SOIL SURVEY AND
ELECTROMAGNETIC INDUCTION –
A MARLBOROUGH VINEYARD CASE STUDY

A thesis presented in partial fulfilment
of the requirements for the degree of

Master of Applied Science in
Soil Science

Massey University

Institute of Natural Resources
Palmerston North,
New Zealand

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2004

Alliaume Florencia (2003). Soil Survey and Electromagnetic Induction – A Marlborough Vineyard Case Study. Unpublished. M.Appl.Sc Thesis, Massey University, New Zealand.

Abstract

Differences in soil texture, soil nutrient status, available moisture and soil drainage, among other soil properties, contribute to the variability in fruit quality and yield within a vineyard. Accurate mapping of this variability could lead to an improved soil and vine sampling and management process, hence to a more uniform grape quality. Generally, maps derived from traditional soil surveys do not adequately account for the spatial variability of soils, making interpretation and soil management difficult. A geographic information system, a real-time kinematic differential global-positioning system and an electro-magnetic sensor, together with field work, are used to assess a soil survey in a ninety eight hectare vineyard in the Marlborough Region, New Zealand. Apparent electroconductivity (EC_a) surveys were made during both dry (March) and wetter (September) soil conditions. Percentage and depth of gravel, gley horizons, soil bulk density, total available water content, chemical properties and depth to water table were all either measured in the field or estimated. Extremes in soil texture are found to correspond to high or low EC_a values. The deep and shallow EC_a survey made in March depicts soils with a high and a low percentage of coarse gravels. The deep EC_a survey made in March also depicts deep soils with particles finer than 2 mm deeper in the profile. The highest and lowest total available water content estimates were also associated with highest and lowest EC_a values. The EC_a survey made in September apparently responds to water tables within 120 cm below the surface. Furthermore, from the contour survey made with the differential global-positioning system, a series of hollows and ridges are detected. A tendency for lower fertility on the ridges is observed. Nevertheless, it is not possible to accurately define soil variability from the EC_a surveys. Although the information generated by the electro-magnetic sensor is useful, both field observations and the topographic survey are the main influences defining and mapping the five soil-geomorphic units identified in this project. The implications of the results for soil management are discussed. Suggestions for improving future trials using the electro-magnetic sensor for soil variability assessment and potential future research are also given. Finally, a lack of correspondence between potassium concentrations in soils and plants is investigated. A high potassium concentration in the water used for irrigation is found to be the possible cause of such results.

Keywords: precision viticulture, soil electroconductivity, electromagnetic induction, soil properties, soil survey, GIS.

A mi hermano y hermana,
mamá y papá,
abuelos y abuelas,
y a toda mi familia y amigos
en Uruguay.

Acknowledgments

To begin with, I would like to thank my supervisors Mike Tuohy and Alan Palmer and for their invaluable advice. Their suggestions, criticism, understanding and support made a difference to this project. To these two friends and tutors, my most special thanks.

I am indebted to Callum Eastwood for kindly putting me in contact with Nobilo Vineyard managers, helping me in field work and for friendly discussions. Thanks are also extended to Mathew Irwin for his professional and patient advice on the use of the software package. Their help was really invaluable for the development of this project.

Research funds, for which I would like to express my great appreciation, were provided by Nobilo Vintners Ltd. and New Zealand Centre for Precision Agriculture I was personally funded by NZODA through a full scholarship and without their support this masterate project would not have been possible.

In the field work I was helped immensely by Tim Laverack and Diane Stewart from Nobilo Ltd. Diane was always there to make sure I had everything I needed, while Tim always accompanied me in the field work and dug more than twenty pits in gravelly soils!!. He kindly measured the water depth in the wells over a period of three months. On many occasions I was also fortunate to count on their ingenious ideas too, which made my work a lot easier and for all that, I am sincerely thankful. Thanks must be extended to Warren Woodgyer who helped carry out the electroconductivity survey in the field.

An important part of the laboratory work was carried out at the Massey University Fertilizer & Lime Research Centre. There I have to thank Lance Currie who made the chemical analysis for the soil samples. I also want to thank Ian Furkert and Glenys Wallace who were very helpful with facilitating the use of the necessary equipment. Anne West helped me with the statistic analysis and interpretations. Thank you very much to all of you.

Special thanks to John Dando; I am very grateful for his tremendous help on the soil texture analyses. He not only facilitated the use of the laboratory and equipment, but was also very generous with his advice and comments.

I would also like to dedicate a special paragraph to Carolyn Hedley who discussed the results with me, sharing with me her knowledge and experience with interpreting the electroconductivity survey and even opening my eyes on some occasions. To her, my very special thanks.

It was a pleasure to work for so many hours at the Precision Agriculture Centre at Massey. There I have to thank John Holland and all the people working there that were always in the best mood, and we shared so many good moments.

Many thanks to all the Latin American, Spanish, Indonesian, yanquis (jeje), Swiss, German, Kiwi and English friends who opened their hearts and made the experience in New Zealand unique. We shared unforgettable moments which will always be part of my life.

Thanks to the unconditional support I received from my parents, Maria del Carmen Molfino and Carlos Alliaume and my brother Javier and sister Inés. Finally, a very special mention to my grannies, Juan Horacio Molfino and Maria Amelia Margenat for the example they set and the support which they have always given me. I could not have done it without having them in my heart and my mind.

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CHAPTER 1

General Introduction

1.1 Viticulture in the Marlborough Region

Viticulture and wine production in New Zealand have been increasing during the last twenty years. According to the Wine Institute of New Zealand (2003), the number of wineries increased from 131 to 398 between 1990 and 2003. In the same period, the producing vineyard area increased from 4,880 to 14,802 ha. The wine industry in New Zealand is decisively export orientated, with a growth from 8 million litres to 23 million litres exported in the last 10 years, representing NZ$ 246.4 millions FOB (free on board).

Marlborough winegrowing area has grown rapidly and is now New Zealand's largest and best-known one, with over 5,000 ha of established grapes (more than forty percent of the total New Zealand grape producing area), which produces half of the total New Zealand grape production. The worldwide interest in Marlborough wines, particularly Sauvignon Blanc and Chardonnay (and more recently Pinot Noir and Riesling), has resulted in a rate of development of about 1,200 ha per year of new vineyards (Wine Institute of New Zealand (2003).

The region's environmental conditions have been crucial to such development. The typical free-draining, alluvial loams with gravelly sub-soils provide optimum growing conditions. High annual sunshine-hours (2450), cool climate during the hottest month (average 18°C), with cool nights and limited rainfall (642mm/year), allow a slow ripening process that contributes to the high quality of Marlborough wines.

1.2 Soils, viticulture and precision technologies

Differences in soil properties, soil nutrient status and available moisture contribute to the variability in fruit quality, ripening and yield within a vineyard. An understanding of this variability and the relationships between manageable soil properties, grape yield and fruit quality could support more accurate soil and vine sampling and management.

The development of new technologies has revolutionised the way in which soil information can be obtained more efficiently. Non-contact sensors based on electromagnetic induction technology have been shown to provide an effective basis for delineating interrelated physical, chemical and biological soil attributes (Johnson *et al.*, 2001a).

One of these technologies is the Geonics electro-magnetic (EM38) sensor, which measures soil's apparent bulk electrical conductivity (EC_a). With the data generated by the EM38, soil-sampling sites can be strategically selected and a targeted soil sample to calibrate the instrument can be taken (Bramley & Proffit, 2000). Once a relationship is established between EC_a measures and one or more soil attributes, accurate maps showing the variability of different soil properties can be produced (Doerge, 2001).

Adopting precision viticulture technologies like the EM38 and site-specific concepts, can lead to more accurate soil surveys and improved management opportunities (Lamb & Bramley, 2000). For example, the use of EM sensors, together with other precision viticulture tools, boosts the opportunity to harvest depending on quality specifications, to make a more effective use of inputs, reduce environmental risk, enhance sustainability and optimize the use of natural resources (Lamb & Bramley, 2000; Bramley & Proffit, 2000; Wolkowski, 2000).

1.3 Research importance, aims and objectives of the project

A winery expansion scheme is being carried out at Rarangi in the Marlborough region, where 600 hectares are being planted. Soil properties are well known to influence vineyard performance, so an understanding of the soil's variability within the vineyard and the relationships that exist among the soil properties and the vines is required to adopt a site – specific vineyard management that could improve the grape production process.

A lack of in-depth knowledge of the spatial variability of soil properties within the Rarangi vineyard planted mainly in 2001, is limiting the successful adoption of site-specific concepts and technology. Another unresolved question in the vineyard is the relatively high potassium concentrations found in plant samples. These values are higher than expected, being poorly correlated with the exchangeable potassium levels in the soils.

EM38 measurements have the potential for mapping some soil properties differences, and some previous work has been done in New Zealand (Pitcher-Cambell, 2002; Hedley *et al.*, 2002). However, the proposed area to be studied is different to the majority of previous similar surveys. The large proportion of gravel and stones and slight soil differences within the area of study constitute an extra challenge for both the interpretation of EM38 readings and the vineyard management. Hence, the growing wine industry in New Zealand will benefit from an increase in our knowledge and understanding of the relationship between soil properties and the electrical conductivity of the soils. A successful survey in this study would not only be helpful in assessing the likelihood of the vineyard response to targeted management, but would also promote the use of tools like the EM38, which promise a more accurate, quicker and cheaper method of mapping soil variability than the traditional manner.

The main aim of this study is to use precision technologies (EM38, high-accuracy real-time kinematic differential global-positioning system (RTK - DGPS)) and geographic information systems (GIS)) to produce accurate maps showing the distribution of main soil properties. A second aim of this project is to investigate possible reasons for the high potassium levels found in vines despite the low levels in soils.

To achieve these aims, this project had the following objectives:

1) Carry out a detailed topographic and electromagnetic survey of the 98 ha of vineyard using the EM38 and RTK - DGPS, and map the variability found.

2) Identify and survey soil properties that are most important for the vines performance with a view to assessing the feasibility of crop response to targeted management.

3) Compare the EC_a data with the detailed soils information collected in the traditional manner and interpret the electrical conductivity variability in terms of those characteristics identified in the previous above mentioned exercise.

4) Map the soil types and the variability of specific soil properties within the study area, implementing a geographic information system.

5) Determine the nutrient status of the soils.

6) Investigate the potassium (K) availability of the soils and possible causes for the high values found in plant samples compared with the low K values in the soils.

CHAPTER 2

Literature review

2.1 Introduction

A background to the soil properties and variability affecting grapegrowing is presented. Potassium dynamics in the soil and soil-plant interface are analyzed. Key precision agriculture technologies are presented and the concepts of soil electrical conductivity, modern methods for measuring it and its relation to soil properties are discussed. Finally, the role that precision viticulture has on modern viticulture and the opportunities and applications of different precision technologies are reviewed.

2.2 Soil properties affecting vine performance

If assessment of the soil suitability for grape production is very important when defining a new grape growing area (Northcote, 1998; Maccarrone, 1993; Berry, 1990), it is also true that using detailed soil mapping as a guide to vineyard design and management can reduce fruit variability within a vineyard (Smart, 1997).

People in the Australian wine industry recognize the importance of fruit homogeneity and its relation with soil properties.

> 'Wine quality is enhanced by fermenting homogenous lots of fruit.... principal causes of variability in fruit composition (and hence wine quality) are differences in soil moisture status within the block..... managing our vineyards using the terroir approach and subdividing the vineyards on the basis of soil properties is the way that we are incorporating European approaches" (Lester, quoted as personal communication by Smart, 1997 p. 60, 61, and 63) .

Notwithstanding the difficulty of isolating the effects of the whole environment and vineyard management, the influence the soils have on composition of grapes and quality of wines, has been extensively acknowledged and described. Soils play a role in the water and nutrient availability to the plants, in the microclimate due to its heat-retaining and light-reflecting capacity and in root growth due to its penetrability. Sustainability factors, such as slopes less than 15% to decrease soil erosion risks, should also be considered.

Viticultural '*terroirs*' for *Cabernet Sauvignon* in Hawke's Bay have been proposed (Tesic, 2001), such as 'Gravels' on sites of extremely permeable gravelly soils. This author introduced the concept of Soil Factor (SF) that characterizes the environmental conditions at a given site. This SF integrates: soil temperature at 30 cm, volumetric soil moisture content (0-30 cm), depth of the main rooting zone, and soil texture index (average value for textures in the rooting zone). Many attributes of vine growth, fruit composition and wine quality were correlated with the SF.

A four to ten-fold yield variability among blocks was detected in vineyards in Coonawarra, Padthaway, Sunraysia, Riverland and Clare Valley (in Australia) during 1999 and 2000. Soil depth variation was an important factor in creating this variability (Bramley, 2001). The root distribution in non-irrigated vineyards was found to be affected mostly by soil moisture, compacted layers and percentage stone in a study of Sauvignon Blanc grapes in South Africa (Conradie *et al.* 2002). The same author found differences of up to 12 days for time of harvest associated with soil types at the same locality.

The main physical and chemical properties that affect vine performance are described below.

2.2.1 Physical properties

Soil characteristics that facilitate grape production are:

- ease of root penetration,
- adequate oxygen availability in the root zone,
- readily available moisture holding capacity,
- ease of water infiltration at the soil surface,
- stable structure.

An optimal soil will limit the effect of climatic fluctuation such as either droughts or excess rainfall (Berry, 1990).

Topsoil colour indicates the presence of organic matter (dark or black colours), or presence of iron oxides under aerobic conditions (rich browns and reds). In subsoils, gley colours and/or mottles (yellow, blue and grey), indicate periods of anaerobic conditions (O'Connor *et al.*, 1993). The soil colour affects heat absorbance and reflectance. While darker soils absorb more heat and lead to earlier root growth in the spring, lighter coloured soils reflect more light affecting the incidence of light onto leaf surface and foliage temperature (Gladstones, 1992). The latter is often preferred because it reflects heat back onto underside of grapes.

The proportion of different size particles (soil texture) affects the available water holding capacity, drainage, heat retention and the distribution of the vine's root system (McLaren & Cameron, 1997). Textures considered good for growing grapevines are loamy fine sandy, sandy loam, loam, silt loam, clay loam, or subplastic clay at least 15 cm thick, with a friable subsoil, passing to a free draining C-horizon without an impeding layer (Northcote, 1998). It appears obvious that in places such as New Zealand where the rainfall is high, soils with low clay and silt percentage are preferred.

The vines potential for deep root exploration in gravelly soils (more than 35% of stones and 30% of sand in the first 20 cm) could compensate for a lack of water and extract water from deeper layers than those on silty clay loam soils, make gravelly soils also suitable for grape growing (Winkel *et al.*, 1995).

Stony or gravelly soils have been traditionally preferred for viticulture because of rapid drainage, infertility, which maintains a vine balance and fruitfulness in cool, summer-rainfall climates, resistance to erosion and their heating properties. Through heat re-irradiation to the bunches at night, the stones in the soils play a role in grape ripening at the cool limit of viticulture (Gladstones, 1992). In Hawkes Bay, soil temperatures at 15 and 30 cm depths were found to be higher in gravelly and sandy soils when compared with silty and clayey soils (Tesic, 2001).

The soil depth determines the volume where the roots can grow and so it is associated with the water, nutrients and oxygen available for root growth. It is in the topsoil where most of the nutrients are concentrated. Soil depths with abundant roots of 70 and 30 cm are considered deep and shallow soils respectively. Shallow soils can readily alternate between waterlogging and drought, depending on the rainfall (Gladstones, 1992). The horizon sequence and depths also affect root growth. The presence of an impeding layer that obstructs root growth and water movement, sometimes causing waterlogging, is undesirable (Northcote, 1998). Similarly, water tables near the surface, deprive the vine of oxygen for respiration, depress yields and may lead to vine death (O'Connor *et al.*, 1993).

The available water content of soils for plant growth is a crucial property for determining vineyard management and performance. While this is a major concern in places with low rainfall, in places with high rainfall, as in New Zealand, an increase of both above and below ground diseases might be a problem. Also high rain between veraison and harvest induces excessive uptake of water, which cause splitting of the berries and dilution of the juice (Coombe & Dry, 1988). Consequently, excessively high water content in soil during that period may produce lower quality wines.

The ability of soil to transmit water vertically, known as soil permeability, depends on the size, number and connectivity of pores. Sandy soils have a high permeability even when saturated. This property, together with the topography and the depth to water tables, determines the waterlogging risks. When measured by the soakage test, a permeability less than 3 cm/day is considered unfavorable for irrigation, while between 3 and 20 cm/day is too slow to provide adequate leaching where salinity is a problem (O'Connor *et al.*, 1993).

2.2.2 Chemical properties

Soil chemical properties affect both vine nutrition and, indirectly, physical soil conditions. Soil nutrient deficiencies are easier to correct and do not limit the use of a soil. However, acidic soils, or soils with unsatisfactory supply of water and oxygen at depth, should be avoided (Northcote, 1998).

Grapevines can be grown on a wide range of soil types, but some nutritional problems may occur, especially on coarse textured soils (Caspari, 1996; Coombe & Dry, 1992). The supply of mineral nutrients available in the soil will depend upon several factors: concentration and balance of mineral elements in the soil; holding/fixation of nutrients; soil pH (acidity); previous agricultural practices; rooting depth of the soil; water supply; method of vineyard floor management (clean cultivation, cover crops, mulching, etc.), extent of correction of problems through provision of soil drainage, addition of organic matter and addition of fertilizer (Pool, 2000).

Although vines can grow over a range of pH from 4 to 8.5, below pH 5.6 soils are too acid, phosphates became unavailable, and manganese and aluminium may be available to plants in toxic quantities. In general, a pH of 6 to 7 ensures a good supply of most elements, with the exceptions of iron, manganese, zinc, copper and cobalt (Coombe & Dry, 1992).

Grape plants are classified as moderately sensitive in a relative salt tolerance classification determined by Blaylock (1994). Plants in this classification are expected to lose 25% of potential yield where soil salinity is between 2.7 and 6.3 dS/m and 50% if the salinity is between 4.2 to 9.5 dS/m. The effect of irrigation with saline water depends on soil texture.

In a study that tested the influence that irrigation water salinity levels from 0.37 to 3.47 dS/m have on the yield of sultana grapevines, the effect was much more severe in the most heavily textured soils (Prior *et al.*, 1992).

2.3 Potassium

In order to find a possible explanation for the high petiole values found in the vineyard studied, a brief literature review on potassium in grapes and soils is presented bellow.

2.3.1 Potassium in grapes

The role of potassium (K) in the vine and the influence that this element has on the sugar and acid balance and therefore on the must[*] composition have been subject of an extensive debate and is widely discussed in the literature. Although this is not the topic of this research, it has to be highlighted that usually, high fruit K concentration results in high pH musts, which produce unbalanced, unstable wines (Garcia, 1999; Pool, 2000), and that has been a matter of major concern for viticulturists.

Moreover, extremely high K levels may also induce a magnesium deficiency (Hellman, 1997). Petiole calcium (Ca) and magnesium (Mg) showed highly significant negative correlations with petiole K, while manganese (Mn) decreased only slightly (Morris, 1980). Potassium content also varied with the rootstock used. The K:Mg ratio, and hence the incidence of waterberry [stalk necrosis], was also affected by rootstock. Twenty-seven percent of bunches on vines on rootstock Malegue 44-53, with a K:Mg ratio of 15.9, were affected by waterberry, compared with 3.6% of bunches on vines with a K:Mg ratio of 3.7, on rootstock 1103P (Soyer *et al.*, 1992). These three elements also compete for entry into plants, particularly with drip-irrigated vineyards. Applying calcium over the years to improve water infiltration has reduced potassium and magnesium levels in the vine (Peacock 1999).

On the other hand, grapevines' need for potassium is relatively high when compared to the need for nitrogen, since much of it is removed in the fruit (Peacock, 1999). The potassium concentration in grapes can range from 1% to 4% on a dry weight basis, and values from 1.5 to 2.5% were considered adequate for petioles sampled at flowering time (Robinson, 1992).

Dundon *et al.* (1984) found no predictable relationship between exchangeable K in soil and K concentrations in grapes. They established that it is difficult to manipulate grape quality through the use of K- based fertilisers. Furthermore, regardless of an elevated leaf K content, it was not redistributed to the permanent organs at the end of the season and there was no evidence of an associated response in wine K^+ composition. In accordance with these results, Porter (1994) affirmed that in cool humid climates, the

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[*] must - refers to the expressed juice of the grape, or other fruit, before fermentation.

effects of luxury potassium availability are likely to be minimal, but K-deficiency in vines causes lack of fruit colour and sugar content.

2.3.2 Potassium in the soils

Potassium exists in soil in different forms and different degrees of availability for plants. Readily available K for plant uptake is found in the soil solution and in the cation exchange sites of clay minerals and organic matter and represents a very small fraction of the total K in soils. As plants remove potassium and, depending on the type and amount of primary and secondary minerals present on the parent materials, the K diffuses from the soil parent materials to replenish the soil solution (Metson, 1980).

Structural potassium forms part of primary minerals (principally in sands and silts) such as mica (muscovite and biotite), feldspar (orthoclase and microcline), and volcanic glass (Tisdale *et al.*, 1985). When altered, secondary layer silicates are formed and might incorporate K in their crystal structure as well. During the process of weathering, K is depleted, inter-lattice spacing increases and secondary minerals are formed. The K in the structures of all these minerals constitutes a long-term K reserve.

Secondary minerals present mainly as minerals 2:1 layer type clays, are very important as sources of K in soils in the medium term. The K^+ ion participates in fixation and release reactions in the inter-layers of the micaceous clays (hydrous mica, illite and vermiculite). Due to its particularly small size, the K^+ ion can be trapped in the selective hexagonal holes of micaceous clays. With time, due to removal of K from the soil by either uptake, leaching or microbial utilization, this fixed K can be released. This type of potassium is known as non-exchangeable K (Metson & Lee, 1977).

Therefore, the long-term capacity of a soil to supply potassium for plant growth is usually not well determined by the exchangeable potassium (Ke) level of a soil. Other forms of potassium can be available for a crop in the medium or long term, and different methods have been used to determine these potassium reserves. The K that is not exchangeable but is more easily released in the medium-term, is generally named "step" K (Metson & Lee, 1977).

Nevertheless, a widely used method of assessing non-exchangeable potassium releasing power in New Zealand is the Kc reserve. This method was developed by Metson & Lee (1977), and represents the long term K reserve that is more difficult to release. Reserve Kc reflects the soil mineralogy and gives an indication of the potential non- exchangeable K release of the soil in the long term. Some descriptive ratings have been developed (Table 2.1) for comparing different New Zealand soils.

Table 2.1 Potassium levels ratings of different types of potassium

Rating	Exchangeable K (meq./100g)	Reserve K (Kc)* (meq./100g)	Total K (meq./100g)
Very high	>1.2	>0.5	>50
High	0.8-1.2	0.35-0.5	35-50
Medium	0.5-0.8	0.2-0.35	20-35
Low	0.3-0.5	0.1-0.2	10-20
Very low	<0.3	<0.1	<10

* Indicates potential non-exchangeable K release of the soil in the long term (Metson & Lee, 1977). Source: Metson (1980).

Total K^+ values and Kc supplying power was summarized according to the generic groups and subgroups of New Zealand soils (Metson, 1980). All weakly weathered soils from basic rocks, rendzinas and recent soils from alluvium derived from sedimentary rocks were found to have high values of Kc. On the other hand, in soils where low amounts of 2:1 clays, feldspars, and volcanic glass are present, the amount of Kc is then also low (Haylock, 1956).

Another aspect that influences K levels in soil solution and plant absorption is its relationship with Ca and Mg. If soil K levels are quite low, it may be due to an overabundance of Ca^{++} or Mg^{++} (Peacock, 1999). These three elements compete for fixation sites on soil particles, and a large excess of any one element can cause reduced availability of one or both of the other elements. This situation is difficult to correct, requiring massive applications of K fertiliser to correct an excess Ca^{++} or Mg^{++} problem.

Several different methodologies have been developed to estimate the availability of medium-term K levels, and these methods were compared for New Zealand soils (Metson, 1980). The Fertilizer & Lime Research Centre Laboratory use the modified sodium tetraphenylboron method developed in New Zealand as an accurate method (Jackson, 1985). This method determines short to medium-term availability of K, and is sensitive to changes in K status caused by K uptake by plants. It identifies potassium uptake from soil reserves after minimum levels of exchangeable K are reached and has been shown to be better related to K plant uptake than other methods, including the Kc. In summary, high K levels in grape juice, that might be detrimental to wine quality, are not necessarily related to exchangeable K levels in soils. Soils may have different sources of medium and long-term K reserves that might be being extracted by plants. Moreover, the relationships with Ca^{++} and Mg^{++} concentrations in the soil solution might affect vine K nutrition. Therefore, a more complete study of K dynamics in the soils of the studied vineyard should be carried out. The results of these analyses are presented and discussed in Chapter 5.

2.4 Precision Agriculture

Precision agriculture (PA) applies concepts that existed before the advent of mechanization, when the farmer worked in smaller fields, observed the progress of each part of the field, and managed the crops on a site-specific basis (Plant, 2001). PA is a management process that deals with spatial variability (across a field), temporal variability (from year to year) and predictive (assumptions about the future) agronomic variability (Blackmore & Larscheid, 1997). If there is no variability within a farm, then precision agriculture has less application. The Australian Centre for Precision Agriculture (ACPA, 2003, online) defines PA as "Observation, impact assessment and timely strategic response to fine-scale variation in causative components of an agricultural production process."

To be able to manage agronomic variability it is necessary to first measure and understand it. The process that allows the full potential use of PA is illustrated in Figure 2.1.

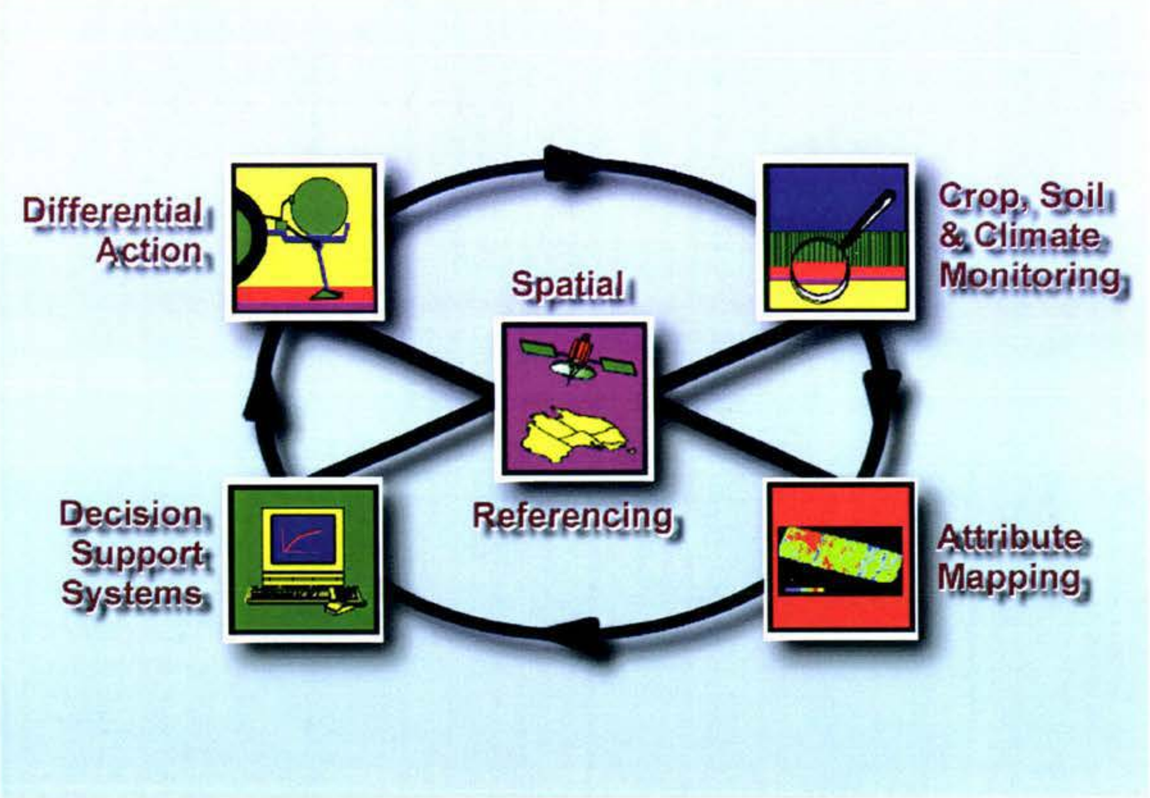


Figure 2.1 Main processes for a site-specific management system.
Source: ACPA (2003).

Once the variability has been understood, differential treatment of field crop production can be considered (as opposed to the uniform traditional management system). This facet of PA is known as Site Specific Management defined as "Matching resource application and agronomic practices with soil attributes and crop requirements as they vary across a field" (ACPA, 2003, online).

To be able to manage crops on a spatial scale smaller than that of the whole, it is necessary to identify not only the variability of a production system but also the size of the minimum manageable zone (McBratney &Taylor, 1999). This concept was introduced to reduce the complexity of more than one factor influencing yield, and is defined as zones where 1) yield differences between zones are substantially greater than those within zones and 2) the principal set of factors that influence yield within a zone are the same (Plant, 2001).

The potential of using information technologies such as the global positioning system (GPS), the yield monitor, variable rate chemical application, geographic information systems and remote sensing, together with agronomic knowledge is to:

- maximise production efficiency
- maximise quality
- minimise environmental impact
- minimise risk

(McBratney &Taylor, 1999).

In the majority of cases studied so far, the main interest has been in measuring crop yield. Yield monitors installed in harvest machines have been developed for grain, but also for a variety of other crops, including cotton, forage, peanuts, potatoes, straw, sugarbeets and tomatoes (Plant, 2001).

Major efforts have been in the development of technologies for the acquisition of spatially referenced data on soil and plant properties (Plant, 2001). The infrared spectrometer, used for determining plant water status; the soil electrical conductivity meter (discussed in the following chapter); and the leaf chlorophyll meter, used for assessing plant nitrogen status have all been studied and implemented. The photosynthetic status of a crop can be estimated through the crop canopy reflection in the red and near infrared regions of the electromagnetic spectrum. Remotely sensed data, obtained either by satellite or aircraft are used to characterize reflection and emission from the crop canopy. A number of vegetation indices as indicators of crop health and yield have been formulated.

The economics and social implications of PA technologies must also be considered. PA places an increased value on information and knowledge and this implies a cost. While Site - Specific Management is in the early adoption stage of technological innovation" (Plant, 2001, p 23), cost-benefit and socioeconomic analyses of this practice need to be carried out. One critical issue is that this technology disproportionately benefits large farms. An effect of SSM may be to promote the further consolidation of farms into large entities employing primarily highly skilled workers, affecting the economic and social structure of rural communities. Similarly, a negative impact may be expected in lesser-developed countries, which are not capable of directly benefiting from this technology (Plant, 2001). All these considerations should be addressed and mitigation of negative effects should be considered.

2.5 Precision Agriculture Technology

2.5.1 Geographical Information Systems

Geographic Information Systems are becoming a common tool to manage and analyse spatial and attribute data. The possibility of integrating various types of information needed to manage production on a site-specific approach is the explanation for such a development. 'Geographic' refers to the possibility of knowing or calculating the locations in terms of geographic coordinates (e.g. latitude and longitude). 'Information' refers to data which is organized to generate knowledge in the form of coloured maps and images, statistical graphs and tables that can be interactively queried. 'System' denotes that it consists of several interrelated and linked components with different functions (Bonham-Carter, 1994). GIS was defined as:

> "......an organized collection of computer hardware, software and geographic data designed to efficiently capture, store, manipulate, analyse, and display all forms of geographically referenced information" (Dangermond, 1992, p. 14).

With GIS, spatial data from diverse sources can be brought together into a unified database, usually employing different digital data systems. The different phenomena are represented in a series of spatially registered data layers (e.g. geology, routes, lakes, airborne images) that can be perfectly overlapped at all locations. Three main functions make GIS so useful:

- the capability of manipulating data, by overlaying, joining and desegregating;
- the capacity of querying the data, formulating hypotheses, testing assumptions, defining potential relationships and developing theoretical constructs;
- the facility to relate the two and three dimensional locations of earth surface, features and characteristics, dynamically, in the space and time

(Sombroek & Antoine, 1994).

The ability to represent multiple layers with enormous amounts of differing information, and to process map and attribute data simultaneously, provides the user with the prospect of a more holistic environmental and socio-economic representation of the real-world (Badcock, 1998; Bonham-Carter, 1994).

It can be easily deduced that the key to a successful GIS is the utility to support decision-making, which is a direct function of the accuracy, quality and scale of the data contained in the system (Kleynhans *et al.*, 1999). In the following items, the principal tools for accurate data collection are described.

2.5.2 Global Positioning Systems (GPS)

Global navigation satellite systems (GNSS) are able to calculate accurately positions on the surface of the earth using satellites as reference points. Two GNSS are currently in operation, the US NAVSTAR GPS (navigation system with time and ranging — global positioning system), and the Russian GLONASS (global navigation satellite system) (Keicher & Seufet, 2000).

Since GPS and GLONASS became available for private use in 1995, they have quickly become indispensable in a wide range of applications. Today GPS is widely used by the community (Lechner & Baumann, 2000).

The basis of GPS is the creation of a trilateration from any point on the earth's surface to the satellites in view. To do that, a GPS receiver measures the distance to the satellites by the time the radio signal needs to reach the receiver. The exact location of the satellite in space is crucial and the orbits should be very stable and predictable. The satellites are observed and controlled by ground stations, which put the spatial information into the signal. The data are known as "ephemeris data" (orbit of one satellite) and "almanac data" (relation between all of the satellites).

A minimum of three satellites must be available to determine a three-dimensional position. All points, which have the same distance to one satellite, form a spherical surface with the satellite in the centre, and the three spherical surfaces intersect points define the position on the earth surface. To eliminate the time difference between the satellite's atomic clocks and the receivers' quartz clocks, a fourth signal is necessary. Finally, another satellite is needed for integrity, quality control and identification of satellite malfunction.

The main influences on GPS accuracy are:

- the geometric position of the satellites;
- clock errors of the satellites;
- ephemeris errors;

- tropospheric and ionospheric conditions;
- multipath effects;
- inaccuracies of the receiver; and
- GPS: artificial deterioration of clock and ephemeris data for civil users by the US Department of Defence (SA) (Lechner & Baumann, 2000).

Differential GPS (DGPS) can improve the horizontal accuracy to a few metres, eliminating timing errors signals that go into the position calculation. Two receivers, one that is stationary and another that is moving around making position measurements are needed.

When two receivers are close to each other (a few hundred kilometres), the signals that reach both of them will have traveled through the same slice of atmosphere, and so will have the same errors. The stationary receiver ties all the satellite measurements into a solid local reference. The timing errors are measured by this receiver, and then provide correction information to the other receivers moving around. This is possible because it uses its known position to calculate timing, determining what the travel time of the GPS signals should be, and comparing it with what they actually are. In that way, an error correction factor is calculated for each satellite. Once the moving receivers get the list of errors, the corrections are applied for the particular satellites in use.
(Trimble Navigation Limited, 2003a).

The transmission of the correctional data can be realised with either terrestrial radio signals, mobile communication systems or satellites (Lechner & Baumann, 2000).

Real Time Kinematic GPS (RTK-GPS) technology is a variety of DGPS that achieves sub-decimetre accurate measurements in both horizontal and vertical directions. It is based on differential corrections from a local reference station and on the GPS time code carrier wave phase difference measurements (Keicher & Seufet, 2000). A base station placed on a known, surveyed point transmits corrections via radio to the mobile receivers in the field.

The receivers used in RTK-GPS systems are dual-frequency and also track the second carrier phase signal, which makes data transmission to the roving receivers more reliable. This also allows the system a quicker initialization, needing less than one second to output the data (Trimble Navigation Limited, 2003b).

2.5.3 Remote Sensing

Remote sensing can be described as 'eyes' with highly spatial resolution that provide visions of earth resources from an aerial or space point. Remote sensing was defined as:

> " ....the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation " (Lillesand & Kiefer , 2000, p.1).

Using different sensors, it is possible to record the way earth surface features reflect and emit electromagnetic energy. These data are then analyzed using reference data about the resources being studied (such as soil maps, crop statistics), and all the information can be analysed and displayed in a layer, using GIS.

The detection of the electromagnetic energy can be performed either photographically or electronically. While photographs offer the advantage of being cheaper, providing a high degree of spatial detail and geometric integrity, electronic sensors provide a broader spectral range of sensitivity and the ability to electronically store and transmit data (Lillesand & Kiefer, 2000). Digital sensors also provide a more direct measure of true reflectance properties since they avoid the intervening steps of processing the film and scanning the image, using a digital scanner.

These forms of data can be obtained either by satellite or aircraft. At present, the prevailing combination is the aircraft-camera because it is relatively inexpensive and easily available when compared with the digital-cameras (Plant, 2001).

The usefulness of remote sensing is due to its capability of characterizing reflection by, and emission from, the crop canopy, providing a detailed, spatially referenced measure of soil conditions or plant growth and development. Generally the data are expressed in the form of vegetation indices, which are algebraic combinations of the reflection in different wavelength bands. These data can be then used as components of site-specific-crop management programs (Plant, 2001).

2.5.4 Continuous soil data sensors

Real- time, continuous sensors and scanners are required for the evolution of agricultural SSM. Continuous soil data sensors have been developed to obtain high spatial resolution of soil data. It was achieved by bringing the sensor into direct or close proximate contact with the soil, either by carrying a portable unit into the field and touching the soil at some locations or by attaching the sensors to an implement and dragging them through the field to obtain a continuous measurement.

Electrical-conductivity is probably the most common form of continuous sensing (Plant, 2001). This technology is described more extensively in section 2.8.

Another example of continuous soil data sensors is a mechanism for "on-the-go" soil pH measurement (Viscarra & McBratney, 1997).

Other contact sensors such as ultrasonic sensors to measure the water level in a flow flume; spectra photometers that work in the near infrared reflectance to determine soil moisture content; optoelectronic based soil organic matter sensors; nitrate sensors using ion selective electrodes, are becoming available (Upadhyaya & Teixeira, 2003).

2.5.5 Variable rate technology

Site-specific information related to soil fertility and soil physical properties, offers means by which inputs can be applied in the correct quantities, where and when they are needed. Variable rate technology is becoming involved with: application of fertilizers, application of soil amendments and management of weeds with flow-rate controlled sprayers that match previously collected weed incidence maps (Usery *et al.*, 1995; LeBoeuf, 2000).

2.6 Evaluation of soils using remote sensing and GIS technology

Aerial photography has been used since the beginning of the last century to locate changes in surface patterns, and to correlate them with soil properties and to delineate contrasting soils (Carrol *et al.*, 1977).

Remote sensing data provide a spatially contiguous, quantitative measure of surface reflectance that is related to soil properties (Agbu *et al.*, 1990). Both physical factors (e.g., soil texture, moisture content and surface roughness) and chemical factors (e.g., surface mineralogy, organic matter content and moisture) influence soil spectral reflectance. Small particle size tends to increase surface average reflectance or albedo and decrease spectral contrast of absorption features, while an increase in organic matter or soil moisture decreases albedo (Irons *et al.*, 1989). Also the presence of iron and iron-oxides, hydroxyl bonds in clays and adsorbed water help to derive surface mineralogy (Goetz, 1989; Irons *et al.*, 1989).

Light colours are generally associated with sandy soils with lower water holding capacities and lower levels of organic matter, while darker colours represent clay soils with higher water holding capacities and higher levels of organic matter; they can also indicate drainage problems (LeBoeuf, 2000).

Traditionally, remote sensing has been used to classify soil units through photo-interpretation or digital image processing. Significant improvements are made when remotely sensed information is combined with ancillary information such as thematic maps or vegetation cover. Some examples of research of soil studies assessed by remote sensing follow.

Multispectral aerial photographs have shown to be effective in soil mapping, especially in places where differences in natural soil drainage exist, such as valleys with flat and rolling areas (Rijkse, 1977). They are also useful for erosion pattern detection, erosion control surveys and to map differences in geological surface materials such as sandstones and mudstones. However, agricultural patterns tend to obscure soil differences.

With the recent developments in hyperspectral remote sensing, data input to predict soil moisture can be improved. Hyperspectral sensors, such as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) measure a contiguous spectrum in the visible and near infrared that improve the characterization of atmospheric and surface properties (Goetz *et al.*, 1985).

ERS-2 radar images were used for a tall grass prairie ecosystem study in northeast Kansas by Hutchinson (2003). Field data collection of soil moisture, digital image interpretation of optical (NOAA AVHRR and LANDSAT TM) and radar (ERS-2) imagery, and environmental modeling were performed in a geographic information system. The results showed that ERS-2 data might be capable of monitoring soil moisture conditions, even in extremely dense natural grassland vegetation conditions.

Summing up, numerous studies have shown the potential benefits of using remote sensing for soil identification and mapping.

2.7 Electrical conductivity principles and measurement

To take full advantage of GIS capability of analyzing large amounts of spatial data, an efficient way of collecting data is needed. Moreover, a critical layer in GIS when utilized in land management decisions is soil survey information, especially on large scales, when soil variability increases (Mclean *et al.*, 1993). A way to decrease costs of soil data acquisition is the use of techniques for rapidly and non-invasively measuring soil properties across a field. By using either electromagnetic induction or by direct contact, apparent bulk electrical conductivity (EC_a) of earthen materials throughout a field can be measured *in situ*. Soil EC_a measurements have long been used to identify contrasting soil properties (Lund *et al.*, 1999; Morgan *et al.*, 2000; Department of Sustainability and Environment (DSE), Victoria, Adelaide, 2002).

2.7.1 EC principles

Conductivity is the intrinsic property of a material that measures the ability of the material to transmit an electrical charge. Factors influencing soil conductivity include moisture content, amount and type of ions in the soil water, amount and type of clays in the soil matrix, cation exchange capacity, pore continuity, soil depth, soil temperature and mineralogy. Soluble salt concentration is the main factor explaining EC_a variability in salty soils (Williams & Baker, 1982; Doerge, 2001, Sudduth *et al.*, 2000). In non saline soils of humid areas, soil texture, moisture content and cation exchange capacity are important factors determining apparent conductivity (Doolittle *et al.*, 1995; Plant, 2001; Williams & Baker, 1982; Sudduth *et al.*, 1998).

Environmental factors likely to have a significant effect on the EC_a measurements were placed (DSE, Victoria, Adelaide, 2002), in the following order of importance:

Soil salinity> moisture content> surface charge of clay particles> bulk density.

- Soil salt concentration

The concentration of soluble salts present in the soil profile directly influences the conduction of electrical current. Increasing salt (electrolyte) concentration in soil water results in higher EC_a values (Doerge, 2001; DSE, Victoria, Adelaide, 2002). Many studies confirm that correlation (Rhoades & Corwin, 1981; Corwin & Rhoades, 1990; Rhoades *et al.*, 1997; Williams & Baker, 1982; Slavich & Petterson, 1990).

- Moisture content

Current flow is primarily through soil moisture, so for a given level of salt concentration in the soil water, EC_a will increase with moisture until equilibrium is reached and the soil is at its field capacity (DSE, Victoria, Adelaide, 2002; Doerge, 2001). Dry soils have much lower conductivities than moist soils, being generally related to soil texture. Studies that relate EC_a values with soil water holding capacity have been extensively reported (Kachanoski *et al.*, 1988; Hartsock *et al.*, 2000, Morgan *et al.*, 2000).

- Cation exchange capacity (CEC)

High levels of colloids: organic matter and/or 2:1 clay minerals (illite, montmorillonite or vermiculite), give the soils a negative charge. They give the soil the ability to retain positively charged ions (such as Ca^{++}, Mg^{++}, K^{+}, Na^{+}, NH_4^{+}, H^{+}). The higher the concentration of these ions in the moisture-filled soil pores, the higher the EC of the soil (Lund *et al.*, 1999; Doerge, 2001).

The colloidal content and composition is related to both soil texture and organic matter content, so it is difficult to isolate the effect of the CEC by itself. Clays tend to exhibit a negative charge. During weathering, cations are absorbed onto the surfaces of these particles; these cations can partially dissociate themselves from the clay particles and become available for ionic conductivity. A soil with a higher clay or organic matter content (if all other soil properties are equal), will record a higher EC_a reading than a soil with a lower clay or organic matter content (DSE, Victoria, Adelaide, 2002).

Exchangeable calcium and Kjeldahl-measured nitrogen in medium and coarse soils (McBride et al., 1990), exchangeable Ca++ and Mg++ (Hartsock et al., 2000), and soil organic matter content (Banton et al., 1997; Morgan et al., 2000) have been positively correlated with EC_a readings.

- Soil texture

It is difficult to isolate the effect of texture by itself, since it is related to other properties affecting EC_a readings (CEC, soil porosity and soil moisture content). How conductivity depends on the grain size of the soil materials is illustrated in Figure 2.2. If all other soil properties are equal, a soil with higher clay content will record a higher EC_a reading than a soil with lower clay content (DSE, Victoria, Adelaide, 2002).

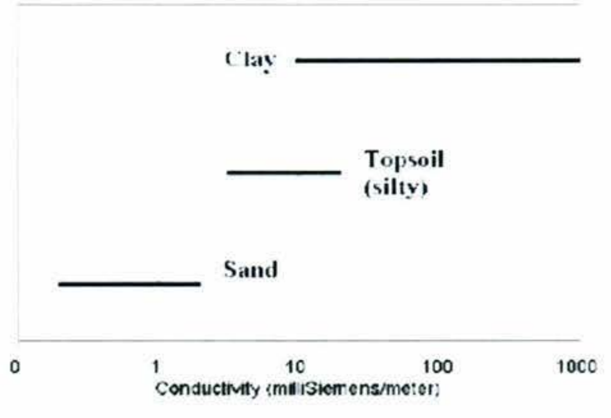


Figure 2.2 Soil electrical conductivity and grain size.
Source: Lund et al. (1999).

- Soil porosity

The number, shape and size of the pores directly affect the ability of the current to flow through the soil medium. Soil porosity is reflected in the soil texture, soil moisture and bulk density (DSE, Victoria, 2002). A clay soil, with numerous, continuous, small water-filled pores usually conducts electricity better than a sandier soil. Also compaction normally increases soil EC (Doerge, 2001).

- Soil temperature

Because the temperature of the soil affects soil water viscosity and the phase state (vapour or liquid), it influences the mobility of salts (DSE, Victoria, 2002). EC decreases in moist soil near freezing point, and below freezing, soil pores become insulated from each other and EC values decline rapidly (Doerge, 2001).

2.7.2 Methods of measuring EC$_a$

Two methods of measuring soil EC$_a$ in situ have been developed: electromagnetic induction and electrical resistivity by direct contact.

The electromagnetic induction (EMI) technique does not make contact with the soil, using instead a transmitter coil to induce a magnetic field into the soil and a receiver coil to measure the response (Figure 2.3). Apparent conductivity is a weighted-average conductivity measurement for a column of earthen materials to a specific depth (Doolittle *et al.*, 2002). The advantage of this system when compared with electrical resistivity is that it is non-invasive and is more sensitive to thin, highly conductive subsurface layers (McNeill, 1980).

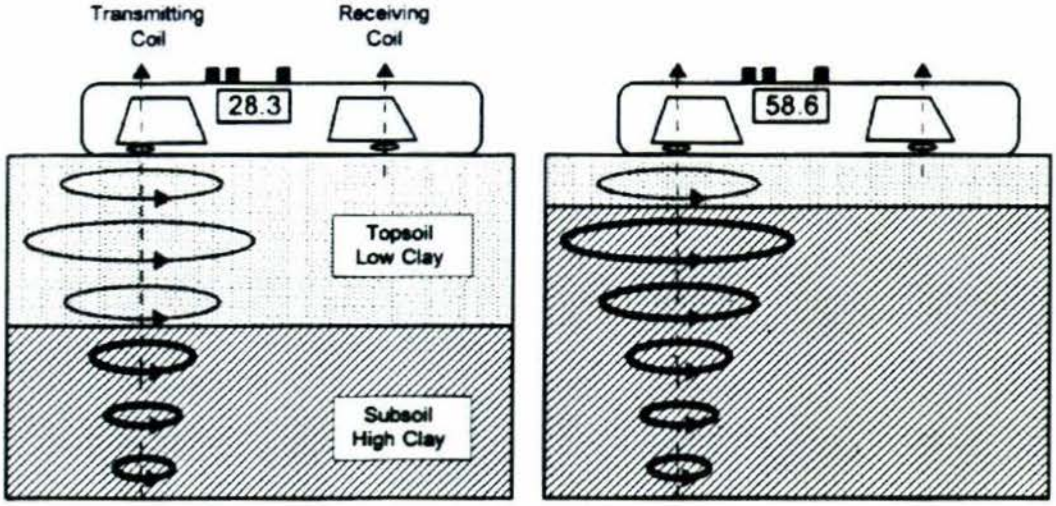


Figure 2.3 Schematic showing the operation of the Geonics EM38 soil conductivity sensor in vertical dipole orientation over deep topsoil (left) and shallow topsoil (right).
Source: Sudduth et al. (2001).

The alternative electrical resistivity (ER) method operates by directly injecting current into the soil using electrodes and measuring the potential difference in current flow between potential electrodes. The Veris 3100 system (Figure 2.4) converts the resistivity (ohm-m) into EC_a (mS/m) units. When mobilized through the field by a cart, the system acquires conductivity measurements and geo-references them using a GPS. The data file is then displayed on standard mapping software (Lund *et al.*, 1999). Full ground contact has to be ensured, otherwise erroneous data can result (Doolittle *et al.*, 2002). Advantages of this system are that it provides better depth resolution and is less susceptible to interference from metal than EMI (McNeill, 1980).

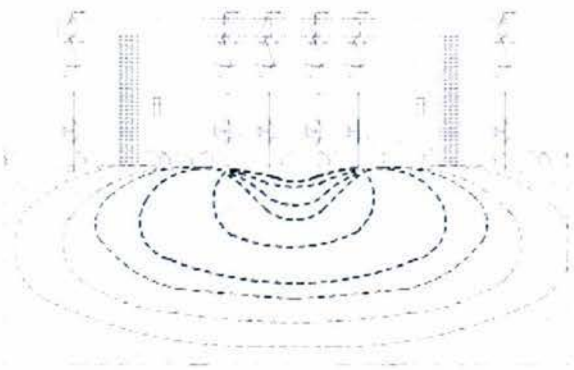


Figure 2.4 The Veris 3100 soil conductivity mapping system employs two arrays to investigate soil at two depths, 0-25 cm and 0-75 cm.
Source: Lund *et al.* (1999).

Experience has shown that the two methods produce similar results (Lund *et al.*, 1999). When comparing EMI with ER surveys, similar gross patterns of EC_a were obtained. However, some differences in EC readings were detected and attributed to differences in sensing depth between the sensors and operating orientations (vertical vs. horizontal for EM38 or shallow vs. deep for Veris 3100) (Doolittle *et al.*, 2002; Sudduth *et al.*, 1998).

2.7.3 Accuracy of electromagnetic induction survey

The EM38 may be operated either in a vertical or horizontal orientated dipole orientation, resulting in different depth and volume of soil profiled. The instrument response to soil conductivity varies as a nonlinear function of depth. The effective observation depths are of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations respectively. Sensitivities in the vertical and horizontal orientations are highest at about 0.4m below the instrument and at the instrument respectively (Figure 2.5) (McNeill, 1992).

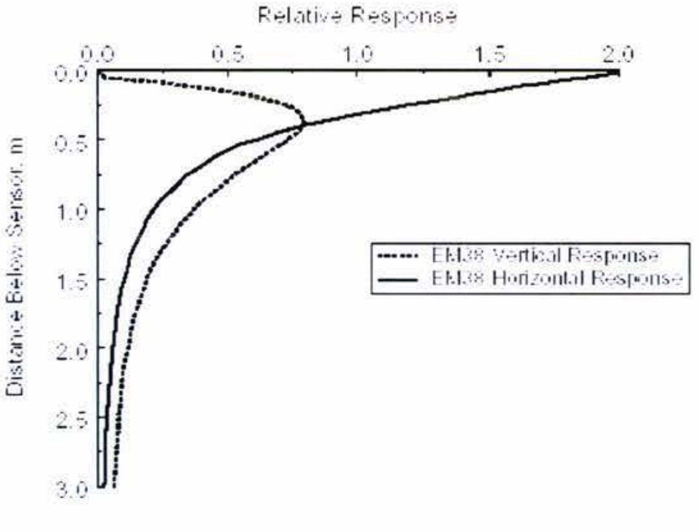


Figure 2.5 Relative response of EM38 sensor versus depth.
Source: McNeill (1992).

Users should be aware of that difference in operating modes. For example, data obtained with the EM38 meter in the vertical dipole orientation was more highly correlated with average clay content of the first 100 cm of soil than in the horizontal dipole orientation (Doolittle *et al.*, 2002).

Use of non-metallic support for EMI sensors is necessary because of the strong response they have to metallic objects within approximately 1m (Sudduth *et al.*, 2000).

Optimum survey distances for taking readings in the field were researched for alluvial and upland landscapes (Miller *et al.*, 2001). The minimum distance between samples at which there is no spatial variance and samples are independent was 20 metres. Even though different results may be obtained from different landscapes, these data give an idea of maximum distances between samples that might be used.

Ambient conditions such as air temperature, humidity and atmospheric electricity; soil conditions such as temperature and moisture content; and operational conditions, can influence EM38 readings. In a study conducted to test the EM38 behavior in claypan soils (Sudduth *et al.*, 2001), the stability of EM38 readings over time was quite variable. Different sources of variability were measured (Table 2.2). These values may change in different soil types and EC_a ranges, but they give an idea of how different operational and ambient parameters may influence the accuracy of the readings.

In some cases the instrument drift was as much as 3 mS/m per hour (Table 2.2). A proposed approach to drift compensation was to establish a calibration transect on each field, where EC_a values along a transect should be read several times during the course of a field survey so that any drift can be documented and compensated.

Another proposed approach was to rezero the EM38 on a frequent basis during the course of the survey (Sudduth *et al.*, 2001).

Table 2.2 Approximate effect of various operational and ambient parameters on EC_a measurements obtained on claypan soils.

Parameter	Effect on ECa
Instrument drift	Up to 3 mS/m per h
Operating speed	-0.4 mS/m per m/s
Operating height	0.3 mS/m per cm
Soil moisture*	1.1 mS/m per %
Soil temperature*	0.2 mS/m per oC

* Effect calculated at a claypan-field average EC_a of 35 mS/m for this nonlinear relationship.
Source: adapted from Sudduth *et al.*, 2001

However, multiple measurements of EC_a for the same location were similar if they were collected at the same time of the year with similar moisture and temperature conditions (Sudduth *et al.*, 2001). A correlation coefficient of 0.97 was obtained for EC_a measurements read in April 1994 and April 1997 in the same area. The correlation coefficients for EC_a measurements read in April 1994 and November 1997 was 0.89, and for EC_a measurements read in November 1997 and April 1999 it was 0.86.

A significant effect of soil moisture and air temperature across measurements on different dates was detected (Sudduth *et al.*, 2001). Thus, it is also recommended, that in order to obtain measurements for different seasons, the effects of variations in soil water content and atmosphere temperature be removed. Although soil conductivity can be temporally variable between dates, the spatial patterns should be consistent (Hartsock *et al.*, 2000).

The mobile acquisition of data can introduce an offset between GPS position and the point where the EC_a value is read. This is due to the distance between the GPS and the EM38, and the time lags. Generally the effect is minimal (Sudduth *et al.*, 2001).

Because EC_a is a function of a number of soil properties, in order to establish a relationship between EC_a measurements with one factor, the influence of the other soil properties needs to be determined, and the differences in one factor should be large enough with respect to variation in the other factors. In that way EC_a can be calibrated as a direct measurement of that dominant factor. Hence, to successfully adopt EC_a measurements as a soil-mapping technique to assist SSM, it is necessary to understand and know how the data is collected, to establish with ground truthing the cause(s) of the changes in EC_a conductivity measurements, and to know the intended application (Sudduth *et al.*, 2000; Kitchen *et al.*, 1996; DSE, Victoria, 2002; Hartsock *et al.*, 2000).

2.8 Research on EC_a - soil property correlations

Interpretation of EC_a maps has proven to be useful as an indirect method of studying spatial variations in a number of soil properties.

Soil salinity is, perhaps, one of the most studied parameters affecting EC_a readings. Average root zone salinity can be adequately predicted from an EM38 survey after a ground truth calibration. It can then be used to assess likely plant response or warn of possible secondary salinization (Slavich & Petterson, 1990; Rhoades & Corwin, 1981; Corwin & Rhoades, 1990).

Several studies have found a strong correlation between conductivity and soil texture (Hedley *et al.*, 2002, Banton *et al.*, 1997; Williams & Hoey, 1987; Morgan *et al.*, 2000). Accurate predictions of the depth of top soil over a clay layer have been carried out (Doolittle *et al.*, 1994; Hartsock *et al.*, 2000; Sudduth *et al.*, 1998). A prediction of soil depth variability was made using EM38 in the Terra Rossa soils of the Coonawarra in Australia (Bramley, 2001).

Depth to sand beneath a loamy topsoil was mapped using EC_a readings by Kitchen *et al.* (1996). Differences in soil water content and air temperature and humidity also caused differences in EC_a readings. The location of areas of coarse-textured soils surrounded by poorly drained soils was possible using electrical induction techniques (Doolittle *et al.*, 2002).

Variations in soil water content of the first 0.5 m of soil were highly correlated with EC_a variations, independently of the wide range (2.5 to 44%) in soil texture tested (Kachanoski *et al.*, 1988; Headley *et al.* 2002).

To assist mapping soil variability at Bankhouse Station in the Marlborough Region, New Zealand, the EM38 together with DGPS, and remote sensing were successfully used. Soil textural boundaries were located, providing the viticulturist with precise information that would help in vineyard design and management (Pitcher-Campbell, 2002).

Landscape differences were found to influence EC_a (Clay *et al.*, 2001), which was lower in the well-drained soil of the summit areas than in the poorly drained soils of the toeslope. This was also attributed to soil forming process such as water erosion which transports topsoil material to lower areas, water leaching salts from summit areas and capillary flow of water and salts from subsurface to surface soils in the hollows.

Different alluvial soils could be identified and mapped using EC_a data (Anderson-Cook *et al.*, 2002). The soils ranged from coarse-loamy, mixed, thermic, Hapludults to fine-loamy, mixed, thermic, Ultic Hapludalfs. EC_a classified the soils correctly in two categories with over 85% accuracy. A significant relationship between EC_a readings and crop yields was also found.

Correlations between EC_a measurements and chemical properties have also been reported. Soil exchangeable calcium and magnesium content could explain a large amount of the variability in fields with large concentrations of these nutrients (Hartsock *et al.*, 2000). EC_a was also strongly correlated with exchangeable Ca^{++}, Mg^{++}, Kjeldahl N concentration and CEC in non-saline, medium and coarse textured forest soils in Ontario (McBride *et al.*, 1990).

Management practices, such as old animal confinement areas and high manure application rates, were found to influence EC_a measurement, increasing the EC_a (Clay *et al.*, 2001).

2.9 EC_a mapping applications

The measurement of soil EC_a variability can be applied for a more efficient sampling of the field, guide management decisions such as input dose (irrigation, fertilizers, pesticides) rates and help to interpret yield monitoring maps. Potential uses of EC_a maps have been summarized by Doolittle (Table 2.3).

Table 2.3 Potential uses of EC_a maps.

Application of EC Mapping	Soil Properties Estimated
Delineation of Management Zones	Soil texture, organic matter, CEC, drainage conditions. Soil factors that most influence yield, particularly plant available water content.
Directed soil sampling within more accurate soil boundaries.	Soil texture, organic matter, CEC, drainage conditions.
Variable rate seeding.	Topsoil depth, CEC
Variable rate nutrient application based on soil productivity	Depth to claypan, subsoil or parent material, soil texture
Variable rate herbicide application	Soil texture, organic matter and CEC
Interpretation of yield maps	Soil factors that most influence yield, particularly plant available water content
Refining soil type boundaries and identifying unmapped inclusions	All soil factors
Guidance for placement and interpretation of on-farm tests	All soil factors
Soil salinity diagnosis	Electrolytes in soil solution
Drainage remediation planning	Water holding capacity, sub-soil properties, water content

Source: Doerge, 2001.

◆ Directing soil sampling

Variability of important physical properties that affect productivity, and indirectly, mobile nutrients that follow soil textural patterns can be mapped using EC_a. Identifying soil variability can help in choosing representative sample locations. This targeted sampling according to soil management zones identified with a soil conductivity map can significantly reduce the cost of acquiring soil analysis data compared with the evenly spaced grid method (Lund *et al.*, 1999).

EC_a survey can potentially be applied to assess temporal impacts of management of soil condition (Johnson *et al.*, 2001b). A geo-referenced soil-sampling scheme was undertaken, based on EC_a mapping that separated fields into four EC_a classes. EC_a classification proved to be effective in delimiting distinct zones of soil condition. Bulk density, % clay, pH, soil moisture, total C and N, microbial biomass, and other soil properties influenced EC_a readings.

◆ Delineating management zones

Bulk soil electrical conductivity maps, together with topographic attribute maps (slope, elevation and compound topographic index) and yield maps, were the inputs to delineate within-field management zones in a study carried out by Fraisse *et al.* (2001). Both elevation and soil EC_a were the most important attributes included when performing unsupervised classification in claypan soils. Supporting this result, Johnson *et al.* (2003) performed an unsupervised classification of EC_a data within a field, to establish appropriate minimum manageable zones for the SSM of winter wheat in a semiarid system.

◆ Variable input applications

With the new technologies of variable rate planters, sprayers and applicators, classification based on EC_a will help in the most effective use of these tools for better management, improving both economic and ecological outcomes in agriculture (Johnson *et al.*, 2001b).

Proper variable-rate use of herbicides based on soil texture and organic matter can save money, increase herbicide effectiveness and protect the environment. Similarly, applications of fertilizer based on site-specific conditions and yield goals can also improve efficiency. Promising results have been obtained in a study of N application rates on a site-specific basis in three regions of the United States (Lund *et al.*, 2001). The research was conducted in regions where commercial soil EC mapping and variable rate N have been adopted by growers. The authors affirmed that as economic and environmental pressures increase, the incentive to develop these practices would further increase as well.

- Variable rate seeding

In fields where corn production is limited by topsoil depth, varying corn plant population based on EC_a maps has been shown to increase net income (Lund *et al.*, 1999).

However, a study of yield response to variable corn seeding showed that in many locations, choosing the correct hybrid was more important than minor variations in plant population (Doerge, 2000). Supporting these results, from an economic evaluation of variable seeding rate, Lowenberg-DeBoer (1997) concluded that profitability is improved only if part of the field is substantially more productive than other low productivity soil, so that farmers with a mix of medium and high potential land are better off with uniform rate seeding.

- Drainage and irrigation planning

Textural discontinuities within the profile and potential salinity hazard can be mapped and are important properties for planning irrigation and waste-water disposal systems (Williams & Hoey, 1987). Lower N application on lighter soils can be accurately recommended to prevent leaching (Lund *et al.*, 1999).

- Interpretation of yield maps

Correlations of EC_a with yields have been found (Lund *et al.*, 1999; Johnson *et al.*, 2003). However, Kitchen *et al.* (1996) found that conductivity measurements explained only part of yield variability.

2.10 Precision viticulture opportunities

The prospect of overcoming the soil and landscape variations that exist within a vineyard and so improve the grape quality is likely to benefit from the adoption of precision viticulture technologies. Winegrape industry characteristics are ideal for the adoption of these technologies. Viticulture is intensive, highly mechanized, has high value adding potential and is generally dominated by large companies. Thus it has been one of the first horticultural crops in Australia to adopt PA methodology (McBratney &Taylor, 1999).

Precision technologies are applicable if both the variability in the system and the ability to manage zones differently exist. Otherwise, traditional uniform management is preferable. Because viticulture tends to employ narrower applicators which travel at speeds slower than that in cropping, the minimum manageable zone for a vineyard is considerably smaller than other situations (McBratney &Taylor, 1999).

The main objectives of adopting a precision viticulture approach are listed below.

1 - Maximizing yield and quality:

Specific objectives are: to search for places for vineyard expansion; to improve vineyard design; to sample vineyards more precisely; to aid management decisions; and to harvest according to quality specifications (Bramley et al, 2000).

A careful initial selection of places to plant vines and planting vines in zones of similar environment or "terroir" is very important.

Site selection and ongoing management of vineyards using GIS have been analysed in the Adelaide Hills district. The 'rule of thumb' used by wine consultants in the industry when searching for a new vine growing region was provided by inputs which replicated decision-making processes using GIS. Topography and soils were concluded to be the main environmental factors influencing viticultural site selection within a small region (Badcock, 1998). Even if it was not completely successful, this study illustrated the potential for using GIS in viticulture.

Block subdivision of a vineyard into low and high vigour zones can be made based on high-spatial resolution multispectral imagery acquired by an airborne digital camera system (Johnson *et al.*, 1996; Johnson *et al.*, 2001b). A normalized difference vegetation index (NDVI, calculated as [infrared-red]/[infrared+red]) was derived to emphasize differences in the amount of leaf area per unit of ground area. The percent of photosynthetically active solar irradiance, and leaf water potential was also measured. Ground based measurements showed a clear differentiation between low and high vigour zones with respect to shoot vigour, vine water status, and fruit and wine character. This zoning allowed the production of reserve quality highest value wines.

Areas of vine stress can be detected using remote image and leaf reflectance analysis. This approach is being used in some Australian vineyards (Fuller, 1995), where images are analyzed to detect 'weak' areas, which can be correlated with: over-watering, lack of irrigation, soil problems, fungal diseases and insect damage (being able to warn growers of *phylloxera* infection spread two to three years earlier than ground observations). By analysing visible and near-infrared images of vineyards, patterns of leaf area can be mapped. Year to year changes in canopy can be assessed and in *phylloxera*-infested vineyards, earlier recognition of the need for replacement enables plans to be made (Johnson *et al.*, 1996).

The impact of environmental stress on grape canopy metabolism can be evaluated. A leaf disorder in grape that causes >50% reduction in photosynthetic rate in grapevines growing in central Washington (blackleaf) was detected through leaf spectral reflectance measurements early in the season, before symptom expression, when changes in vineyard management could then alleviate stress conditions (Lang *et al.*, 2000). Remote-image capture was tested using 35 mm colour and infrared slide film from a helium blimp 15.3 to 42.7 m altitude and an aircraft 305 m altitude.

A set of quality management standards (ISO 9000) and environmental management standards (ISO 14000) have been developed and many wineries are using Hazard Analysis Critical Control Points to ensure the quality of their products. If through remote or proximal sensing, for example, quality can be mapped just before, or at, harvest, a segregation of grapes can be made, leading to the production of better and more profitable wines (McBratney & Taylor, 1999; Small, 1999).

Soil electrical conductivity measurements have been used to produce geo-referenced maps showing the variability of soil properties. An in-depth knowledge of soil variability within a vineyard can be used to guide soil sampling, design on-farm trials, and determine the need for nutrients and crop protection chemicals (Lund *et al.*, 1999).

2 – Minimizing environmental impact:

Specific objectives are: more efficient use of inputs (fertilizer, sprays, water); ability to show that best practice has been used in grape production; and more precise sampling of vineyards (Bramley *et al.*, 2000).

Irrigation and the use of chemical fungicides are the main environmental impacts that concern viticulture. Since fertigation is often used, loss of water to groundwater usually also means loss of nutrients to groundwater. Hence, a differential watering regime is some times desired to maximize the irrigation efficiency and minimise ground water pollution. A continuous monitoring of water table levels may help to adjust management accordingly (McBratney & Taylor, 1999).

A better understanding of the areas most prone to outbreak of either diseases or pests may lead to more accurate chemical applications. This would be more cost effective and less environmentally damaging (McBratney & Taylor, 1999).

The risk of insect pests and disease, grape harvest dates and yield predictions were determined with high accuracy integrating ground-based weather and plant-growth measurements in different GIS software applications in California (Thomas, 2002). These data are distributed daily over the Internet as regional weather, and insect and disease risk maps, and are used by farmers to make disease and cultural practice decisions. Grape harvest projections are made by analysing aerial imagery collected from vineyards in the blue, green, red and near infra-red bands using an airborne, multi-spectral sensor.

Environmental macro-scale information in southern South Australia and an existing project (AusVit) that involves the use of weather stations and biological models could be integrated in a GIS (Badcock, 1998) to determine the optimum spraying regime to eliminate pests and diseases.

GIS can be used to assist in improving efficiency of policy formulation, in quantifying policy impacts, in evaluating agricultural land-use and in planning environmental protection. An example of this was the prediction of existing gully erosion in vineyard parcels (Meyer & Martinez-Casanova, 1999). Twenty three potential factors related to the development of gullies in vineyard parcels were analyzed from soil samples, using ArcInfo. The ranking of probable factors causing erosion may be used in the prioritization of soil conservation planning at catchment level.

Another example was a model developed for Sonoma County in California to understand vineyard expansion patterns on a landscape scale (Merenlender & Heaton, 2000). Agricultural areas and land use change were mapped and logistic regression was used to identify which landscape characteristics were associated with sites that had become vineyards versus those that did not. The results were analyzed together with new regulations that address soil erosion and water quality issues. Areas that would be more affected by new regulation were quantified. The possibility of this approach to assist the public and policy makers in both agricultural development and environmental protection was demonstrated.

In the province of Cremona, Italy, the evaluation of the hazard levels (particularly to groundwater) of farming activities was done using ArcView and its Spatial Analyst extension (Trevisan *et al.*, 2000). This methodology provided the mechanism to measure potential for pollution of agronomic origin taking into account site characteristics and was useful for management and policy goals.

Hazard levels (particularly to groundwater) of farming activities can be evaluated using ArcView Spatial Analyst extension tools. This methodology can provide the mechanism to measure potential for pollution of agronomic origin taking into account site characteristics and can be useful for management and policy goals. (Bach *et al.*, 2001; Trevisan *et al.*, 2000).

3 – Minimizing risk:

Specific objectives are improved harvest scheduling and improved quality control, leading to segregation of crops at harvest and an improved basis for paying grape growers (Bramley *et al.*, 2000).

In a vertically integrated industry such as viticulture in Australia, it is accepted that by decreasing the variability of the system the economic risk can be reduced. Wineries will be able, for example, to analyze local and overseas vintages, weather and market predictions and determine what sort of wines are limited (McBratney & Taylor, 1999). Badcock (1998) also suggested the potential of GIS for use in the financial aspect of viticulture.

2.11 Conclusion

Producing fruit of homogenous quality is crucial to producing wine of high quality. Soil properties within a vineyard are an important component influencing fruit variability. Thus, a detailed map showing distribution of the soil characteristics will enhance the opportunity for more efficient soil sampling and management of the soils. The possibility of overcoming the soil and landscape variations that exist within a vineyard and so improving the grape quality is likely to benefit from the adoption of precision viticulture technologies.

Major efforts have been made in the development of technologies for the acquisition of spatially referenced soil data. A way to decrease costs of soil data acquisition is the use of electromagnetic induction that measures apparent bulk electrical conductivity (EC_a) of earthen materials throughout a field. Since the factors influencing soil conductivity include soil moisture content, amount and type of ions in the soil water, amount and type of clays in the soil matrix, cation exchange capacity, pore continuity, soil depth, soil temperature and mineralogy; soil EC_a measurements have long been used to identify contrasting soil properties. The EC_a data can be accurately geo-referenced through the use of a global navigation satellite system, and by implementing a geographic information system, the efficiency and capability of spatial data analysis is significantly increased.

Precision viticulture technology research has been focused on data acquisition, quantifying the variability of the system, environmental monitoring, mapping of attributes and identifying the minimum manageable zones to determine its applicability.

Specific application objectives have been:

- to search for places for vineyard expansion;
- to improve vineyard design;
- to more precisely sample vineyards to aid management decisions;
- to harvest according to quality specifications, subdividing a vineyard into low and high vigor zones;
- to detect areas of vine stress;
- to use Hazard Analysis Critical Control Points to ensure that the quality of their products match management standards (ISO 9000) and environmental management standards (ISO 14000);
- to use inputs more efficiently.

Winegrape industry characteristics (intensive, highly mechanized, high value adding potential and generally dominated by large companies) are ideal for the adoption of these technologies. An effect of precision agriculture may be to promote the further consolidation of farms into large entities employing primarily highly skilled workers. Although this could be an advantage for the resource use efficiency, it also could affect the economic and social structure sustainability of rural communities. In that sense, a critical issue is that this technology could disproportionately benefit large farms. Similarly, a negative impact may be expected in lesser-developed countries, not capable of directly benefiting from this technology. This is an issue to be addressed, and efforts should be taken by governments to use this technology for a global social benefit.

CHAPTER 3

Description of the study site

3.1 Location of Rarangi vineyard

The research was conducted in a new vineyard close to Rarangi Beach, about one and a half kilometres north of the Wairau River Diversion and eleven kilometres northeast of Blenheim, in Marlborough, New Zealand. The 98.11 ha vineyard is part of the Nobilo expansion scheme, with the sea to the east and Rarangi Road to the west (Figure 3.1).

Figure 3.1 Location of Rarangi vineyard (pink polygon), Marshland and Tuamarina. Approximate scale: 1:55,000.
Source: Image cropped from the Topographic Map Sheet P28 downloaded from the Massey Image Web Server (NZCPA, 2002).

3.2 The climate and its implications for viticulture

An average of 800 mm of annual rainfall has been registered from 1904 to1985 at Marshland station (Fig. 3.1), the nearest (location shown in Figure 3.1) meteorological station with historical data (Rae *et al.*, 1987). Rainfall is almost evenly distributed throughout the year, with a maximum generally in May (85 mm) and a minimum during February (40 mm) (Rae *et al.*, 1987).

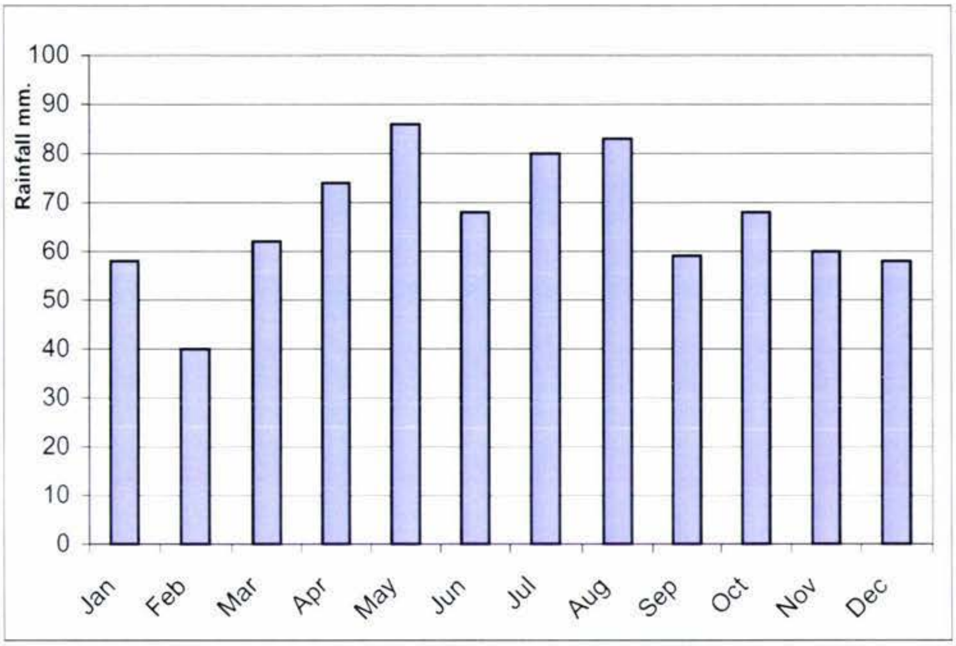


Figure 3.2 Monthly rainfall normal at Marshland Catchment Station.
Source: Adapted from Rae *et al.* (1987).

The rainfall variability is historically high in Blenheim and wet and dry periods occur. Rainfall is more variable in summer and less variable in winter. Rae *et al.* (1987), recognized as wet periods the years: 1913-15, 1929-33, and 1956-61 and as dry periods the years: 1950-53, 1973-81 and mild dry 1902-06, 1915-18, and 1927-29, although the exact connotation of those wet and dry periods was not specified.

The Wairau River and its tributaries place Blenheim and its surrounding areas at risk of floods. Ninety eight kilometres of stopbank have been built along the Wairau floodway and are maintained to prevent floodwaters breaking out on to the Wairau floodplain. A stopbank has also been built along the Pukaka drain, about 750 metres west of the vineyard. The chance of a "major flooding" is now estimated to be 1 in 100 years (Rae *et al.*, 1987), the last one occurring in July 1983 when the river broke out of the floodway stopbank. Moderate floods, with potential damage to farms, houses and property occur once every five years and the last one occurred in July 1998 (Marlborough District Council, 2000).

Percent annual probability of return periods of 2.33 up to 100 years for flood flow discharges of 2,005 up to 5,223 m^3/s respectively were estimated for the Wairau River at Tuamarina (underlined on the map in Figure 3.1), about 4 kilometres west of the vineyard (Table 3.1), (Rae *et al.*, 1987).

Table 3.1 Predicted estimates of flood flows for the Wairau at Tuamarina.

Return period (years)	% annual probability of occurrence	Peak discharge (m^3/s)
2.33	43	2,005
5	20	2,743
10	10	3,343
20	5	3,919
50	2	4,664
100	1	5,223

Source: Rae *et al.* (1987)

Blenheim has a high probability of dry spells occurring each year. If a dry spell is defined as 14 days or more with less than 1 mm of rain per day, Blenheim has 4.14 such dry spells per year on average. Drought occurrence is even more frequent during summer, so vineyards need to be irrigated at least in that period. Rainfall probabilities for Blenheim are shown in Table 3.2.

Table 3.2 Probabilities of monthly low rainfalls at Blenheim. Equal or lower rainfalls than values showed are expected with the correspondent probability.

% prob.	J	F	M	A	M	J	J	A	S	O	N	D	Annual
						Monthly mm							
Minim.	0	1	3	6	13	8	10	5	3	2	5	1	398
5	3	5	4	11	18	10	13	20	9	6	10	6	427
10	6	10	6	14	25	14	28	20	15	11	16	10	452
20	14	12	15	24	34	22	36	32	21	21	19	19	529
50	43	33	36	48	61	48	56	60	48	49	42	39	639
90	103	101	86	123	130	104	106	126	85	110	83	101	762
Maxim.	141	129	108	173	183	155	166	157	192	155	147	123	922

Source: Rae *et al.* (1987).

From the table, for example the probability in January of a rainfall of 103 mm or less is 90 % and there is 50% of probability of receiving less than 43 mm rain in the same month.

Mean annual temperature for Blenheim is 13 °C although it is also highly variable (Rae *et al.*, 1987). The summers are warm and the winters mild. Mean temperatures of about 7°C have been registered for the coldest month, July, and 18°C for the hottest month, January. Extreme temperatures of 44°C and -10°C have been reported (Figure 3.3).

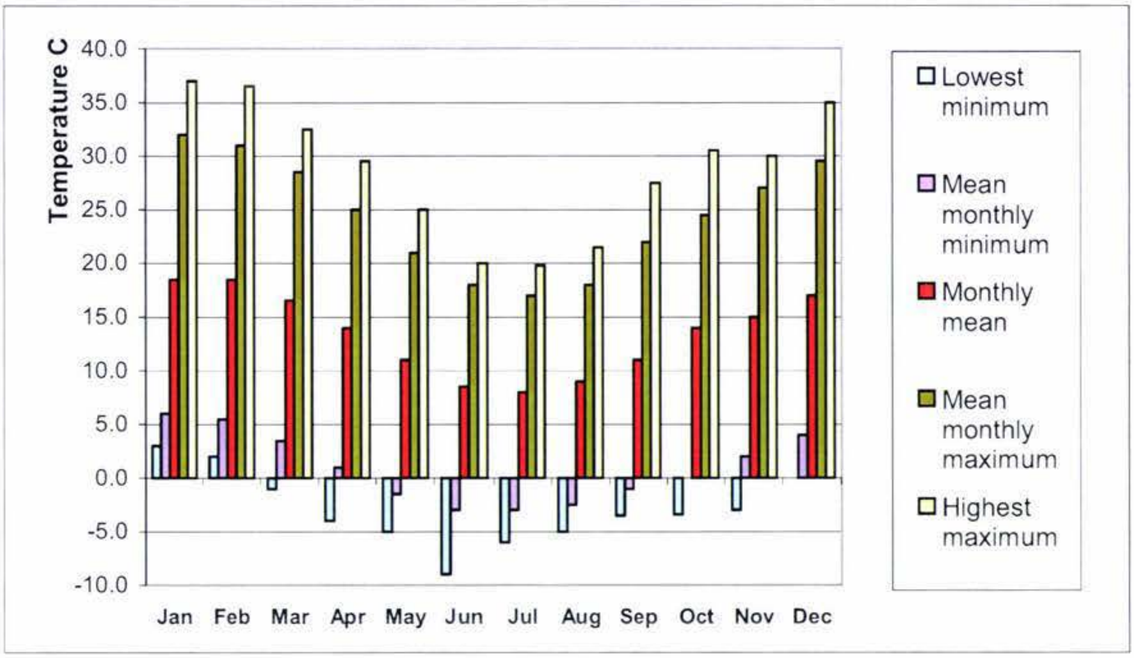


Figure 3.3 Monthly mean, lowest and maximum temperatures at Blenheim station. Source: adapted from Rae *et al.* (1987).

Growing degree days (GDD) is a parameter that has a direct relevance to viticulture production. An average of 1282 annual GDD (air temperature) occurs at Blenhiem when 10°C is taken as the base temperature (Rae *et al.*, 1987). Ten degrees is taken as the base temperature since it is the most common "vegetative zero" used for grapevines (Tesic, 2001). According to this average of GDD, the most suitable cultivars for New Zealand are those that require the least heat accumulation. This was deducted from definitions given by Amerine & Winkler (1944).

Another approach to further separate the heat accumulation requirements of the cool winegrape cultivars was reported by Jackson & Cherry (1988) who defined the Latitude-Temperature Index (LTI) as:

$$LTI = MTWM * (60 - latitude)$$

where MTWM = the mean temperature of the warmest month.

Applying this equation, the LTI for the different main grape growing regions was estimated (Table 3.3). LTI for Blenheim is 342, which places it in the group IC (cultivars were grouped according to heat requirements by Jackson & Cherry, 1988). Some varieties that potentially reach their best qualities in this region are, Cabernet Sauvignon, Merlot, Sauvignon Blanc and Semillon.

Table 3.3 Latitude-Temperature Index (LTI) estimated for main New Zealand grape growing regions and localities.

Region	LTI*	Group
Auckland	453	II
Blenheim	342	IC
Christchurch	280.8	IC
Haws Bay	384	II
Napier	388.1	II
Nelson	320.1	IC

* LTI and cultivars groups are explained by Jackson & Cherry (1988) as the mean temperature of the warmest month multiplied by 60 – latitude.

Blenheim is susceptible to frosts. The dates of first and last air frosts and of the air frost season are the main climatic factors affecting viticulture production. The average length of the air frost-free season at Blenheim is 233 days. The average number of days of ground and air frost by month is shown in Table 3.4.

Table 3.4 Average numbers of days of ground and air frost at Blenheim. Bold numbers indicate possibility of damage to vines.

Frost	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Ground	0.1	0.1	0.8	**3.2**	9.9	17.1	18.3	14.6	**10.3**	**4.3**	1.1	0.4	80.7
Air	0.0	0.0	0.1	**0.2**	2.4	9.4	10.9	6.5	**2.1**	**0.4**	0.1	0.0	32.0

Source: adapted from Rae *et al.* (1987).

There is a slight to moderate risk of having either an early (late March) or a late frost (mid- September) that coincides with harvest and bud burst season respectively, causing damage to the crop. For example, the chance of having a frost by the 24th April is 0.10, while the chance of not having a late frost later than the 25th of September is 0.5. The average dates for the first and last frost at Blenheim are 14th May and 22nd September (Table 3.5).

Table 3.5 Probabilities of frost occurrence, date of first and last frost, and duration of frost-free season at Blenheim (1947-1975).

	Probabilities							
	Min.	0.1	0.25	0.5	0.75	0.9	Max.	Mean
Date of first air frost	28/3	24/4	4/5	12/5	24/5	15/6	15/6	14/5
Date of last air frost	20/8	26/8	4/9	25/9	8/10	18/10	1/11	22/9
Air frost-free season*	158	180	219	234	256	281	292	233

*** Air frost-free season was measured in days.**
Source: adapted from Rae *et al.* (1987).

The surface wind is predominantly westerly or easterly, with prevailing speed between 6 and 19 km/hr (Figure 3.4). Sea breezes are the most frequent wind events near the Bay (Rae *et al.*, 1987).

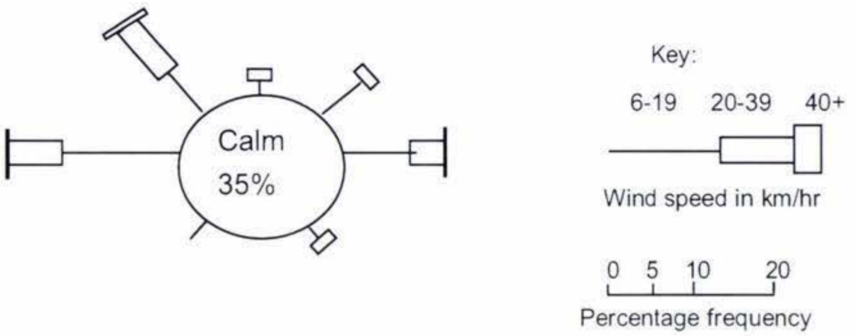


Figure 3.4 Frequencies of surface winds at Blenheim.
Source: Adapted from Rae *et al.* (1987).

Annual sunshine-hours recorded at Blenheim are 2,414, 564 of which are received during autumn (March, April and May) and 492 during winter (June, July and August) (Rae *et al.*, 1987). This high sunshine is favourable for viticulture development (Coombe & Dry, 1988).

The meteorological data collected in Rarangi vineyard since the year 2001 (Tim Laverack, October 2, 2003, personal communication) are within the ranges presented above.

3.3 Geology and Landscape

The sequence of glacial and interglacial periods, tectonic activity and erosion processes have played a fundamental role in shaping the landscape of the Wairau catchment. The material forming the different geological formations in the Wairau catchment determines the existence of aquifers and provides the parent material that influence soil characteristics.

A series of northwesterly faults determines the existence of terraces in that direction within the catchment. The majority of rocks found south of the Wairau fault are from the Triassic and Jurassic epochs (230 to 160 million years) of the Mesozoic era, and consist of greywacke (sandstone, formed from sand and coarser sediments) and argillite (mudstone formed from finer sediments) (Rae *et al.*, 1987).

It was during the last 2 million years that the valleys began to take the present shape. The flood plains of the Wairau River are made up from alluvial deposits that were laid down and reworked during the Quaternary period.

The sea level during the last glacial event was about 180 m below the present sea level, and the coastline was probably 40km off the present day coastline (Rae *et al.*, 1987).

Massive amounts of eroded material were carried seawards and at the downstream limit of the glacial advance, it was either dumped forming glacial moraine, or carried on downstream by the rivers and deposited to form terrace gravels. During interglacial times, sea levels rose and rivers re-deposited glacial outwash material nearer the coast.

The accumulated glacial outwash deposits within the valley formed a surface and are referred to as a glacial outwash formation. So each glacial event has an outwash formation associated with it. In the uplifted part of the catchment, the glacial outwash gravels are preserved as flights of terraces. While in subsiding areas near and beyond the coast the gravels are stacked one on top of the other, and inter-finger with finer grained marine sediments that were deposited during interglacial high sea level periods.

During the cold climate periods, the Wairau River received alluvial gravel carried by melt water from the glaciers. During the warmer interglacial periods, the Wairau River took material deposited upstream and redeposited gravel, sand and silt towards the coast. The plain surface of today is formed from reworked outwash gravels deposited on top of the glacial outwash deposits about 14,000 years ago (Speargrass Formation). The reworking process cleaned the original outwash deposits. A material more permeable than its parent outwash material resulted.

In the Rarangi Vineyard area, the surface of Speargrass Formation is about 40 metres below sea level (Rae *et al.*, 1987), and is buried underneath the Rapaura (Aranuian postglacial fluvial) and Dillons Point (Aranuian postglacial marine) formations. The Speargrass Formation has more clay and silt, and is less permeable than the overlying Formations. Rapaura Formation consists of very permeable gravels deposited and reworked from 6,000 to 14,000 years ago, during the Holocene rise in sea level.

From 6000 years ago to the present, the Rapaura and Speargrass Formations became buried beneath deposits of marine sand, silt and clay, including shells and peat, lagoon and estuarine mud, dune and swamp deposits and beach gravels. The accumulation of that material occurred during the coastal progradation once sea level had stabilized, about 6,000 years ago. All these deposits have been grouped together as the Dillons Point Formation (Begg & Johnston, 2000 and Rae *et al.*, 1987).

Since then, a series of earthquakes have affected postglacial deposits. Subsidence of 1.5 and 0.45 metres respectively of the Cloudy Bay coastline occurred after the 1848 and 1855 earthquakes. It was suggested that these subsidences were caused by earthquake compaction of the water saturated sand, silt and clay sediments (Rae *et al.*, 1987).

The geology of the area under study was mapped by Begg & Johnston (2000), mostly as Fan Deposits (Q1b) and also Alluvial Deposits (Q1a) in the western part. The Fan Deposits consists of estuarine and Holocene marginal marine deposits of poorly sorted gravels. The Alluvial Deposits consists of well sorted floodplain gravels.

At Rarangi Vineyard, a sequence of ancient gravel beach ridges with hollows between them, trending north-south and parallel to the coast, form the gently rolling to flat morphology of the land. On the eastern seaward side of the property, these ridges and hollows are narrower than on the western inland side of the vineyard.

3.4 Hydrogeology

The sequence of different permeable materials has formed two aquifers in the area. A shallow sandy aquifer named Rarangi Shallow Aquifer extends to a depth of 10 m below ground level at the Wairau Mouth (Marlborough District Council, 2003). Underlying that aquifer, there is the confined lower Wairau Aquifer with probably less risk from seawater intrusion since it was thought to be separated from the sea, although some doubts have recently been expressed (Marlborough District Council, 2003). Electrical conductivities are also being monitored for the Wairau Aquifer at the Wairau diversion mouth. Values since 2000 have been around 40.0 mS/m (The Ministry of Health's drinking water limit is 118 mS/m, Marlborough District Council, 2003).

The height of Rarangi Shallow Aquifer above sea level is being monitored for a well at Rarangi Golf Club, located approximately 2.5 kms. north-north-east of the vineyard site, by the Marlborough District Council (Figure 3.5).

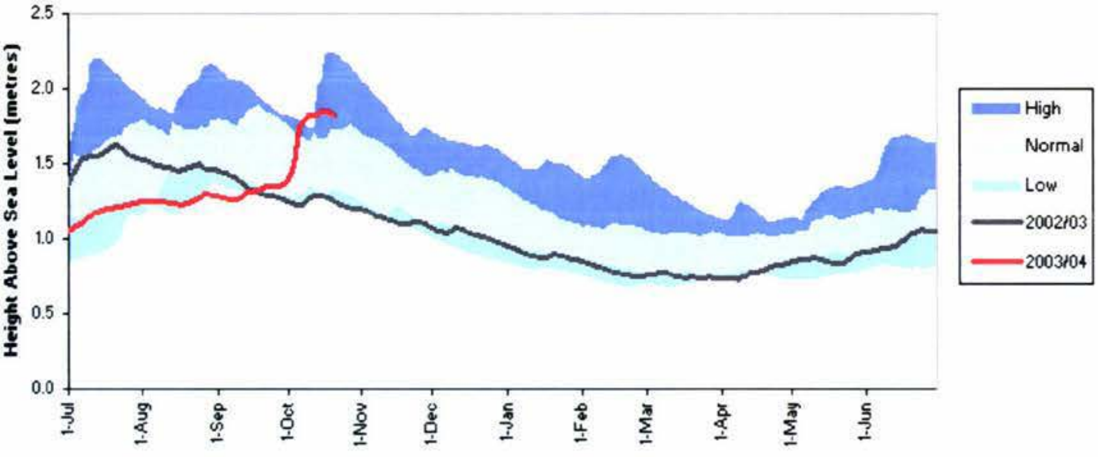


Figure 3.5 The height of Rarangi Shallow Aquifer above sea level at Golf Club well #1901. High, normal and low values were calculated from data since 1989.
Source: Marlborough District Council, 2003.

The level of the Rarangi Shallow Aquifer normally varies by 0.5 to 1 metre in any year. The lowest normal levels of about 1m above sea level at the Golf Club (Figure 3.5) are measured in April and May, while the highest levels of about 1.5 m above sea level are measured in September and October.

The conductivity of the Rarangi Shallow Aquifer water (measured in a well around 1500 m south of the vineyard) rises from about 20 mS/m at times of lower groundwater levels to about 40 mS/m at times of higher groundwater levels. The Marlborough District Council (2002) suggest that this is due to salt and sea spray leaching down to the aquifer during rainfall and storm events, while in drier seasons, the groundwater moves further below the gravel surface and the conductivity levels are reduced with the flow of fresh water. They have concluded that the conductivity fluctuations are responding to saltwater sea spray from above rather than to invasion of the aquifer by the nearby seawater.

Monitoring of the chemistry comparing the Wairau and Rarangi Aquifers (Marlborough District Council, 2002), revealed higher levels of calcium and bicarbonate in the Rarangi Shallow Aquifer.

Marlborough District Council is monitoring the Wairau Aquifer for elevated levels of Cl and Na. High conductivity was detected north of the Wairau diversion and seawater intrusion of the Aquifer was suspected (Close, 2001). Chemical analyses of samples taken from a well in the studied vineyard from 1999 and 2000 showed higher values of alkalinity, conductivity, Cl, Na, K and Mg (Table 3.6) when compared to samples from other wells in the Wairau Confined Aquifer.

Table 3.6 Water chemistry data from Wairau Confined Aquifer from a well in the studied vineyard.

Well	Date	pH	Alkal. (mg/l HCO_3)	Cond. @ 25° (mS/m)	Cl	NO_3N	SO_4	Na (mg/l)	K	Ca	Mg	Fe	Mn
3439*	07/98	7.7	144	73	140	0.03		110	12	12	9.3	0.22	0.05
3439	05/00	7.9	140	67	130	0.05	0.2	99	9.9	10	8.2	0.28	0.04

*Well 3439 is in the Rarangi vineyard, grid reference 2594292/5975274 easting/northing.
Source: adapted from Close (2001).

Conductivity values can be compared to indicative criteria of 115 mS/m which corresponds to the New Zealand Drinking Water Aesthethic Guideline (mentioned in Close, 2001). It was suggested (Close, 2001) that a coastal management zone should be set up including wells with elevated conductivity (> 25 mS/m) to ensure that water quality is not significantly changing. A suggested trigger level for Cl was 250 mg/l, as the standard level for drinking water. At this level, there is not considered to be a health risk, but the taste of the water is deemed to be undesirable and action should be taken. Moreover, an increase on the levels should be of concern rather than waiting until the limit value is reached, when it could be too late.

The water used for irrigation at the studied vineyard comes from the Wairau Confined Aquifer, through a well 30 metres deep. The depth of the monitored well 3439 is not specified in the report, but depths of other wells in the same Aquifer are from 11 to 48 metres (Close, 2001). The risk of drawing poor quality water by pumping was considered low.

> " ......more permeable zones of the aquifer, which are likely to contain better quality water than lower permeability poorly flushed zones. As a result, no special management restrictions are proposed to deal with this issue" (Marlborough District Council, 2002, page 14).

However, as specified by the Marlborough District Council (2002), users of the water of the Wairau Aquifer should be aware of the existing risk.

3.4 The soil pattern and implications for growing vines

The soils present in the region have been mapped at a scale of 1:253,440 (DSIR Soil Bureau, 1968) as theTaumutu Soil Set. These are recent alluvial soils, mainly formed from sandy and silty material eroded from the catchment and deposited in layers during flood events. The soils were classified in the old NZ system as yellow brown sands (Regosols), but this is most likely an error, because of scale limitations of the map. The ridges at Rarangi Vineyard are marine beach ridges composed of gravels rather than sand dunes implied by the yellow-brown sand classification.

A more detailed survey has been made by Keith Vincent to a scale of 1:5,000. This soil map (Vincent, 1999) was scanned and rectified and is shown in the Results section (Figure 6.1). A summary of the soil characteristics found by Vincent is given below.

In general the topsoil horizons are shallow sandy loams to depths of around 0.18 metres, sometimes mixed with gravels, that overlie fine gravel (3-6 millimetres in diameter), occurring in layers of different thickness. Following is a typical description of the soils "over much of the site" (Vincent, 1999):

0 - 0.11 m	moderately permeable, very dark brown sandy loam;
0.11 - 0.18 m	rapidly permeable, dark brown fine gravelly sandy loam;
0.18 – 0.33 m	very rapidly permeable, very dark greyish brown sandy fine gravel;
0.33 – 1.2 m	very permeable, very dark greyish brown fine gravel, with layers of sandy gravel.

The exceptions that Vincent (*op cit.*) mentioned were the coarse gravelly soils found on the easternmost narrow ridge and the deep sandy soils found in the hollow in the northern part of the property (Fig. 5.1).

Vincent (*op cit.*) also estimated soil total available water contents (TAWC) to 1.2 m depth. For the most typical soils (with fine earth to 0.45 m deep), the TAWC ranged from 43 to 83 mm, while for the deepest soils (fine earth to 0.9 m deep) the estimation was approximately 100 mm.

Soils on the ridges have weathered (brownish) colours, do not have evidence of periodic soil wetness to 1.2 m depth and were considered to have somewhat excessive drainage. In the hollows, the gravels are generally grey and have mottling, indicating periods of waterlogging due to temporary rises in the local level of the groundwater. The depth of waterlogging was found to be variable, and the drainage was considered to be from moderate to poor (Vincent, *op cit.*). However, artificial drainage was not considered feasible because the subsoils are already very permeable and the groundwater is thought (Vincent, 1999, *op cit.*) to flow at a rate that keeps the water aerated.

Most of the subsoils were described by Vincent (*op cit.*) as very gravelly and permeable, with the exception of the deep soils in the northern part of the property where the sandy subsoils are only slowly permeable and strongly gleyed.

The soils are considered suitable for vine production under irrigation (Sutherland, 1999). The extremely high permeability of these soils, combined with high evapotranspiration rates and low rainfall, means that irrigation water requirements are higher than for vines on other parts of the Wairau Plains.

3.5 Summary

Climatic conditions of the area are in general favorable for the best quality winegrape production; although in some years problems might occur. High annual sunshine-hours (2,414), cool climate during the hottest month (average 18°C in January), cool nights and limited rainfall (800mm/year) are the main climatic characteristics of the area. However, the conditions are quite variable among years and both floods and droughts may occur in Blenheim. Also there is a risk of having late frost (middle to end of September) that coincides with the vine burst period, causing damage to the crop.

Soil characteristics of the vineyard present some advantages and some disadvantages. The free-draining, alluvial loams with gravelly and stony subsoils described in the vineyard provide optimal conditions of vines to grow premium quality grapes. The low fertility of these soils, avoided for many other horticultural crops, is thought to be an advantage for grapevine production. Due to both the relatively low rainfall and somewhat excessive drainage characteristic of the soils, irrigation is a must in the studied vineyard. A possible limitation is the waterlogging due to fluctuations in water table depth in the hollows. However, according to Vincent (1999), it is unlikely that anaerobic conditions will be found at depth because groundwater flow is at a rate that keeps it aerated.

CHAPTER 4

Soil electro-conductivity and topographic assessment

4.1 Introduction

As was pointed out in the Chapter 2, studying the variability of soil electrical conductivity can be an easy and more accurate way of assessing the distribution of some important physical soil properties such as soil textural boundaries (Pitcher-Campbell, 2002, Hedley et al., 2001, Banton et al., 1997; Williams & Hoey, 1987; Morgan et al., 2000; Doolittle et al., 2002; Hartsock et al., 2000; Sudduth et al., 1998 Bramley, 2001) and soil water content (Kachanoski et al., 1988; Hedley et al., 2003). Chemical properties like Ca++ and Mg++, concentrations and cation exchange capacity have also been found to be related to soil electrical conductivity (Hartsock et al., 2000; McBride et al., 1990). Changes in the land topography have an influence on soil properties (Jenny, 1941) and soil EC_a (Clay et al., 2001). Mapping the soil EC_a variability in order to correlate the data with soil characteristics is of both scientific and commercial interest.

The survey described in this chapter had the aim of mapping the EC_a variability and landscape features of Nobilo's vineyard at Rarangi. Specific objectives were:

1) to collect detailed topographic and electromagnetic data of the 90 ha vineyard using the EM38 and RTK-DGPS.

2) to compare soil EC_a readings at two different seasons in the year, with dry soil conditions (beginning of March) against wetter conditions (end of September).

4.2 Materials

The core equipment and software packages to complete the soil electro conductivity survey and topographic assessment in the field are described and explained in this section.

4.2.1 RTK DGPS receiver and field computer system

Two portable Trimble AgGPS 214 receivers manufactured by Trimble Navigations were used to locate the coordinates of observation sites: one worked as a base station and the other as a rover unit. A GPS dual-frequency antenna on the base station transmitted radio data ensuring high accuracy GPS corrections directly to the rover unit. Two TRIMCOMM™ 900 radios were used to link the data, one in the base station and the other in the rover unit. The field computer was a Trimble AgGPS 170. The rover receiver and the field computer were mounted on an ATV. These implements are shown in Figure 4.1.

Figure 4.1 Rover radio, Antenna, AgGPS 170 Field Computer and AgGPS 214 receiver.
Source: Trimble (2003c).

The *Ag*GPS 214 is a centimetre accurate real-time kinematic (RTK) DGPS receiver designed for extremely high accuracy agriculture field guidance and topographic field mapping. In order to obtain optimum accuracy, the mobile vehicle-based receivers must be within the range of 10 kilometres (6 miles) from the base station. This range limitation is independent of the range limitations of the line-of-sight transmissions of the TRIMCOMM 900 radios. A radio repeater would be needed if the rover *Ag*GPS 214 is operating out of line-of-sight of the base station and the rover cannot receive the direct base station corrections (Trimble, 2003c).

TRIMCOMM 900M transmits data in a format called Compact Measurement Record (CMR), which is a more compact and robust way than other formats, making data transmission to the roving receivers more reliable (Trimble, 2003c).

The 2-line 16-character screen display of the *Ag*GPS 214 shows all the status information of the GPS receiver (position, altitude, speed, heading, PDOP, HDOP, VDOP, satellites used, position mode, differential RTK status, and status information of the received base station data (Trimble, 2003c).

The Field Computer automatically records a variety of items such as detailed elevation data. It can perform area calculations and is helpful for a range of agricultural operations such as guidance, record-keeping, logging, variable rate soil sampling and field mapping. Its interface to external sensors makes it possible to receive data from an EM38, which output ASCII data.

4.2.2 Electromagnetic sensor (EM38) and vehicle

The electromagnetic sensor used was the EM38 (Figure 4.2) manufactured by Geonics Limited (Mississuaga, Ontario, Canada). The EM38 is one-metre long and very lightweight. Operating at a frequency of 13.2 kHz, it contains calibration controls and a digital readout of EC_a data in millisiemens per metre (mS/m).

Figure 4.2 Non-contact EM38 sensor used to measure soil electrical conductivity. Source: USDA-ARS Photo Gallery.

The EM38 was mounted in a protective case on a rubber mat that was towed by a four wheel all terrain vehicle (ATV) (Figure 4.3).

4.2.3 Geographic Information Systems (GIS)

- ArcView 3.2. & ArcGIS

Both the ArcView and ArcGIS software were developed by the Environmental Systems Resource Institute (ESRI). They are window-based mapping and GIS software. They are both used for the management, display, query, and analysis of spatial information. It is possible to link other data tools such as databases with maps for a completely integrated analysis system (ESRI, 2000; Minami *et al.*, 1999).

The Spatial Analyst extension for ArcView was widely used in this work to: create, query, map and analyse raster data; perform integrated raster/vector analyses; derive new data tables from existing data; query information across multiple data layers; and integrate cell-based raster data with other vector data sources (*i.e.* databases).

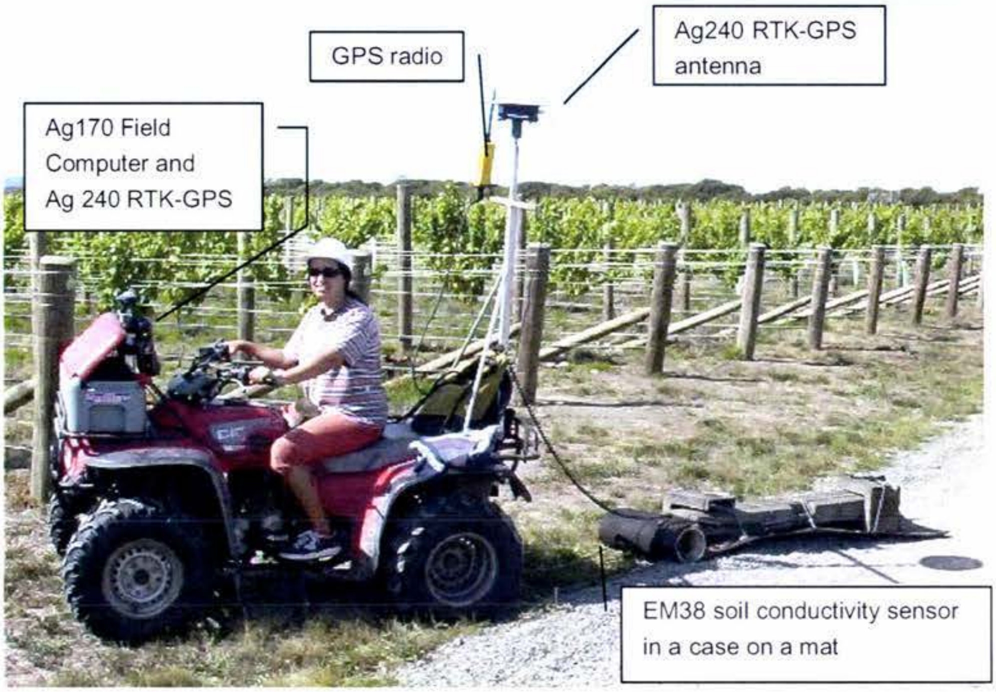


Figure 4.3 RTK-DGPS receiver and EM38 pulled behind an ATV.

- Idrisi Kilimanjaro

Idrisi is a non-profit project developed by Clark Labs, a research centre at Clark University (Clark Labs, 2003). It is a geographic modeling technology that enables and supports environmental decision making. It combines raster and digital image processing modules, allows for multiple data formats to be imported and exported, contains powerful analytical tools, geostatistical operations and is easy to use.

4.2.4 Vesper 1.0

VESPER (Variogram Estimation and Spatial Prediction with Error) is a PC-Windows spatial prediction software, developed by the Australian Centre for Precision Agriculture (ACPA). It allows for spatial prediction to produce a continuous surface map. Unsampled points are predicted and mapped using local variograms and kriging.

Kriging is one of the most common spatial prediction methods of interpolating point data in site-specific management (Plant, 2001). The procedure involves performing a search for the closest neighbourhood for each prediction site, estimating the variogram from the neighbourhood, fitting a variogram model to the data and predicting the value and its uncertainty. The local variogram is modelled in the programme by fitting a variogram model automatically through the nonlinear least-squares method, although several variogram models are available. Punctual and block kriging are available as interpolation options (Minasny, 1999).

4.2.4 Aerial photograph

An orthophoto at 2.5 m resolution corresponding to the lower left quadrant of Sheet P28 of the NZMS 260 series was downloaded from the Massey Image Web Server (NZCPA, 2002). This photo was registered and rectified to the NZMG system and opened into both ArcView and Idrisi.

4.3 Methodology

4.3.1 Topographic and Electromagnetic conductivity survey

Two electromagnetic conductivity soil surveys were made, one in March 2003 when soils had a lower water content, and one in September when the water content of the soils was higher. Data were collected in both vertical and horizontal dipole orientation (deep and shallow respectively) for the March survey, and in the vertical dipole orientation only in the September survey. At the same time height data were collected.

A base Ag240 RTK-GPS receiver and one of the radios were installed near the highest part of the farm (Figure 4.4). The roving data collection system consisted of an Ag240 RTK-GPS, with its antenna, a radio and the Field Computer mounted on an ATV. The EM38 sensor was mounted on a rubber sled to avoid any interference with metallic objects within 1 m of the sensor, and the sensor was suspended slightly above the ground surface (Figure 4.3). The wires from the grape support structure do not interfere with the EC readings (Mike Tuohy, personal communication, March 2003).

Figure 4.4 RTK-DGPS base station installed at the Rarangi Vineyard.

As the vineyard was already established, data were collected following the direction of the rows. Every fourth row was selected, which gave a swathe of less than 10 metres. The EC_a data and the coordinates (latitude, longitude, and height) was read and stored in the Ag170 Field Computer. The field computer recorded EC_a data at one-second intervals via a DL 720 Polycorder data logger. Driving at a speed of 4 to 5 km/h gave a distance of approximately 1.1 to 1.4 m between readings. All the data were saved and then transferred to the PC using a compact flash card as a comma delimited text file.

The Ag240 RTK-DGPS and Ag170 Field Computer system uses the World Geodetic System 1984 (WGS84) coordinate system, being the coordinates expressed as latitude and longitude and height as height above the ellipsoid.

4.3.2 Topographic maps

A digital elevation model (DEM), or elevation map was created from the text files containing the topographic data collected in the first field survey (March, 2003). To produce an accurate DEM, these data had to be prepared, projected in a convenient system, and then interpolated to finally display the elevation map.

- Data preparation

When less than 5 satellites are in the sight of the rover RTK DGPS, too few GPS satellite signals are available to calculate an accurate position. Similarly, if the differential correction value is greater than the specified maximum, a low accuracy measurement results. These data points were removed using a filter developed by staff of the NZ Centre for Precision Agriculture at Massey University.

The filtered files were opened in Microsoft Excel and all the irrelevant columns of data were also deleted so each file contained only latitude, longitude and height information.

Because the heights are relative data, measured above the ellipsoid, some negative values resulted. A value of 10 m was added to all the heights and positive values were obtained, but the absolute height was not established. The files were saved as a database (.dbf) file.

- Data projection

The data was converted from the World Geodetic System 1984 (WGS84) coordinate system to a local specific datum to make possible the display in ArcView with aerial photographs projected in the New Zealand map grid (NZMG). The coordinates, expressed in decimal degrees (latitude and longitude), were converted to metres (eastings and northings) to facilitate map interpretation.

The filtered and prepared files were opened in ArcMap, and the conversion into the NZMG projection system and metres coordinates were made using 'Transformation' and 'Add XY data' tools in ArcMap. The resulting database files were saved as .dbf and these attribute tables were exported to ArcView. An example of the .dbf file after the data transformation is shown in Appendix A and a point file resulting from displaying these in ArcView is exposed in Appendix B.

- Map interpolation

To display a continuous elevation map rather than a point map (as it was obtained from the readings), it was necessary to interpolate the data. Height values were estimated for the entire surface from the point values using a process called kriging. The interpolated estimate of $z(x,y)$ is calculated to minimize the variance over all estimates that are weighted means of nearby points. Under certain assumptions, it is the "best" estimate (Plant, 2001).

The database files were imported into Microsoft Excel. All the column headings were removed and the three columns (easting, northings and height) were formatted to three decimal places. The files were saved as comma delimited text files and imported into VESPER (Minasny, 1999) for interpolation.

An ordinary block kriging (10 m block) into a 2 m grid was performed as suggested in a previous work (Pitcher-Cambell, 2002). As a result, an ASCII text file with four columns (eastings, northings, height and variance) was obtained. These files were imported into Microsoft Access to add the headings (Microsoft Excel could not be used because the number of rows exceeded the limit for Excel).

- Map display

The .dbf files were imported into ArcView and converted to a grid using a 2 m output grid cell size. To take advantage of some Idrisi tools, the resulting maps were also exported as a binary raster file (.flt) and then imported into Idrisi using the 'ArcInfo Raster Exchange Format' option.

From the DEM the 'hill shade' was calculated and the graphical display of the relief was enhanced with the 'Compute Hillshade' option in ArcView. The hill shade map calculated for an azimuth of 315° and an altitude of 45° is displayed in Figure 4.5. The contours were derived from the DEM.

- Ridges and hollows

The local geomorphology of the farm is characterized by a series of ridges and hollows. Their spatial distribution was mapped in Idrisi, using the profile tool. Seven lines were drawn covering the whole map from east to west and saved as an Idrisi profile file (.ipf). The height was calculated along each of these seven lines and the data were exported to Microsoft Excel.

In Excel the data was plotted showing the heights in the Y axis and distance from the most western part of the farm along the X axis. Notes of the distances for all the inflection points were made. Back in Idrisi, the inflection points were localized on the different lines and polygons were digitized for each ridge. The polygon vector file was converted into a raster file and then overlaid with a mask file for the whole farm. The ridges and hollows sequence is presented together with the contours in Figure 4.6.

4.3.3 EC_a maps

The data were prepared, projected into an adequate format and interpolated. This was made following the same steps as described in Section 4.3.2, but this time keeping the EC_a data and not the height data. When preparing the data, the text files were opened in Microsoft Excel and all points without EC_a data were removed.

- Map display

The EC_a data displayed in ArcView in 2m grids was classified into 3 to 13 classes, testing for the best number of classes. In Idrisi the EC_a data was clustered also testing for a maximum of 3, 4 and 5 number of clusters. Combining both results, 5 and 4 classes were chosen for the vertical and horizontal dipole orientation respectively as the best depictions of the data. The resulting maps are exhibited and discussed in the Results section (Figures 4.8 to 4.10).

4.4 Results

A hill shade map calculated for an azimuth of 315 and an altitude of 45° (Figure 4.5) was produced so that the microtopography of the vineyard could be observed. The sequence of light and dark grays in the map shows the distribution of slopes facing east and west respectively.

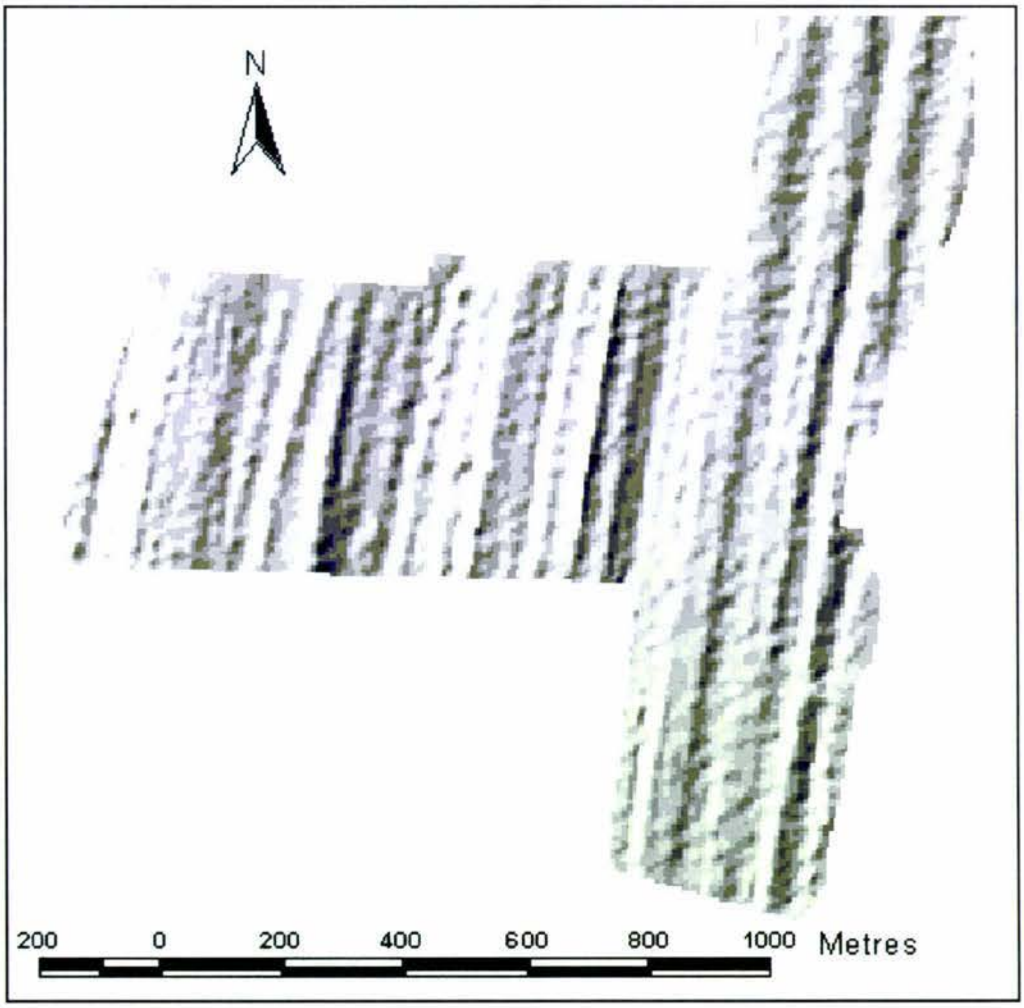


Figure 4.5 Hill shade map of the vineyard calculated for an azimuth of 315° and an altitude of45°.

A sequence of eight hollows and ridges south-north orientated is accurately mapped (Figure 4.6) from the elevation data obtained.

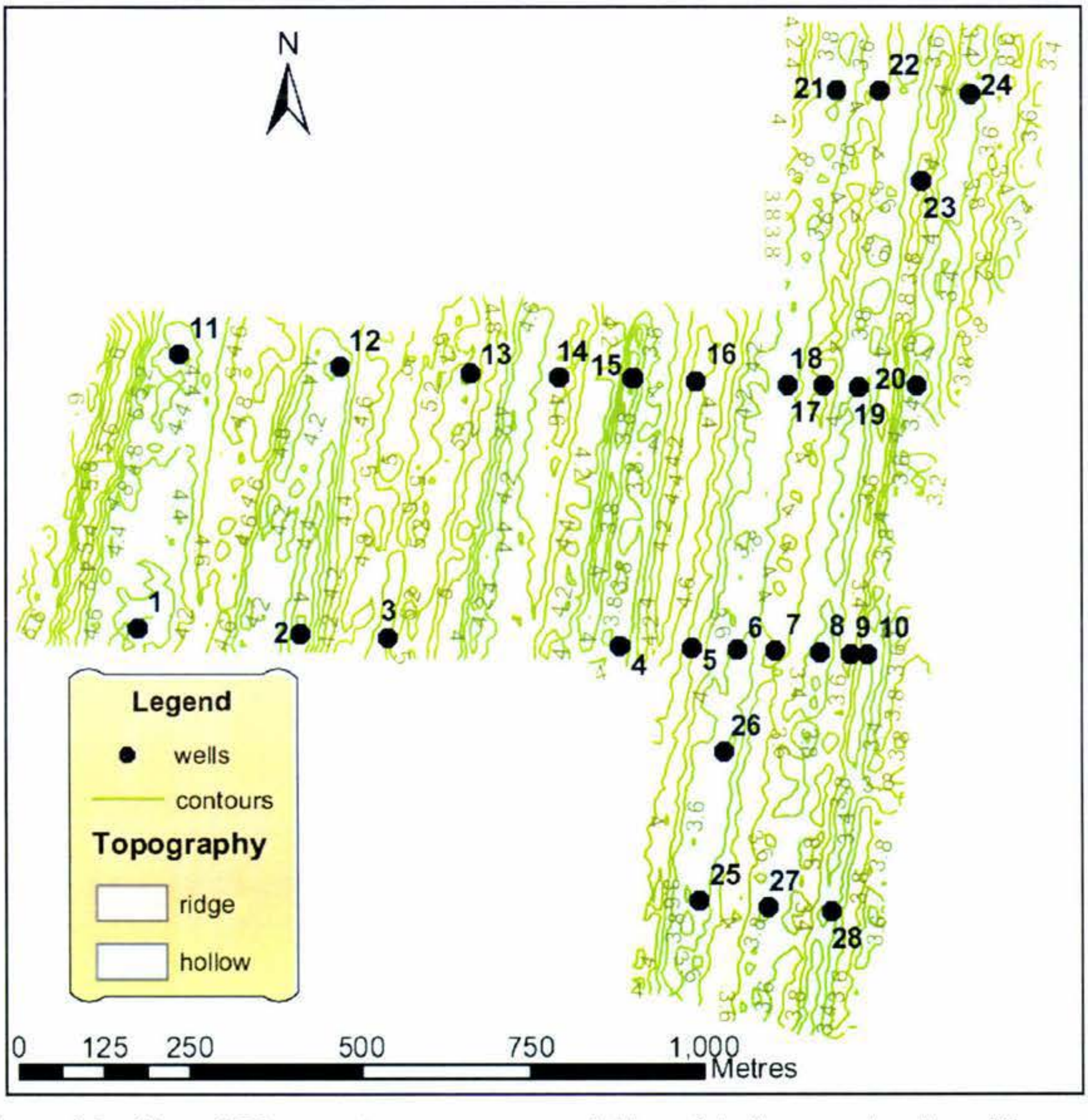


Figure 4.6 Map of 20cm contours, sequence of ridges & hollows, and well positions.

The elevation differs by 3 m from the lowest point in the eastern part of the vineyard to the highest point at the western part of the property. Slopes are very gentle, 79% of the area has slopes less than 1.5 %. Slopes between 1.5 and 3 % are in 19 % of the area, and only 2% of the area has slopes of any consequence (between 3 and 6 %). After analyzing the land morphology, it was possible to select sites for the installation of 28 wells to monitor the water table (positions displayed in Figure 4.6).

The microtopography of the vineyard can also be visualized in the photograph (Figure 4.7), taken looking from the most western ridge (the highest point) towards the east (the lowest point).

Figure 4.7 Photograph of the vineyard taken from the highest point in the west, looking east and showing the micro-topography (arrows are pointing at hollows).

Both soil EC_a surveys (March and September) show a reasonable range of data (20 mS/m for both the deep (vertical) EC_a surveys and 10 mS/m for the shallow (horizontal) EC_a survey made in March) that allow classification of the values into distinct classes (Figures 4.8-4.10). As it was explained in the methodology, this classification was made after performing an interpolation (with the kriging procedure) of the EC_a values to display a continuous map rather than a point map. For the vertical dipole orientation surveys made on both dates, the values were categorized in five classes and due to the more narrow range of the values in the horizontal dipole orientation, only four classes were produced. Note that the values for the classes made on each map are different.

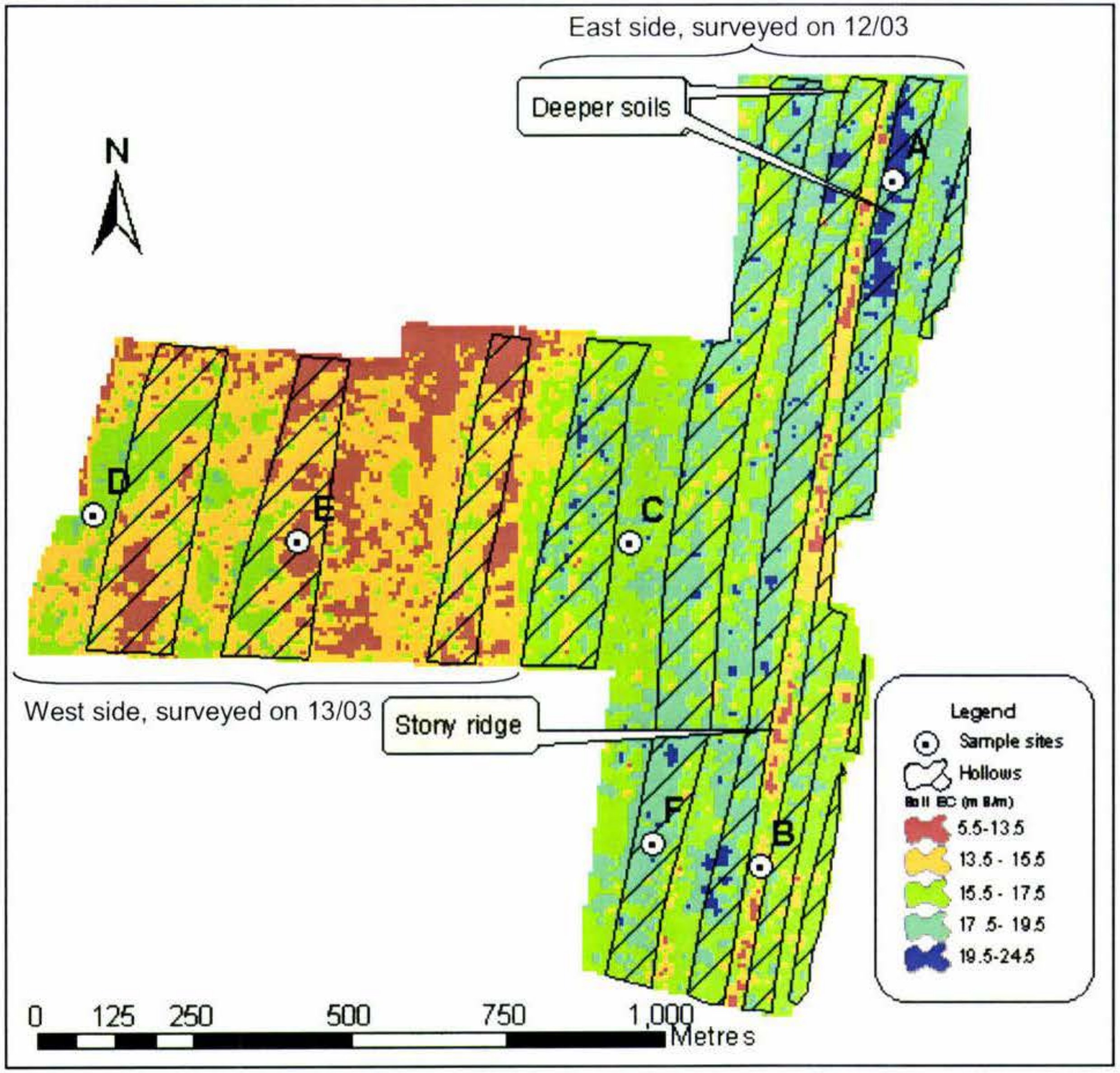


Figure 4.8 Kriged and classified deep electrical conductivity map for the Rarangi vineyard from the March 2003 survey.

Topographic hollow areas, and sites where physical properties were analysed are also shown.

Note: There was no aerial overlap for the surveys conducted on consecutive days.

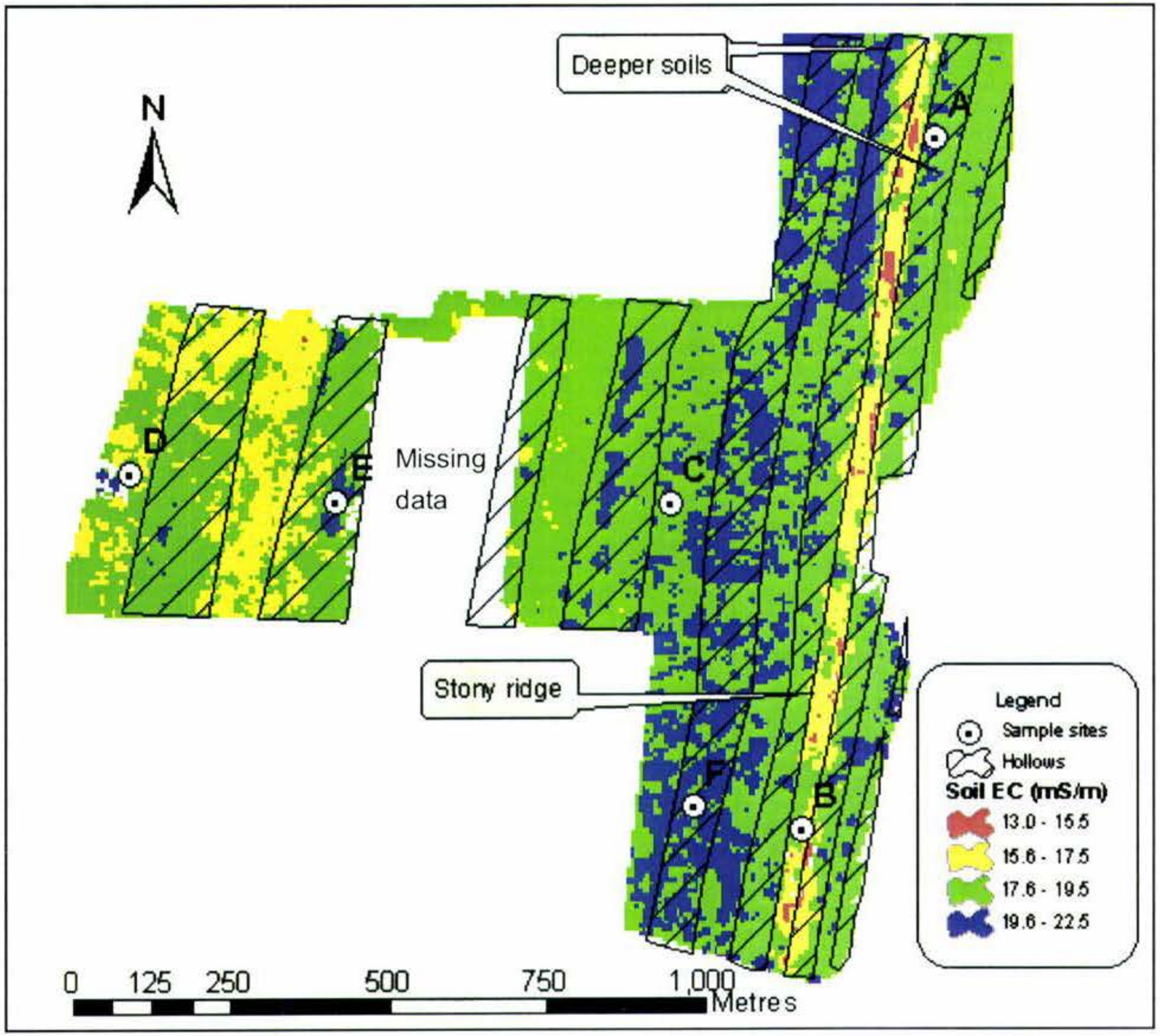


Figure 4.9 Kriged and classified shallow electrical conductivity map for the Rarangi vineyard from the March 2003 survey.

Topographic hollow areas, and sample sites are shown.

Note: The missing data was due to improper recording.

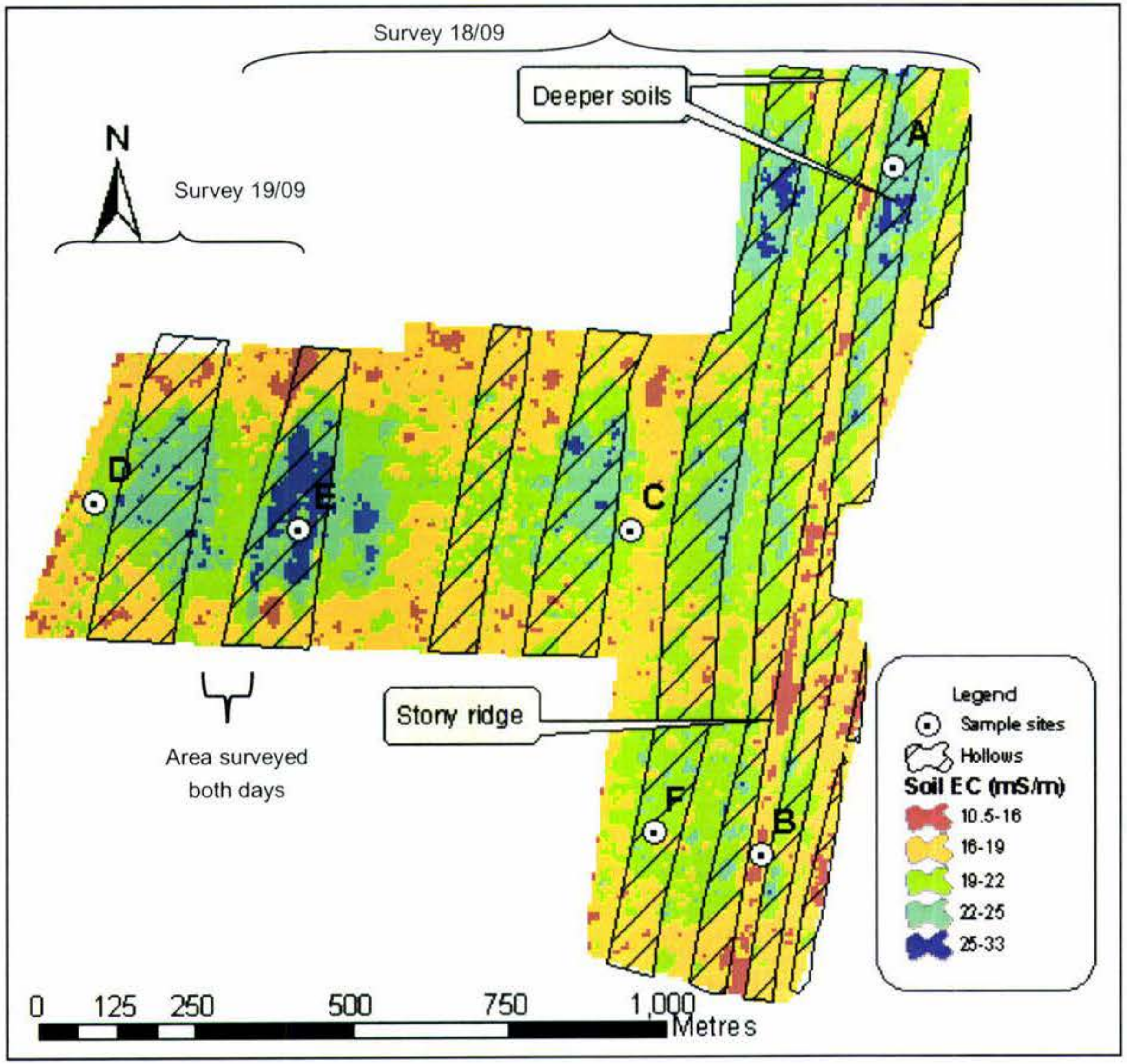


Figure 4.10 Kriged and classified deep electrical conductivity map for the Rarangi vineyard from the September 2003 survey.

Topographic hollow areas, and sample sites are also shown.

The areas, EC_a averages and standard deviation for each 'half' of the property surveyed two consecutive days in March (Figure 4.8), and in September (Figure 4.10) were calculated in ArcView (Table 4.1 and 4.2).

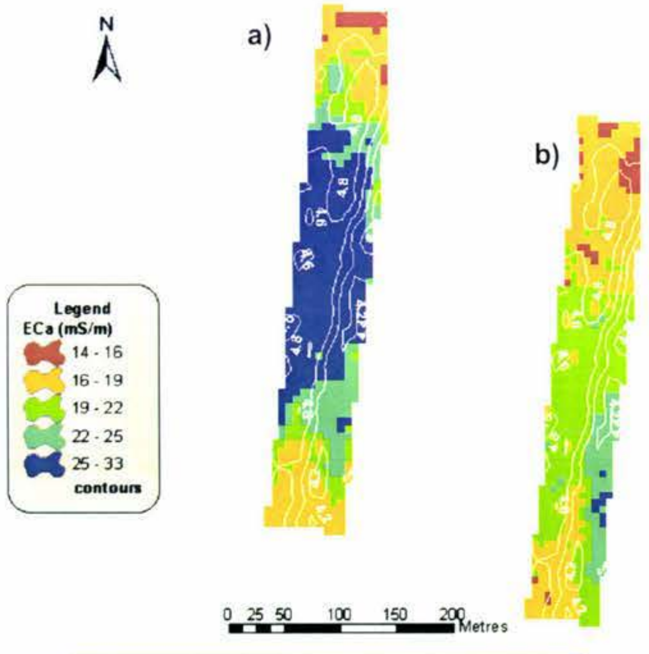
Table 4.1 Average deep soil EC_a data for the western and eastern part of the vineyard, surveyed on two consecutive days in March ("dry" conditions).

Half side	Survey day/month // time (hr)	Area (ha)	Average EC_a (mS/m)	St. dev.
West	12/03 // 15 to17:30	≈ 40	14.8	1.62
East	13/03 // 8 to 11	≈ 60	17.0	1.61

Table 4.2 Average deep soil EC_a data for the western and eastern part of the vineyard, surveyed on two consecutive days in September ("wet conditions").

Area	Survey day/month // time (hrs.)	Area (ha)	Average EC_a (mS/m)	St. dev.
West	18/09 // 12:00-15:45	≈ 86	19.4	2.58
East	19/09 // 10:00-10:40	≈ 15	19.3	2.85

In the September survey, six rows were measured over consecutive dates (Figure 4.11).



Date of survey	Average EC_a (mS/m)	St. dev.
a) 18/09	23.7	4.8
b) 19/09	19.4	2.2

Figure 4.11 Comparison of deep EC_a data of the same area measured on two different days, a) survey on the 18/09/2003 and b) survey on the 19/09/2003.

The northern and southern parts of the compared area (Figure 4.11) showed lower EC_a values (classes 14-16 and 16-19 mS/m), while higher values were measured for the central area on both dates. The difference between dates was in the absolute values obtained for the higher classes. Values as high as 25 to 32 mS/m were registered on 18th Sept. for the central area that had shown values from 19 to 22 mS/m on 19th Sept.

The deep survey made in September revealed an average higher EC_a value than for the survey in March (Figure 4.12 and Tables 4.1 and 4.2 in the discussion).

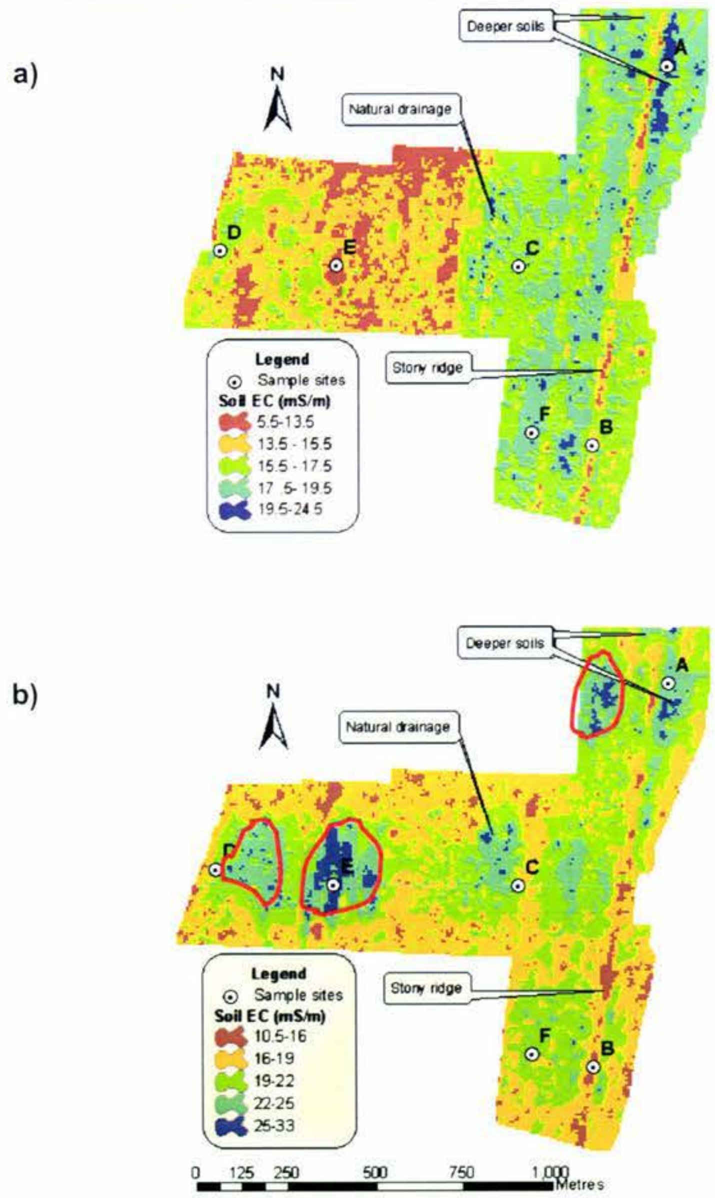


Figure 4.12 Comparison of the deep EC_a surveys made on a) March and b) September 2003 on the Rarangi Vineyard, and the sample sites for physical analysis.

Red circles show areas with high EC_a that did not appear in the March survey. Note that the soil EC scales ranges are different for the two surveys.

4.5 Discussion

Land morphology is recognized as being one of the most efficient environmental indicators needed to characterize the spatial distribution of soils; likewise soil identification is most efficient when it is based on landform characteristics (Park et al., 2001).

Ridges in the eastern part of the vineyard are more pronounced and narrow than in the west. One of these eastern ridges is very gravely from the topsoil, presenting coarse to very coarse gravels in the whole profile. Both deep and shallow surveys showed this eastern very gravely ridge ("stony ridge"), where some of the lowest EC_a values were mapped. In the western part of the property this association with the topography does not exist. Both maps also show high EC_a values on topographically lower areas, which probably correspond to the water content of the soils, because they are areas where the water naturally flows and accumulates. Medium-high values were also detected in both surveys along the hollows oriented north-south, between the natural drainage and the stony eastern ridge. Other soil characteristics, such as the depth to the water table, are associated with the morphology of land. Further discussion of these results in relation to soil characteristics is given in Chapters 5 and 6.

It is known that differences in deep and shallow EC_a allow a quick method for determining whether the topsoil is more or less conductive than material at depth. In that way the uniformity or not of the conductivity of the soil to a depth of about 1.5m can be assessed (Geonics Limited, 1999). Shallow EC_a variability differs in many areas from the deep EC_a variability. In general, the electro-conductivities measured from the shallow survey are slightly higher than the values obtained from the deep survey, which was expected due to finer texture of the topsoils.

When visually analysing the EC_a values for the March vertical survey (Figure 4.8), it became apparent that there is a division of the vineyard in two halves: lower values in the western half when compared to the eastern half of the vineyard. The division coincides with the boundary between the two consecutive dates of survey. The difference in the deep average EC_a data for the two halves of the vineyard was 2.2 mS/m (Table 4.1), which is higher than the range of 2 mS/m chosen for the classes for the data classification (Figure 4.8). The difference could correspond either to differences in the soil, groundwater levels, or to a drift of the readings from one day to the next. Analysing the three surveys at the same time, it seems apparent that the last explanation is the most likely. The sharp limit with higher EC_a values in the March vertical survey is not observed in either in the March horizontal survey or in the September survey. This suspicion is based on findings that ambient conditions and operational conditions can influence EM38 readings. In a study conducted to test the EM38 behaviour (Sudduth *et al.*, 2001), the stability of EM38 readings over time was quite variable and in some cases the instrument drift was as much as 3 mS/m per hour.

The shallow EC_a survey was made on the same day, from 11 to 17 hrs shows the same general trend of lower values in the western and higher in the eastern, but there was no apparent disparity between eastern and western sides of the vineyard (Figure 4.9), which support the hypothesis that from one day to the other some drift occurred. A proposed approach to drift compensation was made by Sudduth *et al.* (2001) and depended on the establishment of a calibration transect. EC_a values along this transect should be read several times during the course of a field survey so that the readings can be compared.

A similar approach to the one proposed by Sudduth *et al.*, (2001) for drift compensation was applied on the September survey to discard or confirm drift as a problem affecting the readings. Measurements for six rows were overlapped, and although the average for both dates is the same (Table 4.2), the highest EC_a classes between both dates differ by 6 mS/m (Figure 4.11). In this case, drift was observed only for the highest values, which provides more evidence of drift between values measured on two different days. No logical explanation was found for such results. Rainfall of 12 mm was registered on the evening of the 18th following the survey. The previous rainfall had been 10 mm on the 16th. If the soils were wetter after the rainfall, higher EC_a values not lower, would be expected on the 19th. Average temperatures were the same on both dates (12.5°C). Operation conditions, such as the proximity of the sensor to the soil surface, were the same on both dates.

Nonetheless, the distribution of higher and lower values was the same on both dates. Because it is the variability of EC_a values rather than the absolute values that are important, an interpretation of the data in terms of soil variability is possible and is discussed in Chapters 5 and 6.

The higher EC_a values obtained in September (Figure 4.12) were expected since the water table had risen (more details are given in chapter 5) and the soil water content was probably higher than in March, although they were not measured. Previous research in New Zealand showed correlation between soil moisture content and EC_a values (Hedley *et al.*, 2002).

The very gravelly eastern ridge, referred to as the stony ridge, has very low values in both seasons. The natural drainage (a depression in the topography, with relatively low heights) as well as the deep soils in the northern part of the vineyard had high values on both dates. However, distinctive regions (shown on Figure 4.12 b with red circles) had low EC_a values in the March survey and high values (up to 10 units higher) in the September survey. Possible explanations based on examinations of soil properties are given in Chapter 6. Another difference observed between Figures 4.12 a and b is that, while the values in the eastern half of the March survey appear to reflect the ridges-hollows pattern, this was not repeated as clearly on the same area in the September survey. This is probably because of the presence of high water tables that strongly influence on the EC_a values, overlapping other factors.

4.5 Summary

The topographic survey of the property mapped eight hollows and ridges, allowing for further interpretation of the EC_a surveys. The EC_a range for the deep EC_a surveys was of 20 mS/m; large enough to classify the values into five classes, and the range for the shallow EC_a survey was of 10 mS/m, large enough to classify the values into four classes.

Shallow EC_a values were slightly higher than deep EC_a values in the March survey, which may be attributed to the topsoils of most soils being finer textured and more conductive than the more gravelly subsoils. Some differences were found in EC_a variability between the surveys made in different seasons. Higher values were measured in September than in both surveys in March, which is probably due to either higher soil water contents and/or a rise in the water table. On the other hand, all three EC_a surveys revealed a strip of lower values in the eastern part of the vineyard corresponding to a particularly stony ridge. Regions with high EC_a readings were found on the three surveys in the northern and lower areas of the vineyard.

Data from the deep EC_a survey made in March showed an apparent separation of the vineyard into eastern and western halves. The division coincided with the two different days of the survey, and this seems be the reason for the differences on the EC_a values, because the difference was not repeated in September when readings over most of the vineyard were done on the same day.

In order to either discard or prove and compensate for the existence of drift errors, in the September survey, an area was measured on both days of survey. Differences of about 6mS/m in the highest classes of EC_a values were measured for the same area on the two consecutive days. Lower values were obtained on the second day, after 12 mm of rainfall, when, if anything, higher values might have been expected. Besides drift, no explanation was found for such differences.

For future trials, it is suggested EC_a values be read along a transect several times during the course of a field survey, so that any drift can be documented and compensated for. It is also suggested that detailed sampling of soil moisture be done, particularly between surveys, or if rain falls during a survey.

CHAPTER 5

Soil characteristics and water table assessment

5.1 Introduction

Geology and soil characteristics influence wine quality and accordingly the best management practices needed to achieve better grape quality. Physical soil properties determine quality through the effects of, for example, drainage, soil temperature, soil depth, waterlogging, water availability, penetrability and stone percentage (Gladstones, 1999). Chemical soil properties such as pH, nutrient availability, salinity and sodicity, although in some instances easier to control, also affect grape quality.

A soil survey of the property had already been made by Vincent (1999). All the data generated in that survey was digitised in this project in order to make the analysis easier and to allow the overlay with the EC_a maps produced in this project. A further survey of the area was carried out, digging six pits for soil descriptions and physical analysis, and also installing 28 wells for water table monitoring and profile descriptions. Chemical analysis was made for the first 20 cm (except for site F where the topsoil is 15 cm depth) of ten different sites.

The final goal of the survey described in this chapter is to recognize and identify the differences in soil properties and then map those that might affect grape quality and production within the vineyard.

5.2 Materials

Tools used to examine the soils included spades, knives, graduated tapes, a Munsell colour table (Munsell Colour Company, 1975), scales to weigh larger gravel fractions, nylon bags, calibrated cylinders to measure water volume, and sieves of 20 and 2 mm. PVC tubes with 8 mm holes drilled in them were used to assess the water table levels. Back in the laboratory tools used included sieves of 1.4, 1, 0.5, 0.25, 0.125 and 0.064 mm, an oven and scales. Clay and silt separation was achieved in the Landcare Research soil physics laboratory, using the pipette method.

5.3 Methodology

5.3.1 Soil maps and vine rows

A map showing soil and pit distribution (Vincent, 1999) was scanned and exported to ArcView to be digitised. A vector polygon file showing soil boundaries was created. This file was exported to Idrisi for registration. The orthophoto was used to determine the coordinates of 10 different control points on the farm and create a correspondence (.cor) file. The vector polygon file showing soil boundaries was then resampled using this correspondence file. The digitised map showing the soil boundaries, together with the sites sampled in this thesis are shown in Figure 5.1.

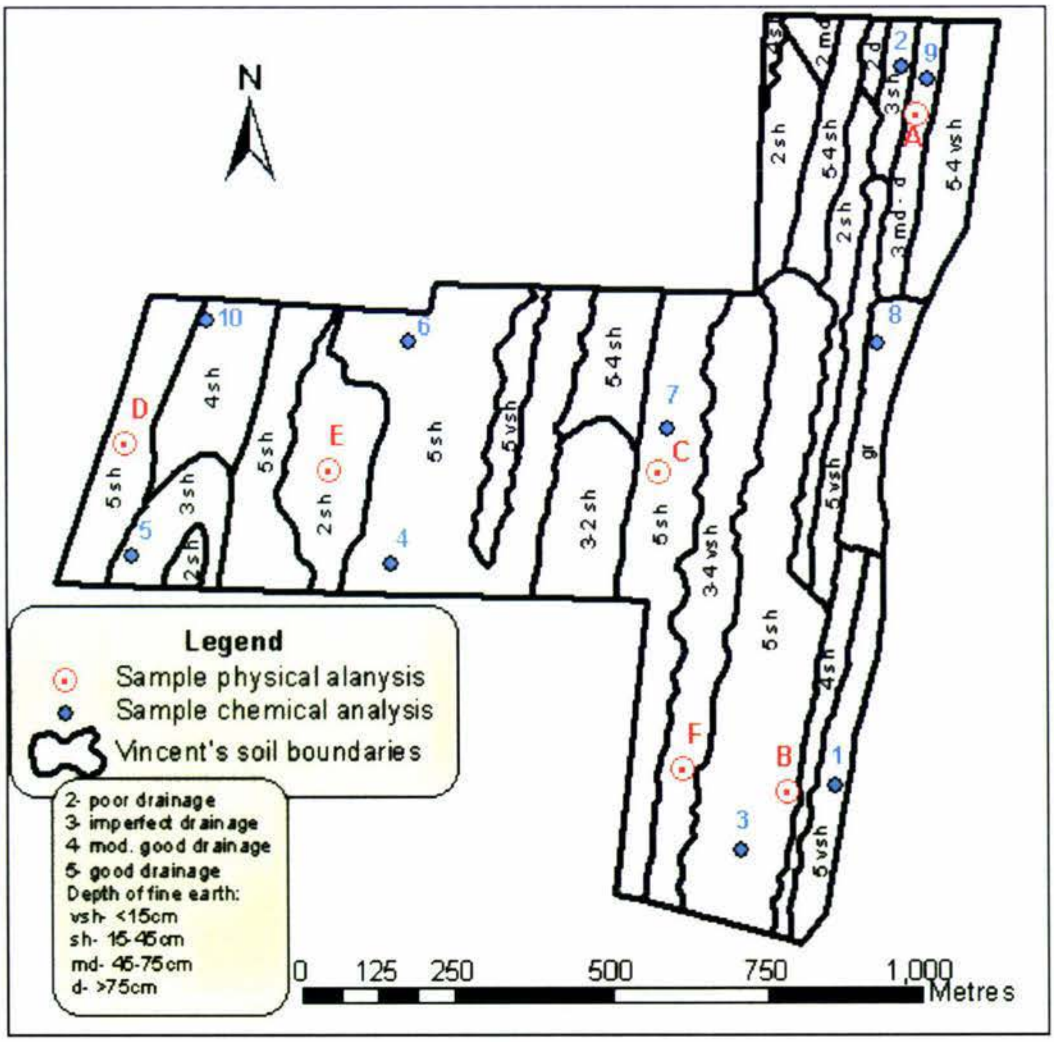


Figure 5.1 Soil unit boundaries as mapped by Vincent (1999) (in black) and sample sites for physical and chemical analysis taken in this project.

The distribution of vineyard rows had already been mapped and the file was available in Autocad (.dwg) format. This file was imported in ArcGIS and opened applying the NZMG1949 coordinate system. This data was then exported as a shapefile (.shp) to ArcView.

5.3.2 Soil wells

The depth of the water table was monitored from March until November 2003.

- Location of wells

From the elevation map (Figure 4.6), 28 sites were chosen to monitor the water table. Sites were chosen to represent areas of different landscape morphology and heights. Eighteen wells were installed in hollow areas while ten were placed in ridge areas. A maximum difference of 2 metres elevation exists among the sites selected.

- Well installation

Each well consisted of a 1 m length of 100 mm diameter plastic pipe. At 50 mm intervals, 8 mm diameter holes were drilled. All the wells were numbered. The level of water was measured after each rain by Tim Lavelock. The measurements were done with a marked staff that had two wires exposed at the bottom. When the wires touched the water a circuit was completed, a buzzer sounded and the depth was read from graduations in the staff.

Soil descriptions of the 28 holes opened for installing the wells were made based on the method described by Milne *et al.* (1995). Holes of one metre depth were dug by spade. Soil profile descriptions were made at the same time and photographs were taken. Soil colour was recorded by comparison with the Munsell soil colour charts (Munsell Colour Company, 1975). Refer to Appendix C for soil descriptions.

5.3.3 Soil physical analysis

Six different sites were chosen for the physical analysis. Various sources of information were used to select sites in order to:

- cover the main variation in the EC_a maps, particularly the minimum and maximum values;
- represent the variability of topsoil depths and depths to a gley layer as mapped by Vincent (1999); and

- represent the geomorphological differences (3 sites were chosen on ridges and 3 in hollows).

The locations of the chosen sites (A to F) are shown in Figure 5.1. Pits were located in the field using the RTK DGPS and the positions stored in the field computer. Photos and descriptions of these pits are shown in Figures 5.2 to 5.5 in the results section of this chapter.

Three duplicates samples per site were collected from pits separated by approximately two metres. For each duplicate, three horizons were sampled: the topsoil, the C1 and the C3. However, the site A was an exception and four horizons were sampled: Ap1, Ap2, C1 and C3. Each horizon was sampled separately and analyzed for percentage of gravels. The topsoils and C1 horizons were analysed for bulk density and water content. Clay content of the fine earth was analysed for topsoil samples.

Analysis of variance was performed using SAS software for the results obtained for moisture content, TAWC and bulk density. Homogeneity and normality of variance for these variables were tested.

For the texture analysis, three main fractions were determined: fine earth (<2mm), fine gravels (2-20mm) and coarse gravels (>20mm). Percentage of gravels was determined in the field using a volume estimate for fractions from 20 to 75 mm and a weighing method for fractions between 2-20 mm, following a method proposed by USDA (2002a). A visual estimate of the volume of the 20-to 75-mm fraction was made using the tables in Milne *et al.* (1995).

To estimate the proportion of the 2-20 mm fraction, approximately 5 kg of soil was dried in the oven, sieved with a 20 mm and then 2 mm sieves and weighed. The proportion of these two fractions was calculated as follows:

$$\underset{\text{(mass basis)}}{\%<2\text{ mm fraction}} = \frac{\text{dry weight of material} <2\text{ mm}}{\text{dry weight of the whole sample } (<20\text{ mm})}$$

The fine earth (<2 mm) was sieved to determine the sand size distribution with sieves of 0.064, 0.125, 0.250, 0.500, and 1.4 mm; and the silt and clay fractions were determined in the laboratory with the pipette method (USDA, 1996). Graphs showing the particle size distribution for each site are presented in Figures 5.8, 5.9 and 5.10.

Bulk density was calculated in the field, for the topsoils, using the water replacement method (Cambell & Henshall, 1991). Holes of about 10 cm in diameter and ten centimetres in depth were dug as regular a shape as possible, covered with a plastic film and filled with a measured amount of water. A calibrated container (measuring cylinder) was used to measure the water in terms of volume. The soil sample was dried in an oven at 105°C and weighed.

Because the samples contained coarse fractions, a correction was performed in order to calculate the bulk density of only the fraction less than 20 mm. The bulk density was calculated as follows:

$$\boxed{\underset{\text{(fraction < 20 mm)}}{\text{Bulk density}} = \frac{Wf}{Ve}}$$

where:

Wf = oven-dry weight of <20-mm soil (g)
Ve = excavation volume of <20-mm fraction ($Ve = Vf - Vg$)
Vf = water volume measurement of excavated soil (cm^3)
Vg = coarse gravel volume (>20mm- fraction) (cm^3).

It was calculated by dividing the weight of the >20-mm fraction by the particle density of the gravels. Particle density was estimated using a picnometer, the average being 2.65 g cm^{-3}.

Water content was also measured for the topsoils by the gravimetric method as described by Gardner (1986). A wet sample of approximately 100g was placed in bags and carefully tied, and taken to the laboratory and dried at 105° to completely remove the water content, and calculate the difference wet – dry weight. These gravimetric measurements were then converted to a volumetric basis using bulk density samples previously taken throughout the field.

The total available water content (TAWC) was estimated taking into account the soil order, texture and the depth of each horizon (Griffiths, 1985). Only fine earth was taken into account, making corrections for the percentage of gravels. Data for the different horizons were summed to one metre depth.

5.3.5 Soil chemical analysis

For chemical analysis, the topsoils of ten soil samples were collected in May using a spade. The locations (shown in figure 5.1) were chosen in order to represent EC and soil variability rather than a random sample. Samples of A horizons were sent to the laboratory for analysis.

Technicians at the Fertilizer and Lime Research Centre (FLRC) at Massey University carried out the soil chemical analysis for the following soil properties: pH, Olsen P (µgP/g), sulphate-S (SO4) (µgP/g), potassium (K) (me/100g), calcium (Ca) (me/100g), magnesium (Mg) (me/100g), sodium (Na) (me/100g), cation exchange capacity (CEC) (me/100g) using methods detailed in Blakemore et al (1987) and reserve K. The reserve K was analyzed using the modified sodium tetraphenylboron method developed in New Zealand. This method determines short to medium-term availability of K, and is sensitive to changes in K status caused by K uptake by plants. This method can identify potassium uptake from soil reserves after minimum levels of exchangeable K are reached (Jackson, 1985).

5.3.6 Particle shape assessment

More than 100 stones were measured for their lengths according to the three major axes: long, intermediate and short. The classification of shapes of pebbles was done according to Zingg graphs (see Figure 5.11.).

Textural properties of the grain such as size and shape are an important part of the sedimentary studies due to its genetic significance. Studying the shapes of the pebbles enables an interpretation of the original environment where the soils were formed. Geological agents can either modify or select the shapes of the pebbles (Pettijohn, 1975; Boggs, 2001). It has been found that rounder flatter pebbles with lower sphericity tend to accumulate on beaches, in contrast to the gravels of rivers which are spherical but not as rounded. Earlier soil studies (DSIR, 1968) had implied a fluvial origin for the gravels on the vineyard, but the gravel ridges at the vineyard are aligned parallel to the coast. The measurements were done to try to confirm a marine origin for the pebbles.

5.4 Results

5.4.1 Soil profiles descriptions and classification.

The depth of the fine earth ranges from 10 to 40 cm and depth to coarse gravels ranges from the soil surface to 100 cm. The texture of the topsoil is mainly loamy sand, in some cases including coarse and very coarse gravels (measuring between 2 and 15 cm diameter), and frequently includes fine gravels (2 to 6 mm diameter). The topsoils are friable with either weakly developed crumb structure or structureless. These topsoils are found to overly fine gravel frequently structureless layers. Gravel content of both the topsoil and the subsoil layers, range from no gravels to very gravelly (> 30 %). In general gravels are well stratified by sizes. Grass roots are found in general to a rooting depth of 30 to 60 cm.

The soils of the ridges are found to be more brown coloured compared with the grey colours of the soils of the hollows. Soils on the ridges are somewhat excessively drained.

Mottling is evident in some pits dug in the hollow areas, natural drainage areas (channels) and deep soils of the north end of the property (sample sites A (Figure 5.2) and F (Figure 5.4) and wells 1, 2, 4, 8, 10, 12, 15, 17, 19, 20, 21, and 24 described in Appendix C)). This generally common and distinct mottling occurs just below the topsoils, between 10 and 30 cm, except for site A and wells 8 and 10 where the mottling occurred deeper in the profile.

NZ Classification: **Mottled Orthic Recent Soil**

0-20 Ap_1. Very dark greyish brown (10YR3/2); slightly gravelly loamy sand; friable; weakly developed medium crumb structure; common roots; distinct boundary.

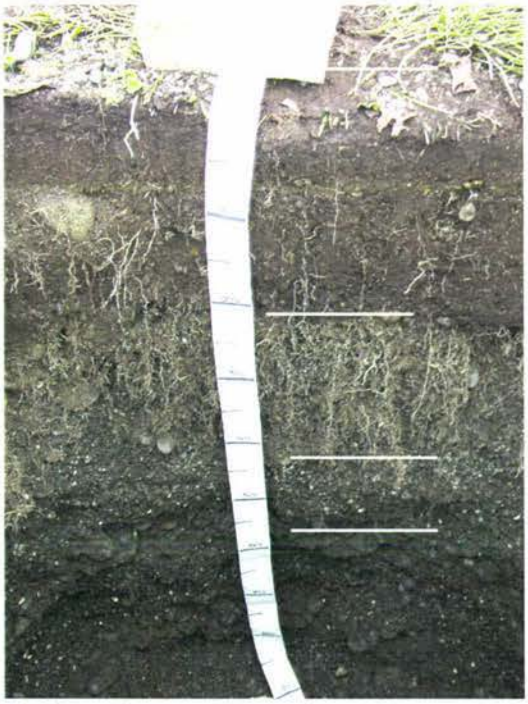
20-45 $2Ap_2$. Very dark greyish brown (10YR3/2); moderately gravelly sand with 10% coarse and very coarse gravels; friable; weakly developed medium crumb structure; common roots; distinct boundary.

45-65 Cg1. Dark greyish brown (2.5YR4/2); loamy sand; structureless; abundant medium distinct (2.5YR4/8) mottles; few roots; distinct boundary.

65-85 C_2. Dark grey (10YR4/1); coarse sand; structureless; few roots; indistinct boundary.

85-100 $2C_3$. Grey 4/10Y chart 1 for gley; moderately gravelly with 25% coarse gravels in a coarse sand matrix; structureless.

Figure 5.2 Soil at Site A, a hollow on the north eastern side of the vineyard.



NZ Classification: **Typic Orthic Recent Soil**

0-20 Ap_1. Very dark grey (10YR3/1); moderately gravelly loamy sand with 5% coarse gravels; weakly developed crumb structure; common fine roots; distinct boundary.

20-50 C_1. Very dark greyish brown (10YR3/2); very gravelly loamy sand, fine gravels and 10% coarse to very coarse gravels; friable; structureless; abundant fine roots; abrupt boundary.

50-65 $2C_2$. Very dark grey (10YR3/1), extremely gravelly in a coarse sand matrix, fine gravels and 75% coarse gravels; structureless; distinct boundary.

65-100 $2C_3$. Very dark grey (10YR3/1); extremely gravelly, fine gravels and 10% coarse gravels; structureless; slightly moist.

Figure 5.3 Soil at Site E, a hollow on the western side of the vineyard.

NZ Classification: **Mottled Orthic Recent Soil**

0-15 Ap_1. Very dark greyish brown (10YR3/2); loamy sand; friable; weakly developed fine crumb structure; common roots; distinct wavy boundary.

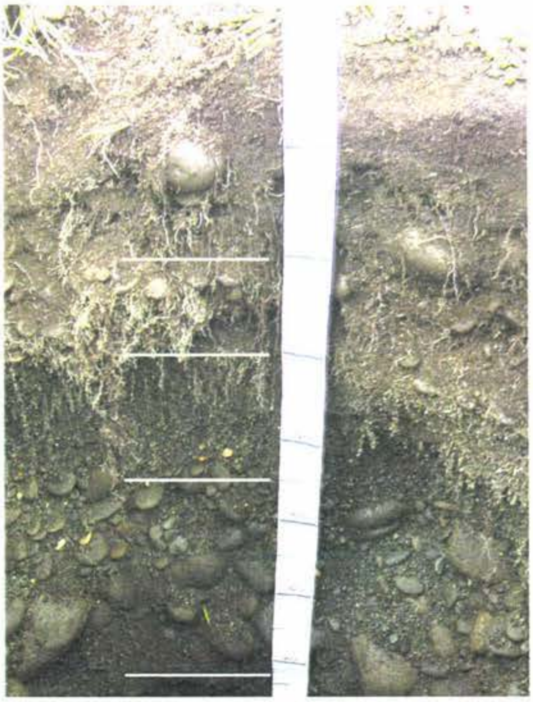
15-30 Cg_1. Dark greyish brown (10YR4/2); very gravelly sand with 50% coarse and very coarse gravels; friable; loose; abundant strong brown (7.5 YR 4/6) medium distinct mottles; common roots, distinct wavy boundary.

30-45 C_2. Dark greyish brown (2.5YR4/2); slightly gravelly coarse sand; structureless; few roots; distinct boundary.

45-60 $2C_3$. Dark greyish brown (2.5YR4/2); moderately gravelly coarse sand with 25% coarse and very coarse gravels; structureless; few roots; distinct boundary.

60-100 $2C_4$. Dark grey (2.5Y 4/1); moderately gravelly coarse sand with 25% coarse gravels; structureless.

Figure 5.4 Soil at Site F, a hollow on the southeastern end of the vineyard.



NZ Classification: **Typic Orthic Recent Soil**

0-19 Ap_1. Very dark greyish brown (10YR3/2); slightly gravelly sand with 10% coarse to very coarse gravels; friable; loose; common roots; indistinct boundary.

19-30 C_1. Dark brown (7.5YR3/2); fine gravels and 25% coarse gravels in a coarse sandy matrix; structureless; abundant roots; abrupt boundary.

30-45 C_2. Very dark grey (10YR3/1), fine gravels in a coarse sand matrix; structureless; few roots; distinct boundary.

45-70 $2C_3$. Very dark grey (10YR3/1), fine gravels and 75% coarse to very coarse gravels in a coarse sand matrix; structureless; abrupt boundary.

70-77 $3C_4$. Black layer, sandy, discontinuous; structureless; abrupt boundary.

77-100 $4C_5$. Very dark grey (10YR3/1), fine gravels in a coarse sand matrix; few roots; distinct boundary.

Figure 5.5 Soil at Site C, a ridge in the centre of the vineyard.

NZ Classification: **Typic Orthic Recent Soil**

0-19 Ap_1. Very dark grey (10YR3/1); very gravelly sand; 25 to 50% coarse and very coarse gravels; friable; stuctureless; common roots; distinct boundary.

19-50 C_1. Dark brown (10YR3/3); extremely gravelly sand with 50 to 75% coarse and very coarse gravels; friable; structureless; common roots; distinct boundary.

50- 100 $2C_2$. Dark greyish brown (10YR4/2); fine gravels and 25% coarse gravels; structureless; few roots.

Figure 5.6 Landscape (top) and profile (bottom) at Site B, the southern end of the eastern stony ridge.

NZ Classification: **Typic Orthic Recent Soil**

0-19 Ap_1. Very dark grey (10 YR3/1); moderately gravelly sand; friable; weakly developed crumb structure; abundant roots; abrupt boundary.

19-32 C_1. Very dark greyish brown (10YR 3/2); moderately gravelly sand with few coarse gravels; structureless; common roots; distinct boundary.

32-60 $2C_2$. Very dark grey (10YR3/1), fine gravels in a coarse sand matrix; structureless; few roots; indistinct boundary.

60-100 $3C_3$. Very dark grey (10YR3/1); fine gravels; structureless.

Figure 5.7 Photographs showing landscape (top) and profile (bottom) at Site D (ridge).

5.4.2 Soil physical analyses

Mass cumulative percentages of particle size from 0.064 mm to 150 mm for the three replicates at the six sites are shown in Figure 5.8 for horizon A, Figure 5.9 for horizon C1 and Figure 5.10 for horizon C3. The spherical diameter (mm) is represented on a ten base logarithmic scale in the X axes (this scale is used to be able to fit the range in a reasonable space).

The finest particle size in the topsoil is at site F, where almost 100% is less than 1.4 mm; and 2.1% of the fine earth (< 2 mm.) is clay (Table 5.1).

Site A is also among the finest textured topsoils although it is highly variable (some evidence of earth removal around the area was observed). While one of the duplicate samples has 90% of the material under 0.5 mm, the other duplicates have less than 40% of fine earth, and 40% are gravels to 20 mm diameter. Clay content at site A is on average 1.8% of the fine earth.

Sites E and C have intermediate particle sizes in A horizons, with 60 and 70 % of fine earth respectively. However, while 2.4% of the fine earth is clay at site E, the clay percentage at site C is only 0.3%.

Topsoils at sites D and B have the coarsest textures. Only about 50% and 30% of the material respectively is fine earth. Gravels are coarser at site B, with an average of 55% by weight between 20 and 100 mm diameter, while at site D the gravels are finer, with 40% by weight between 2 and 20 mm. Clay percentage of the fine earth is 0.3 and 1 % for sites D and B respectively.

Table 5.1 Average percentage of fine earth and clay content of three replicates of A horizons as a percentage of fine earth fractions.

Site	% of fine earth	Clay (%)
A	73	1.8
B	43	1.0
C	70	0.3
D	48	0.3
E	56	2.4
F	95.5	2.1

Site A is the finest textured of the C1 horizons (Figure 5.9), although it is quite variable, with 50 to 100% of fine earth. Site D is the second finest, with an average of 50 % of fine earth, and there are no gravels coarser than 20 mm. Site C and F are next in order, with an average of 40 % of fine earth. However while at site C only about 30 % of the gravels are larger than 20 mm, at site F that fraction represented 60 % by weight. Site E is fourth in order with only about 10 % fine earth and 80% of the material being between 2 and 20 mm. Again Site B has the coarsest particles, with an average of 20 % fine earth and 70% of the material between 20 and 100 mm in size.

In the C3 horizon Site A is again the finest textured, being from 40 to near 100% fine earth, and almost no gravel larger than 20 mm. Site F is second finest, with 40 to 80 % fine earth and 20 to 40 % of gravels between 20 and 100 mm. Site D has only 20 % of fine earth, but all the gravels are smaller than 20 mm. Sites B and C are next, with about 30 and 20 % of fine earth respectively, but both with about 50% of gravels larger than 20 mm. Site E has the coarsest texture in horizon C3, with 80% of gravels larger than 20 mm and only 8% fine earth.

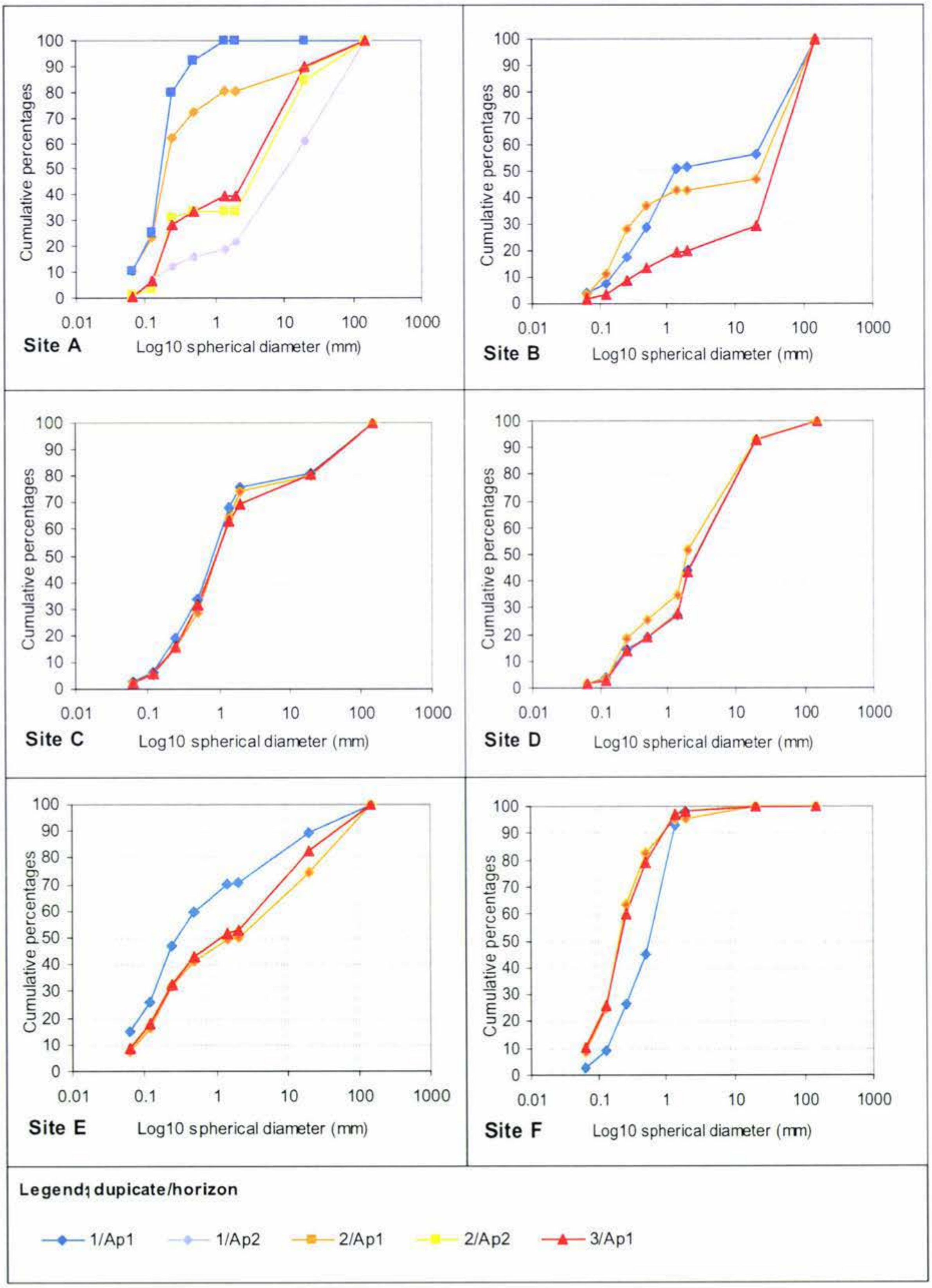


Figure 5.8 Particle size distributions of A horizons. Sites A to F.

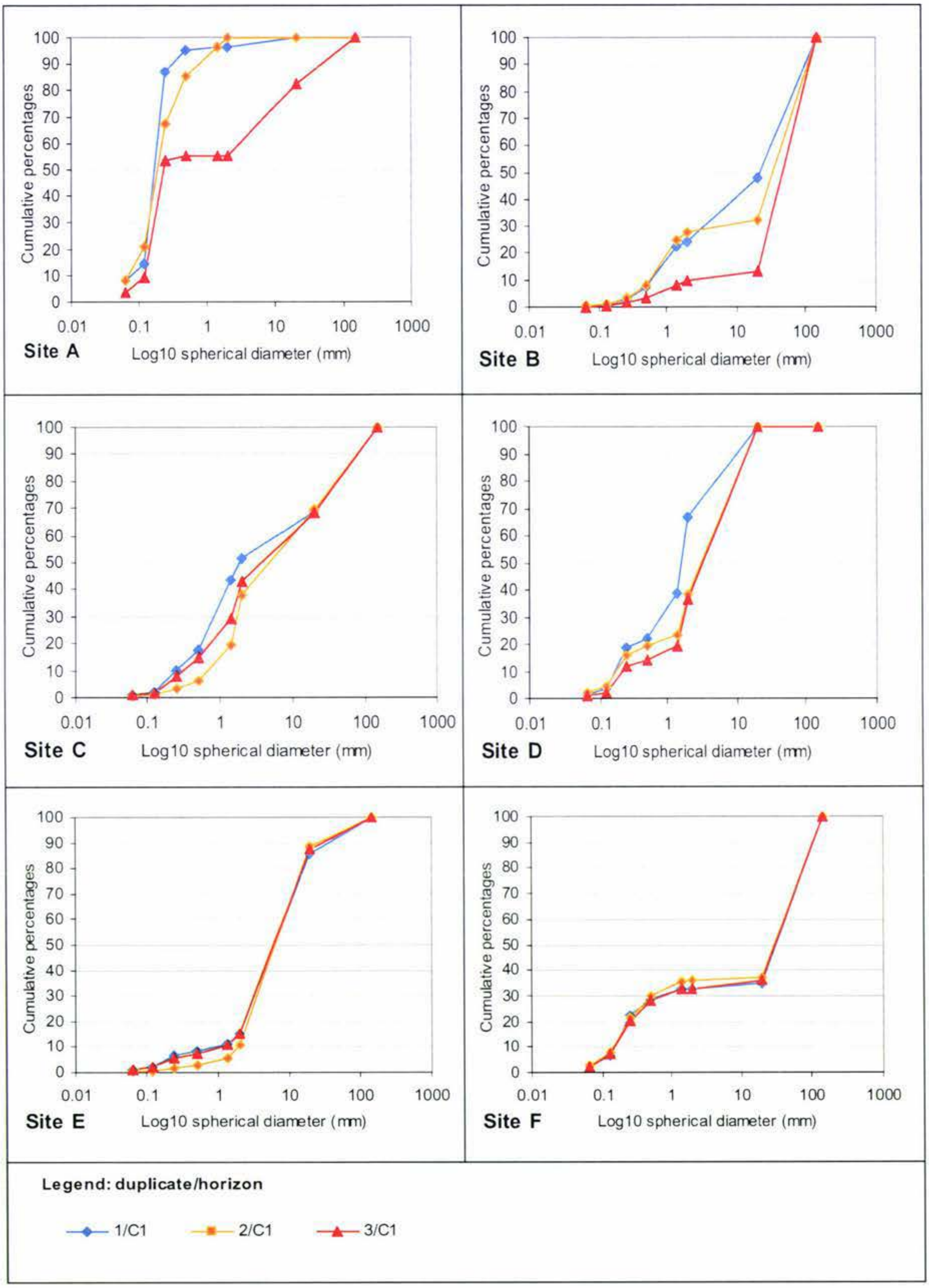


Figure 5.9 Particle size distributions of C1 horizons. Sites A to F.

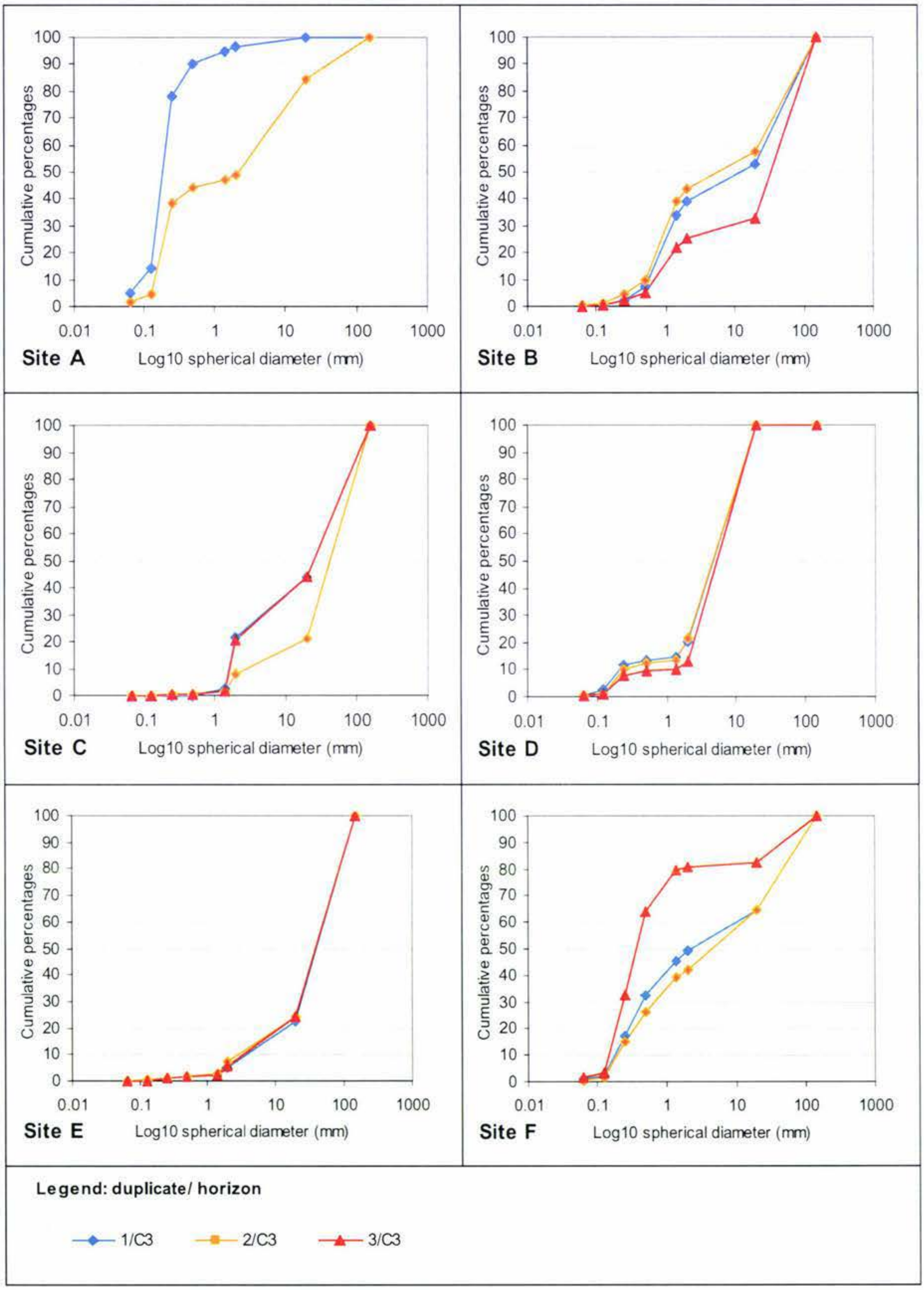


Figure 5.10 Particle size distributions of lowest horizons. Sites A to F.

The results found in this project together with those of Vincent (1999) were used to produce a map showing the distribution of soils according to depth of fine earth (sandy loam or gravelly sandy loam or sand) (Figure 5.11).

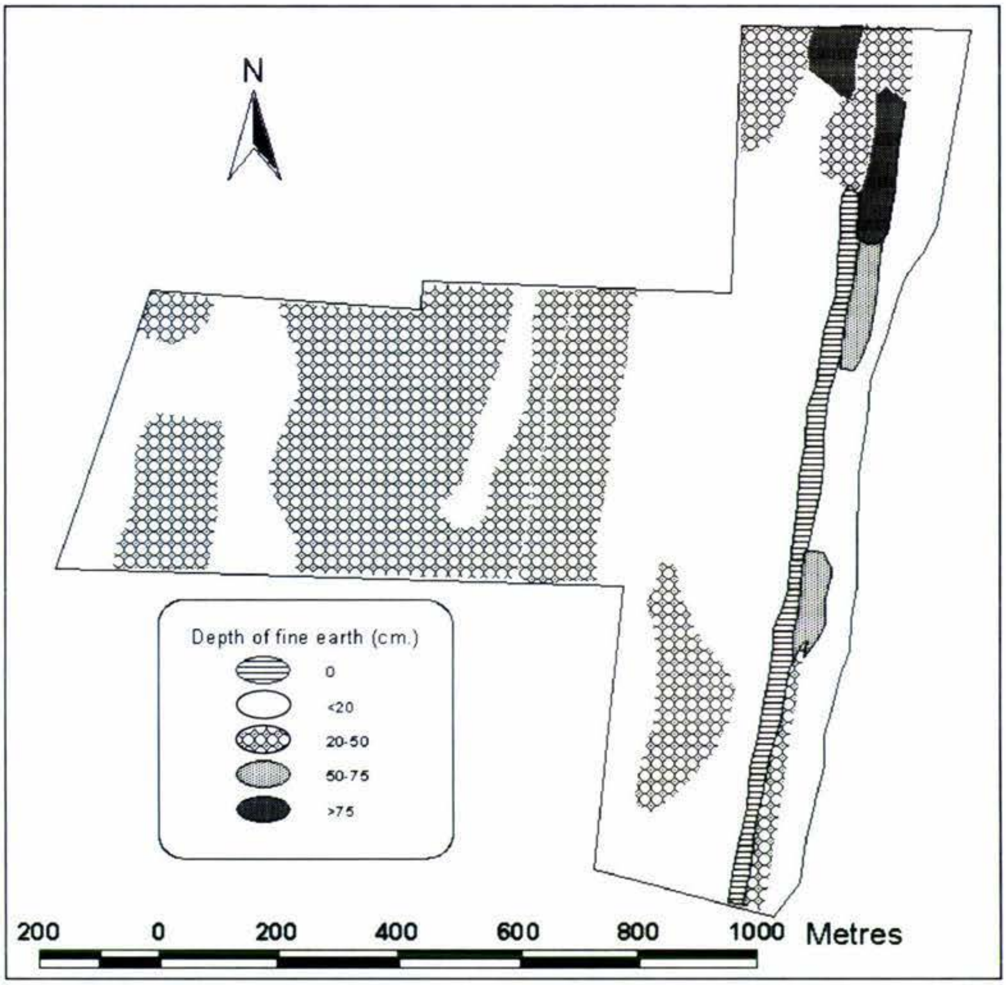


Figure 5.11 Depth of horizons with more than 60% fine earth.
Integrated data from this project and that of Vincent (1999).

Results for bulk density are presented in Table 5.2. The detailed results are presented in Appendix D.

Table 5.2 Bulk density of the < 20 mm fraction for topsoils.

Sample/	1	2	3	4	5	5'	6	7	7'	8	9	9'	10
topography	ridge	ridge	hollow	ridge	hollow		ridge	ridge		hollow	hollow		hollow
Bulk density ($Mg\ m^{-3}$)	1.16	1.13	1.31	1.15	1.03	0.8	1.07	1.05	1.16	1.06	0.89	1.04	0.97

Note: duplicates are indicated by a ' symbol next to the sample number.

Bulk density volume measured as megagrams of air-dry soil per metre was very variable and did not follow any pattern. Values ranged from 0.8 to 1.3 (Table 5.2).

The gravimetric moisture content of the soils, measured in July were higher in the A horizons of sites A, B and F; and lower at sites C, D and E. When comparing the C1 horizons, the highest moisture content was registered at site F, while the others had similar values (Table 5.3.). The variance of moisture values prove homogeneity (equal variances across samples) and normality (normal or nearly normal distribution), fulfilling the assumptions for the analysis of variance.

Table 5.3 Gravimetric soil moisture content of the horizons A and C1 measured in July 2003.

	Moisture A horizon *[1]		Moisture *[1] C1 horizon	
	(%)	Std. Dev.	(%)	Std. Dev.
Site	*[2]		*[2]	
A	27 ab	3.1	9 b	5.5
B	30 a	1.5	9 b	2
C	18 cd	2.0	5 b	1
D	14 d	2.6	8 b	1.5
E	23 cd	4.0	4 b	1
F	29 a	4.4	18 a	6.4
lsd*[3]	6		7	

*[1] Material < than 20 mm

*[2] Values followed by the same letter do not differ significantly at the 0.95 of probability level

*[3] Least significant difference at 0.95 of probability level

The estimated total available water content to 1 m depth in the profiles ranges from 20 to 86 mm on average for the different sites (see table 5.4).

Table 5.4 Estimate of the total available water content (TAWC) to 1 m depth.

	TAWC (mm)	Std. Dev.
Site	*[1]	
A	86.0 a	1.4
B	22.5 c	8.0
C	29.2 c	2.9
D	22.1 c	2.7
E	20.3 c	2.5
F	45.9 b	7.0
lsd*[2]	8.5	

*[1] Values followed by the same letter do not differ significantly at the 0.95 of probability level

*[2] Least significant difference at 0.95 of probability level

The estimated TAWC from different locations within the vineyard are illustrated in Figure 5.12, showing results from this work and from Vincent´s report (1999).

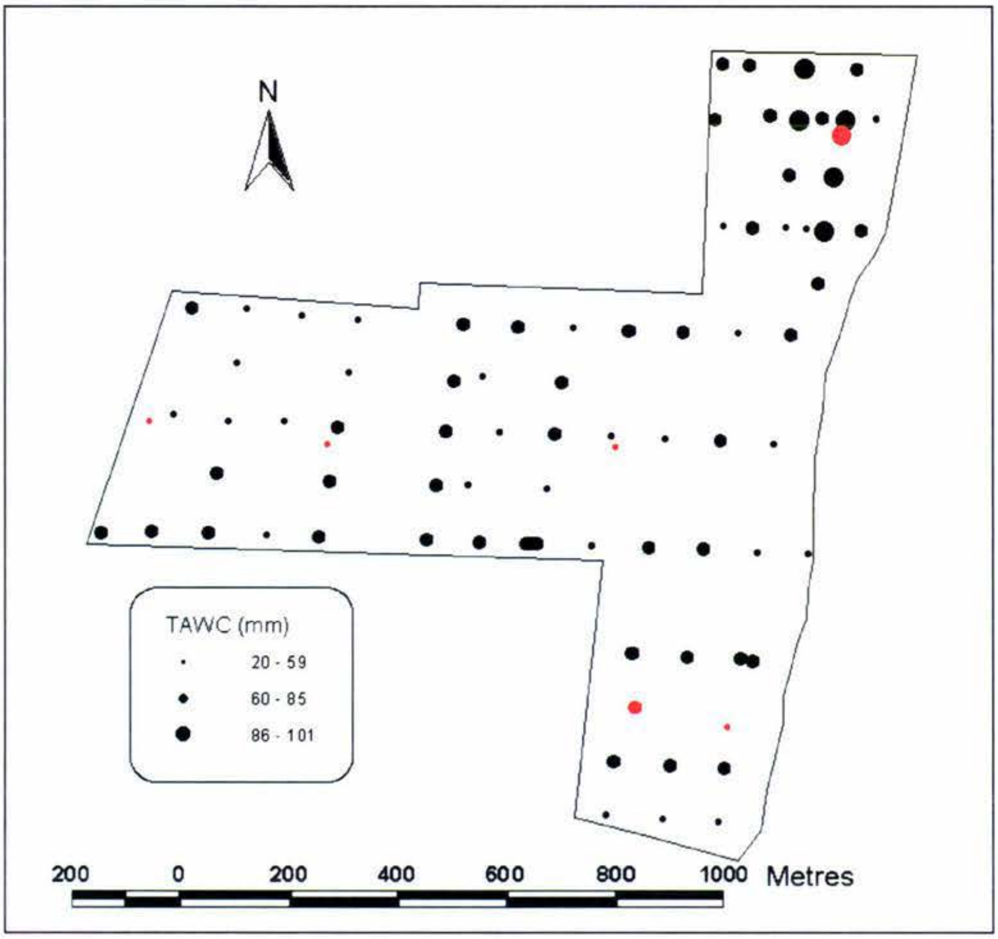


Figure 5.12 Total Available Water Contents to 1 (red dots) and 1.2 m (black dots) depths estimated for samples in this project and by Vincent (1999) respectively.

5.4.3 Water table levels and soil drainage

When wells (Figure 4.6) were installed on Rarangi vineyard in March, all were dry to 1 metre depth. By the 17th of September, two wells showed water and by the end of September, several more (Table 5.5). By mid October, 16 wells had water in them, some at very shallow depths. In 13 days (with 83 mm of rainfall) the level of the Rarangi Shallow Aquifer rose half a metre at the vineyard.

Table 5.5 Free water levels below the surface measured in wells for different dates.

Well N°*[1]	Depth (cm)					
	17/09*[2]	30/09	13/10	20/10	28/10	17/11
2	-	91	42	42	47	62
4	-	-	59	67	73	-
6	-	-	66	78	-	-
8	-	-	76	86	-	-
10	-	-	79	-	-	-
15	75	ND*[3]	0	8	11	31
17	-	-	50	63	73	-
18	-	-	73	-	-	-
19	-	-	73	-	-	-
20	80	65	22	40	45	59
21	ND *[2]	79	26	45	55	71
22	ND *[2]	-	59	81	-	-
23	ND *[2]	-	64	-	-	-
24	ND *[2]	88	42	70	80	-
25	ND *[2]	-	78	87	-	-
26	ND *[2]	-	55	66	72	85

*[1] Wells not numbered in this table did not ever contain water during the survey.

*[2] The reading was interrupted because of a heavy rainfall on 17/09 before finishing the measurements. Wells 21 to 28 were not measured on 17/09.

*[3] The operator did not take a measurement of well 15 on 30/09 (he forgot it).

Rainfall for the period that wells were measured and the water level fluctuations in three of the wells are illustrated in Figure 5.13.

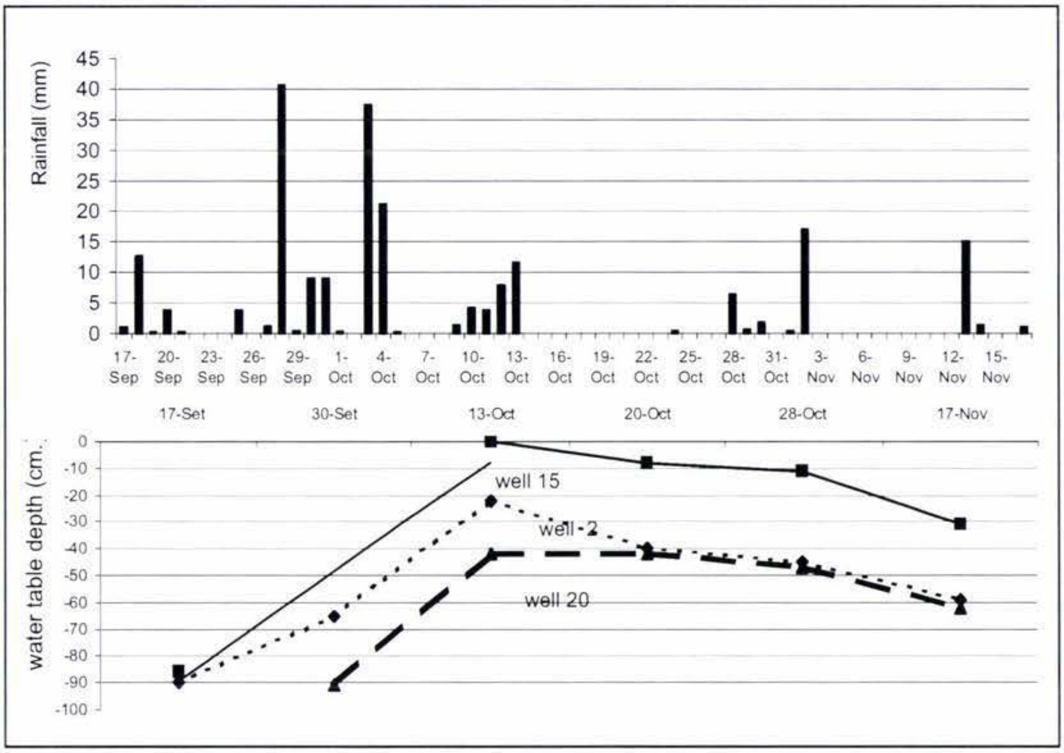
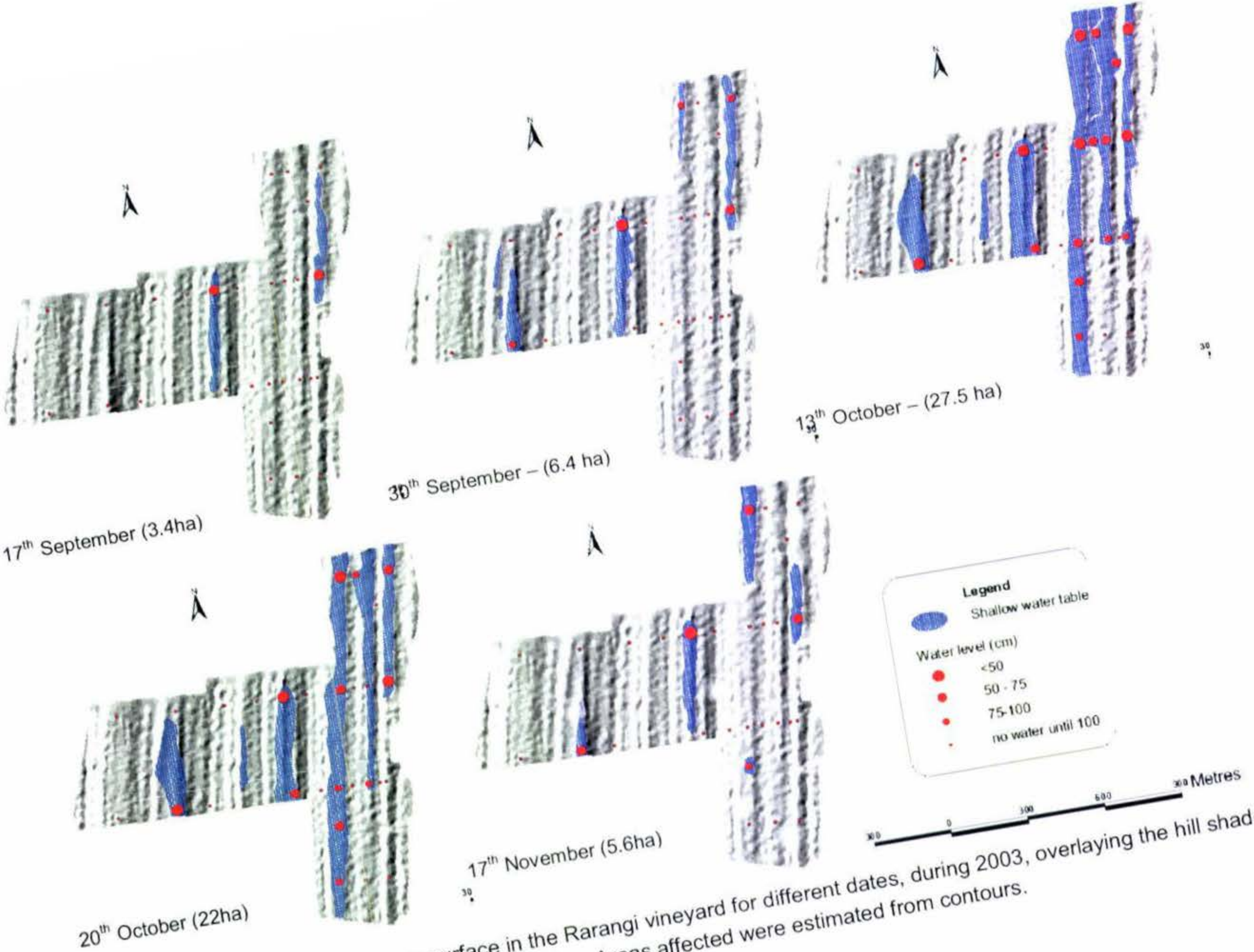


Figure 5.13 Rainfall registered at Rarangi vineyard from middle September to middle November and water level fluctuation in wells 15, 2, and 20.

The highest water table levels were registered on 13th October, following three rainfalls of 20 to 40 mm in late September (Figure 5.13). Lower rainfalls were registered during the rest of October and November, and the water table levels descended significantly by the middle of November.



17th September (3.4ha)

30th September – (6.4 ha)

13th October – (27.5 ha)

20th October (22ha)

17th November (5.6ha)

Figure 5.14 Water tables <75 cm from surface in the Rarangi vineyard for different dates, during 2003, overlaying the hill shade map. Water depths in wells are illustrated in red circles. Areas affected were estimated from contours.

Most of the vineyard is somewhat excessively drained; the water is removed from the soil rapidly (USDA, 2002b). Nevertheless, due to the rise of the Rarangi Shallow Aquifer during spring time, part of the vineyard is moderately well drained (Figure 5.15).

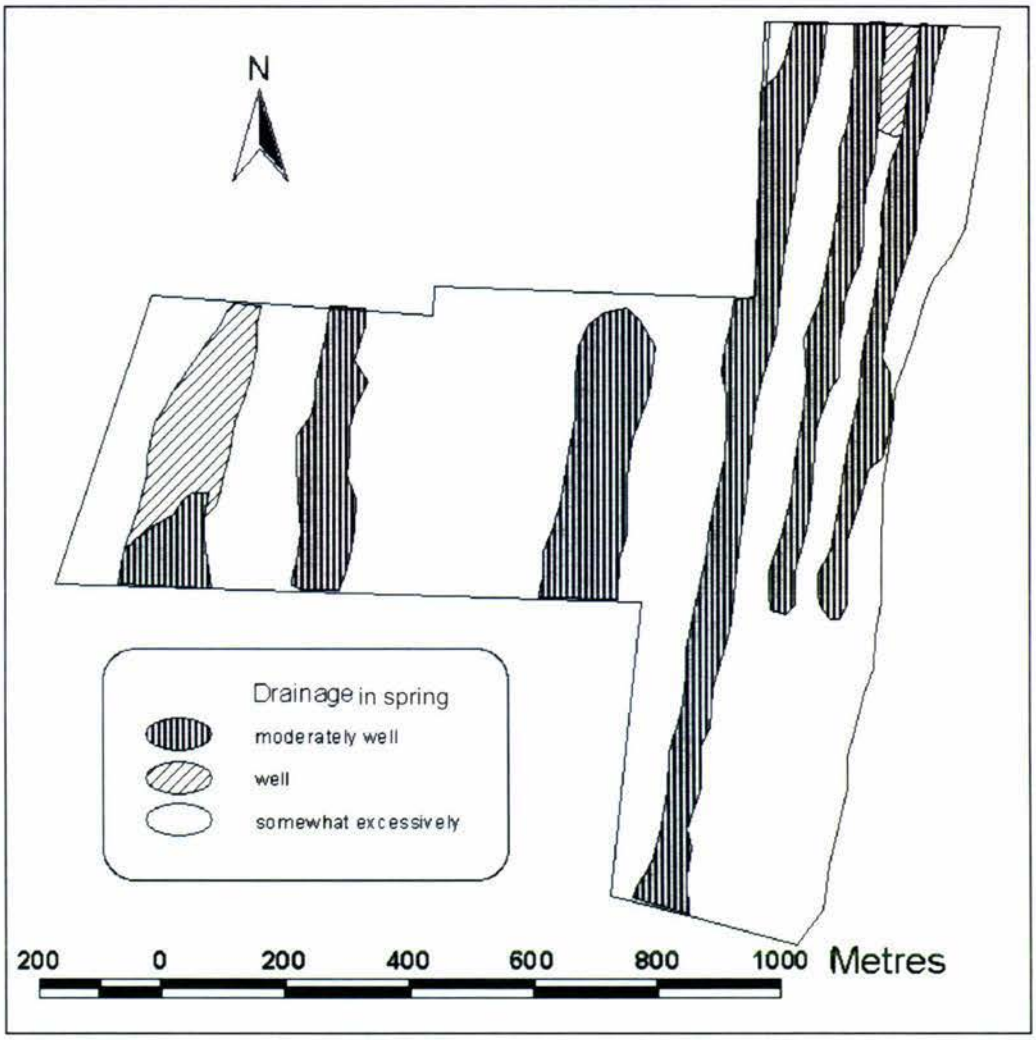


Figure 5.15 Map showing drainage classes. Data used for the classification included observations made in this project as well as the map generated by Vincent (1999).

5.4.4 Pebble shape

The intermediate/long and the short/intermediate ratios of pebbles were plotted onto a Zingg diagram and are illustrated in Figure 5.16. If the gravels were fluvial, as suggested by NZ Soil Bureau (1968), spherical shapes (top right hand field) could be expected.

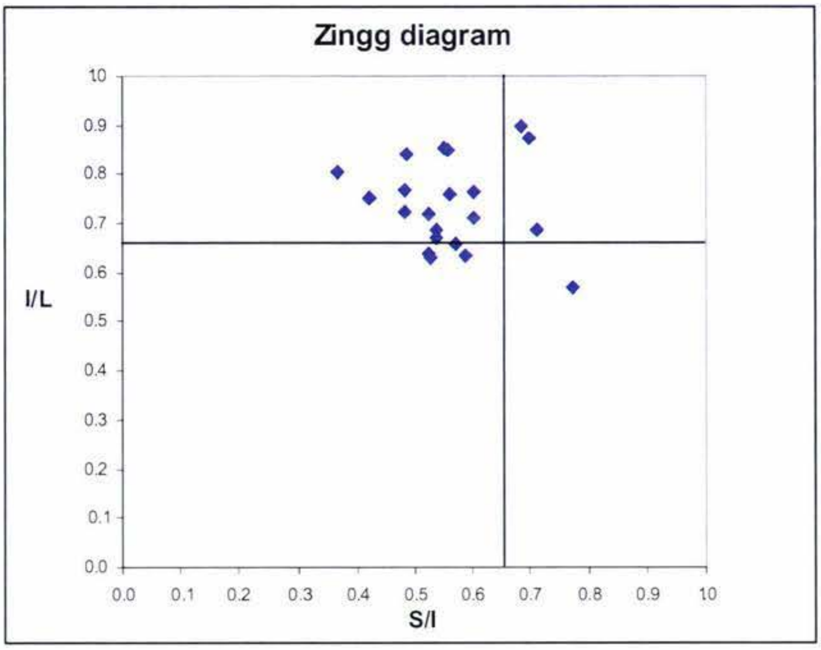


Figure 5.16. Classification of shapes of pebbles according to Zingg indices (Boggs, 2001).

Note: I, S and L refer to the length of the intermediate, short and long axes of the pebbles respectively.

5.4.5 Soil chemical analyses

Standard chemical tests were performed on topsoil samples from selected sites (Table 5.6). There was considerable variation in all the parameters measured.

Table 5.6 Chemical analyses on the fine earth fraction topsoil samples taken in May and July.

Sample/ topography	pH	Olsen P µg/g*	CEC *	K	Ca meq/100g	Mg	Na	Base Saturation %	SO4 µg/g*
1 ridge	5.9	7.1^{*2}	18	0.17	9.5	1.01	0.10	59	2.0
2 ridge	5.0^{*1}	35.7^{*2}	15	0.32	5.7	0.52	0.23	43	14.5
3 hollow	5.6	7.1^{*2}	16	0.22	7.9	0.93	0.21	60	2.5
4 ridge	6.6^{*1}	13.3	12	0.13	7.6	1.05	0.76	79	60.0
5 hollow	5.2^{*1}	10.0	20	0.20	6.4	0.68	0.26	38	28.3
5^{*3}	5.7^{*1}	18.2	25	0.18	10.0	0.83	0.16	45	8.0
6 ridge	5.5^{*1}	36.2	20	0.28	6.0	1.93	0.17	43	4.0
7 ridge	4.8	10.5	15	0.04	3.1	0.23	0.20	24	4.8
7^{*3}	5.2	25.9	16	0.18	3.7	0.66	0.11	29	2.8
8 hollow	6.9^{*1}	8.1^{*2}	23	0.38	18.7	2.66	0.33	95	10.3
9 hollow	6.8^{*1}	12.4^{*2}	21	0.13	15.0	2.40	0.56	88	10.0
9^{*3}	6.6^{*1}	7.2	21	0.21	13.3	2.51	0.22	76	4.5
10 hollow	6.3^{*1}	17.6	17	0.13	10.3	1.02	0.98	71	8.0

* Phosphate, sulphate and CEC are expressed per units of air dry soil.
^{*1} Lime was applied, while the rest of the field received gypsum.
^{*2} Superphosphate was applied.
^{*3} Samples taken in July.

The chemical data was averaged for ridges and hollows separately (Table 5.7) since it was thought that the topography might be influencing some of the chemical characteristics.

Table 5.7 Chemical analysis of topsoil averaged for samples from ridges and hollows. Main differences are highlighted.

Samples position	N°	pH	Olsen P µg/g	CEC meq/100g	K	Ca meq/100g MAF, quick test	Mg	Na meq/100g	Base Saturation. %	SO4 µg/g
Ridges	6	5.5	**21.5**	16.0	0.2	5.9	0.9	0.3	46.2	5.6*
					3	7.7	23.2			
Hollows	7	**6.2**	11.5	**20.4**	0.2	11.7	1.6	0.4	**67.6**	**10.2**
					3	**13**	**36**			

*The value of sample 4 was not averaged because it was to be considered anomalously high.
N° = number of samples.

The lowest topsoil pH is found in a sample from a ridge in the middle of the block (Table 5.6) where values rate as low (strongly acid) when compared to ratings by Blakemore (1987). High pH values (near neutral) are found in a hollow in the eastern (coastal) part of the block (for the positions of the samples, refer to Figure 5.1). Otherwise there was no pattern, all other samples having medium pH values. Olsen P results were variable rating from low (7 µg/g) to high (36 µg/g) (Blakemore, 1987).

Cation exchange capacity rates as medium in all cases (but remember this is on a stone free basis). Slightly higher values are found in a hollow in the western part of the vineyard and in hollows in the eastern part.

Potassium values are very low (Blakemore, 1987), except for sample 8 from the eastern hollow that rates as low. High calcium values are found in eastern and northern hollows (samples 8 and 9) and the most western hollow (sample 10). Medium calcium values are found on the central ridges. The lowest calcium value is found on the same ridge in the middle of the block as the lowest pH values (sample 7). The highest magnesium values (rating as medium) were found in western and northern hollows (samples 8 and 9) and one sample from a central ridge (sample 6). The rest of the samples rated as low. Sodium values were very variable, high values are found in the western hollow (sample 10) and on a central ridge (sample 4), while medium values are found in the northern end of the vineyard (sample 9). The rest of the samples classify as low sodium values.

The lowest base saturation (Table 5.6) value is from a central ridge (site 7), rating as low. High BS values are in eastern, western and northern hollows (samples 3, 8, 9 and 10), and one central ridge (sample 4). The rest of the base saturation values rate as medium (Blakemore, 1987). Sulphur values are low, except for one high value in sample 4 on a central ridge.

The pH, CEC, base saturation, Ca, Mg, and sulphur averages are higher for samples taken from hollows than for the samples from ridges. On the other hand, phosphorous levels are higher in samples coming from ridges, although the measurements for phosphorous were very variable.

Reserve potassium showed major differences between sites (Table 5.8).

Table 5.8 Reserve potassium (meq/100g) for topsoil samples.

Sample	1 r	2 r	3 h	4 r	5 h	6 r	7 r	8 h	9 h	10 h
Reserve K *	0.48	0.39	0.26	0.27	0.12	0.38	0.03	0.90	0.27	0.20

* Reserve potassium was determined by the sodium tetraphenylboron method (Jackson, 1985).

Note: abbreviations used are r, ridge and h hollow.

5.5 Discussion

5.5.1 Soil profiles descriptions and classification.

The soils in the vineyard are similar in general morphology, but differences are detected in detailed examination (Figures 5.2 to 5.7). The main distinctions among the profiles are the depth of the topsoil, the percentage of fine earth in the different horizons, the presence and depth of a grey coloured layer in a few profiles and the presence and depth of a mottled layer in others. Mottles found in the hollow areas indicate alternating oxidising and reducing conditions. This might occur either or both as a result of high levels of groundwater in some period during the year and/or from water run off and lateral percolation and perching in slightly finer horizons. The water tables may rise from the normal level from 0.4 to 0.6 m. from early July to mid October in most years (measured at the Rarangi Golf Course, Marlborough District Council, 2003). Even if the rooting depth is 30 to 60cm and there is not a serious anaerobic conditions effect, deeper root exploration is thought to be limited either by the presence at some time of anaerobic conditions, or by discontinuity in the air space, where a significant increase in coarse fractions and large macropores exists.

5.5.2 Soil physical analyses

The distribution of soils according to depth of fine earth was analyzed (Figure 5.11). The eastern ridge, with very gravelly texture from the surface, and only 40 % of fine earth in the topsoil, represents approximately 3.5% of the total area. This soil has 1% clay in the fine earth. Soils with more than 60% of fine earth to less than 20 cm depth are estimated to be over most of the area (51%). These soils have less than 0.5% clay as a percentage of fine earth. Soils with more than 60 % of fine earth to 20 to 50 cm depth are found in 39% of the area. Only a small area of the vineyard (1.6%), in the northern part, has deeper fine textured soils with fine earth to 50-75 cm. Fine earth deeper than 75 cm is found in 2.2% of the total area. These soils have more than 2% of clay as a percentage of fine earth.

The deep soil in the north part of the property (site A) has the highest value of estimated total available water content (TAWC) up to 87 mm, followed by the soil of site F also with relatively fine particle sizes, averaging 46 mm of TAWC (Table 5.4). The rest of the soils have very low TAWC values, ranging from 20 to 29 mm. A detailed example of the calculations is shown in Appendix E. These estimates are not exactly the same as estimates made by Vincent (1999). Firstly, his estimates were made to 1.2

m depth and those made in this project are to 1 m depth. Secondly, even though the methodology used in both cases is the same (Griffiths, 1985, adjusted for the percentage of gravels), the gravelly nature of the soils does not allow for a very accurate estimation of the TAWC, and it is very variable over short distances. The estimated TAWC values are, however, in accordance with the texture and depth characteristics of these soils, being higher in sites A and F with finer size particle distribution and deeper topsoil at site A.

The high variability over short distances of these gravelly soils and a sample size that was too small resulted in very heterogeneous estimates for bulk density (obtained from the water replacement method). With such a wide range, the averages for each sample are meaningless. The same happened with the analysis made to estimate water content. The higher water contents of A horizons at sites A and F is expected, due to the finer particle size distribution. However, the relatively high moisture content of the A horizon at site B and of the C1 horizon at site F do not correspond to their coarse particle size. The methodology used in this experiment is not considered accurate because of the small size of the samples and the inaccuracies due to the gravelly nature of the soils.

Although percentage of macropores was not estimated, because of the coarse particle sizes, it is assumed to be high in these soils. On one hand, the gravelly texture of the soils and high macropore percentage facilitate root exploration. Stony or gravelly soils are preferred for viticulture because of: rapid drainage; infertility, which maintains a vine balance and fruitfulness in cool summer-rainfall climates and resistance to erosion. Through heat re-irradiation to the bunches at night, the stones in the soils also play a role in grapes ripening at the cool limit of viticulture (Gladstones, 1992). As an example, in Hawkes Bay, soil temperatures at 15 and 30 cm depths were found to be higher in gravelly and sandy soils when compared with silty and clayey soils (Tesic, 2001).

On the other hand, the shallowness of most of the soils of the vineyard determines that the volume where the roots can grow and obtain water and nutrients for root growth is limited. Moreover, shallow soils can readily alternate between waterlogging and drought, depending on the rainfall (Gladstones, 1992), determining that water supply or drainage should be very carefully managed.

5.4.3 Water table levels and soil drainage

The depth to the water table fluctuates during different seasons. The level of the Rarangi Shallow Aquifer is being monitored by the Marlborough District Council (2003) at the Golf Club (2.5 km north-north east of the vineyard). From March to September

2003 the water level rose half a metre in that well and a half metre more by the end of October (Figure 3.5).

A maximum total area of 27.5 ha (28% of the vineyard area) was estimated, in this work, to be affected by the rise of the aquifer by the 13th of October in 2003 (Figure 5.14). However, because of the coarse nature of the soils, this water remains in the profile for only a short period of time. While 16 wells had water on the 13th of October, only 8 had water on the 28th of October, and 5 on the 17th of November (5.7 ha were estimated to be affected by this date, which is less than 6 % of the total area of the vineyard). Most of the wells where water was detected were in hollows (Figure 5.14), with the exception of wells 18, 22 and 23 that were on a ridge in the north-east part of the vineyard. In accordance with that, Vincent (1999) suggested that due to the fast flowing rate of the water table in the area studied (Figure 5.14), the water is permanently being aerated and anaerobic conditions are not expected to occur during medium-long periods of time. On the other hand, he stated that some implications for vine growth would result, although no detrimental effects were mentioned.

Findings in this work suggest that Vincent's appointment may not be correct. Moderately well drained soils have a high water table during part of the year, which was detected not only in the well measurements, but also from the gley and/or mottled horizons in many of the profiles. According to the classification given in USDA (2002b), this drainage class is for soils that are wet for a short time within the rooting depth during the growing season, and most mesophytic crops are affected. Well drained soils are those where water is removed from the soil readily, internal free-water commonly is deep or very deep; and wetness does not commonly inhibit growth of roots. The mottles and gley colours observed in some of the profiles described, suggest that the anaerobic conditions are long enough and may probably cause detrimental effects on the vines production (soil descriptions made for pits excavated when wells were installed are included in Appendix C), classifying as moderately well drained according to the USDA classification. Barriers such as water tables restrict root depth, and if the root activity is restricted in spring, probably spring growth would also be restricted. Hence, it is suspected that a poor root activity in spring may be one of the factors for failure of bud burst or restricted shoot growth in the following season (Coombe & Dry, 1988). It was concluded that the high water table, even if temporary, may have some connotation for vine growth.

5.5.4 Pebble shape

Most pebbles described (Figure 5.16), are tabular or oblate, typical of a beach environment (Boggs, 2001). Fluvial pebbles would be expected to plot in the top right hand corner of the diagram (spherical).

The study of the pebble shapes reinforced the idea that the soils at the Rarangi vineyard were originally formed in a marine environment. If a quick calculation is done, taking into account a really rapid (for example 1m per year) progradation of the sea, inland beach ridges can be expected to be at least 1,500 years older than coastal ridges. This calculation is made in this work in order to have an idea of the possible different ages that the ridges may have.

5.5.5 Soil chemical analyses

The soil fertility of all samples is in the middle-low class of Webb & Wilson (1995) as indicated by the values of cation exchange capacity, and available sulphur, and low for potassium (Table 5.6). Field levels are even lower than the results found by the test, as it was made on the fine earth fraction, which means that in some cases a large amount of stony, inert material has been removed from the sample prior to analysis.

Some of the pH values registered are below the optimum range (5.8-6.8) for vine development (Caspari, 1996). Although vines can grow over a range of pH from 4 to 8.5, most plants do not prosper in soils below pH 5.6. If soils are too acid, phosphate becomes unavailable, and Mn and Al may be available to plants in toxic quantities (Coombe & Dry, 1992). Because lime causes a greater rise in pH than does gypsum, it was expected that samples that came from places where lime was added, would have higher pH values, but this is not always so. Similarly, a connection between application of superphosphate and higher phosphorus values is not found. This could be either because the amount, the moment, or the soil condition when the fertilizer was incorporated was not appropriate to note the difference.

Potassium and phosphorus contents are low (Table 5.6) when compared with the range recommended by MAF (Caspari, 1996) for grape growing (Table 5.9). Magnesium and sulphur are within the recommended ranges.

Table 5.9 Recommended soil quick test soil levels (MAF units) for wine grapes in New Zealand.

pH	Ca	P	K	Mg	S(SO4)
5.8-6.8	10+	30+	15-20	20-40	10+

Source: Adapted from Caspari, 1996.

No explanation was found for such variability in phosphorous analysis (Table 5.6). Fertilizer is applied according to the vine plant's age and variety. The differently fertilised blocks of the Rarangi vineyard (year 2003) are illustrated in Figure 5.17 (amounts were not given due to commercial sensitivity). The variability of chemical properties does not respond to the differential fertilization.

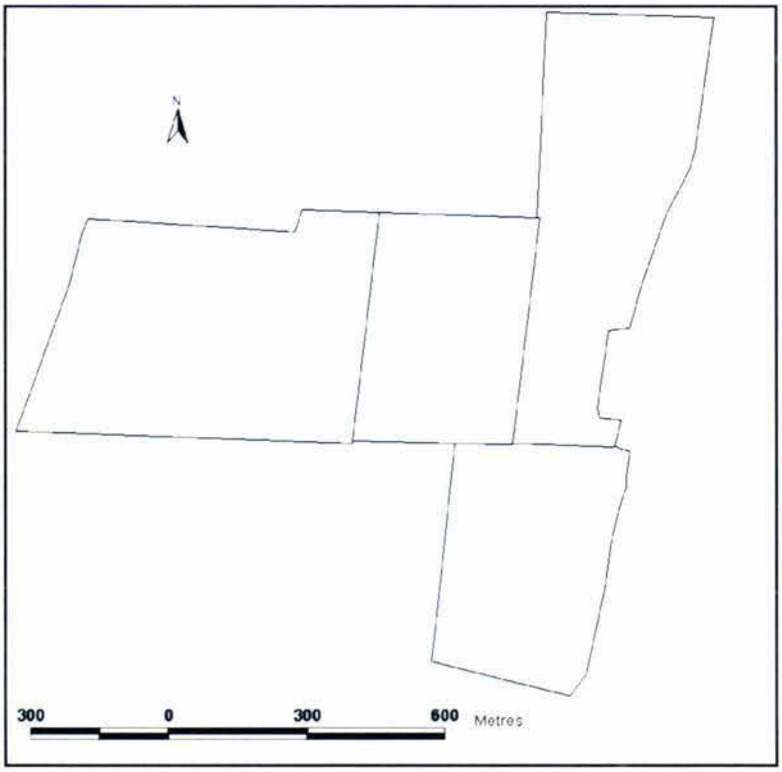


Figure 5.17 Map showing differently fertilised blocks of the Rarangi vineyard according to the schedule in 2003.
Note: amounts were not given due to commercial sensitivity.

The higher fertility found in hollow areas might be a response to higher moisture values (either higher TAWC and/or less leaching) of these areas, and hence, higher organic carbon contents. It is recommended that organic carbon contents be analysed in the future. It is also suggested that hollow and ridges areas be sampled separately.

5.5.6 Potassium in vines and soils

Exchangeable K values (0.2 meq/100g average) found in the soils of the vineyard are very low values according to Metson, 1980, and are also low when compared to the recommended levels by MAF (Caspari, 1996). These low values are not reflected in the high values (3.2%) found in petioles at flowering (Diane Stewart, December 2002, personal communication).

A hypothesis for the high K content of vines was the possibility of high reserve potassium content. Due to the sand and gravelly composition of the soils, K may be present as mica. Two methods available to assess reserves of K in soils are the modified sodium tetraphenylboron or TPB (Jackson, 1985) and the Kc (Metson & Lee, 1977). The TPB was the method used in this project, and results are shown in Table 5.9. The TPB method yields in general higher values than the Kc method, and in a study made with both methods for a range of different soils, while the Kc ranged from 0.10 to 0.76 meq/100 g; the TPB ranged from 0.36 to 4.2 meq/100g (Jackson, 1985). Although no rating classes are available for the TPB method, average values of 0.3 - 0.4 obtained for the soils in the studied vineyard, are low when compared to the values obtained in the mentioned experiment. No pattern of higher and lower values is identified (Table 5.8).

The hypothesis that the high K content of vine petioles comes from high soil reserve potassium content, was definitely discarded after low values of reserve K were found. Another hypothesis is that the high potassium content in the vines is being provided with the water irrigated in the vineyard. This hypothesis seems to be the most likely. Potassium levels tested in a well in the vineyard that takes water from the Wairau Confined Aquifer, were 9.9 and 12 mg/l in the years 2000 and 1998 respectively (Close, 2001), being one of the highest values detected for all the wells and aquifers studied in the region.

Furthermore, the fact that the soils have such low clay content practically eliminates the possibility that the K added with water is fixed. On the other hand, it is also true that because of the large amount of macro-porosity, leaching would quickly take place. However irrigation of gravels is done in small frequent intervals to guard against inefficient deep percolation. The analyses of the nutrient status of the vines were carried out in December/January, when the vines were being irrigated with this water.

It is therefore likely that high K values found in vine petioles are because of the high values of the water used for irrigation.

5.6 Summary

Soil physical and chemical characteristics of soils in the Rarangi vineyard were found to be in general homogenous; however some differences in properties could be described. Topography, groundwater depth as well as particle size distribution in the profiles played an important role in determining these differences. Results of chemical analyses were quite variable among samples.

Soils have in general 20 cm of gravely topsoil. The most common soils are represented by samples on sites C, D and E. These samples have more than 50% of sand in the topsoil. Sites C and D have 0.3% of clay as percentage of fine earth; however site E has the highest clay content (2.4%). The C horizons in these soils (from 20 cm depth onwards) are very gravelly. Moreover, sites C and E have more than 60% of gravels coarser than 20 mm in deeper horizons (from 45-50cm). The coarsest particle size distribution is found in the eastern stony ridge, represented by site B where, even in the topsoil, more than 40% of the mass is gravels coarser than 20 mm.

Soils in the north of the vineyard have the finest particle size, with more than 50% of fine earth (<2mm) in all the horizons and almost no gravels coarser than 20 mm. Site F has similar particle sizes to site A both in the topsoil and in the lowest horizon, but a C1 horizon occurs at 15 cm depth with 60% of gravels larger than 20 mm.

Soil fertility as indicated by the CEC and nutrient content was low in all the samples. In same cases pH was lower that that desired for optimum grape growing. A slight difference was found between the samples from ridges and hollows, being that the hollows were less acid and had higher fertility. So it is recommended to maintain the schedule of applying lime to increase pH, especially in ridges areas. It is thought that the higher fertility is related to higher organic carbon values, though it could not be proved because organic matter content was not analysed. It is recommended to perform an organic carbon analysis from both hollows and ridges in order to achieve a final conclusion on the distribution of these differences and formulate an adequate differential management strategy. Vines are planted parallel to beach ridges and hollows, which would facilitate adoption of this practice.

Particle size distribution is reflected in the estimations of TAWC. Site A has the higher values with an average of 86 mm to 1 m depth; site F has 46 mm, and the rest of the sites between 20 and 29 mm. These low TAWC values correspond to the high gravel percentages of the soils, and determine the necessity of irrigation during the vine's growing-season.

Because of the gravelly nature of the soils, where percentage of gravels changes in a short distance, large samples must be taken to accurately estimate bulk density and moisture content. In this study the samples were too small and results obtained are not reliable.

Most of the vineyard is extremely well drained. Nevertheless, wells installed both in ridge and hollow and intermediate areas, allowed an estimate to be made of areas affected by a high water table (within one metre below the surface) during part of the year. Hence, because of the rise of the Rarangi Shallow Aquifer, and notwithstanding the coarse texture of the soils, part of the vineyard in hollows areas was classified as moderately well drained.

The high (3.2%) K levels found in vine petioles during flowering could not be associated with the concentration of exchangeable K nor with K reserves in soils. Because of the high K levels reported for a sample of the water used to irrigate the vineyard, it is suspected that this is the explanation for such high levels. Before a final conclusion, it is suggested to take more samples of the water.

CHAPTER 6

Correspondence of soil properties to EC_a values

6.1 Introduction

The distribution of EC_a values, the physical and chemical properties analysed in the present study, the descriptions made when the wells were installed, the descriptions and soil physical properties noted by Vincent (1999), and the geomorphology map (ridges and hollows), were all considered when compiling the map of soil variability of the property. The variability reflected:

- textural variations in the profiles (depths of different textures and percentages of gravels),
- total available water content of the soils and cation exchange capacity, both of which reflect the texture of the soils, and
- the height to which the water table rises in spring time.

6.2 Methodology

Electroconductivity maps (Figure 4.7 to 4.9) obtained from the survey made in March for both dipole orientations and the survey made in September for the vertical dipole orientation, were analyzed and compared to define the EC_a values distribution over the property in different soil moisture conditions. The differences and similarities between the maps were noted and explained. Different EC_a values for the same areas in two different seasons allowed some interpretations related to soil properties. On the other hand, it was not possible to create an integrated EC_a map because of the large variability in the data.

All layers of digital information were subsequently overlaid and cross-table analysis was performed within ArcView and Idrisi. The relationships between EC_a class distribution and soil properties (water content averaged to 1m depth, depth of fine earth, and depth to a gley layer) were established visually. An association of EC_a values with different soil properties was examined. Soil data used included data generated in this project as well as the survey made by Vincent (1999).

The different values in the EC_a maps were interpreted in terms of soil properties and geomorphology. Based on the EC_a maps, topography and soil interpretations, and using on-screen digitizing, a map of soil-geomorphic units was produced (Figure 6.1). Two attribute data tables were also created and added to the database describing soil variability (Tables 6.2 & 6.3).

6.3 Results

As a result of the integrated analysis of soil data, well measurements, contour survey using a RTK-DGPS and EC_a surveys using the EM38, five soil-geomorphic units were identified:

- 'deep', in the northern part of the vineyard, more than 60 % of fine earth to more than 75 cm depth;
- 'stony ridge', in the eastern part of the vineyard, very gravelly, coarse gravels from the surface;
- 'ridge wet', in the northern part of the vineyard, very gravelly from the surface, presence of temporary high water table;
- 'shallow', mainly ridge areas, with more than 60 % of fine earth mainly to 20 and some places to 50 cm;
- 'shallow wet', mainly hollow areas, with more than 60% of fine earth mainly to 50 cm and some areas to 20 cm, presence of temporary high water table.

The corresponding observations, samples and total area for each unit are summarized in Table 6.1. A discussion of how these units were defined and the soil properties that define each unit is presented in the following sections.

Table 6.1 Geomorphic position and availability of physical, chemical and water table information for the six soil-geomorphic units.

Soil-geomorphic Unit	Topo-graphy	Samples for physical analysis	Samples for chemical analysis	Wells*[1]	Area (ha)
Deep	hollow	A	9	24	2.0
Stony ridge	ridge	B		9	4.3
Ridge wet	ridge	-------	2	23	1.3
Shallow	ridge	C, D	1, 4, 6, 7	3, 7, 13, 14, 16, 18	
	hollow	-------	3, 5, 10	11, 22, 27, 28	63
Sh. wet	hollow	E, F	8	1, 2, 4, 5, 6, 8, 10, 12, 15, 17, 19, 20, 21, 25, 26	27

*[1] Descriptions of these profiles are presented in Appendix C

6.3.1 Soil-geomorphic units

The distribution of the five soil-geomorphic units identified is shown in Figure 6.1. For an easier interpretation, the map is presented overlaying the aerial photo of the vineyard.

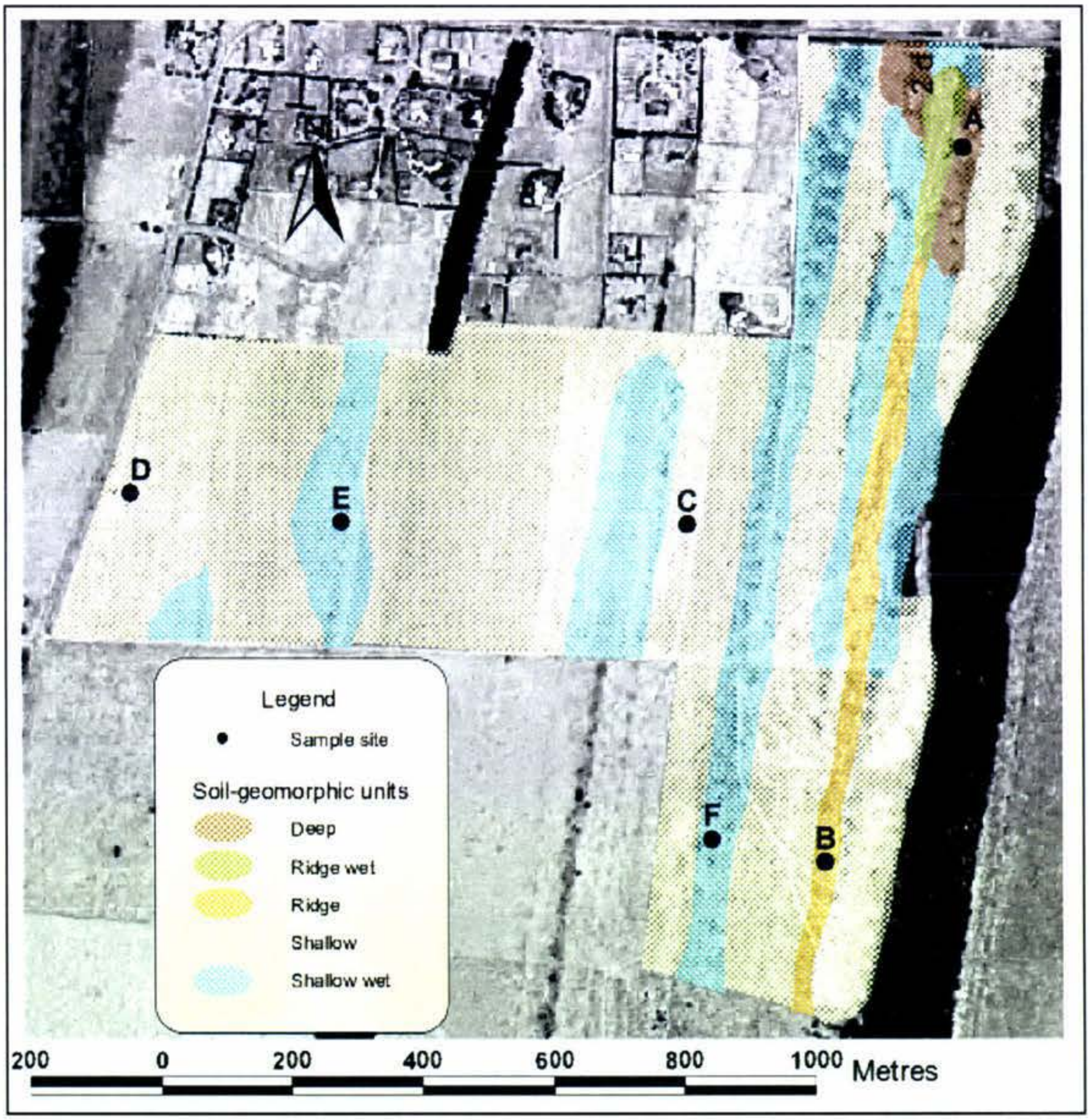


Figure 6.1 Aerial photograph of the Rarangi vineyard showing the sample sites for physical properties analysis and the soil-geomorphic units after an integration of the EC_a maps with the soil and landscape data collected in the traditional way.

Table 6.2 A summary of soil chemical analysis for each soil-geomorphic unit.

Soil-geomorphic units	Hz.	N	pH	Olsen P µg/g	CEC	K	Ca meq/100g	Mg	Na	SO4 µg/g	Soil volume g cm $^{-3}$	Base Saturation %	Res. K meq/100g
Deep	A	1	6.7	9.8	21.0	0.20	14.2	2.5	0.4	7.3	1.00	82.0	0.3
	C	1	6.4	3.8	6.0	0.05	3.8	0.95	0.11	2.5	1.38	80.0	nd
Ridge Wet	A	1	5.0	35.7	15	0.32	5.7	0.52	0.23	14.5	1.13	43.0	0.4
Shallow	A	7	5.6	16.2	17.7	0.20	7.2	0.9	0.3	13.4	1.10	49.8	0.2
	C	2	5.5	15.9	7.5	0.10	1.4	0.2	0.1	2.8	1.50	25.5	nd
Sh. Wet	A	1	6.9	8.1	23.0	0.38	18.7	2.66	0.33	10.3	1.06	95.0	0.9

Note: The Stony Ridge unit was not represented by any sample. Hz represents horizon and N represent the number of samples that describe each unit.

Table 6.3 Soil morphological properties summarized for each soil-geomorphic unit.

Abbreviations used: Hz, horizon; gr, gravely; L, loamy; Sa, sandy; c, coarse.

Soil-geomorphic unit: Deep
Microtopography: Hollow

N.Z. Soil classification: Mottled Orthic Recent Soil
Drainage: Moderately Well Drained

Hz	Bottom (cm)	Colour	Texture	Gravel %, size	Structure	Roots	Mottles	TAWC (mm)
Ap_1	20 to 32	Very dark greyish brown	grLSa	5, fine	weak, crumb	common	----------	
$2Ap_2$	45	Dark/Very dark greyish brown	LSa/grSa	10/25, fine/coarse	weak, crumb	common	----------	
Cg_1	65	Dark greyish brown	LSa	-----------	structureless	few	abundant, 2.5YR4/8	
C_2	85	Dark grey	cSa	-----------	structureless	few	-----------	
$2C_3$	100	Grey	cSa	25, fine/coarse	structureless	---------	-----------	86

Soil-geomorphic unit: Shallow Wet
Microtopography: Hollow

N.Z. Soil classification: Mottled/(Typic) Orthic Recent Soil
Drainage: Moderately Well / Well Drained

Hz	Bottom (cm)	Colour	Texture	Gravel %, size	Structure	Roots	Mottles	TAWC (mm)
Ap_1	15/20	Very dark grey/greyish brown/ Dark brown	grLSa	5/25, fine/coarse	weak, crumb	common/ abundant	----------	
(Cg_1)	0/30	Dark greyish brown/Dark brown/Dark yellow.brown	grSa	50, fine to very coarse	Structure-less	common	abundant, 7.5YR 4/6,5/8	
C_2	45/50	Dark/Very dark greyish brown /Very dark grey/Dark grey/ Grey	grcSa/ grLSa	5/10, fine to very coarse	Structure-less	few to abundant	-----------	
$2C_3$	60/65	Dark greyish brown to Very dark grey	grcSa	25/75, coarse/ very coarse	Structure-less	few	-----------	
$2C_4$	100	Very dark/Dark grey/ Dark greyish h/Dark brown	grcSa/ gravels	25/100, fine/coarse	Structure-less	---------	(abundant, 10YR 5/6); (water)	20 to 54

Soil-geomorphic unit: Shallow
Microtopography: Ridge

N.Z. Soil classification: Typic Orthic Recent Soil
Drainage: Somewhat Excessively Drained

Hz	Bottom (cm)	Colour	Texture	Gravel %, size	Structure	Roots	Mottles	TAWC (mm)
Ap_1	20	Very dark grey/greyish brown	grSa/grLSa	10/25, fine/coarse	weak, crumb	common/ abundant	----------	
C_1	30	Dark/V. dark greyish brown/ Dark brown/Dark yellowish brown/Brown	grcSa/ gravels	25/75, fine-coarse	structure-less	common	---------	
$2C_2$	45/60	Very dark greyish brown/ Dark brown	grcSa	50, fine	structure-less	few	----------	
$(3C_3)$	70/100	Very dark grey/Dark brown/Dark yellowish brown	grcSa	25/75, coarse/ very coarse	structure-less	few	----------	
$4C_4$	100	Very dark grey/Dark brown	grcSa/ gravels	25/100, fine	structure-less	----------	----------	20/32

Soil-geomorphic unit: Stony Ridge **N.Z. Soil classification: Typic Orthic Recent Soil**
Microtopography: Ridge **Drainage: Somewhat Excessively Drained**

Hz	Bottom (cm)	Colour	Texture	Gravel %, size	Structure	Roots	Mottles	TAWC (mm)
Ap$_1$	20	Very dark grey	grSa	25-50, coarse/ very coarse	structure-less	common	----------	
C$_1$	50	Dark brown	grcSa	50-75, coarse/ very coarse	structure-less	common	---------	
2C$_2$	100	Very dark greyish brown/ Dark brown	gravels	100, fine/coarse	structure-less	few	----------	20/27

Soil-gemorphic units: Ridge Wet **N.Z. Soil classification: Typic Orthic Recent Soil**
Microtopography: Ridge **Drainage: Well Drained**

Hz	Bottom (cm)	Colour	Texture	Gravel %, size	Structure	Roots	Mottles	TAWC (mm)
Ap$_1$	20	Brown	grLSa	5, fine	structureless	common	----------	
C$_1$	50	Dark greyish brown	grSa	25-50, fine	structureless	common	---------	
2C$_2$	100	Dark greyish brown	gravels	100, fine/coarse/ very coarse	structureless	----------	----------	n/d

6.3.2 Presence of water table

The electoconductivity survey made in late September (Figure 4.10) was compared with the presence of a high water table on 30th September. High EC_a values are commonly found in soils with high water tables.

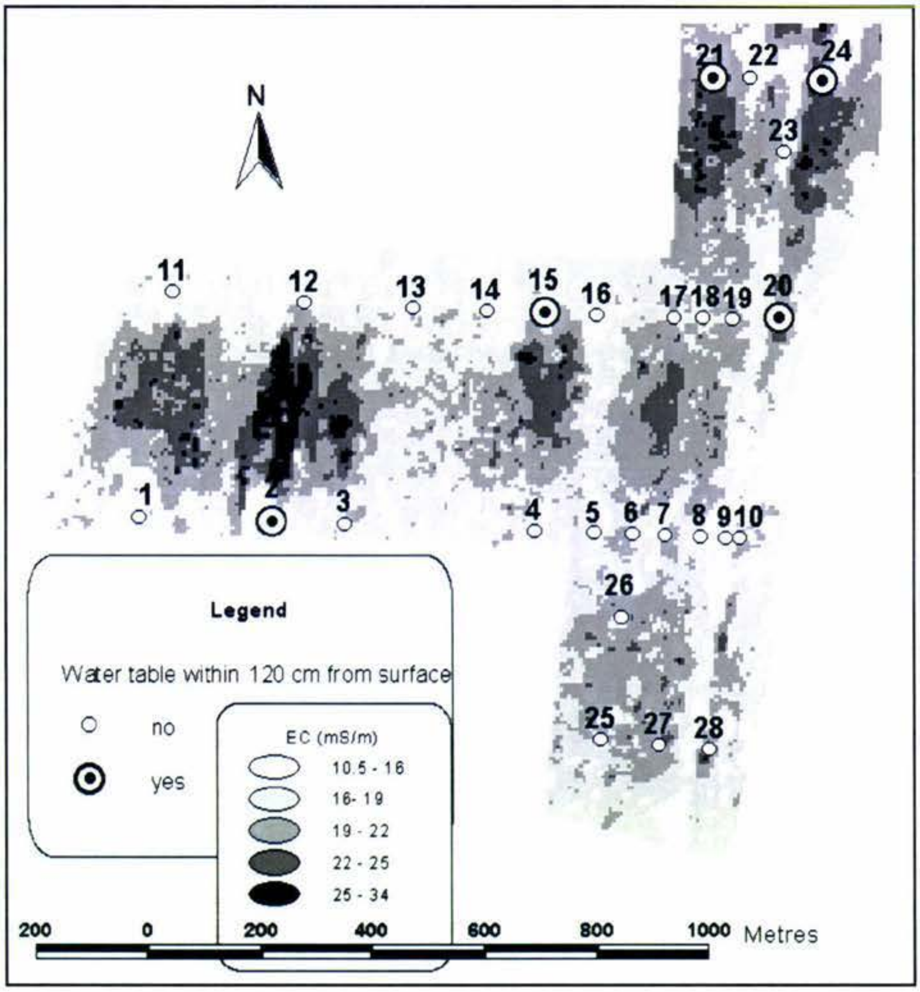


Figure 6.2 Wells with water within 100 cm below the surface on 30th September, and soil conductivity map for 18th and 19th September.

Measurements of water table depths were made in the wells on 17th Sept. and 30th Sept. In places the water table rose about 25 cm between these two dates. On the 17th Sept., only wells 15 and 20 had water within 100 cm of the surface; on 30th Sept. water was also found in wells 2, 21, 24 and 26 (Figure 5.14). All these wells had water within 120 cm depth by this date (Figure 6.2). Because the deep-mode EC_a values are an average of the first 150 cm below the surface (Sudduth *et al.*, 1998), it was expected that high water table levels within 120 cm from the surface would be reflected in the readings.

6.4 Discussion

6.4.1 Soil texture variation

The EC_a survey was sensitive to a large percentage of material larger than 20 mm in the A horizons. This was demonstrated by the lowest EC_a values being found on the stony eastern ridge for all the surveys (Figures 4.8 to 4.10):

- shallow EC_a measurements in March less than 15.5 mS/m
- deep EC_a measurements in March less than 13.5 mS/m
- deep EC_a measurements in September less than 15.5 mS/m.

This stony ridge was represented by sample B, with the highest percentage of material coarser than 20 mm in the A horizon (more than 50%). The ridge had been identified in the survey made by Vincent (1999) as '5vsh' ("good" drainage and very shallow, having fine earth to less than 15 cm). The distribution of this soil-geomorphic was defined more accurately by EC_a survey than by the traditional soil survey (Figure 6.3).

With the EC_a survey it was also possible to distinguish the deep soils in hollows in the northern part of the vineyard; here the gravels tend to be deeper in the profile. This area showed high EC_a values for all the surveys:

- shallow and deep EC_a measurements in March more than 19.5 mS/m
- deep EC_a measurements in September higher than 22 mS/m.

This area was delineated better in the March survey than in the September survey. In September, high values were also found in areas with shallow gravels. This could have been due to the presence of high water tables and will be discussed in the water table section.

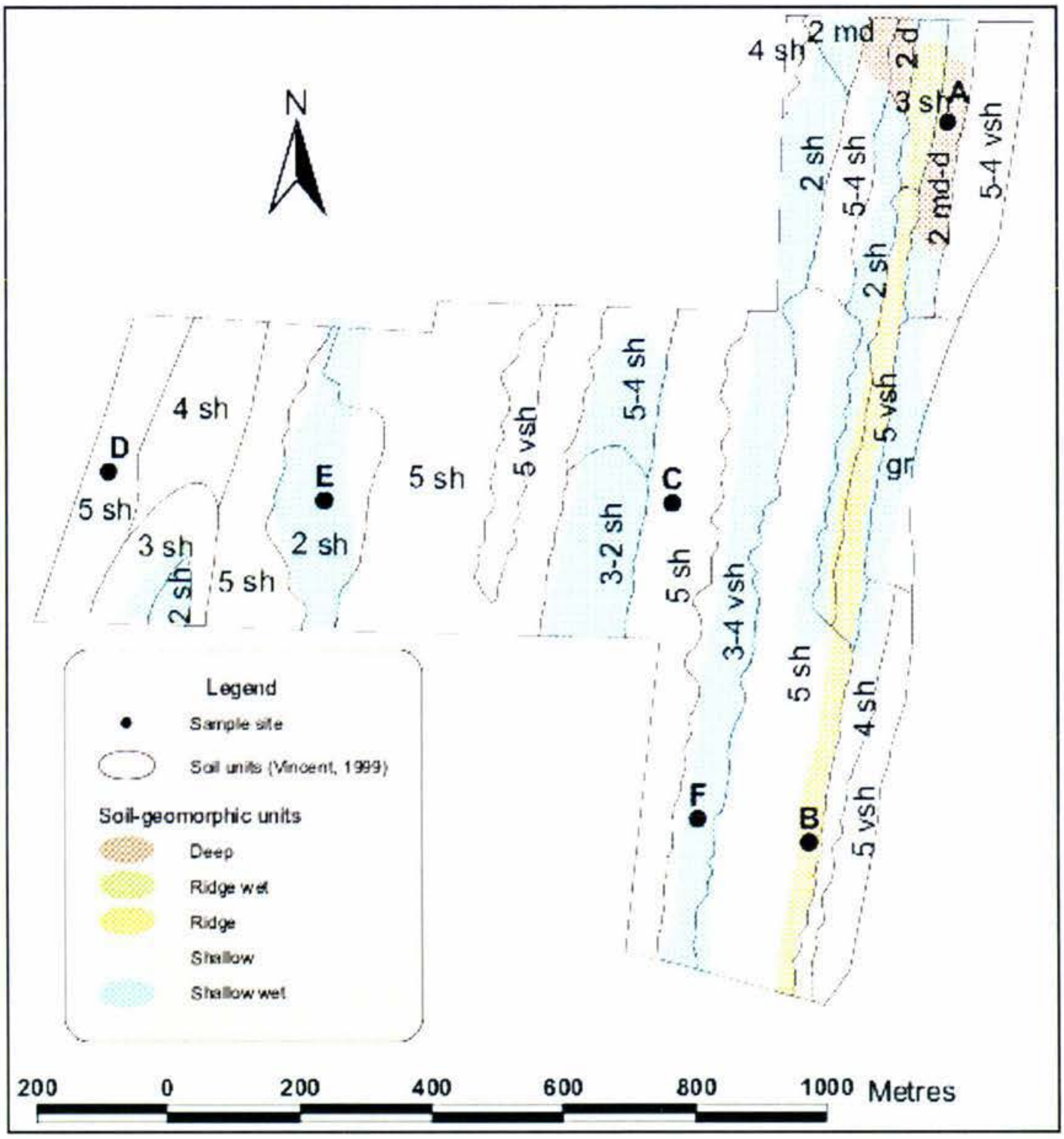


Figure 6.3 Comparison of soil-geomorphic units obtained after integrating EC_a data with soil landscape data and soil units identified using the traditional soil survey method by Vincent (1999).
Note: Numbers represent classes for drainage: 2, "poor"; 3, "imperfect"; 4 "moderate good" and 5, "good". Depth of fine earth is represented as follows: vsh, <15 cm; sh 15-45 cm; md, 45-75 cm and d, > 75 cm.

A 'Deep' soil unit, with almost the same distribution as the 'Deep' soil-geomorphic unit was identified by Vincent (1999) – see Figure 6.3. He named the unit '2 md-d' - "poorly drained and moderately deep to deep, fine earth to more than 45 – 75 cm."

On the other hand, minor differences in fine earth percentages of topsoils, are not detected by the EC_a survey. Soils samples A, C, E and F are all included in areas with the highest EC_a values (class 19.5-22.5 mS/m) for the shallow-mode survey made in March.

Soil samples A, C and F, have the most fine-grained particles in the topsoils (Figure 5.8), with an average of more than 75% of fine earth. However, sample E had an average of less than 50% of fine earth and yet has high EC_a values (Figure 4.9). On the other hand, samples B and D, with similar fine earth percentages as sample E, have lower EC_a values in the shallow mode.

In the western part of the vineyard, the deep-mode EC_a survey measured in March (Figure 4.8) showed very different EC_a values for samples D and F (around 16 compared to values of around 11 mS/m respectively). Both soils have less than 50% of fine earth in the A horizon. This lack of a relationship between soil variability and soil EC_a data was also reported by Pitcher-Cambell (2001) in stony soils.

Finally, due to the low clay content of these soils (Table 5.1), it was not unexpected that no relationship existed between EC_a values and clay content. Samples E, F and A, all from hollow areas, have between 1.8 and 2.4% of clay as percentage of the fine earth on the A horizons. Samples B, C, and D, all from ridge areas, have even lower clay contents (between 0.3 and 1%). Topsoils in hollow areas have slight higher clay contents than on ridge areas, but it is not enough to be detected by the EC_a survey.

6.4.2 Soil chemical properties

Chemical properties and total available water are strongly related to the clay content of soils, and have been reported to influence EC_a readings in previous works. However, the soils of the vineyard studied have very low clay content, and the variability observed in soil chemical properties (pH, cation exchange capacity and base saturation, P) did not follow a clear pattern. Although a trend of higher fertility in hollows when compared to ridges was noted (as discussed in Chapter 5).

The main differences among chemical data are: higher pH, CEC, Ca^{++}, Mg^{++}, and base saturation values in both the 'Shallow Wet' and 'Deep' (Table 6.2) soil-geomorphic units. The highest CEC values, 23 and 21 meq/100 g respectively are measured for the topsoils of these units, while CEC values of 17.7 and 15 meq/100 g were measured for topsoils of the 'Shallow' and 'Ridge Wet' soil-geomorphic units respectively.

Likewise, the highest values of pH for the topsoils were 6.9 and 6.7 for the 'Shallow wet' and 'Deep' soil-geomorphic units respectively; a pH value of 6.4 was measured for the C horizon of the 'Deep' unit. These units also have the highest base saturation percentage of 95 and 82 for the topsoils and 80% for the C horizons.

Due to a lack of samples per soil-geomorphic unit in this study, chemical data were not analysed statistically and the results should be taken only as indicative evidence. In spite of this, a targeted sampling for chemical analysis based on the soil-geomorphic units identified here is recommended.

Deep-mode EC_a values for the eastern part of the vineyard in the March survey show higher values in hollow areas. However, this could not be associated to the higher fertility of the soils. The higher EC_a values were more likely to be related to texture and moisture content. This was more evident in the September survey.

6.4.3 Total Available Water Content

Total available water content was found to be strongly related to soil texture and depth of soils.

Sample A, with the highest estimated TAWC (86 mm to 1 metre depth), had the highest EC_a value in March (>19.5 mS/m), and is represented as the 'Deep' soil-geomorphic unit (Figure 6.1). The intermediate value of TAWC (46 mm/m), estimated for sample F, is in the area labelled as "shallow-wet" soil-geomorphic unit and showed medium-high values of EC_a (17.5-19.5 mS/m) in March. The rest of the samples, with even lower TAWC estimated (from 20 to 29 mm/m), have lower EC_a values (< 17.5 mS/m) in March (See Table 5.3 and Figure 4.8).

These results confirm that water content is an important parameter influencing the EC_a readings (Mc Neill, 1980; Hedley et al, 2002; Kachanoski *et al.*, 1988; Hartsock *et al.*, 2000, Morgan *et al.*, 2000, Hedley *et al.*, 2003; DSE, Victoria, Adelaide, 2002; and Doeger, 2001).

6.4.4 Water table

In the September survey, regions with high EC_a values (>19mS/m) were detected in close proximity to wells estimated to have free water within 120 cm of the surface (Figure 6.2). Areas with EC_a values lower than 19 mS/m did not have free water within 120 cm of the surface. This result is in accordance with Doolittle *et al.* (1995) who stated that values of apparent conductivity were higher on flood plains and low terraces than on the dissected upland. These authors attributed high EC_a values to wetter soil conditions and higher water tables, apart from other soil characteristics. Also Kravchenko *et al.* (2002) mentioned that the slopes and the EC measurements were among the main factors used to separate "somewhat poorly drained" and "poorly drained" soils from "moderately" and "well drained" soils.

On the other hand, well 28 was also in an area with high EC_a values and paradoxically, no water was detected in this well for any of the dates (Figure 6.2). Unfortunately, not all areas with high EC_a values were monitored for the water table levels; data from more wells could have helped formulate a definite conclusion.

6.5 Implications of findings for vineyard management

For site-specific management, it is important to capture spatial variations across the vineyard as accurately as possible. If no information about soil variability is available, a dense soil sampling is needed in order to obtain sufficient information. Since a tendency for higher soil fertility and pH values is often connected to higher soil moisture content in hollow areas, the results can be used to plan a targeted sampling schedule. In future, locations for sampling can be chosen so that the soil variations are accurately identified. This targeted sampling will reduce the number of samples required, improve the accuracy of the results and reduce the cost of sampling. Management decisions regarding soil fertility and low pH problems can be better addressed.

Similarly, the soil-geomorphic units and associated database could be used to adjust the present irrigation schedule. A differential watering regime may be adopted to maximize the irrigation efficiency and minimize loss to ground water. The deeper soils identified in the northern part of the vineyard named 'Deep' soils, have an estimated TAWC of 85 mm/m of soil on average, while the rest of the vineyard have TAWC estimated values of 20 to 46 mm/m of soil. The frequencies and amounts of water irrigated should take these results into account. For example, the more gravelly soils could be irrigated more frequently and with lower application rates while on the other hand, deeper soils could be irrigated less frequently but with higher application rates. Since the vines are planted following the direction of the hollows and ridges, a differential management would be easier to implement.

Furthermore, if it was the case that the moderately well drained areas ('Deep' and 'Shallow wet' soil-geomorphic units) were seriously affecting vine performance, some deep artificial drainage may be required. Presently, there is no practical solution because the water tables are due to rises in the Rarangi Shallow Aquifer and hence very difficult to control.

6.6 Opportunities to improve future trials

Even when some association is found between EC_a values and different soil properties, it is not always clear. This could be explained in part by the highly variable nature of these alluvial gravelly soils within short distances, especially when only a small size sample is taken. For future trials it is highly recommended that point EC_a values be recorded where the profiles are described and samples taken, besides the mobile EC_a survey. In that way, it will be possible to know the EC_a values that correspond exactly to the soil described and sampled.

Samples taken from places only few metres apart show markedly different gravel contents. An accurate physical study of these soils should involve larger amounts of soil being taken for each sample. For that reason, the methodology used in this project to study moisture content and bulk density did not ultimately prove to be adequate and is not recommended for use in future research.

Because different soil properties can be detected when EC_a surveys are made in dry and wet soil conditions, it was regarded as very beneficial to do so, and it is highly recommended that the same practice be followed in future investigations.

Both the March and September EC_a surveys were made in two days. In accordance with a report made by Sudduth *et al.* (2001), instrument drift readings were determined when comparing measurements taken on two consecutive days. A similar approach to that suggested by these authors to compensate drift problems was made in the September survey, when EC_a readings were made both days for a certain area. However, this approach did not prove to be good enough and compensation could not be carried out. For future trials, it is suggested that EC_a values be read along a transect several times during the course of a field survey, so that any drift can be documented and compensated. It is also highly recommended that a trial be performed to calibrate the EM38 and measure drift effects.

Finally, to be able to make conclusions about the correspondence of high EC_a values and a high water table, a different distribution of wells could have been used. In order to check for high water tables in the middle of the field where high EC_a values were read in September, more wells would have to be installed.

CHAPTER 7

Conclusions

Variability in soil texture, total available water content (TAWC), fertility and drainage, all influence yield and homogeneity of grape production. Hence, accurate mapping of this variability across a vineyard is of great importance for improving management decisions such as those on fertilization and irrigation schedules. In this project, the use of an electromagnetometer (EM38) sensor, and a real-time kinematic differential global-positioning system (RTK - DGPS), together with soil descriptions and analysis, allows an assessment of soil variability and a map of soil-geomorphic units to be produced. The resulting map moderately corresponds to a soil map produced with the traditional soil survey methodology.

A comparison of the deep and shallow electroconductivity (EC_a) surveys confirms the finer texture of topsoils since higher values are observed for the shallow survey across the entire field. Similarly, higher values are measured for the September deep survey when compared with the March survey. This confirms the expected higher EC_a values in spring due to the higher moisture content of the soils.

The variations in the shallow EC_a survey made in March depicts the extremes in soil textures, showing the lowest values (13.5 to 15.5 mS/m) along the stonier ridge. Likewise, variations in the deep EC_a survey made in March depicts texture variations, showing the lowest values (5.5-15.5 mS/m) for this stonier ridge and highest values (19.5-24.5 mS/m) for the deepest soils. Furthermore, the highest EC_a values found in this survey also correspond to the highest estimate of TAWC (86 mm/m against 20 to 46 mm/m for other soils).

A relationship between micro-morphology and the EC_a survey made in March is also observed, connecting higher values to hollows. Also higher fertility (higher CEC, pH, %BS, Ca, and Mg contents) is associated with hollows, as result of higher moisture content. A targeted sampling for chemical analysis based on micro-topography (ridges and hollows) is recommended. This targeted sampling reduces the number of samples required, and at the same time improves the accuracy of the results.

Nevertheless, none of the EC_a surveys could explain all the variation in the soils. Field observations and the topographic survey are the main influences defining and mapping soil-geomorphic units.

For future work, it is recommended that static EC_a readings be carried out in exactly the same positions where the profiles are described and samples taken, besides the mobile EC_a survey. This will allow for more precise correlations between electoconductivity values and soil properties. If a mobile survey is made, it is recommended that readings are made along a transect several times during the course of a field survey, so that any drift can be documented and compensated for.

The EC_a variability in the September survey apparently corresponds to the presence of a high water table. Soils with a gley layer and water table detected within 120 cm from the surface generally have higher EC_a values in the survey made in September. Nevertheless, to verify the correlation, more wells need to be installed.

The present research identifies potential future research. To begin with, it should be proved that areas showing high EC_a values in September in the western part of the vineyard always correspond to high water tables. In addition, once the vineyard is in full production, it would be very interesting to monitor yield, and, using a GIS, create maps of yield variability. These maps could then be compared with the EC_a variability maps and topography maps, and, within-field management zones could be delineated.

Overall, it is concluded that the use of precision agriculture tools together with a traditional soil survey, provided more information about field soil spatial variation than the traditional soil survey alone. Stronger relationships with soil properties could be found in more clay rich soils, however, the EC_a survey made in these gravelly soils helped to depict the main soil texture and moisture content differences. The information generated can be useful for management decisions, maximizing the efficiency of use of resources and improving grape homogeneity.

This study was conducted in gravelly soils, which are generally preferred by viticulturists. Soil surveys using EM38 have scarcely been conducted before in this type of soil. Hence, viticulture and soil study in New Zealand will benefit from the knowledge generated by this study. This project provides opportunities for improving future research.

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Appendices

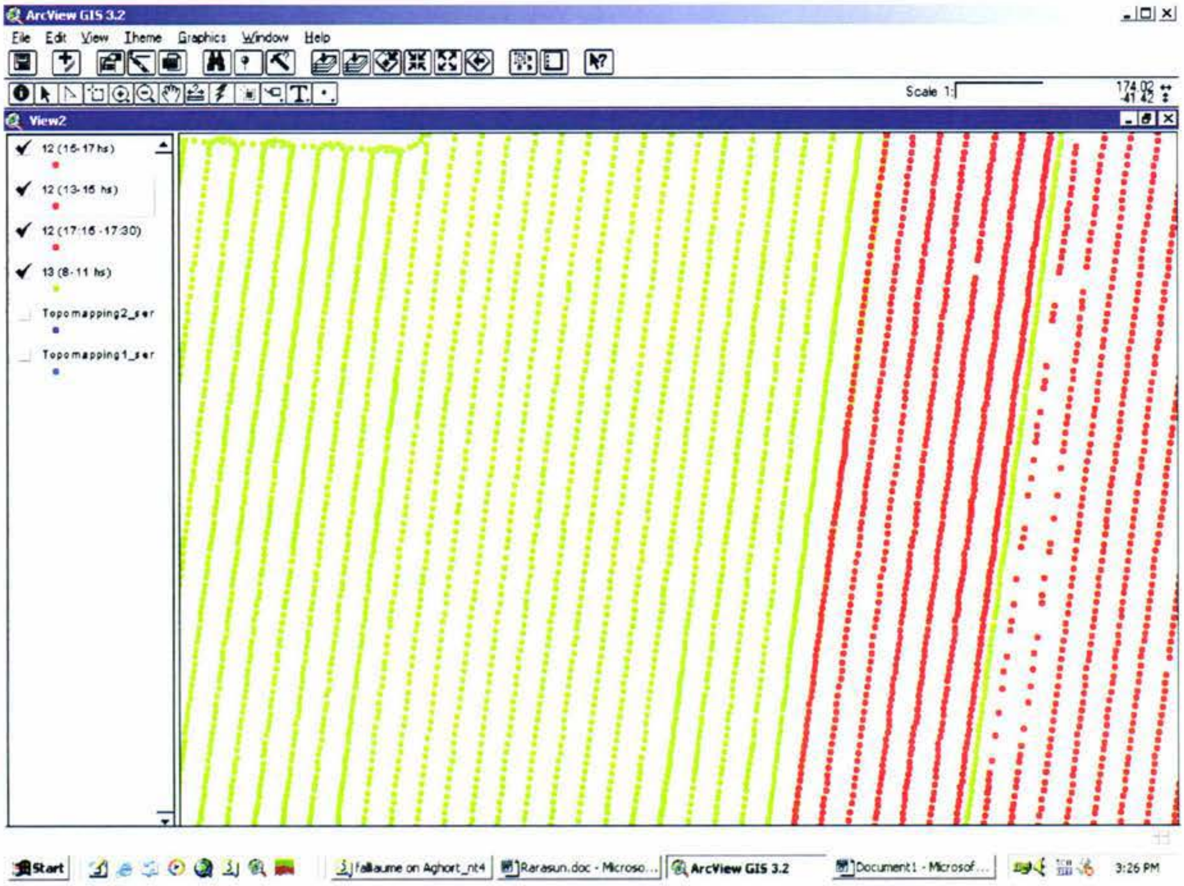
Appendix A.

Data base (.dbf) file after data transformation in ArcMap. X and Y are easting and northing coordinates respectively.

Latitude	Longitude	Height	X	Y
-41.4188573300	174.0233352000	3.51200	2595532.802170	5975943.636700
-41.4188573400	174.0233353000	3.51200	2595532.810510	5975943.635490
-41.4188573300	174.0233353000	3.51300	2595532.810530	5975943.636600
-41.4188573300	174.0233353000	3.51300	2595532.810530	5975943.636600
-41.4188573400	174.0233353000	3.51100	2595532.810510	5975943.635490
-41.4188572700	174.0233353000	3.51100	2595532.810600	5975943.643260
-41.4188573400	174.0233353000	3.51000	2595532.810510	5975943.635490
-41.4188593000	174.0233355000	3.49400	2595532.824680	5975943.417640
-41.4188731900	174.0233326000	3.43300	2595532.564180	5975941.878070
-41.4188979900	174.0233339000	3.53800	2595532.640540	5975939.122870
-41.4189225400	174.0233331000	3.56000	2595532.541700	5975936.397490
-41.4189554400	174.0233302000	3.62600	2595532.256440	5975932.746950
-41.4189912600	174.0233281000	3.68900	2595532.034250	5975928.771360
-41.4190279900	174.0233257000	3.69700	2595531.785800	5975924.695020
-41.4190668300	174.0233249000	3.70100	2595531.668340	5975920.382810
-41.4190907100	174.0233248000	3.69100	2595531.628880	5975917.731150
-41.4190907100	174.0233248000	3.69100	2595531.628880	5975917.731150
-41.4190907100	174.0233248000	3.69100	2595531.628880	5975917.731150
-41.4194555900	174.0233122000	3.70500	2595530.100420	5975877.225290
-41.4194556400	174.0233122000	3.72000	2595530.100360	5975877.219740
-41.4194566700	174.0233126000	3.70900	2595530.132450	5975877.104970
-41.4194709700	174.0233117000	3.68500	2595530.038600	5975875.517900
-41.4194978900	174.0233119000	3.68500	2595530.020250	5975872.528370
-41.4195313800	174.0233088000	3.71600	2595529.717510	5975868.812500
-41.4195694900	174.0233063000	3.75000	2595529.458910	5975864.583020
-41.4195917900	174.0233055000	3.78000	2595529.362990	5975862.107490
-41.4196446100	174.0233056000	3.83900	2595529.302550	5975856.241980
-41.4196850600	174.0233023000	3.87500	2595528.974030	5975851.753430

Appendix B.

Point map as displayed in Idrisi.



Source: Zoomed point file generated in this ArcView.

Appendix C.

Profile descriptions for the wells sites.

- Soil-geomorphic units: Deep gley

Well 24

Position: north block, row 100, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-32 Ap$_1$. Very dark greyish brown (10YR 3/2); loamy sand; friable; weakly developed blocky structure, medium; common roots; distinct boundary

32-45 Ap$_2$. Dark greyish brown (2.5YR 4/2); loamy sand; weakly developed blocky structure, medium; abundant medium (2.5YR4/8) mottles, distinct; common roots; distinct boundary.

45-80 C1. Dark grey (10YR 4/1); coarse sand; estimated 10% gravels 1 to 4 cm. large; few roots; indistinct boundary.

80-100 Cg$_2$. Gley (4/10Y) chart 1 for gley; fine gravels and 25% gravels 3 to 5 cm. large in a coarse sand matrix.

- Soil-geomorphic unit: Ridge gley

Well 23

Position: north block, row 75, ridge.
NZ Classification: Typic Orthic Recent Soil

0-20 Ap$_1$. Brown (10YR 3/3); fine gravelly loamy sand; estimated 5% gravels to 10 cm. large; loose; common roots; diffuse boundary.

20-50 C$_1$. Dark greyish brown (10YR 4/2); fine gravelly sand and estimated 25-50% gravels to 10 cm large; friable; stuctureless; common roots; indistinct boundary.

50-100 C$_2$. Dark greyish brown (10YR 4/2); estimated 30 %fine gravels and 70% coarse and to very coarse gravels; slightly moist.

- Soil-geomorphic unit: Stony ridge

Well 9

Position: south block, row 465, ridge.
NZ Classification: Typic Orthic Recent Soil

0-20 Ap$_1$. Very dark grey (10YR3/1); very gravelly sand; estimated 25 to 50% coarse and very coarse gravels; friable; structureless; common roots; distinct boundary.

20-100 C$_1$. Dark brown (10YR3/3); extremely gravelly sand with 50 to 75% coarse and very coarse gravels; friable; structureless; common roots.

- Soil-geomorphic unit unit: Shallow

Well 13

Position: Centre block, row 235, ridge.
NZ Classification: Typic Orthic Recent Soil

0-12 Ap$_1$. Very dark greyish brown (10 YR3/2); moderately fine gravelly sand; friable; weakly developed crumb structure; abundant roots; abrupt boundary.

12-20 C$_1$. Dark brown (10YR 3/3) and strong brown (7.5YR 5/8); fine gravels in a loamy sand matrix; structureless; common roots; distinct boundary.

20-40 2C$_2$. Very dark grey (10YR3/1), fine gravels in a coarse sand matrix; structureless; few roots; indistinct boundary.

40-100 3C$_3$. Very dark grey (10YR3/1); fine gravels; structureless.

Well 3

Position: Centre block, row 205, ridge.
NZ Classification: Typic Orthic Recent Soil

0-10 Ap$_1$. Very dark greyish brown (10 YR3/2); fine gravelly sand; friable; weakly developed crumb structure; abundant roots; distinct boundary.

10-30 C$_1$. Very dark greyish brown (10YR3/2); fine gravels in a sandy matrix; structureless; common roots; distinct boundary.

30-40 2C$_2$. Very dark greyish brown (10YR3/2); fine gravel and estimated 50-75% gravels 5 to 10 cm large; structureless; few roots; abrupt boundary.

40-100 3C3. Dark brown (10YR 3/3), coarse sand and fine gavels.

Well 7

Position: Centre block, row 420, ridge.
NZ Classification: Typic Orthic Recent Soil

0-10 Ap_1. Very dark grey (10 YR 3/1); fine gravelly sand; friable; moderate developed crumb structure; abundant roots; distinct boundary.

10-20 C_1. Very dark greyish brown (10YR 3/2); fine gravels in a sandy matrix; structureless; common roots; indistinct boundary.

20-40 $2C_2$. Dark brown (10YR 3/2); fine gravel and estimated 50% gravels 5 to 10 cm large; structureless; few roots; indistinct boundary.

40-100 3C3. Dark brown (10YR 3/3), coarse sand and fine gavels.

Well 11

Position: Centre block, row 70, hollow.
NZ Classification: Typic Orthic Recent Soil

0-13 Ap_1. Very dark grey (7.5YR 3/1); fine gravelly loamy sand; friable; weakly developed crumb structure; abundant roots; distinct boundary.

13-26 C_1. Dark greyish brown (10YR4/2); fine gravelly loamy sand; structureless; common roots; indistinct boundary.

26-38 $2C_2$. Dark greyish brown (10YR4/2); fine gravelly loamy sand; common roots; distinct boundary.

38-100 3C3. Very dark grey (10YR3/1); fine gravels and 20% coarse gravels in a coarse sand matrix.

Well 14

Position: Centre block, row 285, ridge.
NZ Classification: Typic Orthic Recent Soil

0-23 Ap_1. Very dark grey (10 YR 3/1); fine gravelly loamy sand; friable; weakly developed crumb structure; abundant roots; abrupt boundary.

23-34 C_1. Very dark greyish brown (10YR 3/2); fine gravelly sand; few gravels 2 to 3 cm large; structureless; common roots; indistinct boundary.

34-65 $2C_2$. Dark yellowish brown (10YR 4/4) and strong brown (7.5 YR 5/8); fine gravels; loose; common medium mottles, distinctive; common roots; indistinct boundary.

65-100 3C3. Very dark grey (10YR3/1); fine gravels.

Well 16

Position: Centre block, row 360, ridge.
NZ Classification: Typic Orthic Recent Soil

0-11 Ap_1. Very dark grey (10 YR 3/1); fine gravelly loamy sand; estimated 25% gravels 5 to 10 cm. large; friable; loose; common roots; indistinct boundary.

11-40 C_1. Dark brown (7.5YR3/2); fine gravels and estimated 25-50% gravels 5 to 10 cm. large in a coarse sandy matrix; common roots; abrupt boundary.

40-55 $2C_2$. Very dark greyish brown (10YR3/2); fine gravels; loose; few roots; indistinct boundary.

65-100 3C3. Very dark greyish brown (10YR3/2); fine gravels.

Well 18

Position: Centre block, row 430, ridge.
NZ Classification: Typic Orthic Recent Soil

0-18 Ap_1. Very dark grey (10YR3/1); fine gravelly loamy sand; estimated 5% gravels 2 to 10 cm. large; friable; loose; common roots; distinct boundary.

18-35 C_1. Brown (10YR5/3); 50% fine and coarse gravel in a coarse sandy matrix; common roots; indistinct boundary.

35-50 $2C_2$. Dark greyish brown (10YR4/2); 75% fine, coarse and very coarse gravels in a coarse sandy matrix; few roots; indistinct boundary.

50-100 3C3. Dark greyish brown (10YR4/2); fine and coarse gravels.

Well 28

Position: south block, row 75, ridge.
NZ Classification: Typic Orthic Recent Soil

0-20 Ap_1. Very dark greyish brown (10YR3/2); gravelly loamy sand weakly developed crumb structure; common roots; distinct boundary.

20-40 C_1. Dark greyish brown (10YR4/2); fine gravelly sand; friable; loose; abundant roots; distinct boundary.

40-100 C_2. Dark greyish brown (10YR4/2); fine gravels and estimated 50% gravels 3 to 8 cm. large.

Well 27	**Well 22**
	
Position: South block, row 75, hollow. NZ Classification: Typic Orthic Recent Soil 0-16 Ap$_1$. Very dark greyish brown (10YR 3/2); loamy sand; friable; weakly developed crumb structure; common roots; distinct boundary. 16-58 C$_1$. Dark greyish brown (2.5YR 4/2); fine gravelly coarse sand; 25% gravels 3 to 10 cm large; common roots; distinct boundary. 58-100 2C$_2$. Dark grey (2.5Y 4/1); fine gravelly coarse sand; 25% gravels 3 to 15 cm. large, abundant roots.	Position: North block, row 50, ridge. NZ Classification: Typic Orthic Recent Soil 0-12 Ap$_1$. Very dark grey (7.5YR 3/1); gravelly loamy sand; 25% gravels 2 cm. large; abundant roots; distinct boundary. 12-45 C$_1$. Dark greyish brown (10YR 4/2); fine gravelly coarse sand; 25% gravels 3 cm large; common roots; distinct boundary. 45-100 2C$_2$. Very dark grey (10YR 3/1); fine gravelly coarse sand; 25% gravels 2 to 13 cm. large; slightly moist.

- Soil Unit: Shallow gley

Well 1

Position: Centre block, row 64, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-18 Ap$_1$. Dark brown (7.5YR 3/2); loamy sand; 5% gravels; friable; weakly developed crumb structure; common fine roots; distinct smooth boundary.

18-45 Cg$_1$. Dark brown (7.5YR 3/2); loamy sand; 5% gravels; friable; weakly developed crumb structure; friable; loose; abundant strong brown (7.5 YR 4/6) mottles, distinct; common fine roots, distinct wavy boundary.

45-75 2C$_2$. Very dark grey (10YR 3/1); fine gravelly and 20% very coarse gravels in a coarse sand matrix; slightly moist; common fine roots; distinct boundary.

75-100 3C$_3$. Very dark grey (10YR 3/1); fine gravels; slightly moist; structureless.

Well 4

Position: Centre block, row 335, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-15 Ap$_1$. Very dark greyish brown (10YR 3/2); loamy sand; estimated 5% gravels 3cm large; weakly developed crumb structure; slightly sticky; abundant fine roots; distinct boundary.

15-30 C$_1$. Dark greyish brown (10YR 4/2); fine gravelly coarse loamy sand; estimated 10% gravels 2 to 8 cm large; weakly developed coarse blocky structure; common strong brown (7,5YR 4/6) mottles; abundant fine roots; indistinct boundary.

30-100 2C$_2$. Dark grey (10YR 4/1); fine gravels and estimated 75% gravels 10 cm large; structureless.

Well 2

Position: Centre block, row 155, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-10 Ap$_1$. Very dark grey (10YR3/1); loamy sand; weakly developed crumb structure; friable; common fine roots; indistinct boundary.

10-42 C_1. Very dark greyish brown (10YR3/2); fine gravelly loamy sand; estimated 30% gravels 3 to 10 cm large; friable; weakly developed very coarse blocky structure; few strong brown (7,5YR 4/6) mottles; slightly moist; common fine roots; abrupt boundary.

42-70 $2C_2$. Very dark grey (10YR3/1); fine gravelly in a coarse sand matrix; common fine roots; distinct discontinue boundary.

50-100 3C3. Dark greyish brown (10YR4/2); fine and coarse gravels.

Well 5

Position: Centre block, row 375, edge ridge/hollow.
NZ Classification: Typic Orthic Recent Soil

0-15 Ap_1. Very dark greyish brown (10YR3/2); fine gravelly and 20% gravels 5 cm. large in a coarse loamy sand matrix; loose; few roots; distinct weavy boundary.

15-25 C_1. Dark grey (10YR 4/1); fine gravels, 50-75% gravels 3 to 10 cm. large in a coarse sand matrix; structureless; few roots; diffuse boundary.

25-85 $2C_2$. Fine gravels, 50-75%gravels 2 to 8 cm. large in a coarse sand matrix; few roots; structureless; abrupt boundary.

85 + Water-

Well 6

Position: Centre block, row 400, hollow.
NZ Classification: Typic Orthic Recent Soil

0-18 Ap_1. Very dark greyish brown (10YR3/2); fine gravelly coarse loamy sand; 10% gravels 5 cm. large; friable; very weakly developed crumb structure; abundant roots; distinct boundary.

18-25 C_1. Dark greyish brown (10YR4/2); fine gravelly sand; 40% gravels 3 to 10 cm large; friable; structureless; abundant roots; distinct boundary.

25-100 $2C_2$. Very dark greyish brown (10YR3/2); fine and coarse gravels; common roots.

Well 8

Position: Centre block, row 445, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-10 Ap_1. Very dark grey (10YR3/1); fine gravelly coarse loamy sand; friable, weakly developed crumb structure; abundant roots; distinct weavy boundary.

10-30 C_1. Dark brown (7.5YR3/2); fine gravelly coarse sand; loose; common roots; distinct boundary; structureless; common roots; distinct boundary.

35-60 $2C_2$. Dark grey (10YR4/1); fine gravelly coarse sand; few gravels 3 to 8 cm large; few roots; indistinct boundary.

60-73 $3C_3$. Brown (10 YR 4/3); fine to very coarse gravelly in a coarse sand matrix; structureless; friable; coarse and abundant strong brown (7.5 YR 4/6) mottles, distinct; distinct boundary.

73-100 4 C_4. Very dark grey (10YR3/1); structureless; friable; fine gravel.

Well 10

Position: Centre block, row 475, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-5 Ap_1. Very dark greyish brown (10YR 3/2); loamy sand; friable; weakly developed crumb structure; friable; abundant roots; indistinct boundary.

5-22 Ap_2. Dark greyish brown (10YR 4/2); loamy sand; friable; weakly developed crumb structure; common; roots; distinct boundary.

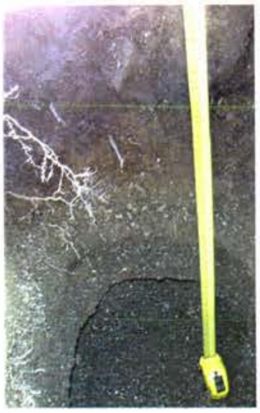
22-40 C_1. Grey (10YR 4/2); fine gravelly coarse sand; structureless; friable; common roots; abrupt boundary.

40-55 $2C_2$. Brown (10YR 4/3); fine gravelly coarse loamy sand; friable; few medium strong brown (7.5 YR 4/6) mottles; abrupt boundary.

55-100 $3C_3$. Greyish brown (10YR5/2); friable; structureless; coarse sand.

Well 12

Position: Centre block, row 160, hollow.
NZ Classification: Mottled Orthic Recent Soil



0-18 Ap_1. Very dark greyish brown (10 YR3/2); gravelly loam; friable; structureless; abundant roots; abrupt boundary.

18-32 C_1. Dark yellowish brown (10YR 4/4); fine gravels in a loamy sand matrix; friable; structureless; common, medium strong brown (7.5 YR 5/8) mottles, distinct; common roots; abrupt boundary.

32-65 $2C_2$. Very dark grey (10YR3/1); fine gravels in a coarse sand matrix; friable; structureless; indistinct boundary.

65-100 $3C_3$. Very dark grey (10YR3/1); fine gravels; friable; structureless; slightly moist.

Well 15

Position: Centre block, row 325, hollow, natural drainage.
NZ Classification: Mottled Orthic Recent Soil

0-13 Ap_1. Very dark grey (10YR3/1); gravelly loamy sand; friable; weakly developed crumb structure; common roots; distinct boundary.

13-32 C_1. Dark greyish brown (10YR4/2); coarse gravelly loamy sand; friable; structureless; few medium strong brown (7.5 YR 4/6) mottles, distinct; common roots; distinct boundary. .

32-100 $2C_2$. Dark grey (10YR4/1); coarse sand; abundant yellowish brown (10YR 5/6) mottles; very slightly moist.

Well 17

Position: Centre block, row 410, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-12 Ap$_1$. Very dark greyish brown (10YR3/2); fine gavelly sand loam; friable; weakly developed crumb structure; common roots; distinct boundary.

12-32 C$_1$. Dark greyish brown (10YR4/2); fine gravelly sand loam; 25% gravels 2 to 5 cm large; friable; loose; common strong brown (7.5 YR 4/6) mottles, distinct; common roots, distinct boundary.

32-50 2C$_2$. Dark grey (10YR4/1); fine gravelly sand; 30% coarse gravels; friable; structureless; abundant roots; indistinct boundary.

50-100 3C$_3$ Dark grey (10YR4/1); fine gravels and 20% coarse gravels in a coarse sand matrix; slightly moist.

Well 19

Position: Centre block, row 450, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-10 Ap$_1$. Very dark greyish brown (10YR3/2); gravelly sand loam; friable; weakly developed crumb structure; common roots; distinct boundary.

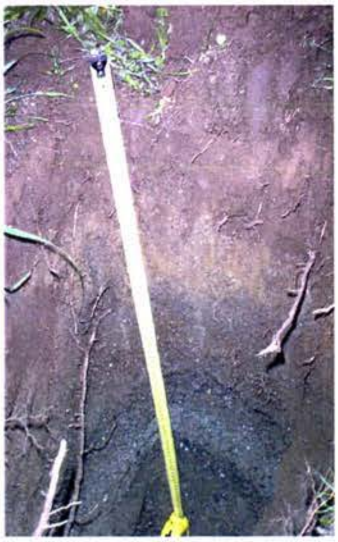
10-25 C$_1$. Dark greyish brown (10YR4/2); fine gravelly coarse sand; 25% gravels 2 to 5 cm large; friable; loose; common medium strong brown (7.5 YR 4/6) mottles, distinct; common roots; distinct boundary.

25-50 2C$_2$. Dark grey (10YR4/1); fine gravelly sand, 25% coarse gravels; abundant roots; indistinct boundary.

50-100 3C$_3$. Dark grey (10YR4/1); fine gravels sand, 25% coarse gravels; slightly moist.

Well 20

Position: Centre block, row 480, hollow.
NZ Classification: Mottled Orthic Recent Soil



0-17 Ap$_1$. Very dark greyish brown (10YR3/2); loamy sand; friable; weakly developed crumby structure, medium; abundant roots; distinct boundary.

17-29 C$_1$. Very dark grey (10YR3/1); loamy sand; weakly developed crumb structure; medium common dark yellowish brown (10YR 4/6) mottles, fine; common roots; distinct boundary.

29-53 2C$_2$. Dark grey (10YR4/1); coarse sand; friable; structureless; few roots; distinct boundary

53-63 3C$_3$ Dark grey 4/N chart 1 for gley; coarse sand, 30% gravels 3 to 5 cm.; abrupt boundary

63-100 4C$_4$ Dark grey (10YR4/1); coarse sand.

Well 21

Position: North block, row 25, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-14 Ap$_1$. Dark yellowish brown (10YR 3/4); loamy sand; friable; weakly developed blocky structure, medium; common roots; distinct boundary.

14-27 C$_1$. Very dark greyish brown (10YR3/2); fine gravelly coarse sand; friable; loose; common medium dark yellowish brown (10YR 4/6) mottles, distinct; few roots; distinct boundary.

27-38 2C$_2$. Dark grey (7.5YR4/1); fine gravels and 25% coarse gravels in a coarse sand matrix; few roots; distinct boundary.

38-70 3C$_3$. Dark grey 4/N chart 1 for gley; fine gravels and 25% gravels 3 to 5 cm. in a coarse sand matrix; few roots; abrupt boundary.

70-100 3C$_3$ Dark grey (10YR4/1); fine gravels.

Well 25

Position: South block, row 35, hollow.
NZ Classification: Typic Orthic Recent Soil

0-18 Ap$_1$. Very dark greyish brown (10YR3/2); loamy sand; friable; weakly developed crumb structure; common roots; distinct boundary.

18-42 C$_1$. Dark greyish brown (2.5YR4/2); fine gravelly coarse sand; friable; common roots; distinct boundary.

42-100 2C$_2$. Dark grey (10YR4/1); fine gravelly coarse sand; 25% gravels 3 to 15 cm. large; abundant roots.

Well 26

Position: South block, row 40, hollow.
NZ Classification: Mottled Orthic Recent Soil

0-20 Ap_1. Dark greyish brown (10YR 4/2); loamy sand; 30% coarse gravels; friable; structureless; common roots; distinct boundary.

20-40 C_1. Dark greyish brown (10YR 4/2); fine gravelly sand; common roots; distinct boundary.

40-100 $2C_2$. Very dark grey (5Y 3/1); fine gravelly sand; 40% gravels 3 to 8 cm. large.

Appendix D

Soil bulk density estimated for the two first horizons of three duplicates at six different sites.

Site	Duplicate	Bulk Density (gr.cm^{-1})	Site	Duplicate	Bulk Density (gr.cm^{-1})
	A horizon			C1 horizon	
A	1	1.22	**A**	1	2.46
	2	1.19		2	1.72
	3	1.26		3	1.68
B	1	1.60	**B**	1	2.55
	2	1.28		2	2.30
	3	1.56		3	1.96
C	1	1.41	**C**	1	2.31
	2	1.30		2	2.33
	3	1.47		3	2.29
D	1	1.93	**D**	1	1.59
	2	1.86		2	1.58
	3	1.99		3	1.63
E	1	1.23	**E**	1	2.11
	2	0.94		2	2.27
	3	1.48		3	2.40
F	1	0.97	**F**	1	1.43
	2	1.14		2	1.68
	3	1.25		3	1.58

Appendix E.

Total available water estimation procedure for one repetition of sites 4 and 1 to a 1 m depth.

Site	Hz.	Thick (dm)	<2 mm (%)	Text.	AWC * (ml/dm)	Calculation	AWC
4	Ap	2.0	43	sand	15.0	2dmx15ml/dmx0.43fine earth =	12.8
4	C1	1.2	65	sand	5.0	1.2dmx5ml/dmx0.65fine earth =	3.9
4	3C	6.8	18	sand	5.0	6.8dmx5ml/dmx0.18fine earth =	6.1
4		10				Total	**22.8**
1	Ap1	2.0	70	LSa	18.0	2dmx18ml/dmx0.70fine earth =	25.3
1	Ap2	2.5	21	sand	15.0	2.5dmx15ml/dmx0.21fine earth =	8.1
1	C3	5.5	89	LSa	11.0	5.5dmx11ml/dmx0.89fine earth =	53.6
1		**10**				**Total**	**86.9**

* Available water-holding capacities by soil groups taken from Griffiths (1985)