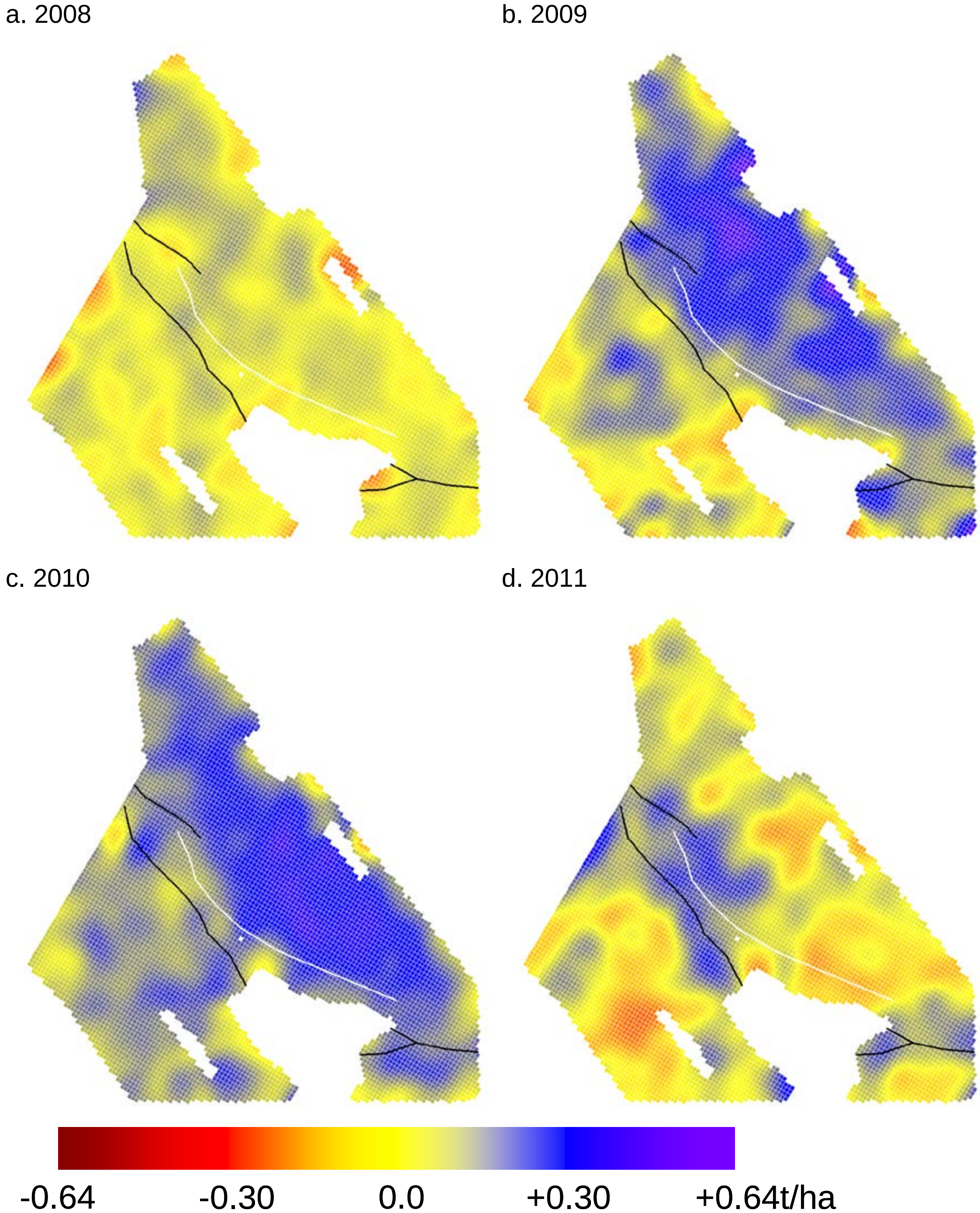
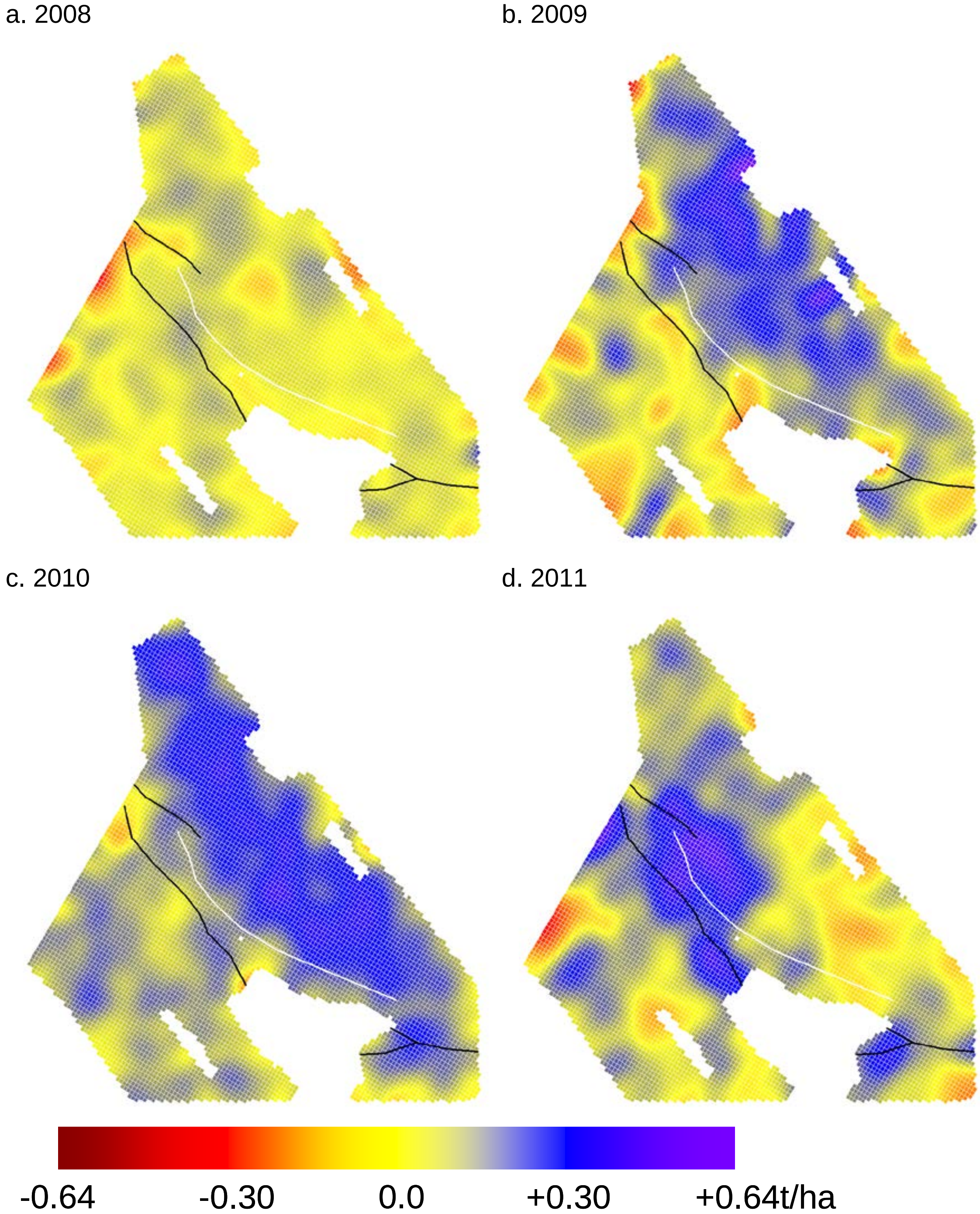
Appendices

Appendix 1



A1. Effect of medium treatment (compared with low) on yield, estimated by Geographically Weighted Regression in a. 2008;b. 2009; c 2010 and d 2011.

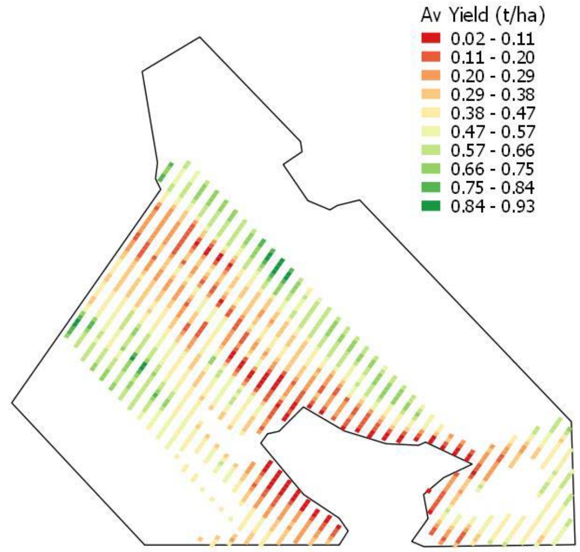
Appendix 2



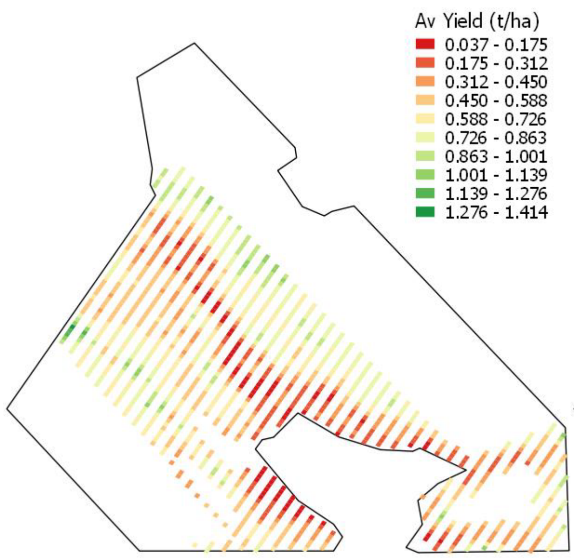
A2. Effect of high treatment (compared with low) on yield, estimated by Geographically Weighted Regression in a. 2008;b. 2009; c 2010 and d 2011.

Appendix 3

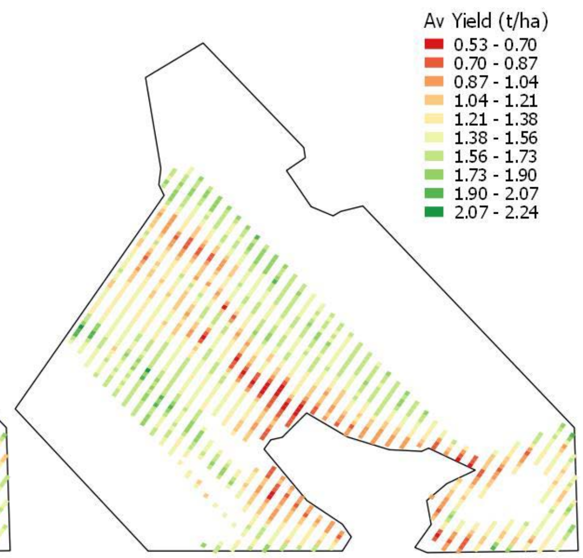
a. 2007



b. 2008

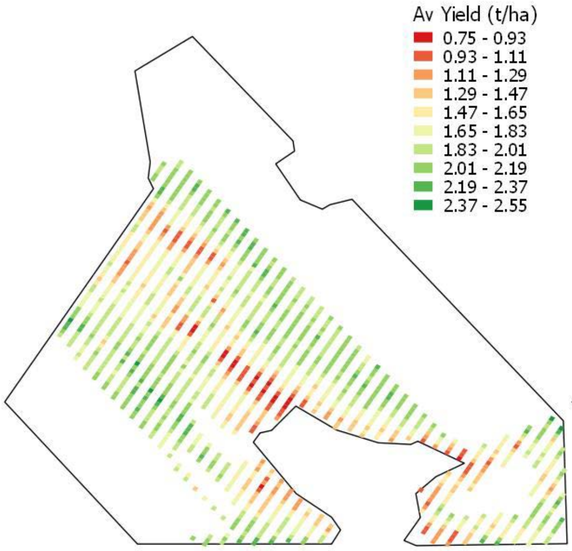


c. 2009



d. 2010

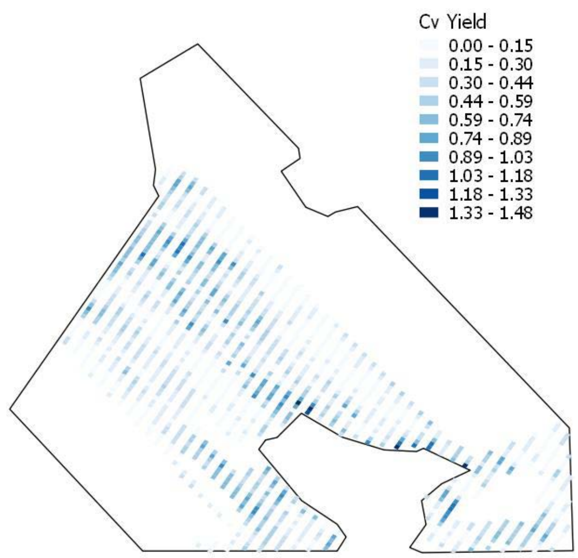
e. 2011



A3. Average yield for the medium treatment over the contiguous part of the field, for years up to and including a. 2007; b. 2008; c. 2009; d 2010 and e 2011.

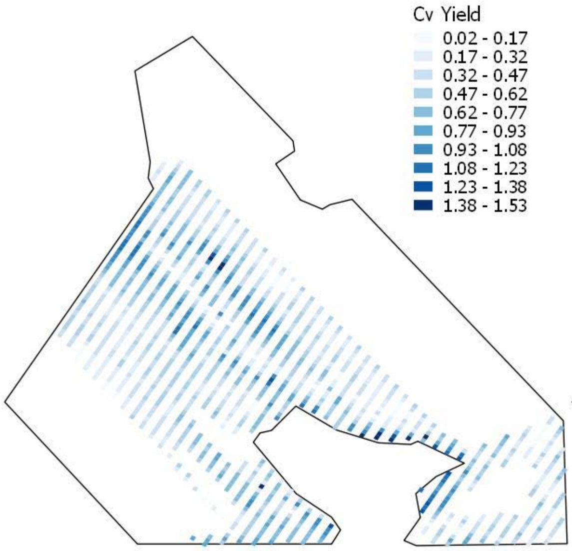
Appendix 4

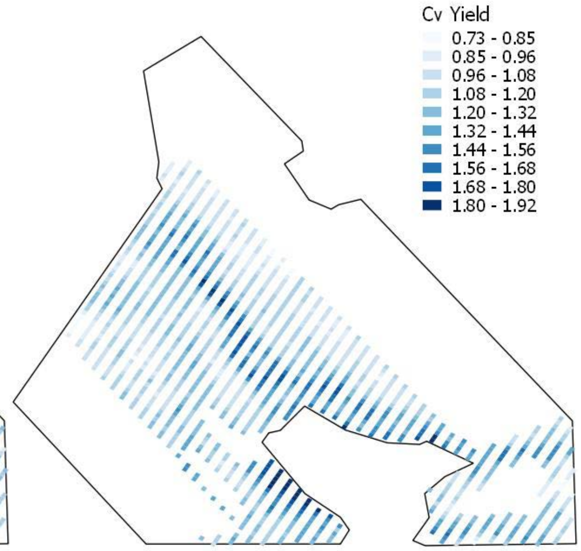
a. 2007



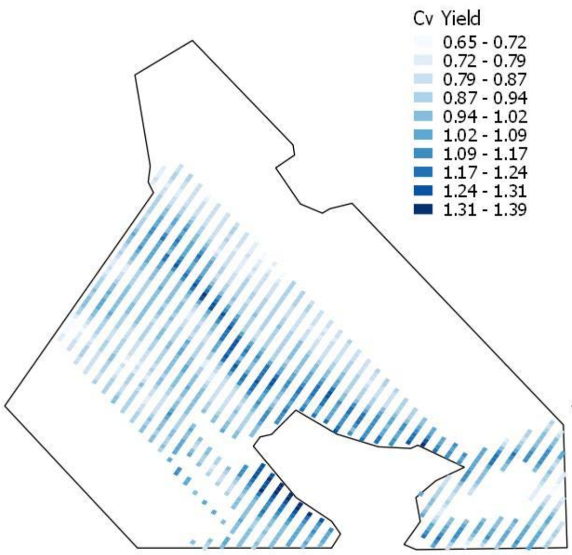
b. 2008

c. 2009

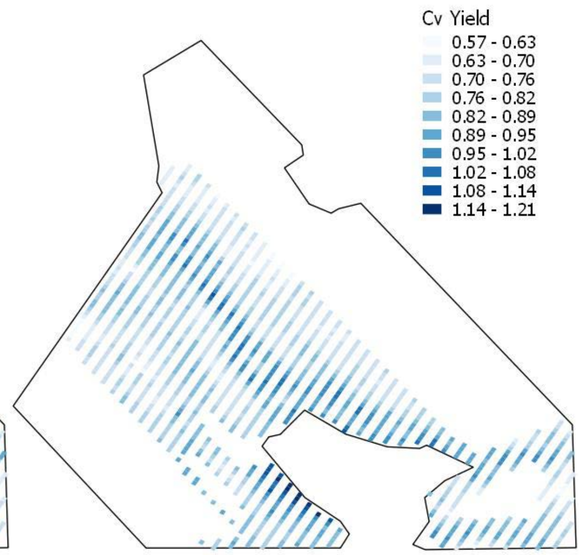




d. 2010



e. 2011



A4. Coefficient of variation of yield for the medium treatment over the contiguous part of the field, for years up to and including a. 2007; b. 2008; c. 2009; d 2010 and e 2011.