Definition and interpretation of potential management zones in Australia

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Abstract
Uptake of the Precision Agriculture philosophy in Australia will be driven by the development of systems that complement or improve the efficiencies in existing farming operations. Of most interest is the possibility for variable-rate application of crop inputs and ameliorants at the within-field scale, mainly due the dominance of inorganic fertiliser and pesticides in the variable costs budget. Variable-rate application options will be governed by quantifiable yield and soil variability along with the operational specifications of the application technology. However, the current accuracy in monitoring and application technology suggests variable-rate application is best served in Australia by the discrimination of significantly different production zones, followed by directed exploratory sampling, and then treatment or experimentation depending on the site-specific nature of the causes of variability. A process for delineating potential management zones is provided that is based on differences in yield, soil electrical conductivity and elevation information. A significance test for the zonal yield differences is shown that uses the kriging prediction variance. Stratified random sampling is subsequently shown to confirm significant differences in influential soil properties between these zones in two dryland paddocks.

Keywords
Kriging variance, k-means clustering, confidence intervals.

Introduction
Site-Specific Crop Management (SSCM), should be considered as part of the continuing evolution in arable land management. Recent developments in technology (satellite navigation systems, geographic information systems, real-time yield and soil sensors) have essentially improved the scale at which we can observe variability in production.

For SSCM to be tested/accepted/adopted across the agroclimatic zones in Australia, it is important that a cost-effective, practical system be offered to assess and partition the within-field variability in crop production. Such a system should aim at investigating causal relationships between soil/crop factors and yield at the within-field scale along with the extent to which these relationships vary across the field. This information should be used to determine whether the observed variability warrants differential treatment and if so, direct a route through a SSCM decision methodology. However, while the concept of SSCM aims to provide more detailed information on the crop production process to improve management, it must be remembered that information itself possesses a number of defining attributes. High on the list of attributes important to SSCM is accuracy and relevance. An understanding of digital map making and the errors implicit in their representations of variability is important.

Potential errors in spatial data gathered for SSCM
The gathering of fine-scale data for SSCM relies on a number of mechanical vehicles, mechanical and electrical/electronic sensors, navigation/location systems and recording devices. The operation of which may introduce errors into the data before any analysis is considered. In general terms these errors are contributed to by:

- GPS spatial error and antenna position bias
- Sampling error in mechanical operation
- Quantitative error in technique/calibration
- Quantitative error due to electrical/electronic interference

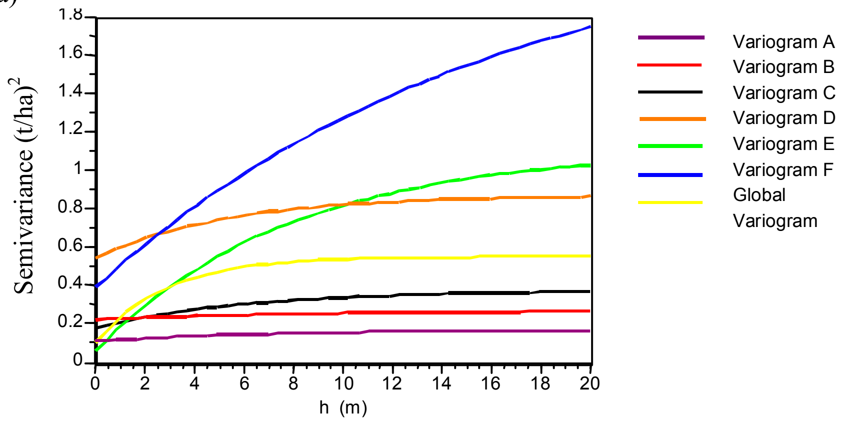
The introduction of any errors from these sources results in uncertainty in the measurement of an attribute at individual points in a paddock.

While the aim should be to minimise the errors at the data collection stage, the functional errors will be a reality for the foreseeable future. Because of this, it is important to understand the magnitude of the errors and attempt to incorporate them in further assessment of the data (1, 2). Operations such as the accurate correlation between layers for interpretation, and then prescribing and assessing outcomes of differential management require such understanding.

Non-stationary covariance

The data provided from the sensors employed in SSCM is spatially dense. Detailed studies (3, 4) made possible by the large number of observations in a paddock (of the order of $10^4 – 10^5$) have shown that observations have a non-stationary covariance structure. That is, besides having different means, some parts of a paddock are more uniform or variable than others. Figure 1 illustrates this for a wheat crop. Different parts of the paddock have different semivariograms (Figure 1a) and the local variance is spatially patterned (Figure 1b).

(a)



(b)

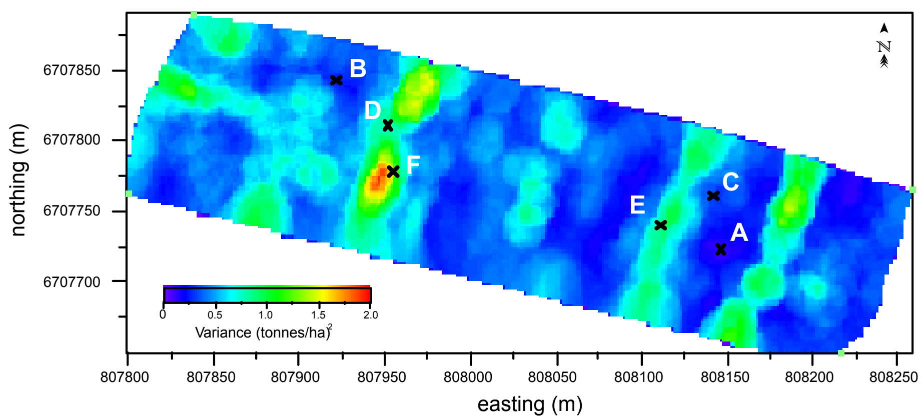


Figure 1. Wheat yield from a paddock in northern NSW. Neighbourhood variograms for different locations in the paddock (1a) and the local variance at each location the paddock (1b) for the six variograms (A-F).

Spatial prediction

In order to incorporate data gathered by these sensors into a GIS, they have to be estimated onto a raster common to other data layers (i.e. yield or remotely/proximally-sensed imagery). Spatial prediction methods used in PA should accurately represent the spatial variability of sampled field attributes, the inherent errors, and maintain a principle of minimum information loss. Having recognised this, and the non-stationary covariance, Whelan et al. (3) have developed software that does local ordinary block kriging with local neighbourhood variograms and provides estimates for prediction error. This is used to ensure that the spatial resolution of digital maps reflects the inherent uncertainty in the attribute estimates.

Management zones

In the United States, variable-rate application (VRA) began prior to the advent of yield mapping, using the analytical testing (chemical analysis of nutrients) of topsoil samples collected on a 100-yard grid. This approach is expensive (in Australian terms) and may be logically flawed. The idea presupposes that all areas in a paddock have the same yield potential and in order to reach that potential the optimum amount of fertiliser has to be applied at each point. Research in Europe and Australia (and only recently in the US) has suggested that it would be better to recognise areas within paddocks which have different yield potentials (and therefore management requirements), but which may be managed uniformly within the defined boundaries. These areas, called management zones are in essence, small fenceless fields within much bigger fields. This approach may be regarded as a risk-averse compromise between uniform management with little or no spatial information and continuous management under temporal uncertainty.

There have been a number of techniques used in the delineation of potential management zones. They include:

- Polygons hand-drawn on yield maps or imagery (5, 6)
- Classification of remote sensed imagery from an aerial or satellite platforms using both supervised and unsupervised procedures (7, 8, 9)
- Identification of yield stability patterns across seasons at fixed map nodes using correlation co-efficients (10), weighted taxonomic distance (11), temporal variance (12); normalised yield classification (13)
- Fuzzy multivariate cluster analysis using seasonal yield maps (14, 15)
- Morphological filters or buffering (16)
- Spectral filters using Fast Fourier Transform (16)
- Multivariate analysis by hard k-zones (17)

Other options that have been raised are the classification of a soil fertility index calculated by factor analysis and the simple use of standard deviation and the frequency distribution to partition yield/soil maps or imagery.

Relevant data layers for Australia

Layers of accurate, spatially-dense, georeferenced information are required to begin the process. Maximising practicality and minimising cost are the major constraints. Crop yield maps obviously contain information on seasonal production that is essential to this process. Beginning this process without information on the spatial variability in the saleable product would appear to be financially imprudent.

It is, however agronomically sensible to include some information on soil and landscape variability in the decision process. Many studies have shown that the most dominant influences on yield variability (other than climate) are the more static soil physical factors such as soil texture (15, 18, 19) associated structure, and organic matter levels (20, 21, 22). These are known to indirectly contribute to cation exchange capacity, nutrient availability and moisture storage capacity of the soil.

Gathering direct data on these attributes at a fine spatial scale is problematic, but a number of correlated attributes can be gathered relatively swiftly. Apparent electrical conductivity of the soil (ECa) has been shown to provide corroboration to the spatial yield pattern in many fields, and correlation with a number of deterministic physical soil parameters (20, 23). Field topography has also been shown to provide an indirect indication of variability in soil physical and chemical attributes - again usually due to a high correlation with a deterministic attribute such as soil texture (8, 22, 24, 25). Topography also provides indirect information on microclimate attributes that influence crop production potential (26).

These soil attributes are, however, extremely difficult or impractical to amend in the short-term. However if the more rigid factors are going to limit yield then it would seem prudent to allow these to influence the application rates of any inputs/ameliorants in the field. Intuitively, factors contributing to variability in the soil moisture regime and physical properties controlling soil water movement and nutrient supply may be the most significant causal factor in the spatial variability of crop yield in the majority of cereal growing regions in Australia. Many of the more easily adjusted soil factors such as available nutrient levels and pH could be expected to vary based on the consequences of variation in the physical properties of the soil. Using the variation in the indicator factors - crop yield, soil ECa and elevation - as a basic data set to delineate areas of homogeneous yield potential may prove useful. The response of inputs/ameliorants to these factors will of course be site-specific, but the significance of their influence may not. Of course other data layers that may be gathered at the same spatial scale may be included if warranted.

Materials and Methods

A method for delineating potential management zones with some certainty

All attributes to be used in the 'zoning' process for each paddock were predicted onto a single, 5-metre grid through local block kriging with local variograms using VESPER (3). With all attributes on a common grid, multivariate k-means clustering was employed to delineate the potential management zones. This is an iterative method that creates disjoint zones by estimating cluster means which maximise the Euclidean distance between the means and minimise the distances within the cluster groupings.

Of the available data layers, crop yield (or the income derived there from) has the greatest bearing on farm management and practices at present. Potential management zones, however they are derived, should therefore display significant differences in yield for VRA to be worthwhile. However, ensuring that the differences displayed in crop yield maps are genuine, let alone significant is difficult. Fortunately, the block kriging process provides an estimate of the mean prediction variance (σ^2_{krig}) from which the confidence interval ($CI_{95\%}$) surrounding the mean yield estimate within a paddock (μ) can be calculated (Equation 1).

$$CI_{95\%} = \mu \pm \left(\sqrt{\sigma^2_{krig}} \times 1.96\right)$$ Equation 1

And the absolute difference between mean zone yields ($\left|\overline{Y}_{zone1} - \overline{Y}_{zone2}\right|$) should then follow Equation 2 for the zones to be considered representative of regions of significantly different yield ($p<0.05$).

$$\left|\overline{Y}_{zone_x} - \overline{Y}_{zone_w}\right| \geq \left(\sqrt{\sigma^2_{krig}} \times 1.96\right) \times 2$$ Equation 2

Directed soil sampling

The basic layers used in determining the potential management zones provide an integrated assessment of changes in production potential using soil, landscape and yield attributes. The next step requires that the zones be interrogated for the cause of the observed yield variability. For SSCM, there are 4 propositions to consider. Whether one (or a correlated combination of) static factor/s can be identified that dominates the changes in yield potential in a field. Whether there is a transient, manipulable factor that is restricting zones of the field reaching seasonal yield potential. Whether complex interrelationships between observable factors needs to be analysed and modeled. And finally, whether the yield variability is caused by a change in the production process that was not measured (e.g. unobserved, localised pest damage or disease)

The first two proposals simplify management responses. The third may be optimal in terms of optimising yield and environmental benefits, but economically unviable (at present). The fourth would probably show up in a correlation with a static factor unless there was a breakdown in normal standard of agronomy management.

At present, soil sampling is undertaken using a form of stratified random sampling with the potential management zones as the strata. Constraints on the random allocation of sample points are imposed to avoid strata boundaries and to target zone centroids. A minimum of 3 separate spatial locations, with segregated samples from the top soil (0-0.3m) and subsoil (0.3 – 0.9m (max)) are targeted for each potential zone.

Results and Discussion

Paddock 1 Data layers

In this 75ha field, the data layers used are yield in the 1998 and 1999 growing seasons (Figures 2a-2b), soil electrical conductivity (Figure 2c) and elevation data (Figure 2d) all collected on a similar spatial scale. The data was collected using (respectively) an Agleader yield monitoring system, the Veris® 3100 conductivity array and an Ashtech™ single frequency plus C/A-code RTK GPS with post-processing.

Paddock 1 Delineating potential management zones

Two and three potential management zones were delineated (Figure 3) for the purposes of testing the validity of the multivariate clustering and significance procedures through subsequent soil analysis. The delineation of zones using this procedure has provided a CI for the two crops in question (Table 1).

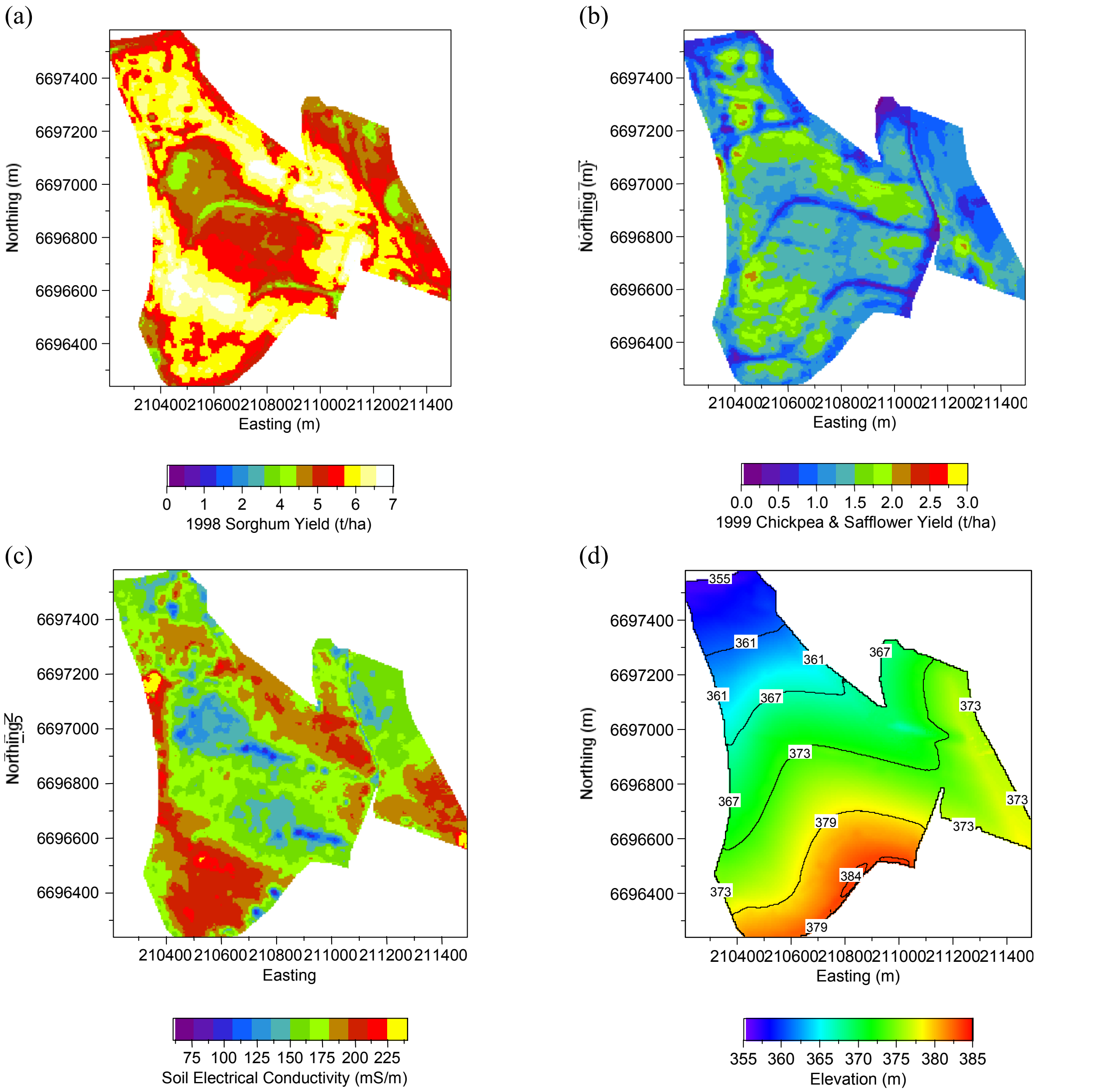


Figure 2. Data layers from a 75 ha paddock in northern NSW – (a) 1998 sorghum yield (b) 1999 chickpea and safflower (c) soil ECa (d) elevation.

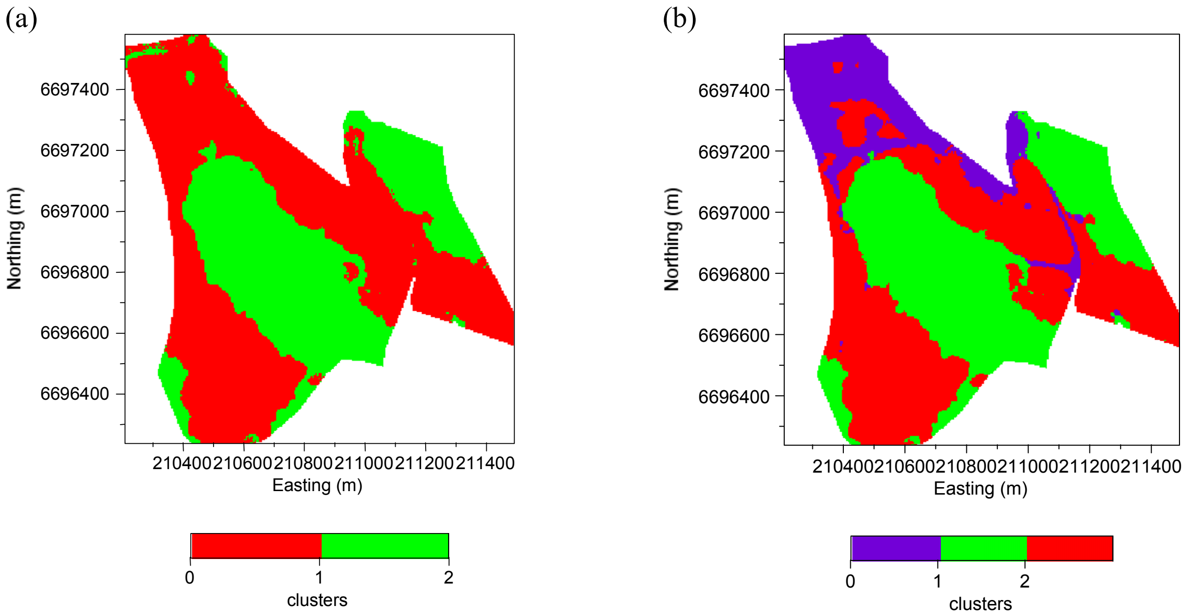


Figure 3. Two (a) and three (b) potential management zones as defined by multivariate k-means clustering.

Table 1. Zonal means for the data layers used in the delineation process. Values for 2 and 3 zone scenarios are shown along with Confidence Interval (CI) values.

	98 Sorghum Yield (t/ha)	99 Chickpea Yield (t/ha)	ECa (mS/m)	Elevation (m)
2 Zones				
Zone 1	5.8	1.4	185	371
Zone 2	4.8	1.1	156	375
3 Zones				
Zone 1	5.9	1.4	189	374
Zone 2	4.7	1.1	155	375
Zone 3	5.5	1.2	173	363
CI (+/- t/ha)	0.2	0.1	13.6	

Concentrating on sorghum, a of ± 0.2 t/ha means that a difference of at least 0.4 t/ha between the mean sorghum yields in the potential zones should be seen to negate the possibility that the variability carried through the mapping and zoning procedures is incorrectly depicting the spatial patterns. From Table 1, the 2-zone difference is 1.0 t/ha and the smallest three-zone difference is 0.4 t/ha. This suggests that a split into 3 zones is on the border of being justified based on the mean sorghum yield differences. For chickpea, a difference of 0.2 t/ha between the mean yields in the potential zones should be seen to warrant further investigation. This is clearly the case for 2 zones but if we increase the number of zones to 3 the differences are not large enough.

Paddock 1 Directed soil sampling

The zones have been delineated using production information gathered in great detail. Soil sampling sites have been directed within each of the 3 zones (Figure (3b)) in an attempt to explore causes for the yield differences (Tables 4 and 5). In Tables 2 and 3, the sample sites have been reallocated to one of 2 zones described in Figure 4(a).

In the case of 2 potential zones, analysis of the top soil (Table 2) shows that zone 2 has produced lower crop yields despite a higher CEC and a lower sand fraction than zone 1. Soil nitrate is also double in zone 2. An examination of the soil below 0.3m (Table 3) shows that the CEC and clay content of zone 2 are significantly lower than in zone 1, and the soil nitrate remains double. The difference in the physical properties of the subsoil, combined with the fact that the soil is on average 40% shallower in zone 2 conspires to restrict the quantity of available moisture in the profile compared to zone 1. This relative limitation in soil moisture in zone 2 would limit crop yield and therefore reduce the nitrogen requirement. Under uniform fertiliser management, accumulation of soil nitrogen reserves (as evident in nitrate and total N levels in Tables 2 and 3) would be expected.

Table 2. Two Zones - soil test results for the 0-0.3 m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Field Mean
pH ($CaCl_2$)	7.5	7.6	7.6
OC (%C)	0.7	0.9	0.8
N03 (mg/kg)	15.0	30.4	22.7
P (mg/kg)	4.5	5.3	4.9
K (meq/100g)	0.7	0.6	0.7
Ca (meq/100g)	45.9	62.3	54
Mg (meq/100g)	20.2	13.2	16.7
Na (meq/100g)	0.8	0.2	0.5
Total N (mg/kg)	868	1026	947
CEC (meq/100g)	67	76	72
Ca/Mg	2.3	4.8	3.6
ESP %	1.13	0.25	0.69
Sand %	14	10	12
Silt %	13	15	14
Clay %	73	75	74
EC	137	163	150

Table 3. Two zones - soil test results for the 0.3-0.9 m soil layer

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Field Mean
pH ($CaCl_2$)	7.9	7.7	7.8
OC (%C)	0.7	0.8	0.8
N03 (mg/kg)	8.7	14.7	11.7
P (mg/kg)	2.8	3.7	3.3
K (meq/100g)	0.6	0.42	0.51
Ca (meq/100g)	42.9	42.1	42.5
Mg (meq/100g)	23.3	9.5	16.4
Na (meq/100g).	2.4	0.3	1.3
Total N (mg/kg)	610	887	749
CEC (meq/100g)	69	53	61
Ca/Mg	1.9	5.2	3.6
ESP %	3.5	0.7	2.1
Sand %	13	17	15
Silt %	11	17	14
Clay %	76	66	71
EC	159	126	143
Soil Depth (m)	1.22	0.71	0.97
Profile avail. H20 at sampling (mm)	118	68	93

If the field is broken into 3 potential zones, the process essentially divides the previous zone 1 into 2 zones. The soil analysis (Tables 4 and 5) shows that the partitioning is reflected in a more refined separation of texture, CEC, depth, soil profile moisture content and nitrogen reserves between all 3 zones. Combining this information with the uncertainty analysis would suggest that in this instance, 3 zones are probably warranted for cereal crops where nitrogen is applied.

Table 4. Three zones - soil test results for the 0-0.3 m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Purple)	Field Mean
pH ($CaCl_2$)	7.8	7.6	7.2	7.5
OC (%C)	0.6	0.9	0.8	0.8
N03 (mg/kg)	10.6	30.4	19.3	20.1
P (mg/kg)	2.7	5.3	6.3	4.8
K (meq/100g)	0.5	0.6	0.9	0.7
Ca (meq/100g)	51.3	62.6	40.5	51.5
Mg (meq/100g)	22.1	13.2	18.3	17.9
Na (meq/100g)	1.0	0.2	0.5	0.6
Total N (mg/kg)	658	1026	1079	921
CEC (meq/100g)	75	77	60	70
Ca/Mg	2.3	4.8	2.2	3.0
ESP %	1.35	0.25	0.92	0.84
Sand %	12	10	16	13
Silt %	13	15	13	14
Clay %	75	75	71	74
EC	136	163	138	145

Table 5. Three zones - soil test results for the 0.3-0.9 m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Purple)	Field Mean
pH ($CaCl_2$)	8.0	7.7	7.8	7.8
OC (%C)	0.6	0.8	0.7	0.7
N03 (mg/kg)	5.6	14.7	11.9	10.7
P (mg/kg)	2.5	3.7	3.0	3.1
K (meq/100g)	0.48	0.42	0.65	0.5
Ca (meq/100g)	47.0	42.1	38.9	42.7
Mg (meq/100g)	24.9	9.5	21.5	18.6
Na (meq/100g)	2.7	0.3	2.1	1.7
Total N (mg/kg)	532	887	687	702
CEC (meq/100g)	74.8	52.3	63.4	63.5
Ca/Mg	1.9	5.2	1.8	3.0
ESP %	3.6	0.7	3.2	2.5
Sand %	11	18	15	15
Silt %	11	17	11	13
Clay %	78	65	74	72
EC	155	126	162	148
Soil Depth (m)	1.24	0.68	1.17	1.03
Profile avail. H20 at sampling (mm)	128	68	108	101

Paddock 2 Data layers and delineating potential management zones

For this 325 ha paddock in northern NSW, wheat yield from the 1999 season, soil ECa and elevation were collected as described earlier. The mean results from delineating 2 zones (Z1 yield = 3.7 t/ha, ECa = 114 mS/m ; Z2 yield = 4.9 t/ha, ECa = 140 mS/m) and 3 zones (Z1 yield = 3.4 t/ha, ECa = 112 mS/m ; Z2 yield = 4.9 t/ha, ECa = 132 mS/m ; Z3 yield = 5.0 t/ha, ECa = 144 mS/m) suggest that there is little increase in management opportunity revealed by the 3 zones. The CI calculation (+/- 0.35 t/ha) adds weight to this assessment. Figure 4 shows the delineation patterns for 2 zones (a) and 3 zones (b) respectively.

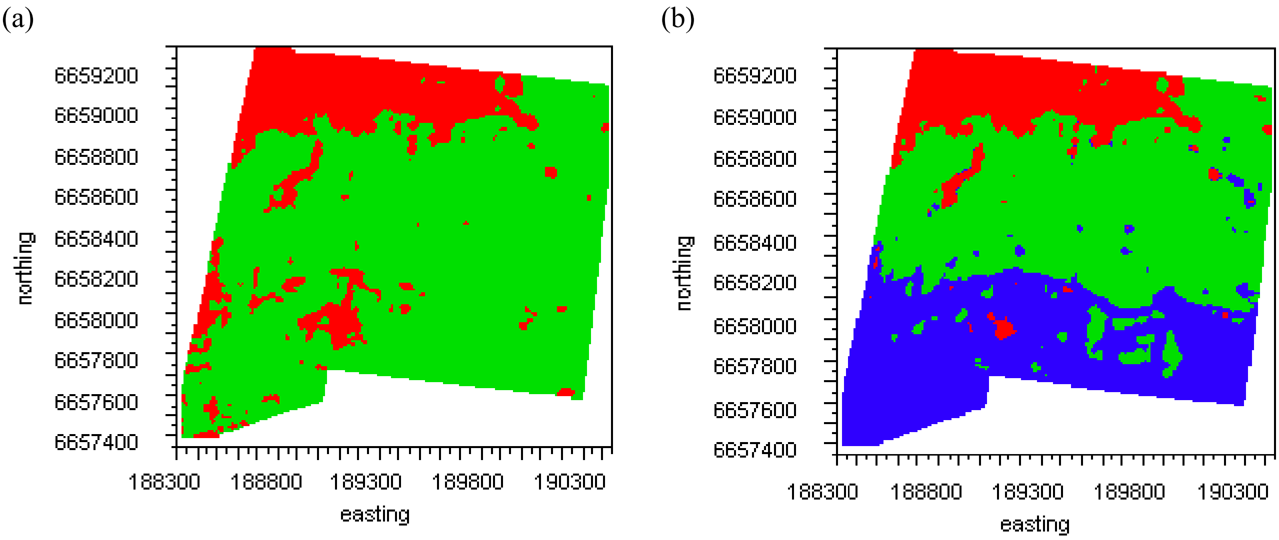


Figure 4. Two (a) and three (b) potential management zones as defined by multivariate k-means clustering. Zone 1 = red, zone 2 = green, zone 3 = blue.

Paddock 2 Directed soil sampling

The results for soil sampling into the 3 zones are shown in Tables 6 and 7. The most striking zone deviations from the estimated paddock mean show up in the ESP%, clay content and profile available moisture. If an ESP% >6 is taken as indicating problematic soil structure, sampling for an average would suggest the paddock was not yet in need of treatment. Zone sampling, however, identifies zone 1 as having a much higher ESP% than the other zones, and importantly, above critical limits in the topsoil (where treatment is more practical). The high ESP% can be hypothesised to be contributing to surface-sealing and reduced infiltration in zone 1. A lower clay content helps magnify the difference in the ability of this zone to store moisture, as seen in Table 7.

The CI calculation suggested that 2 zones were likely warranted in this paddock and this has been born out by subsequent, directed soil sampling. The similarity of soil conditions in zones 2 and 3 reflect the closeness in mean yield observed in the wheat yield map. VRA of gypsum, or directed deep-ripping offer potential remedies.

Table 6. Three zones - soil test results for the 0-0.3 m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Blue)	Field Mean
pH ($CaCl_2$)	7.8	7.8	7.9	7.8
N03 (mg/kg)	9.2	12.2	15.1	12.2
P (mg/kg)	9.7	10.3	8.7	9.6
K (meq/100g)	0.71	1.03	0.97	0.9
Ca (meq/100g)	17.7	21.4	26.8	22.0
Mg (meq/100g)	11.3	14.0	12.8	12.7
Na (meq/100g)	2.4	1.8	2.0	2.1
Total N (mg/kg)	501	600	496	532
CEC (meq/100g)	32.1	38.2	42.7	37.7
Ca/Mg	1.5	1.5	2.1	1.7
ESP %	8.1	4.7	4.7	5.8
Sand %	31	16	16	21
Silt %	22	19	23	21
Clay %	47	64	60	57
EC	0.143	0.113	0.137	0.131

Table 7. Three zones - soil test results for the 0.3-0.9 m soil layer.

Soil Attribute	Zone 1 (Red)	Zone 2 (Green)	Zone 3 (Blue)	Field Mean
pH ($CaCl_2$)	8.3	8.3	8.3	8.3
N03 (mg/kg)	6.0	6.4	9.7	7.4
P (mg/kg)	21.2	12.0	9.7	14.3
K (meq/100g)	0.64	0.81	0.81	0.75
Ca (meq/100g)	17.2	18.6	22.5	19.4
Mg (meq/100g)	14.1	17.6	15.2	15.6
Na (meq/100g)	6.5	5.1	5.4	5.7
Total N (mg/kg)	275	339	419	344
CEC (meq/100g)	38.5	42.1	43.9	41.5
Ca/Mg	1.2	1.1	1.5	1.3
ESP %	17.3	12.1	12.2	14.1
Sand %	27	13	15	18
Silt %	20	23	22	22
Clay %	53	64	63	60
EC	0.373	0.233	0.256	0.287
Soil Depth (m)	0.8	0.85	0.8	0.82
Profile avail. H20 at sampling (mm)	24	58	56	46

In the Australian dryland environment, it is not unexpected that factors controlling the interaction between crops and the climatic environment should be prominently influential in the variability displayed in crop yield maps. This should also be the case in most relatively low rainfall environments around the world. For example, Thomsen et al. (1997) found that in 'dry years' the spatial variability in water holding capacity (calculated by water balance modeling) was a highly significant contributor in yield variability but was not significant in years with 'sufficient' moisture. For management, this suggests that it will be necessary to use this zone information in conjunction with early season environmental indicators and crop response models (or simpler, empirical budget models) to guide differential action decisions.

These decisions should not focus on treating a field to produce a uniform yield unless the potential is uniform. The benefits from this type of analysis will only be realised by acknowledging diversity in yield potential and environmental conditions when formulating field management operations. For example, well-documented areas of low yield potential may be removed from production, have the land-use changed or have their inputs reduced to minimise potential financial losses.

Summary

The process of potential management zone delineation described here offers a relatively simple, practical approach to using production data gathered at a fine spatial scale. The directed soil sampling should identify whether there is a/are manipulatable limitation/s on production or definable variability in crop yield potential. The process described here is not designed to correct poor traditional (managing to the average) agronomy. Farmers will get greater financial gains by ensuring uniform management is reasonable before venturing down the Site-Specific Crop Management path. For those ready to explore improvement on uniform management, 5 steps have been identified:

1. Gather relevant data layers.
2. Spatial prediction onto a single grid using block kriging.
3. k-means clustering using all relevant layers to delineate potential management zones.
4. Utilise the field mean kriging variance (yield) to determine the confidence interval for zone partitioning.
5. Directed soil sampling to assess soil-related causes of between-zone variability.

When contemplating the number of agronomically significant zones, care must also be taken to consider and test for the major limiting factors in each zone. Much research will be required to understand the agronomy of response at the within-field scale, under site-specific conditions.

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