Chapter 5: A protocol for mapping vineyard soil surveys

This chapter is the first in a series of three linked chapters dealing with digital terroir prediction within vineyards. In this chapter a protocol is proposed for extracting spatial information from existing vineyard soil surveys. Chapter 6 examines how new information sources can be incorporated with existing information to provide more accurate and precise vineyard maps. Chapter 7 then utilises the data from the preceding two chapters with some additional ancillary information to predict "digital terroirs" within the vineyards. These predictions are tested against vine response in the form of Vis-NIR imagery and/or yield mapping.

5.1 Introduction

Australian vineyards in the past 10 years have been surveyed and designed based on the ICMS/Wetherby system developed in South Australia by the Loxton Irrigated Crop Management service (ICMS) and Ken Wetherby (McKenzie, 2000). Based on a 75 m grid, soil pits are excavated and field observations recorded. These observations are then used to derive indices to evaluate the suitability of a site for viticulture. The main index derived is Readily Available Water (RAW). Derived relationships between texture and soil moisture and a visual inspection of the potential rooting depth is used to calculate the amount of water that is readily available for plant growth. While highly subjective and qualitative this approach has allowed viticulturists to roughly delineate areas of differing moisture potential and improve vineyard and irrigation design and layout. In the past few years modifications have been proposed such as the SOILpak-PLM system (McKenzie, 1999). Based on the ICMS/Wetherby system it incorporates some basic field tests developed in the cotton industry to produce soil improvement maps. Rather than just recording the local soil conditions, these maps highlight where remedial soil management, such as deep ripping, gypsum-lime application, drainage/mole pipes, may be useful in improving soil and the crop production system. A similar system has also apparently been developed by the Rellney Group in South Australia (McKenzie 2000).

While the ICMS/Wetherby system has been very effective it does have limitations. Many soil attributes are recorded as linguistic rather than numeric variables, for example texture and colour. This makes the interpolation of data more difficult. As a result the data, even numeric data, tends to be presented in point form (see Figure 5.1). Presentation in this form allows a lot of data to be conveyed on a single map however it is difficult to visualize and interpret the maps. Expert knowledge is required to interpret these maps and delineate potential "digital terroirs". Basic soil physical properties are also not recorded, for example soil hydraulic conductivity, bulk density, field capacity and permanent wilting point. Most of these parameters are too difficult and/or time consuming to measure in the field. Over the past 10-15 years a variety of pedotransfer functions (PTFs) have been derived for various soil types and properties to overcome this problem. A PTF is simply a predictive function for a certain soil property that utilises other soil properties that are more easily, routinely or cheaply measured (Minasny, 2000). Minasny (2000) has collated and documented over 270 Australian soil profiles and derived PTF's for numerous soil attributes.

The aim of this chapter is to utilise known pedotransfer functions to produce a protocol to convert

An excel macro for converting soil survey data into qualitative data will shortly be available from the ACPA website.

field surveyed soil information into quantifiable soil properties that can be readily mapped, manipulated and modelled.

5.2 Methodologies

5.2.1 Data Collation

5.2.1.1 Sites

Three soil surveys, all conducted based on the ICMS/Wetherby system, were collected from two distinct viticultural regions in NSW. Data was digitised for a survey of 240 pits on a 100 ha site at Cowra (148.6990E°, -33.8347N°) by the Irrigated Crop Management Services (ICMS) in 1993. A 130 ha site at Canowindra (148.6598E°, -33.5587N°) was surveyed with 227 soil pits by Ken Wetherby in 3 phases from 1994 to 1997. In the Hunter Valley (151.3617°E, -32.8419°N), 85 ha of Orlando-Wyndham's Pokolbin Vineyard was digitised from a survey of 89 soil pits conducted by ICMS in 1994.

5.2.1.2 Digitisation of Data

Archival information was retrieved in the form of point maps and tabulated data from each vineyard. Tabulated data for each soil survey pit site for the three vineyards was manually entered. This data included horizon depths, textures, pH, Munsell soil colour, root zone depth and readily available water (RAW). The point vineyard maps, which include the vineyard boundary, were digitised by scanning or taking a digital photographed depending on size. Existing aerial or satellite imagery of the vineyards was also obtained. For hard copy image data where a soft copy did not exist the image was again scanned or digitally photographed.

5.2.2 Data Manipulation

Some of the soil survey data was recorded in numeric form including information on depth of soil horizons, estimation of rooting zone depth and RAW. This data required no further manipulation before mapping. Other information such as soil texture and soil colour did require manipulation into quantitative soil attributes before mapping.

5.2.2.1 Texture and Particle Size Distribution

Field soil texture was recorded as a linguistic variable, for example sandy clay, clay loam. The texture class assigned is subjective to the surveyor and varies with the classification system being used, in this case the Australian Soil Texture triangle (Marshall, 1947). The Australian Soil Texture Triangle consists of eleven textures. However, soil surveyors tend to be more adventurous with their gradings and in total the three surveys yielded 37 different texture descriptions, including classifications of underlying bedrock. This created a need to reclassify and simplify the survey data.

Underlying rock was classed as bedrock (BR) regardless of the rock-type identified. Several classes carried additional qualifiers. Gravelly (G) and coarse (K) qualifiers were ignored and the texture reclassified into the basic texture class thus GLC becomes LC. However fine (F) and light (L) qualifiers were retained. This reduced the number of texture classes to 20. Two of the texture

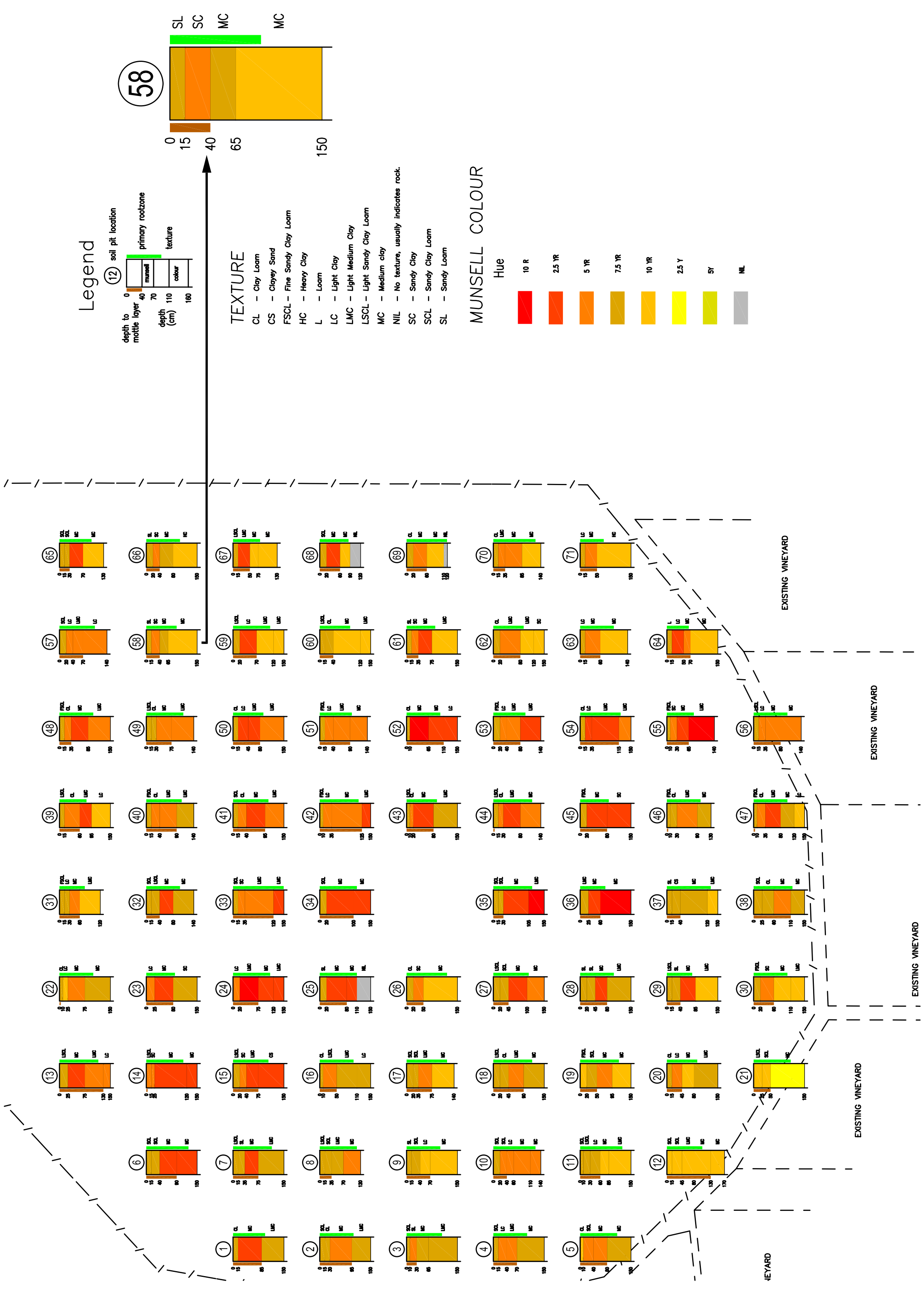


Figure 5.1: An example of the current protocol for displaying vineyard soil surveys as point maps. Point 58 has been enhanced to show the level of detail in the map with horizon depths, textures and colour simultaneously displayed. (Figure 5.1 updated June 2007 using the original vineyard image kindly supplied by Mr Desmond Elliot, DUNHESS P/L, Hillcrest, SA)

classes, BR (bedrock) and WT (watertable), were considered to have no particle size distribution (PSD) and removed. This left 18 remaining textures from the soil surveys. From Marshall's texture triangle two textures, Loam (L) and Silty Loam (ZL) were not included and therefore they were added to the classification to give 20 final textures. The surveyed textures and resultant reclassifications are shown in Table 5.1. (NB. The texture class clay (C) from Marshall (1947) was dropped as it was not used in any of the surveys and has been superseded by more specific descriptions- light clay (LC), heavy clay (HC), light medium clay (LMC) and medium clay (MC)).

From previous studies of the relationships between texture triangles, hand texture grading and particle size analysis, Minasny and McBratney (2001) have produced estimations of the median PSD for soil texture classes for Australian soils. These median values have been assigned to the simplified texture grades extracted from the survey data (Table 5.2). For texture grades from the vineyard surveys that were not identified in their study some expert knowledge and the existing median location of related textures were used to estimate the PSD. The median location of the 20 texture grades, identified in Table 5.2 have been plotted on the Australian Texture Triangle (Figure 5.2). Minasny and McBratney (2001) observed a discrepancy between field textures using Marshall's texture triangle and laboratory analysis of PSD and suggest that the Australian texture triangle is really a "boomerang". This accounts for the mismatches observed in Figure 5.2.

5.2.2.2 Prediction of individual soil properties

Once known, the particle size distribution (PSD) can be used to predict other soil properties. For this study we are using the pedotransfer functions (PTF's) of Minasny (2000) which have been derived for Australian soils. The particle size distribution (PSD) was used to estimate the moisture characteristic curve for each horizon and to predict bulk density. A neural network simulation model, NeuroTheta (Minasny and McBratney, 2002), has been developed in conjunction with the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR) to approximate the moisture retention curve of a soil given its PSD. Estimating the soil moisture characteristic permits the prediction of available water at different moisture potential including field capacity (-10kPa) and wilting point moisture (-1500kPa). For North American soils a similar lookup table has been developed based on the work of Saxton

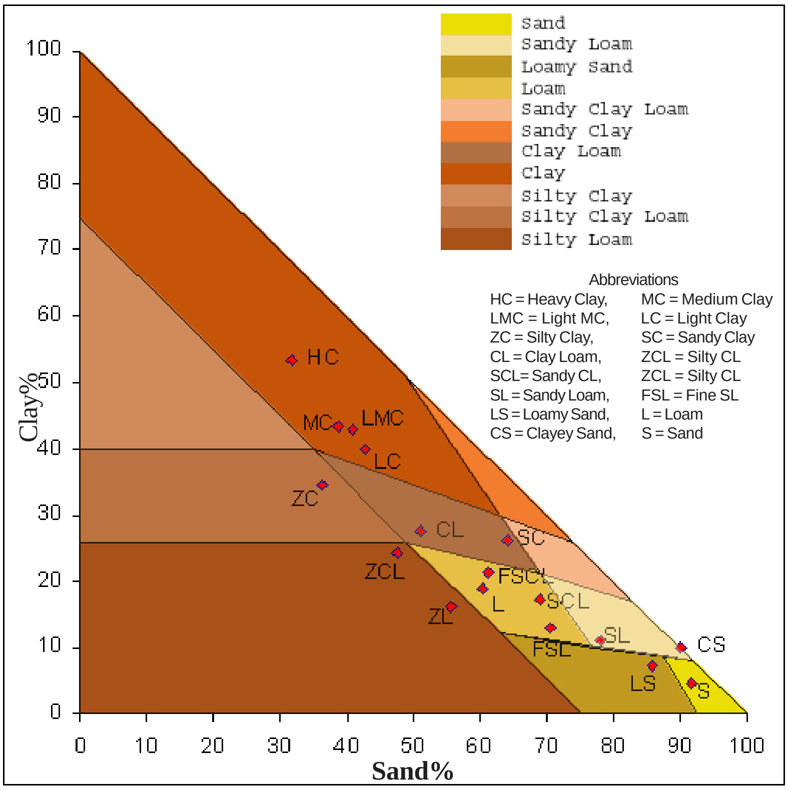


Figure 5.2: The Australian Texture Triangle (after Marshall, 1947) showing the median location of soil textures found in Minasny's (2000) study.

Survey textures		Reclassified textures	
95% SHALE	95% Shale	Bedrock	BR
CKS	Clayey Coarse Sand	Clayey Sand	CS
CL	Clay Loam	Clay Loam	CL
CLFS	Clay Loam, Fine Sandy	Clay Loam Fine Sandy	SCL
CLS	Clay Loam, Sandy	Clay Loam Sandy	SCL
CS	Clayey Sand	Clayey Sand	CS
FSCL	Fine Sandy Clay Loam	Fine Sandy Clay Loam	FSCL
FSL	Fine Sandy Loam	Fine Sandy Loam	FSL
FSLC	Fine Sandy Light Clay	Fine Sandy Light Clay	SC
GFSCL	Gravelly Fine Sandy Clay Loam	Fine Sandy Clay Loam	FSCL
GKS	Gravelly Coarse Sand	Sand	S
GKSL	Gravelly Coarse Sandy Loam	Sandy Loam	SL
GLC	Gravelly Light Clay	Light Clay	LC
HC	Heavy Clay	Heavy Clay	HC
KSL	Coarse Sandy Loam	Sandy Loam	SL
LC	Light Clay	Light Clay	LC
LFS	Loamy Fine Sand	Loamy Fine Sand	LS
LKS	Loamy Coarse Sand	Loamy Sand	LS
LMC	Light Medium Clay	Light Medium Clay	LMC
LOOSE SAND	Sand	Sand	S
LR	Loose Rock	Bedrock	BR
LS	Loamy Sand	Loamy Sand	LS
LSCL	Light Sandy Clay Loam	Sandy Clay Loam	SCL
MC	Medium Clay	Medium Clay	MC
MHC	Medium Heavy Clay	Medium Heavy Clay	MHC
ROCK	Rock	Bedrock	BR
SANDSTONE	Sandstone	Bedrock	BR
SC	Sandy Clay	Sandy Clay	SC
SCL	Sandy Clay Loam	Sandy Clay Loam	SCL
SHALE	Shale	Bedrock	BR
SL	Sandy Loam	Sandy Loam	SL
SLATE	Slate	Bedrock	BR
SLC	Sandy Light Clay	Sandy Clay	SC
SLMC	Sandy Light Medium Clay	Light Medium Clay	LMC
WATER TABLE	Water table	Water table	WT
ZC	Silty Clay	Silty Clay	ZC
ZCL	Silty Clay Loam	Silty Clay Loam	ZCL
Unused Texture Classes (from Marshall, 1947)			
L	Loam	Loam	L
ZL	Silty Loam	Silty Loam	ZL
Discarded Texture Classes (From Marshall, 1947)			
C	Clay		

Table 5.1: Classification then simplification and reclassification of the soil textures used by surveyors in the three soil surveys used in this study.

Texture Class	Clay %	Silt %	Fine Sand %	Coarse Sand %	Sand %	θ (-10kPa) (cm3/cm3)	θ (-1500kPa) (cm3/cm3)	RAW_q (mm/cm)	BD (Mg/m3)
Sand	4	3	40	53	93	0.19	0.06	0.733	1.52
Loamy Sand	6	5	38	50	89	0.21	0.07	0.726	1.51
Clayey Sand	9	8	42	41	83	0.24	0.77	0.326	
Sandy Loam	12	10	46	32	77	0.26	0.10	0.817	1.5
Silt Loam	16	30	45	10	55	0.33	0.14	0.834	1.51
Fine Sandy Loam	16	15	45	24	69	0.29	0.12	0.709	1.46
Sandy Clay Loam	16	10	38	36	74	0.27	0.12	0.690	1.49
Loam Fine Sandy	17	25	44	13	58	0.32	0.15	0.740	
Light Sandy Clay Loam	18	18	44	21	65	0.3	0.14	0.757	1.44
Loam	19	20	44	17	61	0.31	0.15	0.747	1.46
Silty Clay Loam	24	30	36	10	46	0.36	0.19	0.599	1.42
Clay Loam	25	20	39	16	55	0.33	0.18	0.669	1.45
Fine Sandy Clay Loam	26	19	35	19	55	0.33	0.18	0.702	1.47
Sandy Clay	28	8	34	30	64	0.29	0.17	0.534	1.53
Silty Clay	34	32	29	5	33	0.42	0.26	0.555	1.3
Light Clay	40	14	31	15	46	0.35	0.23	0.519	1.44
Light Medium Clay	44	14	28	14	42	0.36	0.25	0.452	1.39
Medium Clay	45	17	27	11	38	0.38	0.26	0.461	1.42
Medium Heavy Clay	53	15	23	9	32	0.39	0.29	0.359	
Heavy Clay	55	14	23	8	31	0.39	0.29	0.308	1.39

Table 5.2: A look-up table for particle size distribution (PSD), available water content, RAW_q and bulk density derived from the reclassified textures in Table 5.1 using the PTFs of Minasny (2000).

(1986). Due to differences in particle size thresholds between texture classifications, PTFs are not directly transferable between classification systems (Minasny and McBratney, 2001).

For ease of interpretation across the vineyards and to coincide with sampling strategies and ancillary data sources, the clay and sand percentages for the depth increments 0-30 cm, 0-90 cm and 30-90 cm were calculated using horizon depth and texture (PSD) information from the soil survey.

5.2.2.3 Calculation of crop available soil moisture

A knowledge of the field soil texture allows the surveyor to approximate the readily available water content of the soil using the available water content (AWC) lookup table of Wetherby (2000). A range of water deficits is available however the range from -8 to -60kPa or -8 to -200kPa is generally used for the calculation of RAW. The lookup table of Wetherby (2000) is a basic PTF as it predicts available waterholding capacity from soil textures. Wetherby's lookup table however is restrictive as it only identifies 10 texture grades and has been based only on soil profiles from South Australia and a heavy clay at Kununurra.

For this study an alternative approach to estimating soil moisture capacity was tried using NeuroTheta. As described earlier NeuroTheta predicts the parameters of the soil moisture curve for a given PSD. These parameters were then used to calculate the available water capacity (AWC_{RAW}) between -10 and -200kPa for each horizon at each soil pit site. The AWC_{RAW} was converted into the standard RAW units, mm/cm, by applying a coefficient of 10. The RAW_q was calculated using the depth and AWC_{RAW} of each horizon up until the soil survey observed rootzone depth. To avoid confusion the Wetherby derived RAW will be referred to as RAW_W and the NeuroTheta derived RAW as RAW_q.

Texture	**-8 to -20kPa**	**-8 to -40kPa**	**-8 to -60kPa**	**-8 to -200kPa**	**-8 to -1500kPa**
S	0.33	0.36	0.37	0.46	0.62
LS	0.45	0.52	0.55	0.65	0.86
CS*		0.55	0.60	0.74	1.01
SL	0.46	0.59	0.64	0.84	1.15
LSCL	0.45	0.65	0.74	1.03	1.37
L		0.69	0.84	1.00	2.34
SCL	0.39	0.61	0.71	1.01	1.43
CL	0.31	0.53	0.65	1.03	1.48
Clay	0.27	0.46	0.57	0.90	1.49
HC**		0.25	0.41	0.49	1.20

* Interpolated value

** Derived from a heavy clay at Kununurra

Table 5.3 Wetherby's Readily Available Water (RAW_W) lookup table (Adapted from Wetherby, 2000).

The calculation of RAW_q analysis has been summarised for the nineteen main texture classes identified in Table 5.1. in a lookup table (Table 5.2). For field surveyed data the lookup table provided (Table 5.2) is sufficient for estimating soil properties as there are inherent errors in the field estimation of texture e.g. experience of the surveyor, time constraints. For laboratory analysis of PSD the clay, sand and silt percentages should be used as a direct input into the PTFs to obtain an estimate of soil properties. As well as NeuroTheta there are arrange of freeware programs available to apply PTFs to Australian soil data. These have been developed at the University of Sydney in collaboration with the NSW Department of Infrastructure, Planning and Natural Resources (DIPNR).

5.2.3 Mapping soil properties

5.2.3.1 Georectification

Ground control points (GCPs) were logged around the vineyard boundary and at any significant internal vineyard features using a DGPS. The geographic coordinates (latitude, longitude) from the DGPS were converted to projected coordinates (Eastings, Northings) (UTM WGS84) in the Coordinate Calculator of ERDAS IMAGINE® (Erdas LLC, 2002). The point soil survey maps were georectified with the vineyard property boundary using the GCPs in ERDAS IMAGINE® (Erdas LLC, 2002). Georectification of the survey map permitted each soil survey pit site to be allocated a geographic location. Pit sites were georeferenced with both geographic and projected coordinates.

5.2.3.2 Interpolation of soil attributes

A $3m^2$ grid was established for each vineyard based on the vineyard layout. The soil survey data and PTF derived data was interpolated using punctual ordinary kriging (POK) in Vesper® (Minasny *et al*, 2002) with a global variogram. The variogram structure was fitted in Vesper®. Exponential, spherical and linear with sill models were tried and the Akaike Information Criteria (AIC) used to select the best model. The variogram parameters are given in Appendix 5.1.

5.2.3.3 Production of maps

The kriged output from Vesper® was collated into a single comma-delimited text file, one file per vineyard, and imported into ArcView® 3.2 where it was mapped using the Spatial Analyst extension. For each vineyard maps of PTF manipulated data (clay %, sand %, RAW_q) and non-manipulated data (Rootzone Depth, Topsoil depth, RAW) have been displayed (Figures 5.5 - 5.8). The protocol for mapping the soil survey data from the vineyards is summarised in Figure 5.3.

5.2.4 Model/Protocol Validation

The protocol described above produces continuous maps of soil properties. The efficacy of the data manipulation and interpolation was tested against an independent validation dataset.

5.2.4.1 Sample site selection

The ordinary kriged clay content, topsoil depth and RAW data was subjected to a 2, 3, 4 and 5 hard k-means cluster analysis in JMP® (SAS Institute, 2002) . Cluster analysis seeks to divide the data into *n* clusters by maximising the difference between the cluster means whilst minimising the within cluster variation (Hartigan, 1975). The results from each of the analyses were mapped and the means of the clusters compared (Appendix 5.2). An optimal number of zones was selected by the operator based on the differences between cluster means and the observed spatial structure of the

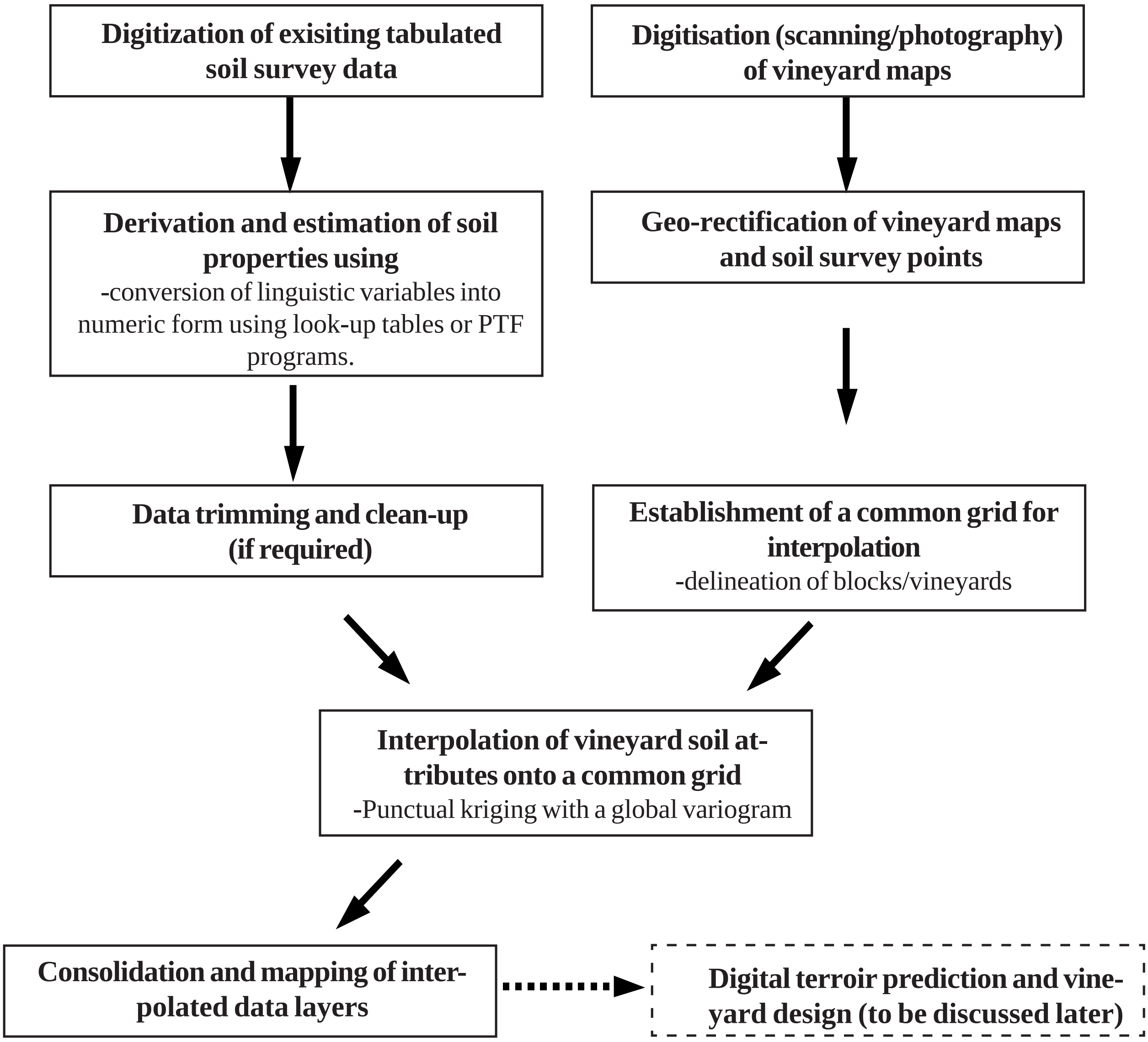
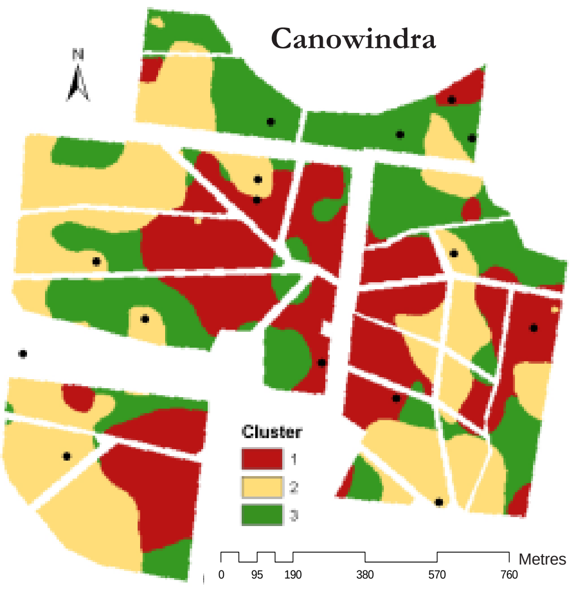


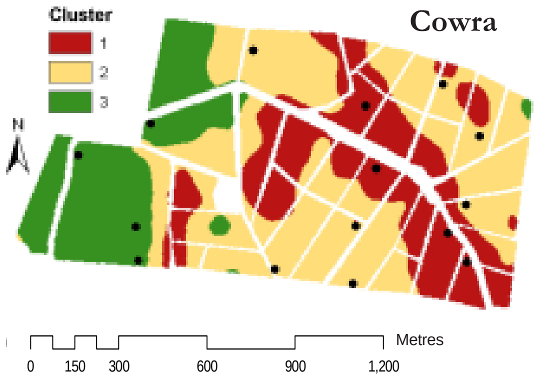
Figure 5.3: Schematic of the process of converting existing point orientated vineyard soil surveys into interpolated raster images. The next step in the process, the prediction of digital terroirs, is also indicated.

clusters. For Cowra and Canowindra three zones were considered optimal and five for Pokolbin. Fifteen validation sample sites were randomly allocated with the number of sites in each cluster roughly proportional to the cluster size. Figure 5.4 illustrates the selected clusters and sample site locations.

5.2.4.2 Soil analysis

At each site a soil core was drilled and two soil samples taken in the range of 0-30 cm (topsoil) and 60-90 cm (subsoil). The location of the sample sites was logged with a 5 minute average of a Garmin GPS unit in geographic coordinates and converted into projected coordinates in ERDAS Imagine® (Erdas LLC, 2002). Laboratory analysis was performed at the University of Sydney. Particle size analysis was performed using the pipette method (Gee and Bauder, 1986). Measurements of pH and electrical conductivity (EC) were performed on a 1:5 soil:water mixture after the method





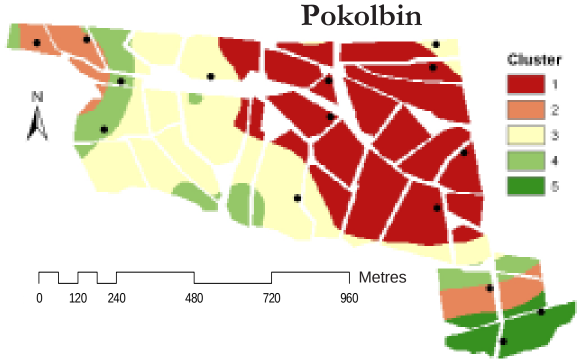


Figure 5.4: Clustering analysis and location of soil samples taken for model validation for the three vineyards in the survey.

of Rayment and Higgenson (1992).

5.2.4.3 Data manipulation

Using the same approach described previously the soil survey attributes were interpolated onto the fifteen independent soil sample sites. The rootzone depth at each of the validation sites was assumed to be the interpolated rootzone depth. This was deemed necessary as it is difficult to determine effective rooting depth from a single core.

The PSD for the 0-30 and 60-90 samples from the validation sample sites was converted into a soil texture class using the median values of Minasny (2000) rather than the traditional soil texture triangle. Soil texture and interpolated rootzone depth were used to estimate RAW_W using Table 5.3. Similarly an estimation of RAW_q was obtained using NeuroTheta and rootzone depth as described previously.

Thus at each validation site a laboratory measured PSD and kriged PSD estimate from the soil survey data existed for the 0-30 cm fraction and the 30-90 cm fraction. RAW_W and RAW_q values also existed firstly from the interpolation of the soil survey data and secondly direct application of Tables 5.2 and 5.3 to the validation site PSDs.

Two statistical approaches to compare the measured and predicted soil properties were used. Firstly scatter plots of the measured versus interpolated soil properties were produced for each soil property in each vineyard (Figure 5.8). The coefficient of determination for a linear fit to the data is shown in the plots. The scatter plots are a good graphical image of how the predicted soil properties compare to the measured properties. However the linear fit is not constrained to pass through the origin with a gradient of 1. The Root Mean Square Error (RMSE) statistic (Equation 5.1) accounts for this and is a common statistic used for comparing measured (Y_i) and predicted ($\hat{Y}_i$) sample data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\hat{Y}_i - Y_i\right)^2}{N}} \qquad \text{Equation 5.1}$$

5.3 Results and Discussion

5.3.1 Discussion of Maps

The interpolated maps for the three vineyards are shown in Figures 5.5 - 5.8. The maps from Cowra shows a strongly consistent trend that coincides with the elevation of the vineyard. The western portion of the vineyard is part of the second terrace of the Lachlan river and characterised by heavy alluvial clay soils. The gully that runs through the vineyard from the SE corner to the NW is characterised by deeper wetter soils. The slopes that lead into this gully are characterised by shallower sandy soils especially on the upper slopes. The strong trended spatial pattern is reflected in the variograms with long ranges (~220 - <1000 m) and relatively small nugget variance.

The Pokolbin vineyard exhibits quite smooth trends across the vineyard for sand and clay. Soil texture is dominated by sandy profiles in the SE and NW corners that lie in different parts of the landscape. The SE corner is an alluvial sand beside a creek while the NW corner is near the crest of the slope that dominates this part of the vineyard. The variogram parameters are intermediate between Cowra and Canowindra (ranges of ~150 - 600m). There is a lot of variation in RAW_W that is consistent with the variability observed in the rootzone depth map. A topsoil depth map was not possible for Pokolbin as the data was not recorded in the soil survey.

The Canowindra vineyard exhibits the opposite relationship between elevation and soil texture that is evident in the Cowra vineyard. Higher elevations tend to have higher clay content than lower lying areas. While trends are evident the interpolated maps are noisier than Pokolbin and Cowra with some spotted patterns in the maps caused by neighbouring points with low autocorrelation. The lesser autocorrelation within the data is reflected in the variogram structures with shorter ranges (~100 - ~250m) and a higher relative nugget than the Cowra vineyard.

For Cowra and Canowindra there is much greater variability in the subsoil clay than the topsoil. For Pokolbin this is reversed with the subsoil clay very consistent over the majority of the vineyard. The RAW_W and RAW_q tended to strongly follow the rootzone depth maps with the exception of the Pokolbin RAW_q map.

The maps shown in Figures 5.5 to 5.8 are certainly easier to interpret than that shown in Figure 5.1. Where the soil survey contains more than 70-80 points interpolation with kriging is preferably to simpler interpolation methods e.g. nearest neighbour , inverse-distance weighting and contour plots (Laslett *et al.,* 1987, Gotway *et al.,* 1996), all of which have been used to present soil survey data in the viticultural industry. Kriging is already being actively encouraged in precision viticulture by the CRCV (Bramley and Williams, 2001) and there should be no problems with adoption of this interpolation method. The primary objective for this chapter was to convert the point maps and tabulated data from vineyard soil surveys into raster maps. These maps are derived from manipulated and interpolated data and as such are subject to errors in the soil survey and/or the interpolation method. These errors and the accuracy of the maps are discussed below.

5.3.2 Accuracy of Maps

Scatter plots of the measured vs predicted soil properties for each vineyard are shown in Figure 5.9. RMSE statistics for the same properties are shown in Table 5.4. For all the scatter plots the range of the predicted variable is less than that of the measured variables. This is due to the use of median values initially in determining PSD and the interpolation method which tends to condense the range of the predicted variable.

From the scatter plots the texture fits for Pokolbin are very linear and the r^2 values high (0.59 - 0.83) The Cowra plots exhibit two distinct populations in the predicted values which shows the difference between the river terrace and the hill slopes. The distinction is not evident in the measured validation set population however the trend between the predicted and measured sets is quite clear for all texture properties except the subsoil clay (r^2 0.38). The Canowindra texture plots do not show the same degree of linear trend (r^2 range of 0.25-0.4) as the other two vineyards. The scatter plots for RAW_W tended toward linearity with some outliers. The outliers tended to drastically depress the r^2 values and when removed r^2 increased for both Pokolbin and Cowra (Figure 5.9). For RAW_q the scatter plots showed little linearity with r^2 values ranging between 0.03 - 0.45.

The Canowindra data set produced the highest RMSE for all attributes except for the topsoil and subsoil sand where Cowra had the worst RMSE despite a strong linear trend in the scatter plots. Cowra produced the lowest RMSE values for both RAW_W and RAW_q and for topsoil clay. For all other attributes the Pokolbin vineyard had the lowest RMSE. The RAW_W estimation provided lower RMSE than RAW_q in all three vineyards.

	Sand % (0-30 cm)	**Sand % (30-90 cm)**	**Clay % (0-30 cm)**	**Clay % (30-90 cm)**	**RAW_W**	**RAW_q**
Cowra	12.97	15.76	5.33	11.17	9.32	12.18
Canowindra	12.17	13.75	8.82	16.58	16.41	17.45
Pokolbin	11.84	13.62	7.64	7.98	12.39	15.21

Table 5.4: RMSE of prediction for predicted soil properties (topsoil and subsoil Clay% and Sand%, RAW_W RAW_q) tested against independent soil samples for the three study vineyards.

The protocol outlined in this chapter has produced maps of vineyard soil properties. The scatter plots and RMSE for Cowra and Pokolbin from the validation sampling indicate that the major trends in soil properties, particularly in texture, are correct. The Canowindra data appears less accurate. There are several major potential error sources in the data. As previously mentioned there will be error associated with the field description of texture and the subsequent use of median texture PSDs. Spatial error will also be present from the georectification. The vineyards were all surveyed in the early to mid 1990s and not georeferenced at the time. The pit sites were identified from the vineyard maps that were georeferenced from the property boundary. No information on the accuracy of mapping either the vineyard boundary or the location of the pit sites on the soil map is known thus

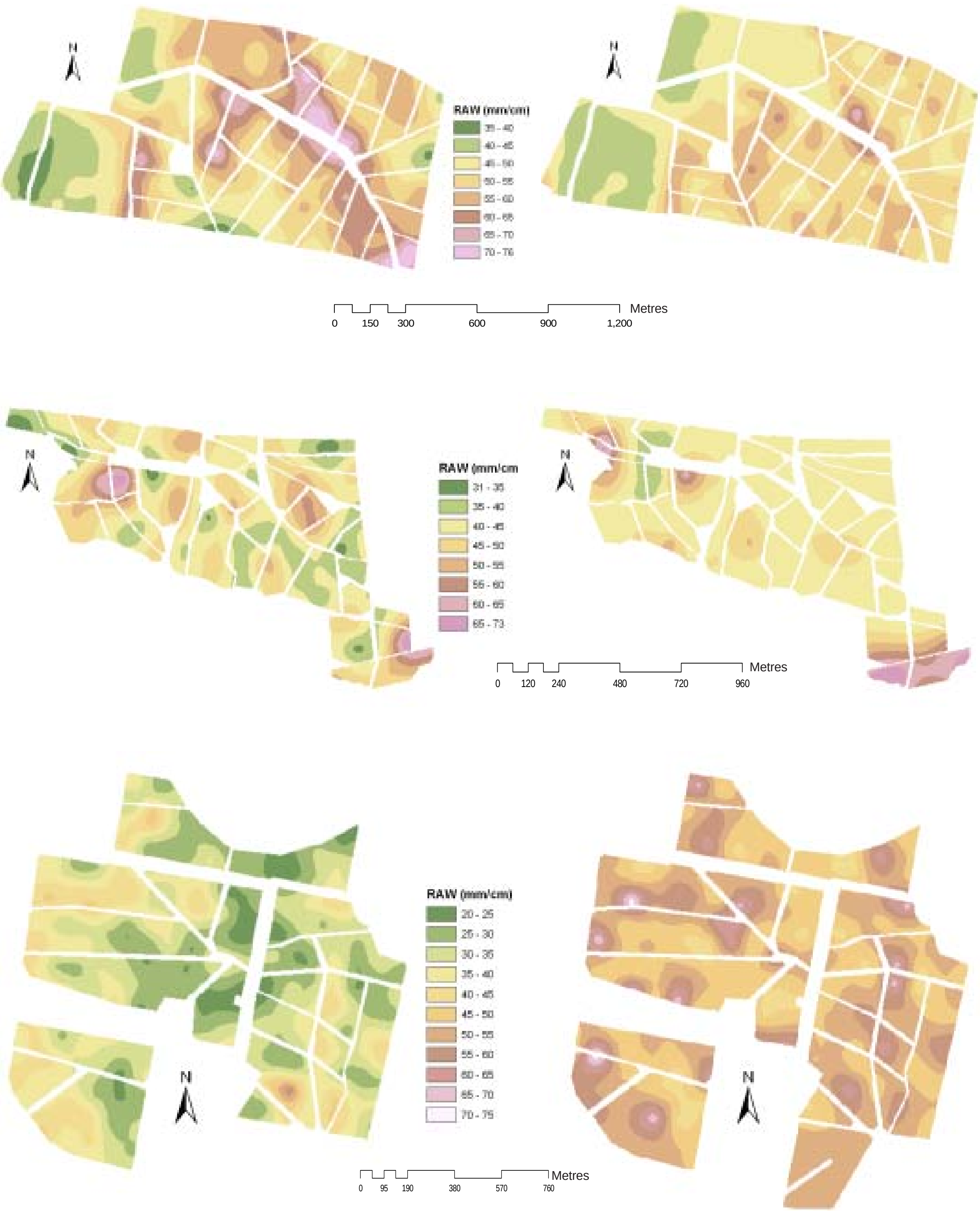


Figure 5.5: Interpolated maps of RAW_W (left) and RAW_q (right) for Cowra (top), Pokolbin (middle) and Canowindra (bottom).

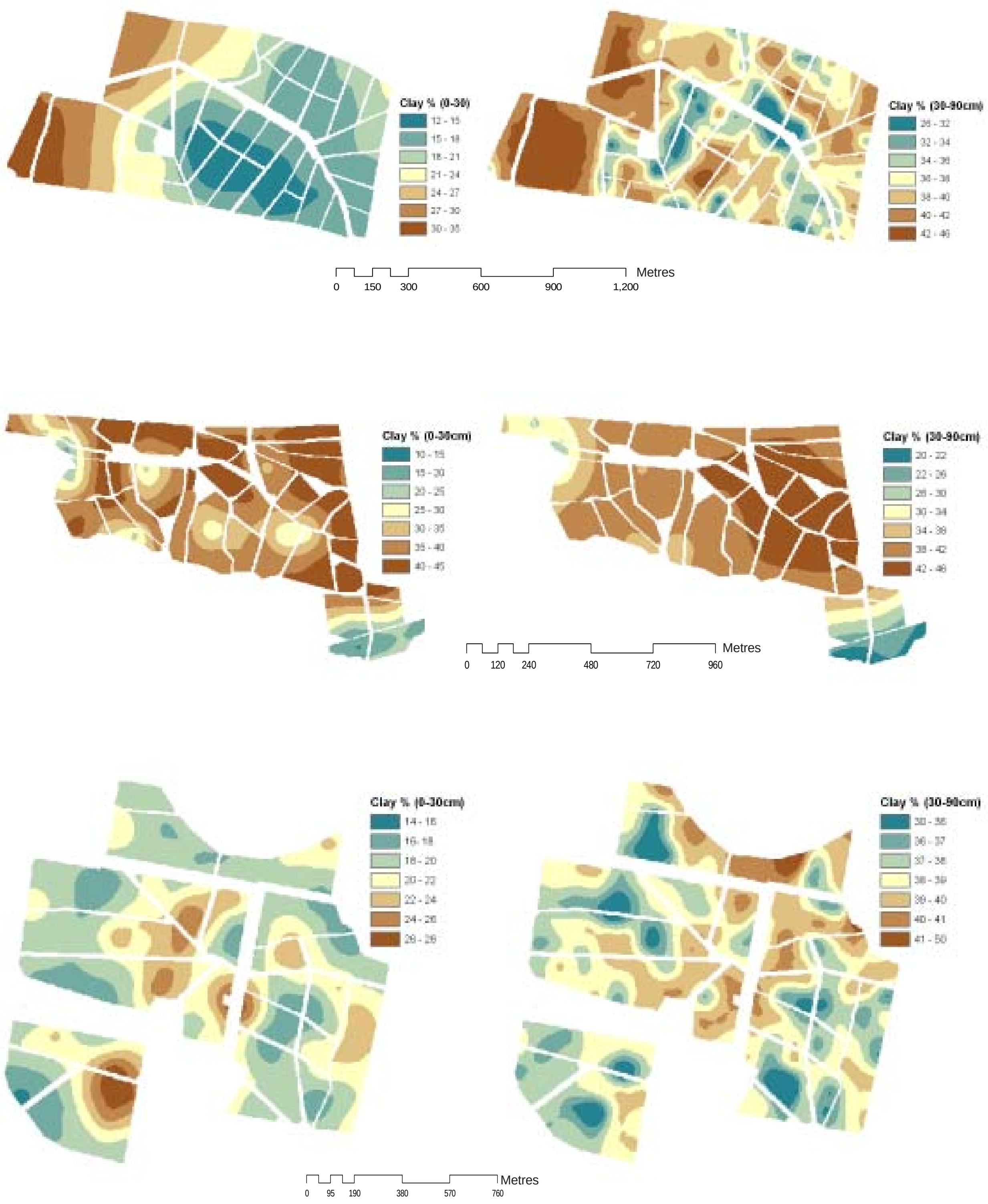


Figure 5.6: Interpolated maps of topsoil (left) and subsoil (right) clay % for Cowra (top), Pokolbin (middle) and Canowindra (bottom).

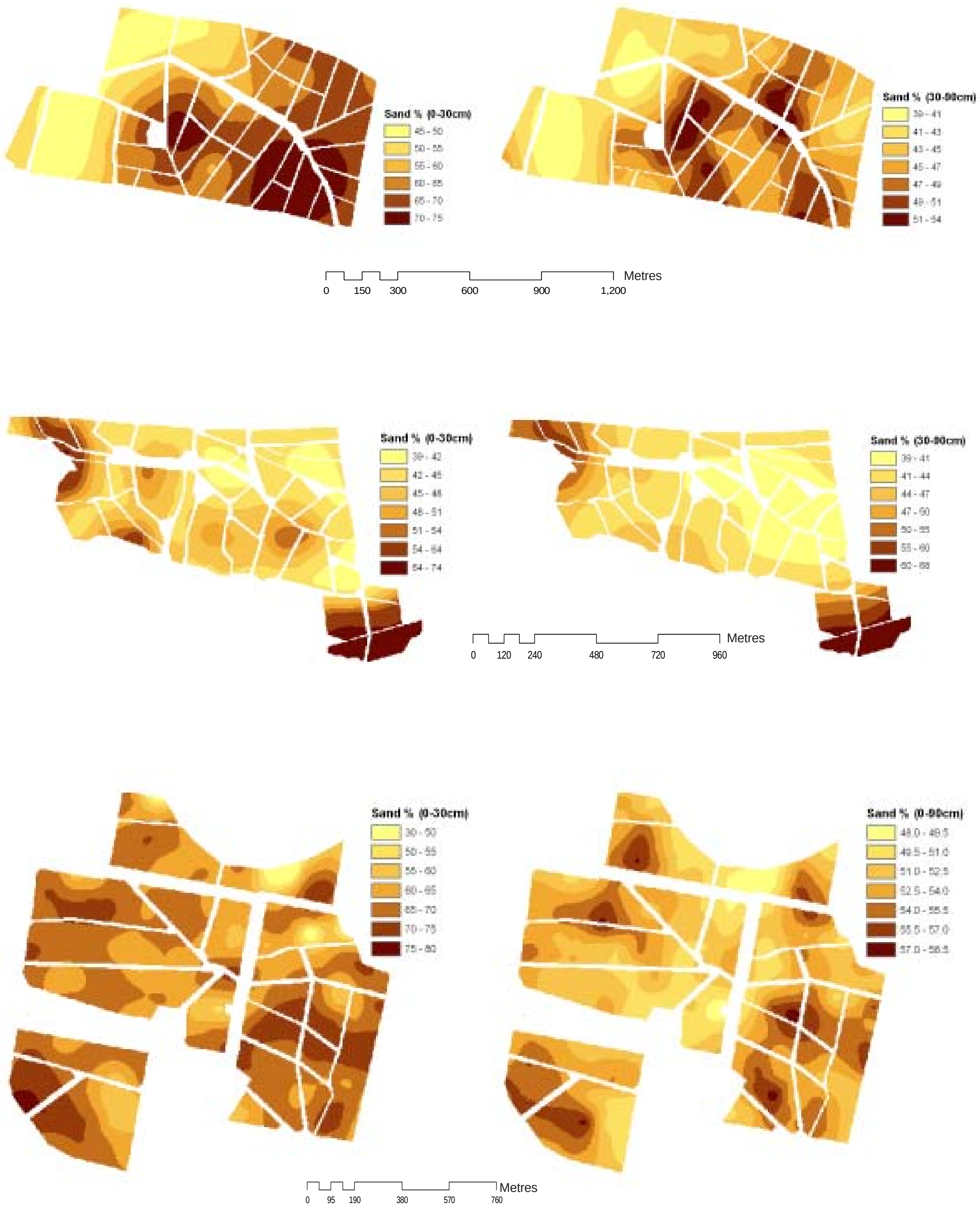


Figure 5.7: Interpolated maps of topsoil (left) and subsoil (right) sand % for Cowra (top), Pokolbin (middle) and Canowindra (bottom).

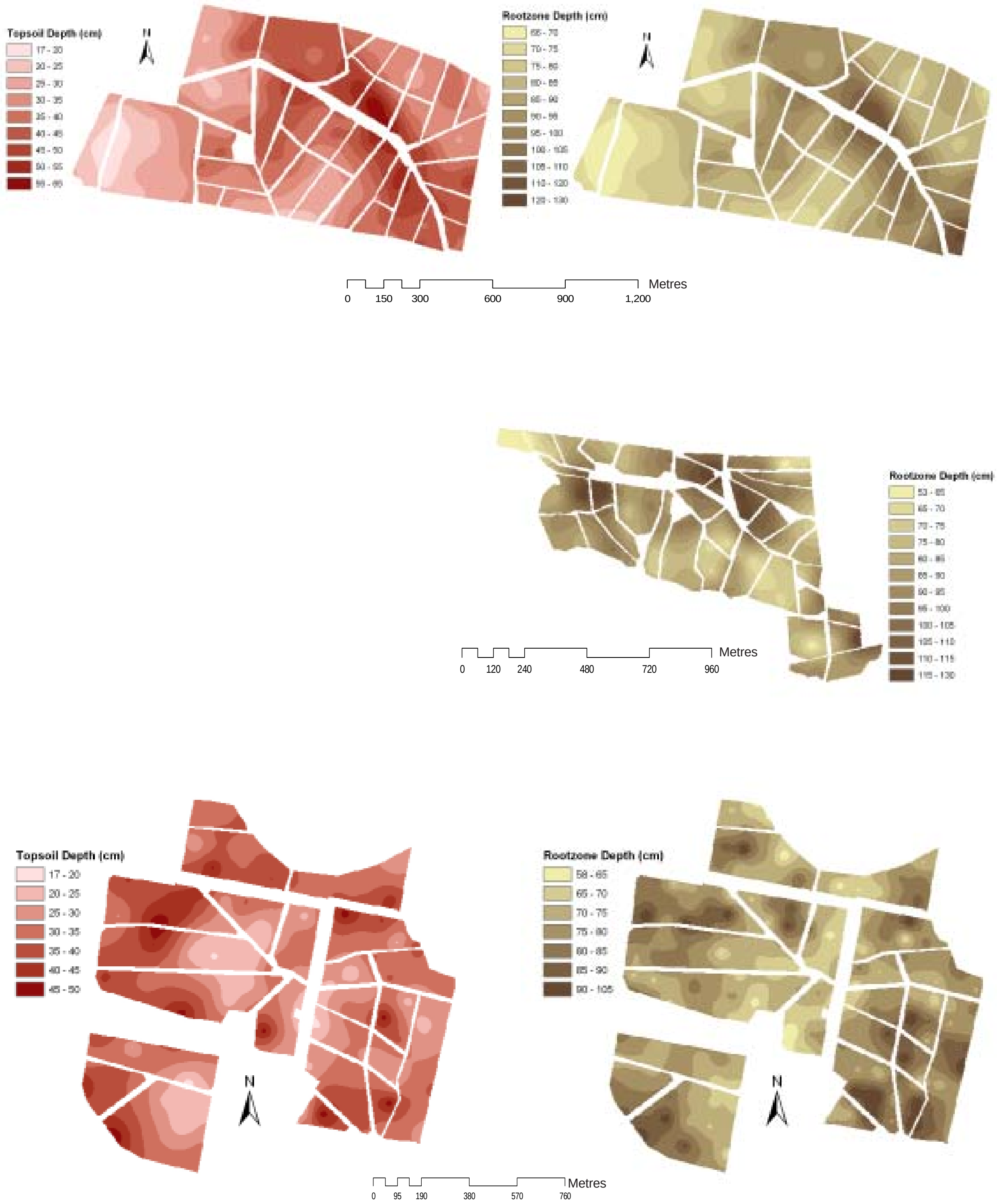


Figure 5.8: Interpolated maps of topsoil depth (left) and rootzone depth (right) for Cowra (top), Pokolbin (middle) and Canowindra (bottom). (NB topsoil depth was not recorded in the Pokolbin survey).

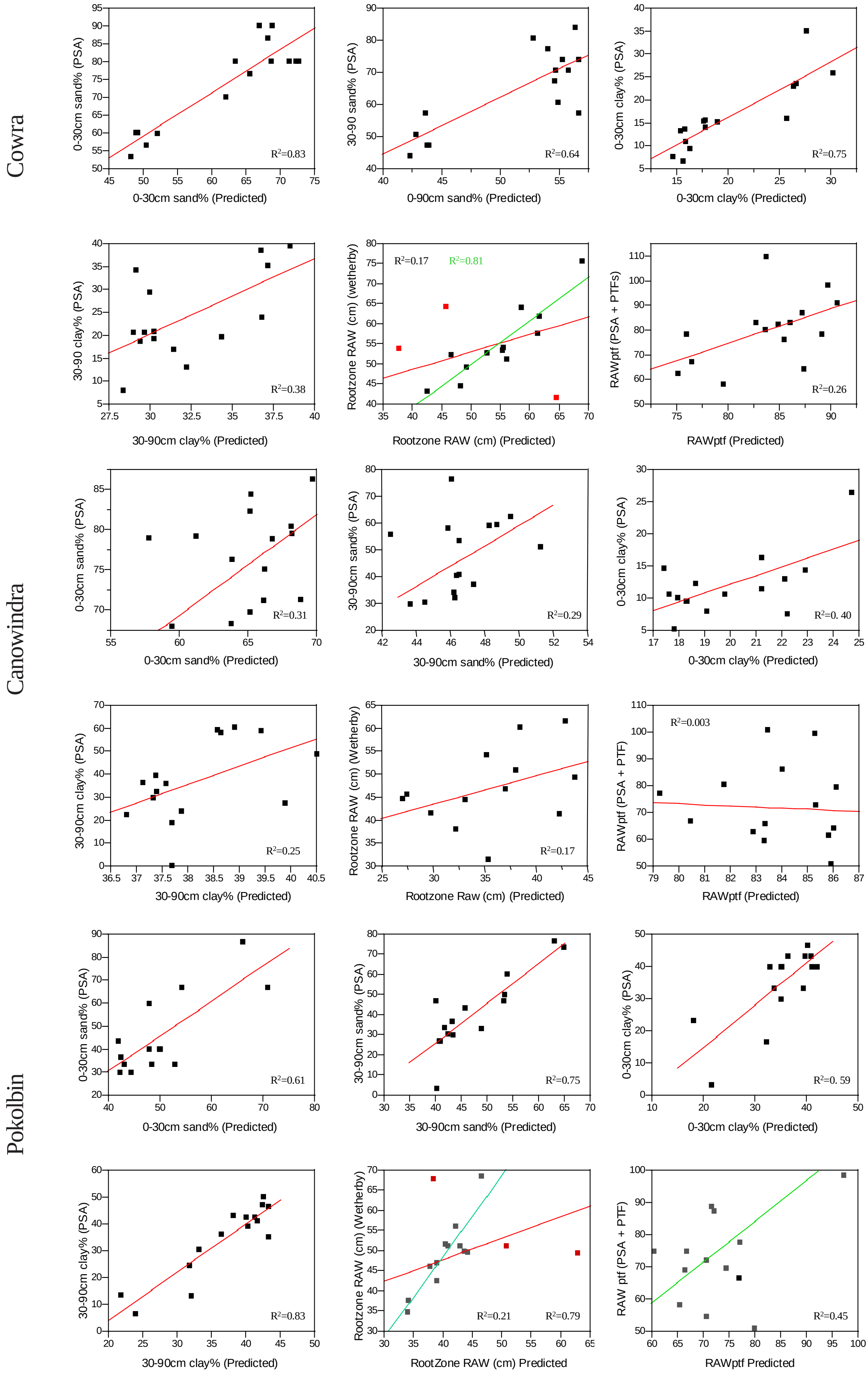


Figure 5.9: Scatter plots of Interpolated vs Measured soil properties from the 15 validation sites plotted individually for the three sturvey vineyards.

soil sites could possibly have a significant error in geo-location. The adoption of GPS to log sites is negating this error now however for past surveys the error remains.

The use of generic 75-100 m grids has been shown to be inadequate for vineyard soils (Brooker *et al.*, 1995, Brooker and Warren, 1997). In recent years directed soil sampling has been shown to be more effective at characterising management zones (digital terroirs) than blanket grid surveying (Pocknee, 2000). While sampling at a density of 1 - 2 samples per hectare is intensive for broadacre industries there appears to still be a lot of information that is being missed. This is illustrated in Figure 5.10 showing a subsoil EC_a map (from the Veris 3100® EC_a cart) and the interpolated subsoil clay content from the soil survey draped over a digital elevation model (DEM) of part of the Pokolbin vineyard. Even though the Pokolbin vineyard had the lowest RMSE for subsoil prediction it can be clearly seen that the grid survey map of subsoil clay has not identified the finger-like protrusions of high EC_a due to a change in soil type. The Normalised Differences Vegetative Index (NDVI) image in Figure 5.10

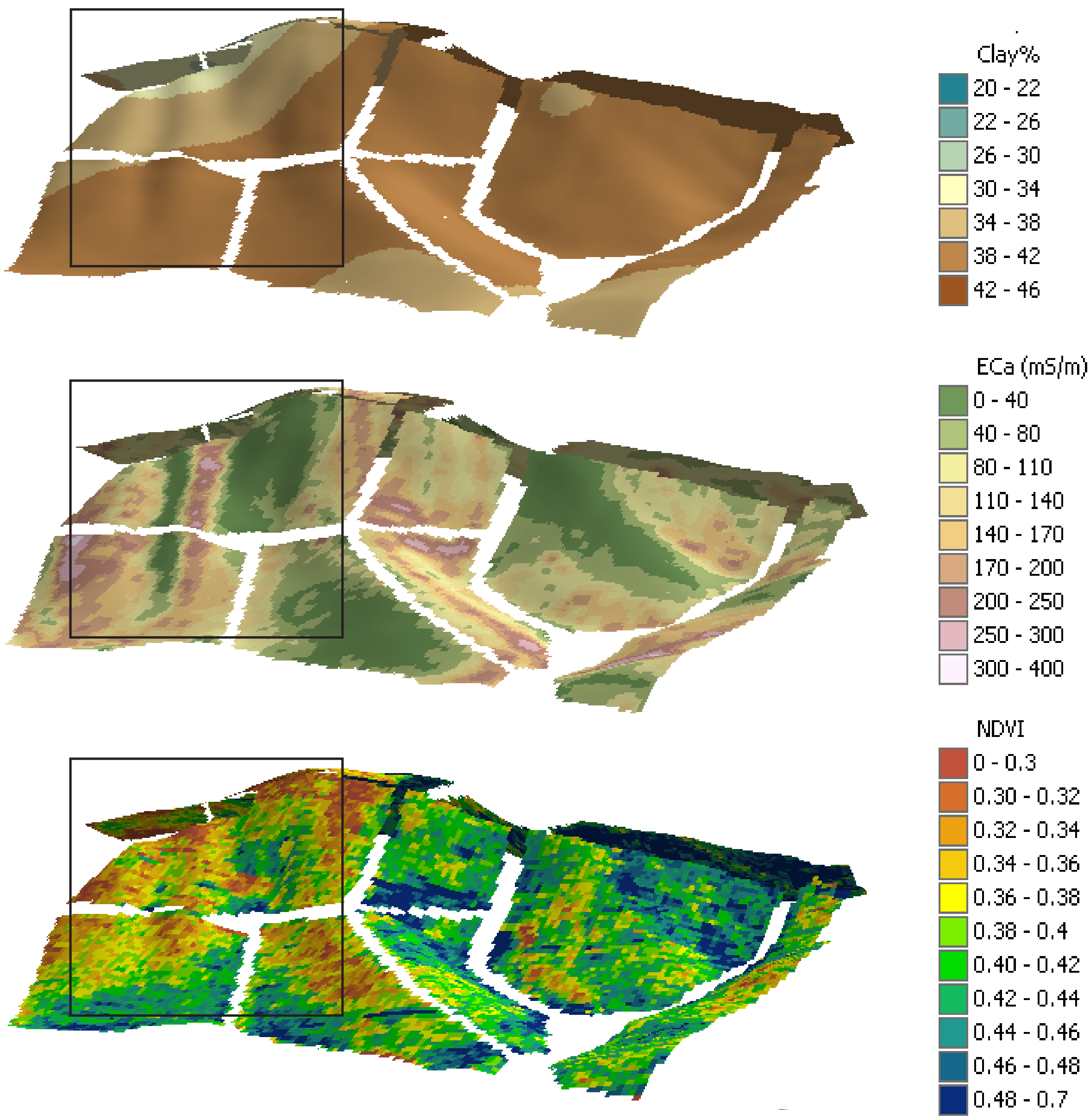


Figure 5.10: Comparative maps of soil survey interpolated 30-90cm Clay % (top), 30-90cm Veris EC_a (middle) and NDVI for part of the Pokolbin vineyard draped over a DEM. The total area shown is 11.3 ha.

does exhibit similar patterns to the Veris 30-90 cm EC_a measurement indicating that subsoil properties are impacting on vine performance.

The collection of ancillary information, primarily digital elevation and EM surveys, is becoming common practice for new vineyard sites in Australia (Ormesher, 2001). This information can be collected much faster and at a higher resolution producing more detailed data. The illustration in Figure 5.10 indicates the potential value of this information. Despite the widespread collection of ancillary data there has been no push from the industry to standardise the collection and analysis of this data. Nor has there been any effort to integrate the ancillary and soil survey information to improve vineyard maps. This will be the focus of the next chapter.

5.3.1 RAW_W versus RAW_q

The RAW_q on average was 29.1 - 49.6 mm per profile greater than the RAW_W estimation. The higher values from Minasny's approach can primarily be attributed to a different response in sandy soils. Figure 5.11 illustrates the different response of RAW_W and RAW_q at low Clay % (high sand %). As mentioned previously Minasny's data set came from 270 samples gathered nationally while Wetherby relied on 360 samples originating between the Barossa Valley and Murray Mallee region. Wetherby (2000) states that the RAW values in Table 5.3 are derived from "detailed field and laboratory studies" but does not indicate what analysis was performed. The PTFs of Minasny (2000) operate by simulating the moisture characteristic curve for a given PSD. Since the RAW is calculated between a very narrow range of potentials (-10kPa to -60kPa) RAW_q is susceptible to the gradient of the moisture characteristic in this range. The narrow range means that the RAW is easily influenced by the shape of the moisture characteristic at high potentials. At moisture potentials of <~100kPa the majority of water in sand is available thus we would expect a large RAW value. However at potentials <~100kPa the majority of moisture has been lost. Conversely clay soils tend to hold water more tightly at high potentials however are able to maintain moisture at much lower potentials thus are able to supply moisture to the plant over a greater range of potential. If RAW was specified for a more effective range e.g. -10kPa to -400kPa a more parabolic structure may be seen in the plot of

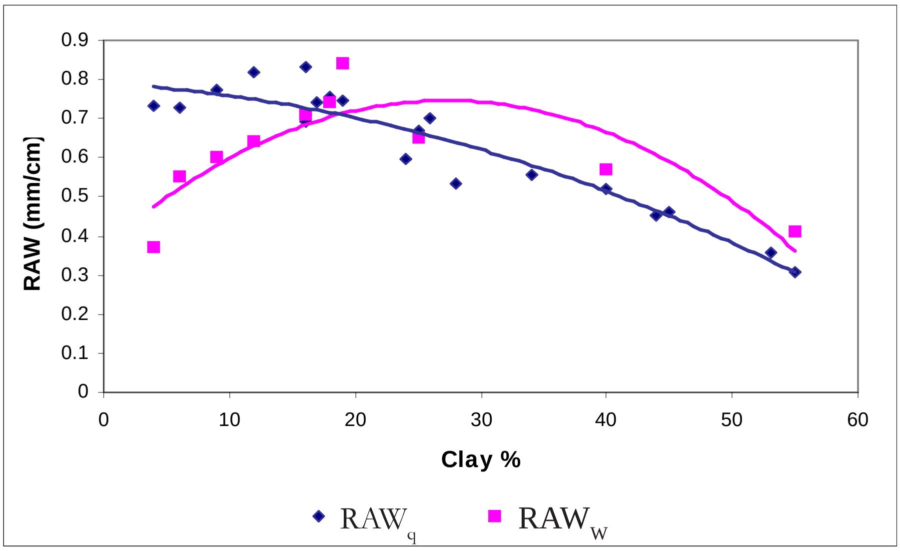


Figure 5.11: Graph of Clay% vs RAW_W and RAW_q (for the range -10 to -60 kPa) highlighting the different response between the approaches of Wetherby and Minasny at low clay %.

texture vs RAW_q. Even though high potentials are used Wetherby may be accounting for the perceived lack of moisture storage at lower potentials in sandy soil in his RAW values.

For vineyard planning the absolute value is not as important as the pattern of RAW. No laboratory analysis of soil moisture was performed to check the actually available soil moisture between -10 and -60kPa at the validation sites. Regardless of the RAW value, as long as areas with similar RAW values are identified and aggregated then irrigation management can be alter to suit the plants needs. Thus if a plant requires a RAW_W of 35 mm under Wetherby's system it may need a RAW_q of 70-75 mm. In this regard the widespread adoption of Wetherby's system has allowed for a lookup table of RAW_W required for certain production systems (Wetherby 2000). The most important point is to identify areas of similar RAW

The RAW patterns between the Wetherby and Minasny (2000) approaches produce visually similar results in the Cowra and Canowindra vineyards but not in Pokolbin where the Wetherby approach shows a lot more variation. When clustered into 2 and 3 clusters, using a hard k-means clustering algorithm in JMP® (SAS Institute, 2002), the κ statistics (coefficient of similarity) for Cowra and Canowindra ranged between 0.37 - 0.39 and 0.42 - 0.52 while the Pokolbin κ values were 0.1 and 0.02 for the 2 and 3 cluster analysis respectively.

From this data set without further soil sampling it is hard to determine whether it is preferable to use RAW_W or RAW_q. RAW_q should offer more detail as it accounts for more texture grades. However when designing vineyards the level of detail required is unknown and RAW_W measurements have certainly served the industry well to date. There is an opportunity for soil surveyors to try both approaches over the next couple of years and Table 5.2 will allow them to rapidly calculate and evaluate RAW_q.

5.4 Conclusions

A protocol for conversion of routine soil survey data into raster maps has been presented. The maps are coherent with the expected variability in the vineyards although the range of environmental variables is condensed. An alternative lookup table has been proposed for use in soil survey that incorporates a wider variety of soil texture classes to produce more definition in soil texture maps. A new set of RAW values, RAW_q, has also been introduced that differs to the conventional approach, RAW_W, for soils with a low clay%. Further use of the new lookup table, across various geographic indications, is required to assess its value compared to the lookup table of Wetherby. An excel spreadsheet will soon be available to automate the conversion of linguistic soil survey data into quantitative soil variables using either Wetherby's lookup table or the new lookup table presented here.

Ancillary data collected in vineyards indicates that considerable variation in soil and vine response can occur at small-scales. The incorporation of ancillary data into the prediction of soil properties may help improve the detail and accuracy of soil maps.

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Appendix 5.1: Variogram Parameters

Pokolbin

Attribute	Model	Nugget	Sill	Range	Sill 2	Range 2
30clay	Sph	30.61	59.89	232.6		
30sand	Dble Sph	24.59	54.46	147.4	652.9	10000
90clay	Sph	22.46	36.31	284.7		
90sand	Sph	23.69	37.80	569.4		
3090clay	Sph	17.46	161.0	1523		
3090sand	Sph	67.07	232.7	1738		
RZdepth	Exp	60.00	623.9	68.63		
TSdepth	Sph	42.28	21.31	722.4		
RZRaw	Sph	55.00	138.1	147.4		
RZRAW (PTF)	Sph	79.64	245.2	1642		

Cowra

Attribute	Model	Nugget	Sill	Range	Sill 2	Range 2
30clay	Dbl Exp	13.95	17.02	81.34	404.2	10000
30sand	Exp	47.69	168.8	212.9		
90clay	Dbl Exp	10.49	8.62	107.5	104.6	7979
90sand	Exp	14.45	51.08	337.9		
3090Clay	Exp	10.22	22.32	73.75		
3090sand	Sph	31.54	21.35	375.2		
RZdepth	Exp	56.98	204.9	124.2		
TSdepth	Exp	92.10	140.2	119.6		
RZRaw	Exp	38.30	87.17	140.1		
RZRAW (Budi)	Dbl Sph	13.12	15.88	188.9	13.29	1220
Colour Red H1	Sph	0.2413	0.3129	219.5		
Colur H2	Dbl Sph	0.8455	0.4285	108.5	1.057	1940.7
ColourH3	Exp	0.1272	0.4485	139.9		

Canowindra

Attribute	Model	Nugget	Sill	Range		
30clay	Sph	14.18	15.14	214.6		
30sand	Dbl Sph	29.94	48.27	189.5	276.1	10000
90clay	Dbl Sph	8.628	10.02	117.3	16.55	10000
90sand	Exp	18.14	11.07	93.28		
30-90clay	Dble Sph	22.12	8.02	112.8	1.784	821.0
30-90 sand	Sph	15.02	30.01	140.5		
RZdepth	Dbl Exp	52.42	158.4	32.33	484.4	10000
TSdepth	Exp	67.08	116.9	74.73		
RZRaw	Dbl Sph	109.4	77.03	114.3	290.5	10000
RAW(PTF)	Exp	24.02	41.97	57.90		

Appendix 5.2: Vineyard cluster means for soil properties used in determining the soil sampling scheme.

Means of clay%, topsoil depth (cm) and RAW (mm) for the clusters derived from hard k-means clustering to derive a soil sampling scheme for the three vineyards. Cluster numbering relates to the legends in Figure 5.4.

	Topsoil Clay%	Subsoil Clay%	Topsoil Depth (cm)	RAW (mm of water)
Pokolbin				
Cluster 1	38.75	42.37	89.76 *	43.68
Cluster 2	29.50	30.73	76.70 *	41.45
Cluster 3	37.55	39.97	88.26 *	45.23
Cluster 4	35.22	36.17	86.90 *	43.96
Cluster 5	19.25	22.94	90.41 *	49.86
Cowra				
Cluster 1	16.61	29.17	45.27	61.92
Cluster 2	18.84	31.98	35.14	52.39
Cluster 3	28.55	37.45	25.01	44.68
Canowindra				
Cluster 1	21.08	39.01	29.53	27.21
Cluster 2	19.00	37.01	35.69	40.51
Cluster 3	19.88	38.29	32.27	33.49

* Topsoil depth was not recorded at Pokolbin and Rootzone depth (am) has been used instead in this analysis