ON-FARM WATER AND SALT MANAGEMENT GUIDELINES FOR IRRIGATED CROPS: LEVEL TWO DECISION SUPPORT

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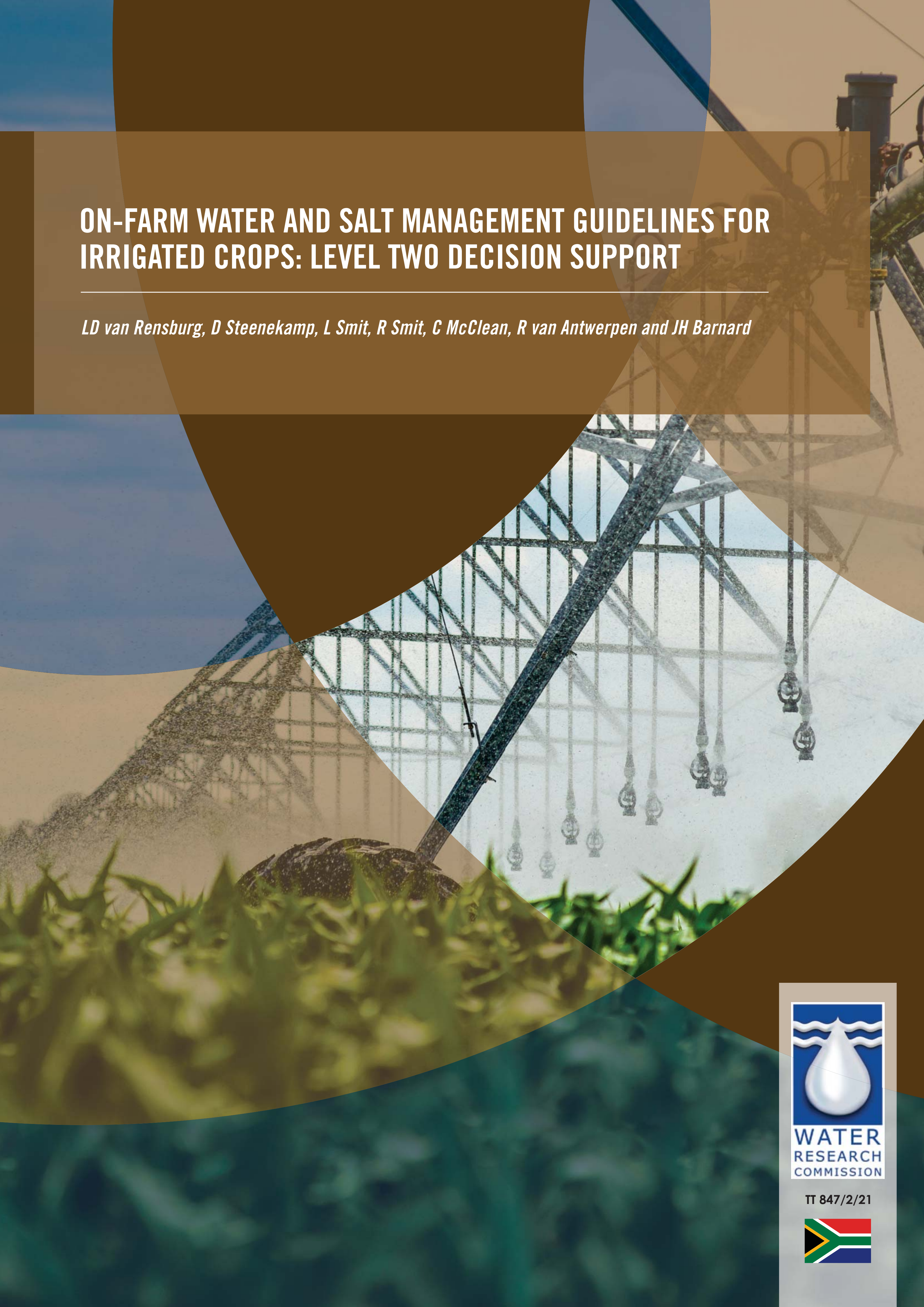

WATER RESEARCH COMMISSION

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On-Farm Water and Salt Management Guidelines for Irrigated Crops: Level Two Decision Support

Report to the
Water Research Commission

by

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The publication of this report emanates from a project entitled *Management guidelines for technology transfer to reduce salinisation of irrigated land with precision agriculture* (WRC Project No. K5/2499/4) and forms part of a series of three reports, namely:

1. On-farm water and salt management guidelines for irrigated crops: Level one decision support. (WRC Report No TT 847/1/21)
2. On-farm water and salt management guidelines for irrigated crops: Level two decision support. (WRC Report No TT 847/2/21)
3. On-farm water and salt management guidelines for irrigated crops: Level three decision support. (WRC Report No TT 847/3/21)

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EXECUTIVE SUMMARY

1. Problem statement

Salt and water accumulation in fields are in most cases a slow process and some researchers describe it as a slow-growing white or black cancer. These processes occur despite very strict measures and procedures applied by scientists in the selection of suitable soils for irrigation. Waterlogging and salinity have affected approximately half the area of the Vaalharts Irrigation Scheme over a period of 40 years after the scheme had commenced. Some farmers experienced water and salt accumulation after only 15 years, in line with the timeline predicted by Thayalakumaran and co-workers for salt equilibrium at rootzone level. Poor irrigation management leads to yield losses and deterioration of land. Up to the mid-seventies, profits made as a result of irrigation in Vaalharts was not sufficient to compensate for the damage caused by the irrigation sector themselves. The government intervened and subsidised subsurface drainage, restoring crop fields in the late seventies. Farmers could not install artificial drains on their own, since they could not afford the technology, mainly due to the cultivation of relatively low-income crops. The landscape of the Vaalharts Irrigation Scheme has changed dramatically over the last decade, however, with approximately 12 000 to 14 000 ha now under perennial crops, mostly pecans. This trend of changing land use to perennial crops is evident in almost all the large irrigation schemes of South Africa. Transforming crop fields from field crops to perennial crops will, according to Thayalakumaran and co-workers, lead to a new salt equilibrium in the next decade. This change in land use demands intensive monitoring and assessment of water and salts in soils to optimise production of every cubic meter of land.

2. Context

In this project three WRC-reports, Volume 1 to 3, were delivered with the theme “On-farm water and salt management guidelines for irrigated crops”. The goal was to cater for all types of farmers, regardless of their scale of operation, whether they are producing food for their families, for the country, or for international communities. Volume 1 reported on the basic methods and procedures for the monitoring rootzone salinity. It is written as a level one decision support guideline (Van Rensburg et al., 2020). This information is in the public domain and any farmer, manager, advisor or behaviour change officer (extensionist) has access to the information. Although Volume 1 is specifically written with BCOs in mind, they would still have to re-pack the information for their clients. The training of BCOs fell outside the scope of this project, but is an important part in the successful dissemination of information to resource-deficient farmers.

Perennial crops require high initial investment, but are seen as high-value crops. With higher incomes, farmers can invest more to intensify water and salt management of their fields. Volume 2 of the three WRC-reports, was aimed at encouraging and supporting those farmers who want to change towards site-specific management, i.e. precision management of water and salts. The latest technology in site-specific management involves electromagnetic induction (EMI) surveys and ground-truthing of soil properties related to soil salts. It is also envisaged that BCOs will play an important role in the process of scaling out of EMI technology. However, training of BCOs is beyond the scope of this project.

Volume 3 in the series of reports, reflects on EMI research (upscaling) conducted on selected irrigation farms in the Northern Cape, Free State, Eastern Cape and KwaZulu-Natal. This is to achieve a deeper understanding of salt-related problems and their medium to long-term management. This type of decision support system (DSS) is on a research level and is aimed at serving the science community, although mega-farmers, cooperatives and companies may also benefit from it in the medium to long-term. In this case, salinity models such as SWAMP, are used to make medium- to long-term estimations of the influence of salts on land productivity.

3. Objectives

The goal of Volume 2 was to report on application of EMI technology in crop fields as a method for site-specific assessment of soil salts in the rootzone. This could be divided into the following specific objectives for the level two decision support:

i. To illustrate the use of a logic framework, using EMI-derived soil properties, to support scientifically sound decisions regarding site-specific assessment of soil salts in the rootzone. The specific objectives with the framework were: (a) to show distribution of salts in the crop field, (b) to show how salts impact on the hydro-physical properties of the soil, such as bulk density, saturated hydraulic conductivity, water storage in the profile, and (c) to couple site-specific procedures to rectify problematic areas. A vineyard case study was used to establish the concept (Chapter 3).

ii. To use case studies on site-specific assessment of water and salts in perennial crops as examples to broaden the base and support that is needed for upscaling local application of EMI technology. Crops used as case studies were lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries (Chapter 4).

4. Logic framework for guiding site-specific assessment of soil salts (Chapter 3)

A vineyard was used as case study to demonstrate the use of a logic framework for site-specific assessment of water and salt management.

Firstly, results for EC_a and terrain analysis, soil forms and soil properties, measured and derived from EC_a readings taken from the top-, sub- and deep subsoil, as well as the profile available water, were presented in the form of 37 maps and 9 tables. Soil properties of interest included drainage (infiltration, internal drainage and external drainage reflected by K_{sat}), particle size distribution, compaction, salinity, sodicity, water storage (saturation point and drained upper limit) and aeration, and also surface properties derived from the terrain analysis and micro-morphological properties observed during the soil classification exercise. All this information needed to be directed towards a comprehensive spatial assessment of water and salt in the rootzone of the crop.

In order to direct water and salt analyses, a logic framework or matrix (Table 3.10) was compiled and its use was demonstrated through the vineyard case study. The properties taken into consideration in the framework include soil types, drainage, compaction, salinity, sodicity, profile available water capacity and aeration (column 1). Column 2 summarises the methods used to obtain results, while column 3 directs the user to the three layers in the profile, i.e. surface (0 to 300 mm), subsoil (300 to 750 mm) and deep subsoil (750 to 1500 mm). The most important column is the fourth, where the status of a particular soil property is indicated. Norms from literature are used to divide results into three categories: severe problems with a particular soil property, moderate problems, or no problems. Column 5 directs the user to where results for each soil property can be found to confirm the magnitude of the area affected. The last column links site-specific procedures to rectify problematic areas or zones, if possible.

With respect to the vineyard case study, the framework was convenient during the discussion of the hydro-physical report with farmers and BCOs. It presents an overview of the condition of the soils and focuses the discussion on the main problems and the rectification thereof. For example, Column 4 indicated that there were severe problems with sodicity, drainage and water storage in the vineyard. Crusting was one of the problems derived from the sodic condition of the topsoil. It was recommended that gypsum be used to reclaim the soil. There were problems with surface drainage that requires the attention of an agricultural engineer. Lateral movement of water between blocks was a challenge at higher elevations in the vineyard. Cut-off drains, designed by an agricultural engineer, were proposed. Lower lying areas with slow draining or impermeable B2 horizons poses a threat to aeration, hence design and installation of artificial drains were recommended. Agricultural engineers can examine EMI-soil property maps further to assist in site-specific allocation of subsurface drains. Water storage in the profile was also identified as an area to focus on, mainly due to the low PAWC of the sandy soils in the vineyard as indicated in the PAWC map. It was recommended that the assistance of professional irrigation scheduling services be called in.

5. Scaling up of EMI technology (Chapter 4)

The main problem in the dissemination of EMI information, however, is the scaling up of the technology. It was argued that perennial crops will be the best platform to launch such an initiative as these farmers are in the best financial position to afford such surveys. Hence, the second objective of the project was to target leading farmers in the industry and convince them to apply EMI technology on their farms. Consequently, seven case studies on site-specific assessment of water and salts in perennial crops were conducted and presented in Chapter 4. It can be concluded that the framework helped to establish examples for lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. This will broaden the base and support for upscaling of EMI technology to crop-specific associations in the near future. Without exception, the case studies were successful in (a) showing where the salts are distributed in the crop field, (b) how it impacts on the hydro-physical properties, such as bulk density and water storage in the profile, and (c) to couple site-specific procedures to rectify problematic areas.

Lastly, it can be concluded from our experience that the framework serves as a template for guiding the hydro-physical report, saving time and resulting in a more efficient service. The framework also contributes towards guiding discussions on salt and water management, saving precious time during consultations with farmers.

6. Recommendations

Literature and practical experience indicated that EMI technology have entered the stage where it can be applied to monitor and assess salts in the root zone of crop fields under irrigation.

The compiled logic framework that was utilised in eight case studies with different crops showed that it can be recommended for use as a guide to compile hydro-physical reports of crop fields. It also helps to direct discussions on water and salt management with farmers and BCOs.

The cost of EMI surveys and assessments have decreased dramatically with the application of the framework without compromising on quality. Today, full hydro-physical and fertility surveys cost farmers between R550 and R1200 per ha, depending on the location, the size of the area to be surveyed and the number of soil samples. This is in ine with costs for detailed soil surveys that do not integrate soil and water management to the level attained using EMI technology.

Land use in irrigation schemes is moving from field crops to perennial crops and this will induce new salt equilibriums in the root zone over the next decade. It is recommended that EMI be used to monitor and assess water and salt management at least once in 10 years, but preferably once every 5 years.

There is an opportunity to develop policies that will guide owners and users of irrigation land towards a higher level of responsibility and accountability in protecting natural resources against water and salt accumulation. EMI-technology provides the means to monitor such impacts as demonstrated in the eight case studies presented in the two content chapters.

It is important for national food security that the problems of waterlogging and salinity be addressed. Conservatively estimated, roughly 90 000 ha of South Africa's irrigation soil are salt-affected and this negatively impacts the livelihoods of farmers across all scales. EMI-technology provides a powerful tool in the fight against salinisation and waterlogging of agricultural land. Use of this technology reflects favourably in light of the World Bank's vision and protocol to prioritise funding for projects that aim to secure and protect irrigated land with the objective to increase land productivity and livelihoods (Kijne, 2011).

In cases where farmers cannot afford EMI-type services, it is recommended that government provide support to encourage them to conduct such services. A good example is the case study on pecans (Section 4.2.4), where irrigation land was allocated to a farmer as part of a land reform project. After listening to a presentation on EMI application, the farmer requested that an EMI survey be conducted on her farm. The survey showed clearly that the land reform initiative poses challenges regarding the sustainability of the irrigation project. Amongst others, recommendations were made to install surface- and subsurface drains, which the farmer cannot afford currently. The case study was submitted to the provincial government for further funding, since the project is destined to fail without implementation of the recommended improvements.

The main obstacle, however, is scaling up the use of EMI-technology in the crop production sector. It is recommended that training should be provided to BCOs, since they play a decisive role in dissemination of information to farmers.

A socio-economic survey conducted amongst irrigation farmers in South Africa (Van Rensburg et al., 2020; Barnard et al., 2020), revealed that farmers believe that the benefits of salinity management outweigh the costs. However, they were also of opinion that the benefit gained do not necessarily justify the effort needed to implement salt management interventions. So, hard and clever work is required to bridge the mindset of farmers and to package EMI-information. It is recommended that demonstration trials on land reclamation be conducted at leading farmers' fields. A good example was the macadamia case study where the farmer insisted that demonstration trials be conducted in some of the affected areas to show the efficiency of the latest subsurface drainage technology. However, case studies on reclamation of sodic soils in South Africa are scarce and such proof is needed to convince farmers to apply recommended procedures. Therefore, we need to test our recommendations in a practical way.

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LIST OF ABBREVIATIONS

BCO	:	behaviour change officer
BD	:	bulk density
CEC	:	cation exchange capacity
DSS	:	decision support system
DUL	:	drained upper limit
EC	:	electrical conductivity
EC_a	:	apparent electrical conductivity
EC_e	:	electrical conductivity of saturated paste extract
EC_i	:	electrical conductivity of irrigation water
EMI	:	electromagnetic induction
ESP	:	exchangeable sodium percentage
FAC	:	field aeration capacity
K_{sat}	:	saturated hydraulic conductivity
LL	:	lower limit (of plant available water)
PAWC	:	profile available water capacity
RSSD	:	response surface sampling design
SAR	:	sodium adsorption ratio
SD	:	standard deviation
SP	:	saturation point

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CHAPTER 1. INTRODUCTION

1.1 Problem/opportunity statement

As explained in the guidelines on water and salt management for level one decision support (L1DS) (Van Rensburg et al., 2020), the opening of a tap to irrigate a crop field, also opens up opportunities to improve livelihoods. It should be realised, however, that irrigation is a man-made intervention and with every drop of water applied to a field, salts are also deposited. Accumulation of salt and water in fields are in most cases a slow process and some researchers described it as a slow-growing white or black cancer (Wood, 2008). As an example, the Vaalharts Irrigation Scheme commenced in the mid-1930s and the groundwater table with its salt concentration gradually rose to levels that severely affected crop yields and livelihoods (Streutker, 1977). The affected area increased slowly over four decades, forcing the government to intervene by subsidising artificial drains in the mid-1970s (Herold and Bailey, 1996). In simple terms, the money that farmers made through irrigation up to the mid-seventies was not sufficient to pay for the damage caused by the irrigation practices. One of the reasons for this was that most farmers cultivated field crops with a relative low market value.

Despite very strict measures and procedures applied by scientists in the selection of suitable soils for irrigation, waterlogging and salinity developed over more than half of the 34 000 ha irrigation scheme. The unexpected rise in water table height and salinity were attributed to over-irrigation as a result of the border-flood irrigation method applied and to the deterioration of the Vaal River's water quality over time (Du Preez et al., 2000). The diagram of Thayalakumaran et al. (2007), depicted in Figure 1.1, gives an indication of the time frame for salt equilibrium to be reached within agro-ecosystems. Some of the pioneering farmers at Vaalharts had experienced waterlogging and salinity within 10 to 15 years after irrigation commenced. On top of that, it took the community another 25 to 30 years to solve the problem at an irrigation scheme level. The drainage intervention at Vaalharts stimulated economic growth in the area for almost another half century after the installation of the drains.

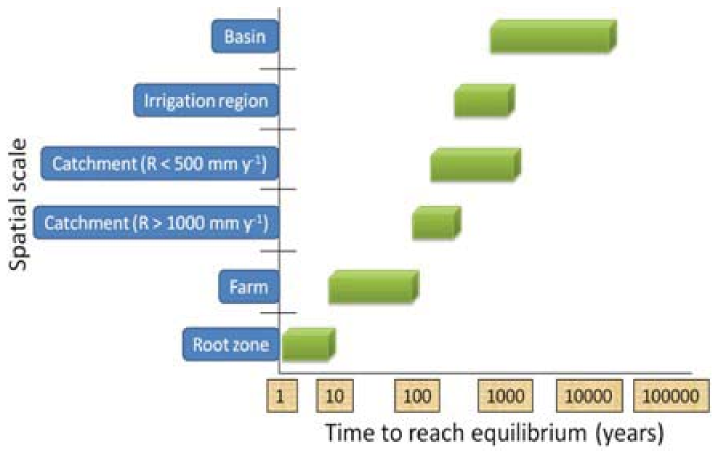


Figure 1.1 Relationship between time to reach salt equilibrium and spatial scale (reproduced from Thayalakumaran et al., 2007).

1.2 Context

Figure 1.1 clearly illustrates how slow the salt equilibrates under land use changes. Apparently, it takes around 10 years for salts to equilibrate in a particular crop field for a given water and salt management practice. The salt-equilibration time scale provides an indication on how often farmers should conduct field surveys to monitor root zone salinity. From this diagram it seems that once every 5 years will be an appropriate recommendation for surveying. The basic methods and procedures for monitoring root zone salinity are available in the form of a guideline in the level one DSS (Van Rensburg et al., 2020). This information is in public domain and any farmer, manager, advisor or behaviour change officer (extensionist) have access to the WRC report.

For a more comprehensive investigation into root zone salts, an EMI-assessment of crop fields is recommended. This involves the spatial characterisation of salts in the crop field with electromagnetic induction (EMI) technology. EMI surveying and associated soil sampling, laboratory analysis and agronomic analyses are expensive and not subsidised. Farmers have to pay for such services and therefore it falls under level two decision support that is available through companies like Revolute, Gyrolag and Van's Lab. From practical experience and from a cost-benefit value, it appears that farmers cultivating perennial crops are more receptive to acquire such services. Hence, getting leading farmers in the perennial crop environment on board with this technology would serve as a good platform for upscaling EMI-salinity assessments.

For a deeper understanding of salt-related problems and their medium to long-term management, a third level of decision support was introduced as Volume 3 in the series of three WRC reports. This type of decision support is on a research level and is aimed at upscaling research on EMI in South Africa. In this case, salinity models, such as SWAMP, are used to make medium to long-term estimations of salt effects on land productivity (Volume 3). Findings that stem from this research can then be filtered back into level one and two decision support platforms.

The three reports (Volume 1, 2 and 3) emanates from the WRC-project entitled "Management guidelines for technology transfer to reduce salinisation of irrigated land with precision agriculture". The goal of this project was to compile guidelines for technology exchange to manage the salt load associated with irrigation at farm and field level with precision agriculture and the specific aims were to:

i. Compile water and salt management guidelines and elicit from stakeholders the acceptability thereof.
ii. Evaluate the methods/procedures employed by advisors for delineating site-specific-water and salt management units on a case study basis.
iii. Develop a software-based decision support system for recommendations to improve site-specific water and salt management.

To accomplish the aims of the project various tasks were initiated and completed (in no specific order). **Firstly**, Water Research Commission funded research, as well as international research related to water and salt management of irrigated fields were reviewed. **Secondly**, general principles of adopting precision agriculture or site-specific crop management were reviewed, specifically concentrating on the reliable and cost effective use of apparent electrical conductivity (EC_a)-directed soil sampling to spatially characterise soil attributes related to salinity management (Corwin and Scudiero, 2016). **Thirdly,** five case studies were identified and used in the investigation regarding the principles of water and salt management with precision agriculture and field-scale EC_a-directed soil variability characterisation. The five sites were located in the Douglas district (Northern Cape Province), near Luckhoff in the Free State Province, near Hofmeyr in the Eastern Cape and two sites in KwaZulu-Natal near Mkuze and Empangeni. **Fourthly,** farmers and agricultural advisors in these provinces were engaged regarding current and best on-farm water and salt management practices, as well as water and salt management with precision agriculture throughout the duration of the project. This was done through questionnaires, farmers' days and ad hoc, in situ spatial assessments of water and salt management problems on farms. A number of farms with perennial crops, such as grapes, lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries were also surveyed with EMI technology. EMI results from these case studies formed the basis of the level two DSS report.

1.3 Objectives

The goal of Volume 2 was to report on application of EMI technology in crop fields as a method for site-specific assessment of soil salts in the root zone. The specific objectives for the level two DSS were:

i. To illustrate the application of a logic framework, using EMI derived soil properties, to support scientifically sound decisions regarding the site-specific assessment of soil salts in the root zone. Specific objectives with the framework were: (a) to show where the salts are in the crop field, (b) to show how salts impact on hydro-physical soil properties, such as bulk density, saturated hydraulic conductivity and water storage in the profile, and (c) to couple site-specific procedures to rectify problematic areas. A case study on a vineyard was used to establish the concept. (Chapter 3)

ii. To use seven case studies as examples for broadening the base and support that is necessary for upscaling local application of EMI technology for site-specific assessment of water and salts in perennial crops. Crops used as case studies were lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. (Chapter 4)

CHAPTER 2. METHODOLOGY

2.1 Background on electromagnetic induction

2.1.1 Use of EMI soil sensors to measure EC_a

Electrical conductivity (EC) is the ability of a material to conduct or transmit an electrical current. Non-contact soil sensors are based on the principle of electromagnetic induction (EMI) and it makes no direct surface contact (Grisso et al., 2009). These sensors measure the apparent electrical conductivity (EC_a). EMI is based on the theory that any conductive material in an electromagnetic field carries a current (Pognant et al., 2013). Soil properties determine the ability of the soil to carry an electrical field (Grisso et al., 2009). One of the most common EMI instruments currently used is the Geonics EM38-MK2. This instrument is also used by Van's Lab. When placed in the vertical position the EM38 takes readings at approximately 1.5 m depth, corresponding roughly to the crop root zone, making it very applicable for agriculture. Horizontally it measures at a depth of 0.75 to 1.0 m (Hanquet et al., 2002; Corwin and Lesch, 2005a; Grisso et al., 2009).

2.1.2 Soil properties that influence EC_a

The main physical and chemical soil properties that influence EC_a include salinity, bulk density, water content and saturation percentage. Bulk density and saturation percentage are influenced directly by organic matter and clay content. The exchange surfaces found on organic particles and clay surfaces provide the solid-liquid phase path through exchangeable cations. Clay content and type, CEC and organic matter are therefore additional factors that influence EC_a (Corwin and Lesch, 2005a). Other indirect factors that also influence the properties that determine EC_a include ionic composition, soil structure, pH, $CaCO_3$ content and nutrient levels. EMI has been used to evaluate these soil properties, as well as exchangeable calcium and magnesium, lithology and mineralogy, soil compaction, field scale solute leaching rates, herbicide partition coefficients, groundwater recharge, soil map unit boundaries, soil drainage classes and available nitrogen (Corwin and Lesch, 2005b; Doolittle and Brevik, 2014).

Another important factor that influences EC_a is temperature. For every 1°C increase in temperature, EC_a increases at a rate of roughly 1.9%. Generally, values of EC_a are expressed at a 25°C reference temperature for purposes of comparison (Corwin and Lesch, 2005b).

The spatial variability and magnitude of EC_a in a field is generally dominated by a combination of the above mentioned factors and differs from one field to the next. This makes the interpretation and use of EC_a measurements very site-specific and soil-specific (Corwin and Lesch, 2005b; Heil and Schmidhalter, 2017).

2.1.3 Inferring soil properties from EC_a

Measurements of EC_a can be applied to predict secondary soil properties that influence EC_a using stochastic or deterministic calibration models (Lesch et al., 2000). The spatial distribution of EC_a in a field can therefore be used to estimate and map the variability of one or more of the soil properties that directly or indirectly influences EC_a (Corwin and Lesch, 2003; Corwin et al., 2006). The correlation analysis between EC_a and measured soil variables (i) serves to determine the main soil property that influences the EC_a measurement within the study area, (ii) helps to interpret the spatial distribution of soil salinity, and (iii) allows prediction of the expected correlation structure between EC_a data and different soil properties (Amezketa, 2007).

Many field studies on EC_a have been performed and have revealed how site-specific and complex EC_a is (Corwin and Lesch, 2005b). It appears that regression constants for the relationships between EC_a and other soil properties can not necessarily be transferred from one site to another, since there are many factors that affect the strength of the EC_a signal data and therefore the relationships. Also, regression quality is often determined by the sufficient range of dependent and independent variables (Heil and Schmidhalter, 2017).

2.2 EMI and terrain surveys

A total of eight farms were surveyed, serving as case studies for the project. Surveys were conducted by Van's Lab and permission was obtained to use the data for this WRC project. Specific information on when the surveys were conducted, area of the crop field, transect width and measuring density will be given in the separate discussion of each case study. For all of the surveys, a Geonics EM38-MK2 soil sensor was used in vertical orientation for scanning the crop field. The sensor (Figure 3.1) was enclosed in a plastic trailer to avoid metallic interference while being drawn over the field with a quad bike for collection of georeferenced EC_a data. At each georeferenced measuring point, geographical elevation data was gathered for all study sites with the Trimble® TSC3 controller with Trimble Access™ software along with the Trimble® R4 GNSS System. Elevation data gathered was used to create high resolution elevation, drainage and slope maps. These maps assist in the visualisation of surface properties that influence soil characteristics.

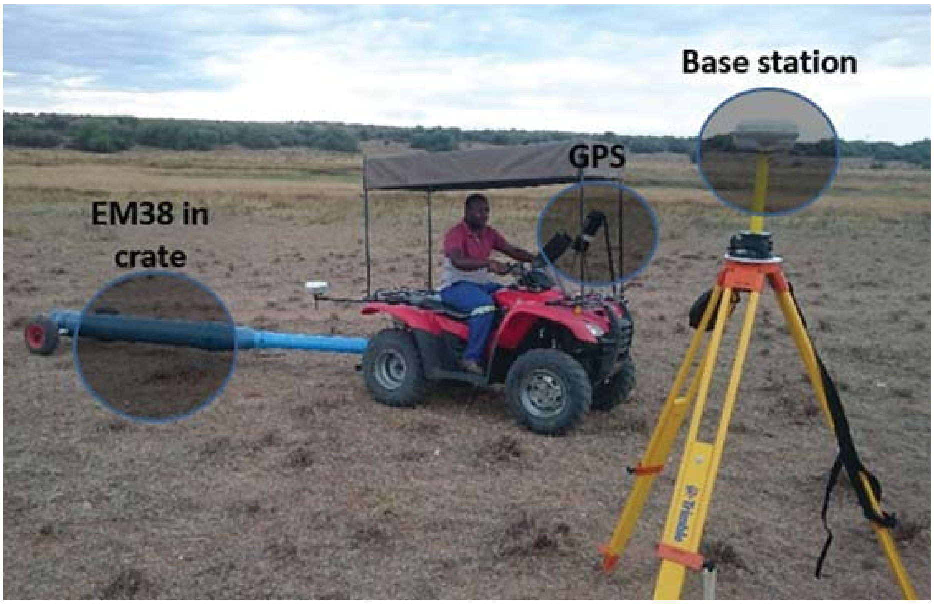


Figure 2.1 Mobile EM38-MK2 sensor unit showing the plastic trailer with the instrument inside linked to the quad bike equipped with a GPS that communicates with the base station.

2.3 Soil sampling and soil classification

The following soil sampling procedure was used in all of the case studies. With the obtained EC_a data, soil sampling points were identified for each site using ESAP-RSSD sampling methodology (Corwin et al., 2006; Wienhold and Doran, 2008). These sampling points represent 95% of the EC_a variability measured at the site. The software used also identifies sampling points to be distributed uniformly over the field surveyed. Soil samples are necessary for site specific calibration.

At each of the sampling points, disturbed soil samples were taken. Separate samples were taken for 0 to 300 mm depth, 300 to 750 mm and also 750 to 1500 mm, if profile depth allowed. Samples were dried at 40°C and thereafter sieved and prepared for determination of specific soil properties in the laboratory. Undisturbed core samples with dimensions of 80 mm in height and 110 mm in diameter were also taken at each of the sampling depths.

For soil classification, profiles were excavated at each sampling point and soils were investigated and classified according to the South African Soil Classification System (Soil Classification Working Group, 1991). Locations of each soil sampling point and the soil form identified are illustrated on all maps.

2.4 Laboratory analysis

For all samples collected at case study sites, the following analysis was conducted. Disturbed soil samples were used to determine soil particle size distribution using the pipette method to identify fractions of sand, silt and clay (Non-Affiliated Soil Analysis Work Committee, 1990). Core samples with inner diameter of 105 mm and height of 80 mm were taken in the profile pit at three depths (0 to 300 mm, 300 to 750 mm, 750 to 1500 mm) if the stone fraction did not dominated. Bulk density was determined from core samples by drying the soil at 60°C until a constant weight was obtained. The weight of the dry soil was divided by the volume of the core. In the case of the presence of rock, rock samples were gathered and the density was determined using the same procedure as the clod method.

Total porosity (P, %) of the soils was calculated with the following equation:

$$\mathrm{P} = (\mathrm{Bd} - \mathrm{Pd})/\mathrm{Bd}) * 100 \tag{2.1}$$

Where Bd represents the bulk density and Pd the particle density taken as 2.65 g cm^{-3}.

The saturation point (SP) and the drained upper limit (DUL) was determined in the laboratory by saturating core samples for 24 to 48 hours. After saturation, samples were weighed to obtain the gravimetric water content at SP. The same samples were then allowed to drain, between 2 to 4 days depending on clay content, whereafter it was weighed to obtain gravimetric water content for the DUL. Bulk density values were subsequently used to calculate the total volumetric weights for both the SP and DUL. Field aeration capacity (FAC) was calculated as the volumetric difference between SP and DUL. The difference between the total porosity and laboratory determined SP was used to indicate hydrophobic characteristics of the soil.

The lower limit of plant available water (LL), or permanent wilting point, was estimated using the clay-plus-silt content to volumetric water content relationship at -1500 kPa reported by Bennie et al. (1988):

$$\mathrm{LL} = 0.00385(\text{silt-plus-clay\%}) + 0.0125 \tag{2.2}$$

The difference between DUL and LL was defined as the water store for each soil layer, expressed either in percentage or in mm over depth of soil layer. The profile available water capacity (PAWC or water store) was defined as the sum of the water content of all layers, also expressed in % or mm.

The saturated hydraulic conductivity (K_{sat}) was determined in the laboratory by means of the constant-head permeameter method using core samples (Klute and Dirksen, 1986). If soil was too loose or hard to take core samples, the double-ring infiltrometer method as described by Smettem and Smith (2002), was used to determine K_{sat} in the field. Soil profile pits were excavated in a stepwise manner to allow the fitting of both rings with diameters of 400 and 600 mm, respectively, at a depth of 20 mm. The rings were filled with water and the falling head over a distance of 10 mm depth was used to determine hydraulic conductivity, with every fall recorded by means of a timer and a calibrated floater. After steady state was recorded for three consecutive times, the K_{sat} constant value (mm h^{-1}) was computed using the formula of Jury et al. (1991).

$$K_{sat} = \frac{L}{t_1} \ln \frac{b_0 + L}{b_1 + L} \qquad 2.3$$

Where L is the depth of the soil layer in question (mm), b_0 the initial depth of total head above the soil column, b_1 the depth that the falling head is not allowed to fall below (mm), and t_1 the time taken for b_0 to fall to b_1 (in hours).

For chemical analysis, soil electrical conductivity was determined using either a soil water extract of 1:5 (Kargas et al., 2018) or from the saturated paste method described in by the Non-Affiliated Soil Analysis Work Committee (1990). Soluble and exchangeable cations, as well as cation exchange capacity (CEC) were determined by the 5-step standard method described by the Non-Affiliated Soil Analysis Work Committee (1990). Cations were determined spectrophotometrically. From the exchangeable sodium and CEC, the exchangeable sodium percentage (ESP) was calculated (Abrol et al., 1988).

2.5 Statistical analysis and mapping

The following procedures were followed for all of the case studies. Multiple-linear regression models were developed between EC_a, elevation and each individual soil property in Microsoft Excel. Model performance was based on the following criteria: Poor = $r < 0.5$; moderate = $0.5 < r < 0.7$; good = > 0.7. Prediction models were subsequently used to estimate soil variables for all other EC_a measurement points on the surveyed site where the soil was not sampled. Estimated values of the soil properties were processed using the Quantum GIS (QGIS) version 2.18 programme, an open source geographical information system programme. For interpolation the deterministic natural neighbor method was used with a pixel cell size of 1 m². The algorithm used by the natural neighbor interpolation tool finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value (Sibson, 1981).

For terrain evaluation, the elevation data collected during the survey was implemented along with the natural neighbor method to create raster layer maps of elevation. Raster elevation files were used to create maps of slope and drainage channel networks by using the SAGA terrain analysis tool in QGIS.

2.6 Norms for evaluation

2.6.1 Soil quality

Guideline norms were compiled from literature to evaluate soil physical and chemical properties that determine soil quality status. Soil properties of concern were those relating to the soil's capability to conduct and supply water to a crop, such as K_{sat}, porosity, salinity and sodicity. A summary of the norms used is given in Table 2.1. These norms can be used for any site to create specific soil maps that delineate the extent and severity of salt affected areas to help classify the soil quality status.

Table 2.1 Norms for soil quality evaluation

Soil property		**Range**	**Description**	**Soil condition**	**Reference**
Slope percentage		< 1	Gently sloping	C1	Soil Science Division Staff (2017)
		1-4	Strongly sloping	C2	
		4-10	Moderately steep	C3	
		10-20	Steep	C4	
		> 20	Very steep	C5	
Bulk density ($g\ cm^{-3}$)	Sands, loamy sands	< 1.60	Ideal	C1	Burt (2014)
		1.60-1.70	Low to moderate effect on root growth	C2	
		1.70-1.80	Moderate to restrictive impact on root growth	C3/C4	
		> 1.80	Restrictive	C5	
	Sandy loams, loams	< 1.40	Ideal	C1	
		1.40-1.63	Low effect on root growth	C2	
		1.63-1.80	Moderate effect on root growth	C3/C4	
		> 1.80	Restrictive	C5	
	Sandy clay loams, clay loams, silts, silt loams	< 1.40	Ideal	C1	
		1.40-1.60	Low effect on root growth	C2	
		1.60-1.75	Moderate effect on root growth	C2/C3	
		> 1.75	Restrictive	C4/C5	
	Silt loams, silty clay loams	< 1.40	Ideal	C1	
		1.40-1.55	Low effect on root growth	C2	
		1.55-1.65	Moderate effect on root growth	C3	
		> 1.65	Restrictive	C4	
	Sandy clays, silty clays, clay loams	< 1.10	Ideal	C1	
		1.10-1.49	Low effect on root growth	C2	
		1.49-1.58	Moderate effect on root growth	C3	
		> 1.58	Restrictive	C4/C5	
	Clays (> 45% clay)	< 1.10	Ideal	C1	
		1.10-1.39	Low effect on root growth	C2	
		1.39-1.47	Moderate effect on root growth	C3/C4	
		> 1.47	Restrictive	C5	
Total porosity		< 5	Very compact	C5	Pagliai and Vignozzi (2002)
		5-10	Compact	C4	
		10-25	Moderately porous	C3/C2	
		25-40	Highly porous	C1	
		> 40	Extremely porous	C1	
Field aeration capacity (%)		< 10	Very restrictive	C5	
		10-15	Restrictive	C4	
		15-20	Below ideal	C3	
		> 20	Ideal	C1/C2	
K_{sat} ($mm\ hr^{-1}$)		< 2	Very slow / impermeable	C5/C4	USDA-NRCS (2019)
		2-5	Slow	C4	
		5-15	Moderately slow	C3	
		15-50	Moderately slow	C2	
		50-50	Moderately rapid	C1	
		152-508	Rapid	C3	
		> 508	Very rapid	C4	
EC_e ($mS\ m^{-1}$)		< 200	Low salinity	C1	Soil Science Division Staff (2017)
		200-400	Very slightly saline/sensitive plants affected	C2	
		400-800	Slightly saline/many plants affected	C3	
		800-600	Moderately saline/Tolerant plants affected	C4	
		> 1600	Strongly saline/high salinity	C5	

Table 2.1 (continued) Norms for soil quality evaluation

*SAR_e ($mS\ m^{-1}$)	EC_e ($mS\ m^{-1}$)	Effect on dispersion		
0-3	< 20	No	C1	Department of Water Affairs and Forestry (1996)
	20-90	No	C1	
	> 90	No	C1	
3-6	< 25	Slight	C2	
	25-130	Slight to moderate	C2	
	> 130	No	C1	
6-12	< 35	Moderate	C3	
	35-200	Slightly	C2	
	> 200	No	C1	
12-20	< 90	Very strong	C5	
	90-310	Strong	C4	
	> 310	Moderate	C3	
20	< 180	Very strong	C5	
	180-560	Strong	C5	
	> 560	Strong	C5	

CHAPTER 3. ILLUSTRATION OF A LOGIC FRAMEWORK, BASED ON EMI-INFERRED SOIL PROPERTIES, FOR SITE-SPECIFIC ASSESSMENT OF SALTS: A CASE STUDY

3.1 Introduction

Most land use problems are caused by salinisation and sodification of soils, especially in irrigated areas of the world (Hanson et al., 2006). The negative effects of the salt load associated with irrigation include its effect on the osmotic potential of soil water, as well as the degradation of soil physical properties, such as crusting, hardsetting, infiltration, internal and external drainage (Hillel, 2004).

Sodium salts tend to degrade soil structure through dispersion of clay particles that disrupt the functionality of pore systems. Macro pores are responsible for absorbing rainfall or irrigation at the soil surface, redistribution of the water in the profile and leaching of salts beyond the root zone (Nimmo, 2004; Kutílek and Jendele 2008; Mengistu et al., 2018). It also plays a significant role in gas and heat exchange with the atmosphere and allow growth of plant roots (Lal and Shukla, 2004; Mengistu et al., 2017). The main function of the meso- and micro pores are to provide storage capacity for water in the profile (Hensley et al., 2011). Residual pores (micro pores) provide water storage around the surface area of clay minerals for important cation exchange and nutrient adsorption (Schoenholtz et al., 2000; Nimmo, 2004). Hence, growth of crops depends heavily on the quality and geometry of soil pores, i.e. soil structure. Degradation of the pore geometry through dispersion of clay particles will cause poor germination, retarded plant growth, decreased grain yields, and in extreme cases total crop failure (Warrence et al., 2002; Isla et al., 2003; Naidoo et al., 2004; Urdanoz et al., 2008; Garcia and Medina, 2013; Shongwe and Wahome, 2014).

Salinity, on the other hand, do not affect soil structure, but rather the osmotic potential of the soil water. The lower the osmotic potential of soil water, the lower the ability of roots to absorb this water (Hillel, 2004). Lower water uptake by crops will directly result in lower yield (Ehlers et al., 2007). Thus, it is important to spatially monitor salts in the soil profile to assess its individual and combined effect on the soil and crop performance.

Electromagnetic induction (EMI) measurements in agriculture was first used to assess salts in soils, i.e. salinity (EC_e) and ESP in crop fields. Results indicated that the technology may also be useful for assessing other soil properties such as clay content, sand content, water content, bulk density and cation exchange capacity (Huth and Poulton, 2002; Sudduth et al., 2005; Grisso et al., 2009). The assessment is based on the site-specific relationship between instrument readings (apparent electrical conductivity, EC_a) and the soil property of interest. This implies that the EMI instruments require site-specific calibration each time the instrument is used. As proof of instrument performance, tables summarising EMI related studies in agriculture can be found in Corwin and Lesch (2005a) and Heil and Schmidhalter (2017).

The most efficient production of grapes is achieved in soils with good internal drainage. In poorly drained soils, roots may penetrate only up to 0.6 m or less, whereas in deep, well-drained soils it can penetrate 1.8 m or more. Subsoil characteristics are important when selecting a site for vineyard establishment because it often indicates the nature of external drainage. Lateral water movement at a given depth below the surface can also result in waterlogged conditions in low lying areas in the field, harming vines. Even a sloped vineyard may have this problem. Operating equipment in wet conditions can also cause soil compaction (Dami et al., 2005).

Compared to other crops, grapes (*Vitis vinifera*) are classified as moderately sensitive to salinity (Walker, 2010; Lanyon, 2011). A threshold soil EC_e, beyond which yield could be expected to decrease, is 150 mS m^{-1}. In addition, a 9.6% reduction in yield is expected for every 100 mS m^{-1} increase in EC_e (Lanyon, 2011). Root zone salinity should be regularly monitored and ideally maintained below the threshold values. Numerous studies have reported vine growth reductions in response to salinity (Walker, 2010). The effect of increasing salinity is first observed by a reduction in vine growth, followed by a decline in vine yield if saline conditions persist (Lanyon, 2011). Salinity affects the timing of budburst, timing of veraison, bunch number, fruitfulness, cane number, berry size and sugar content. Salinity effects on yield are influenced by rootstock type and severely salt affected vines fail to mature fruit (Walker, 2010).

The objective of this chapter was to illustrate the application of a logic framework, using EMI derived soil properties, to support scientifically sound decisions regarding the management of salts in the root zone. The specific objectives with the framework were: (i) to show where the salts are in the crop field, (ii) how it impacts the hydro-physical properties such as bulk density, saturated hydraulic conductivity and water storage in the profile, and (iii) to couple site-specific procedures to rectify problematic areas. A vineyard was used as case study to illustrate the concept.

3.2 Materials and methods

Case study location: In compliance with the ethical protocol, the name of the owner, managers and advisors of this farm will not be made public. This is to protect participant's best interests and also to respect their autonomy. The research team is grateful towards the farm owner, managers and advisors for the opportunity to conduct the research on their property.

EMI- and terrain survey, and soil sampling: The EMI-survey procedures described in Chapter 2 were followed. The 83.08 ha vineyard was surveyed on 29 April 2019 with a 10 m transect, resulting in a measuring density of 1 reading per 27.88 m^2. A total of 12 reference points were identified with the directed soil sampling procedure of ESAP-RSSD. At each of the reference points, a profile pit was excavated and the standard methods were followed for soil classification, as well as taking disturbed and undisturbed soil samples. Three depths were sampled, 0 to 300 mm, 300 to 750 mm and 750 to 1500 mm. All samples were couriered to Van's lab to conduct the laboratory tests.

Feedback to managers and advisors: On top of the hydro-physical report, the manger requested a fertility recommendation as well. Both the reports were e-mailed to him eight weeks after completion of the field survey. The results and findings of the report were discussed with the manager and advisors during a skype interview a week after receipt of the reports. The fertility report fall outside the scope of this project and therefore will not be discussed in this chapter.

Laboratory analysis: Disturbed and undisturbed soil samples were analysed as described in Section 2.4.

Statistical analysis and mapping: Procedures followed as described in Section 2.5.

3.3 Results

3.3.1 Apparent electrical conductivity

The vehicle route map is shown in Figure 3.1 and illustrates where EC_a measurements were taken by the EMI sensor. Two natural water courses divide the vineyard into three sections, A, B and C. The spatial distribution of the EC_a measurements recorded during the survey is presented in Figure 3.2 for the 0 to 1500 mm soil depth. Locations of the 12 soil sampling points are depicted on all maps. EC_a varied between 8 and 97 mS m^{-1} over the vineyard. There are distinct zones of low and high EC_a activity. Zones of high activity are centered around the edges of section B. High EC_a activity is also visible on the western side of section C. There is also a high activity spot just west of points V2 and V7 in section C. Large areas have a low activity (EC_a < 8.25 mS m^{-1}) and a moderate activity (8.25 to 30.5 mS m^{-1}).

3.3.2 Terrain

Elevation data gathered by the Trimble GPS system during the survey was used to compile the high resolution maps for contours (elevation), infield slope, drainage lines and infield aspect maps as seen in Figures 3.3 to 3.6. The vineyard is located on midslope and footslope morphological terrain units (Figure 3.3). The general slope is approximately 8%, falling from the north (91 m above sea level) to the south (30 m above sea level), resulting in a general southern aspect for the terrain as a whole. As mentioned, two natural watercourses divide the vineyards into three sections (Figure 3.3). Section A has a southeast and southwest aspect with predominantly strong (10 to 20%) and very strong (> 20%) slopes. The slopes in section B are similar in magnitude to section A, but the aspect is predominantly south. The slopes of section C are relative flat compared to the other two sections, with a mixture of a south- and southwest aspect. In section A and C vine rows are planted in a north-south direction, while in section B they are orientated in an east-west direction (Figure 3.1). The crop is ridged, forcing runoff in the ridge directions indicated on the drainage line map.

3.3.3 Soil forms and textures

The EC_a-directed sampling method revealed nine soil forms in the 83 ha vineyard. Observations made, i.e. soil descriptions and photos of the 12 profiles, are available in Appendix A, while a summary of the soil forms are presented in Table 3.1 All A-horizons were orthic. The texture class depicted in Figure 3.7a shows that about 80% of the total area is sandy loam, 15% loamy and the rest is loamy sand. About 60% of the total area has sandy subsoil (300 to 750 mm, Figure 3.7b), reflecting on the soil forms that have E-horizons (Cartref, Constantia, Fernwood and Kroonstad), regic sand (Namib), red apedal B (Garies and Bloemdal) and a yellow brown apedal B (Clovelly) subsoils. The deep subsoil comprises of a variety of B2 horizons, from regic sand to yellow brown apedal, unspecified material, gley cutanic, lithocutanic and dorbank. The corresponding texture map (750 to 1500 mm, Figure 3.7c) reflects on the diagnostic changes in the deep subsoil, where the sandy clay texture class dominates, covering 65% of the total area.

Concerning the patterns of activity in the EMI-map (Figure 3.2), there is a striking similarity in the textural classes of the topsoil, subsoil and deep subsoil. The zones of high EC_a activity agree strongly with the loamy sand class of the top soil, sandy loam and loamy sand patterns of the sub soil, and sandy clay loam of the deep subsoil.

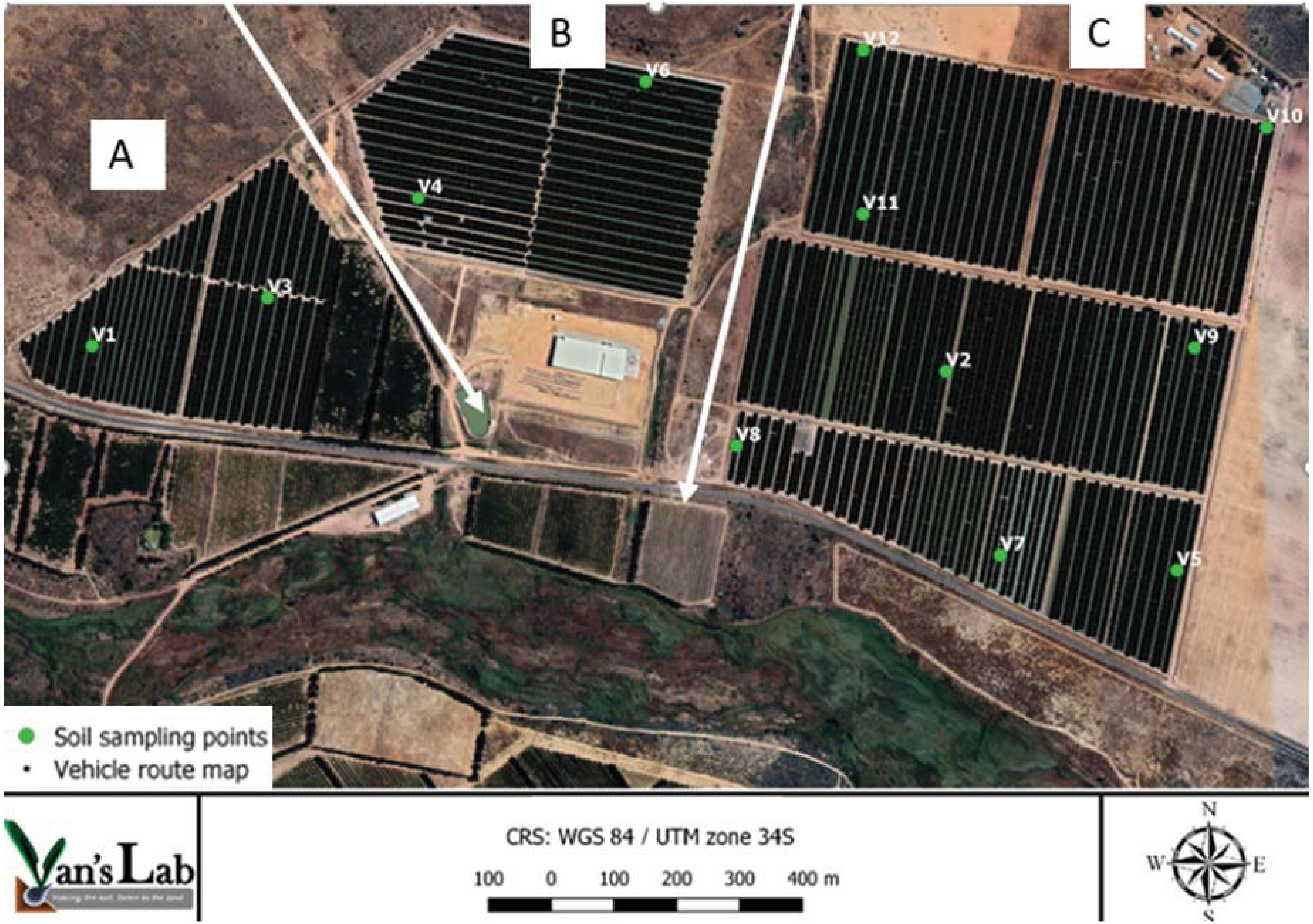


Figure 3.1 Vehicle route map recorded by GPS during field survey of the 83 ha vineyard, points V1 to V12 represent the reference points were soil samples were taken. Natural watercourses divide the vineyard into three blocks (A, B and C).

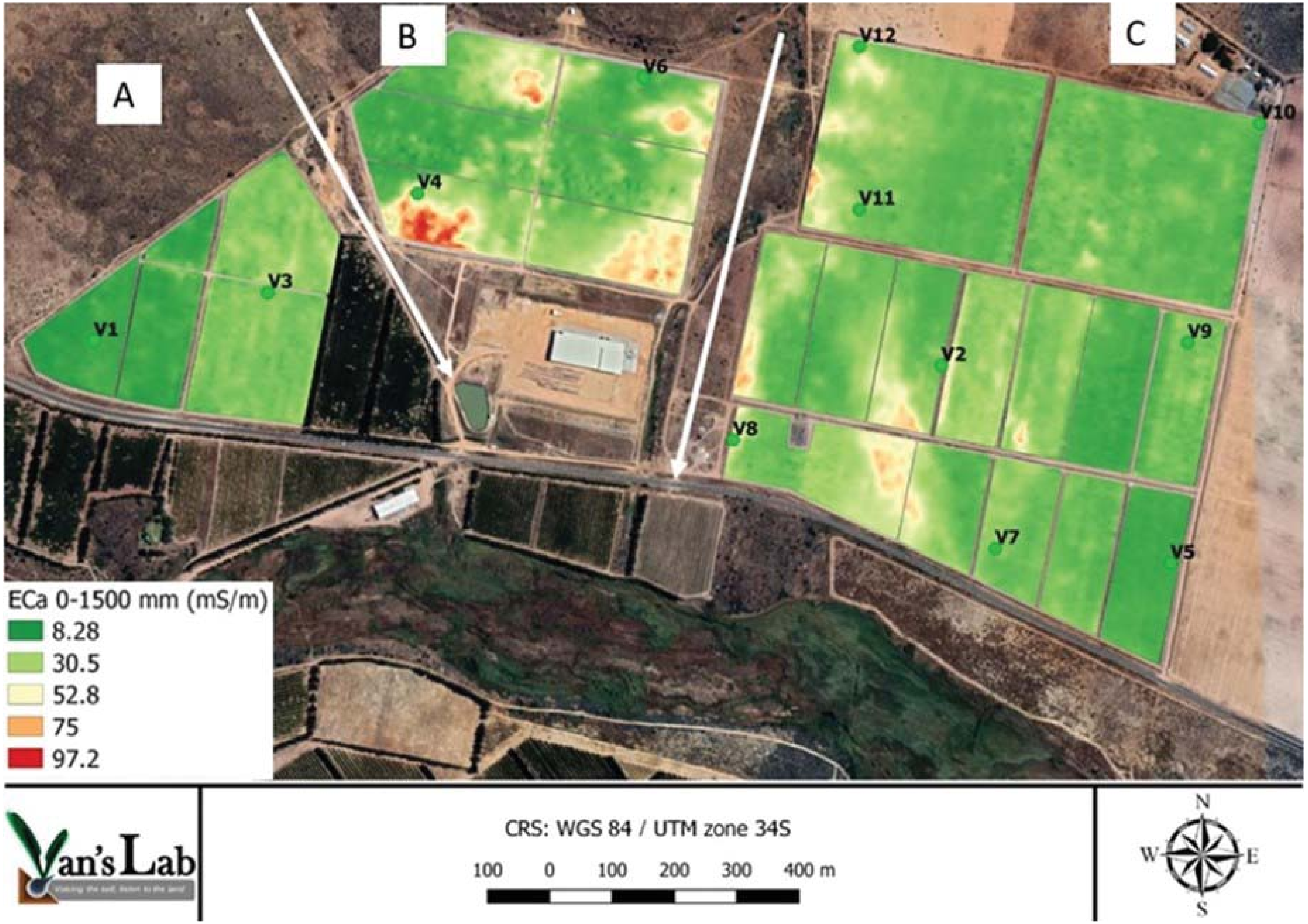


Figure 3.2 Spatial distribution of apparent electrical conductivity (EC_a, mS m^{-1}) in the 0 to 1500 mm soil profile over the vineyard.

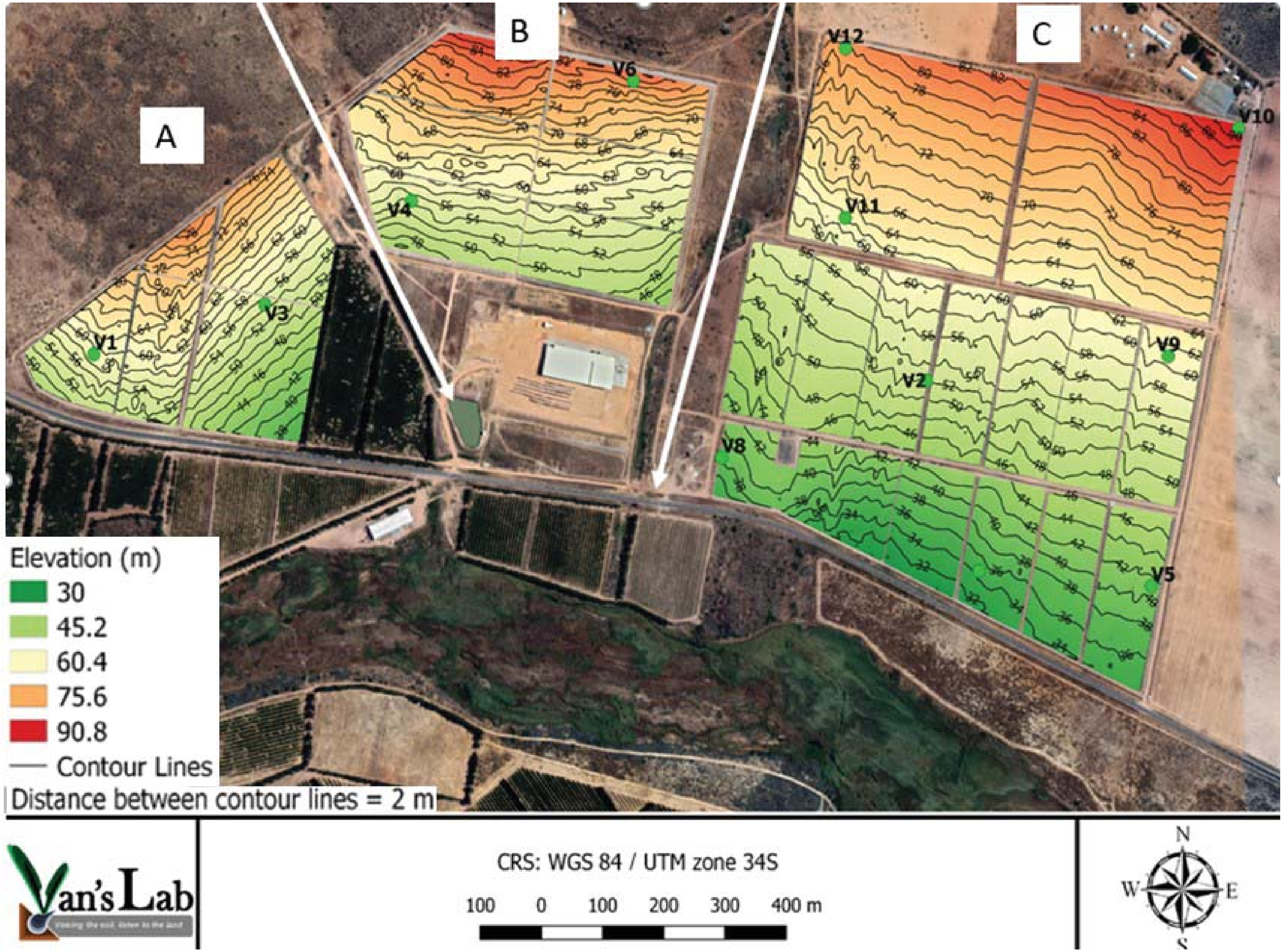


Figure 3.3 Contour map of the vineyard divided into three sections (A, B and C) by the two watercourses.

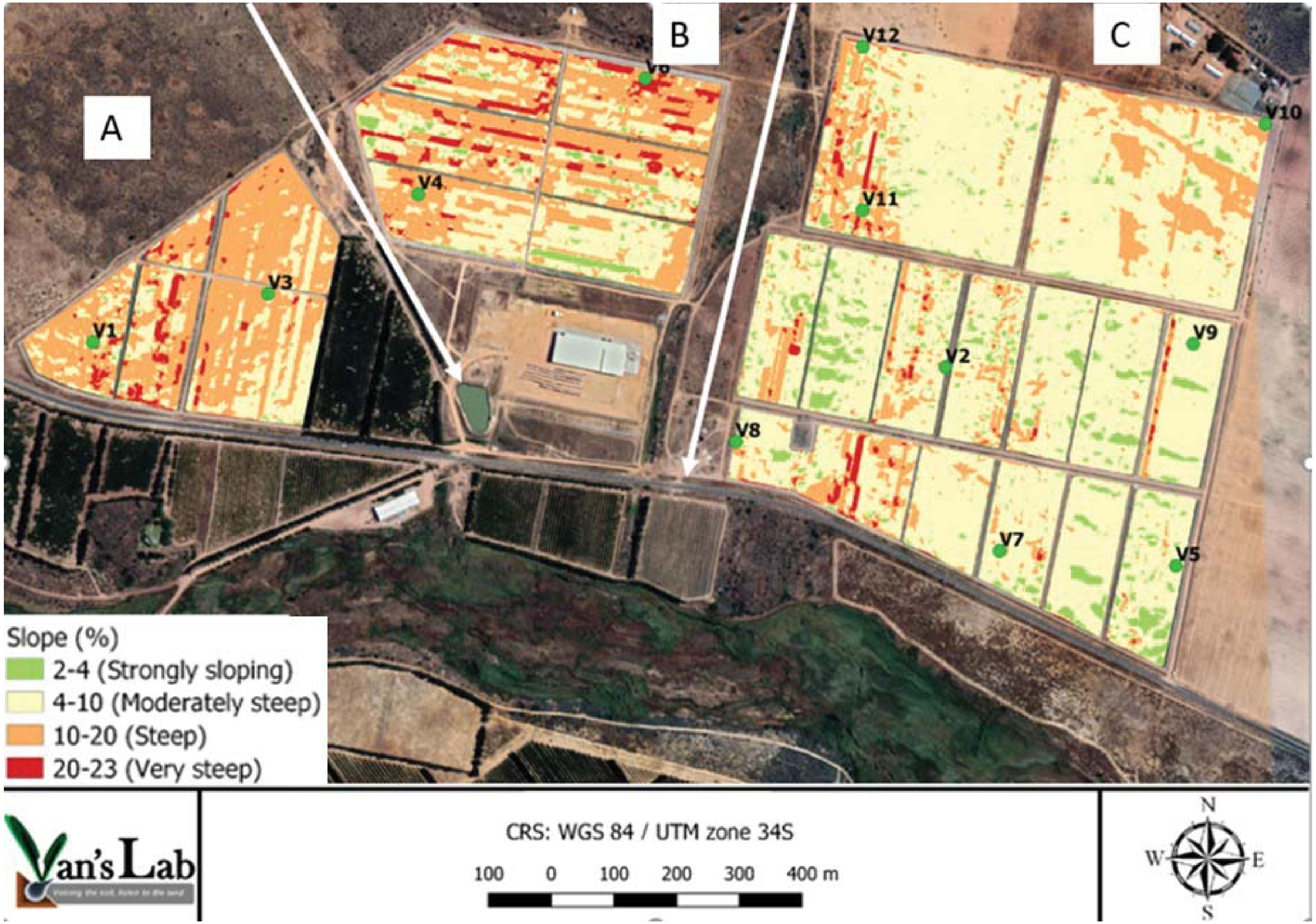


Figure 3.4 Spatial distribution of in-field slopes over the vineyard.

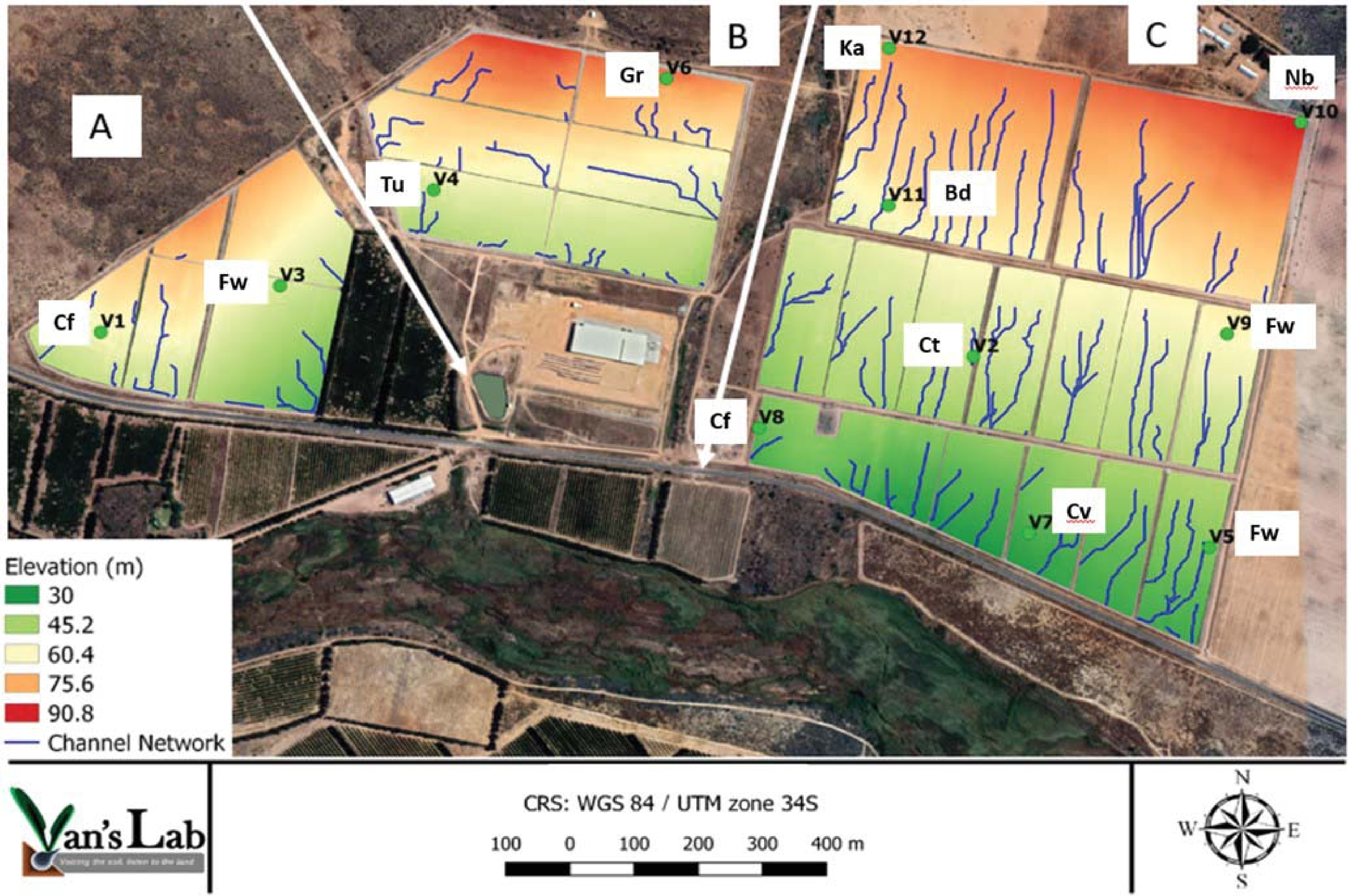


Figure 3.5 Spatial distribution of the in-field surface drainage lines over the vineyard.

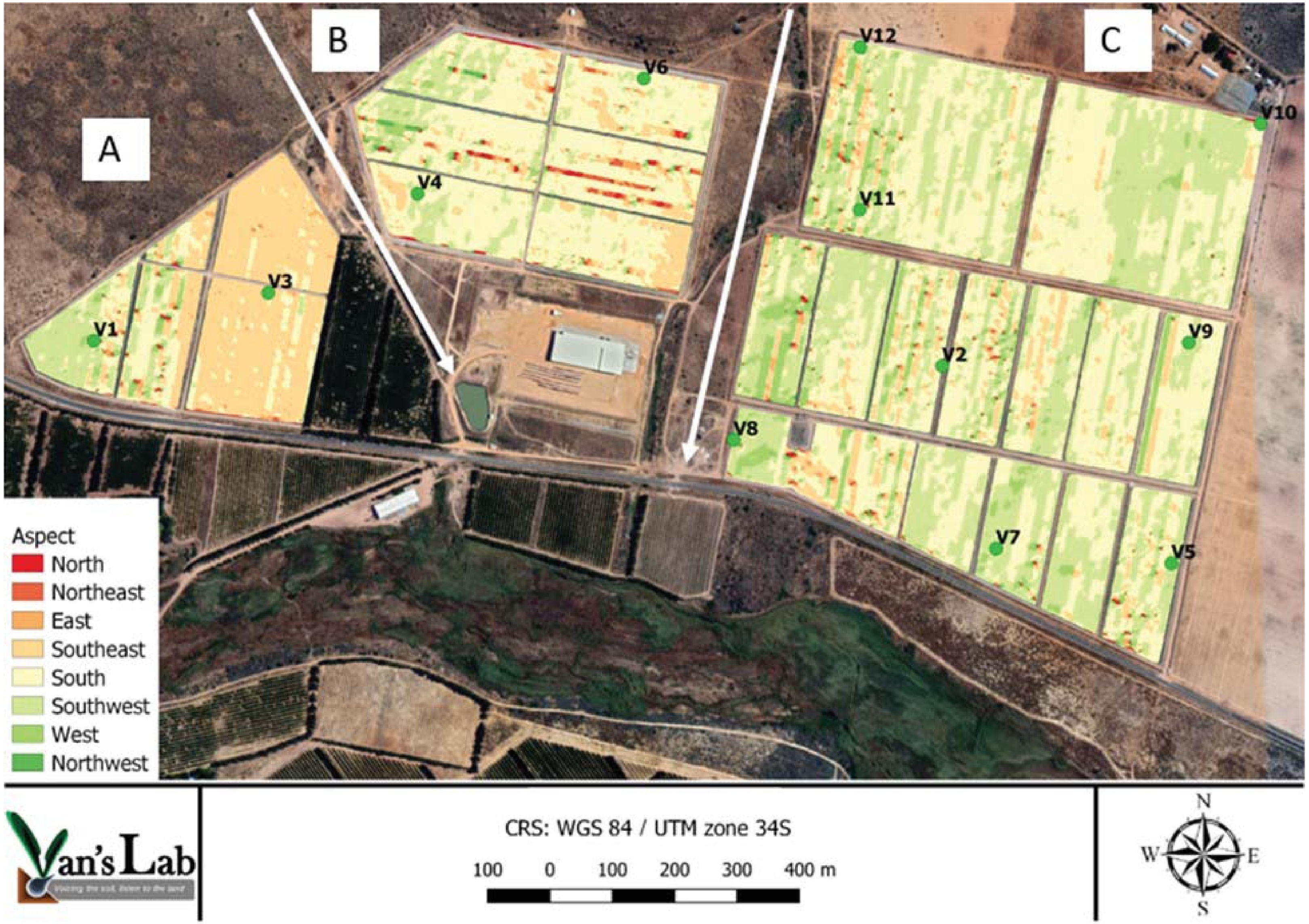


Figure 3.6 Spatial distribution of the in-field aspect over the vineyard.

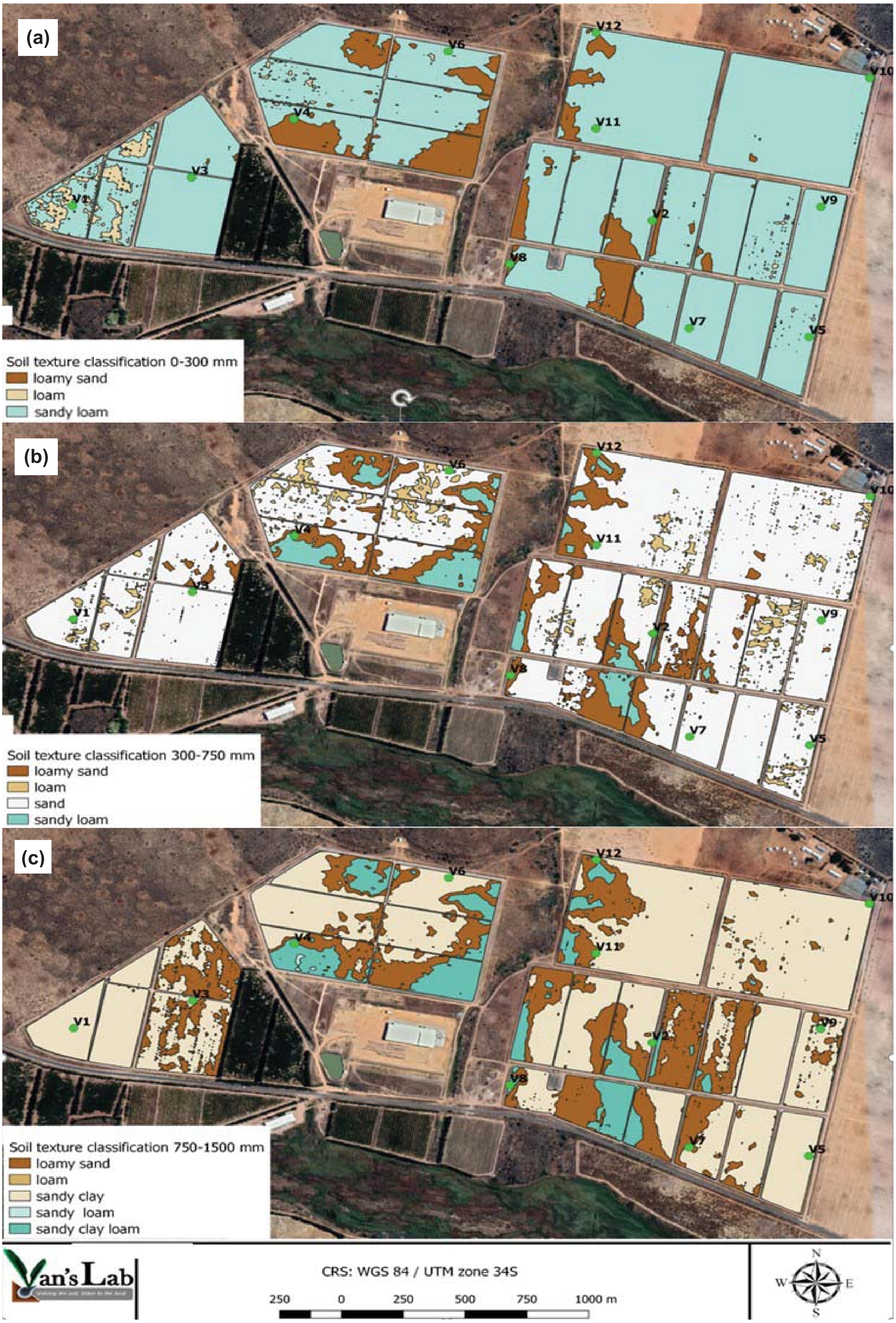


Figure 3.7 Textural classes in the vineyard for the (a) top soil (0 to 300 mm), (b) subsoil (300 to 750 mm) and (c) deep subsoil (750 to 1500 mm).

Table 3.1 Summary of soil forms present in the vineyard

Form	Position	A-horizon	B1-horizon	B2-horizon
Cartref	V1 and V8	Orthic A	E	Lithocutanic
Constantia	V2	Orthic A	E	Yellow brown apedal
Fernwood	V3, V5 and V9	Orthic A	E	E
Kroonstad	V12	Orthic A	E	Gley cutanic
Namib	V10	Orthic A	Regic sand	Regic sand
Garies	V6	Orthic A	Red apedal	Dorbank
Bloemdal	V11	Orthic A	Red apedal	Unspecified wet
Clovelly	V7	Orthic A	Yellow brown apedal	Unspecified
Tukulu	V4	Orthic A	Neocutanic	Unspecified wet

3.3.4 Soil properties of the crop field

3.3.4.1 Topsoil (0 to 300 mm depth)

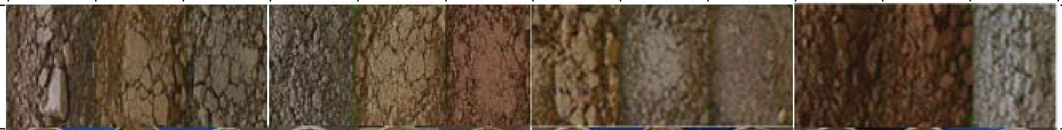
Table 3.2 contains the laboratory results of the soil properties for the 12 reference points, including averages, minimums, maximums and standard deviations. Table 3.3 presents the results for statistical parameters obtained through multiple-linear regression for the models to be used to predict soil attributes from EC_a values. Figures 3.8 to 3.17 depict the soil property maps for the 0 to 300 mm sampling depth. Based on the criteria for prediction models, the K_{sat} map shows poor accuracy, saturation point and total porosity maps are moderately accurate, while accuracy of the rest of the soil property maps can be regarded as good.

It is a drawback that the K_{sat} map is inaccurate, since K_{sat} normally gives a good indication of the quality of pores in terms of its ability to absorb rain and irrigation over the crop field. Using the measured values, it can be concluded that the final infiltration rate of the top soil is on average 244 mm h^{-1} with a standard deviation of 179 mm h^{-1}. This is considered "rapid" (USDA-NRCS, 2019), as is expected for a loam-sandy dominated texture class.

From a soil physical property perspective, patterns on the clay map, clay-plus-silt map and bulk density map, closely resemble patterns on the EC_a map. The higher EC_a zones (yellow, brown and red zones; 52.8 to 97.8 mS m^{-1}) correspond well with: (i) the relatively high clay zone (yellow and green patterns; 6 to 14% clay), (ii) the relatively higher clay-plus-silt zones (yellow, light and green zones; 8 to 16% clay-plus-silt), and (iii) the higher bulk density zone (yellow, brown and red zone; 1.54 to 1.71 g cm^{-3}). On the other side of the scale, the lower EC_a zones correspond well with the lower clay, clay-plus-silt and bulk density zones indicated on the respective maps.

Air and water management indicators included total porosity (%), saturation point (%), field aeration capacity (FAC, %) and drained upper limit (DUL, %). Although the accuracy of the total porosity and saturation point was classed as moderately accurate, it still resembled EC_a patterns. In this case it was an inverse relationship, low pore space values corresponded to high EC_a and vice versa. A similar inverse relationship was found between FAC and EC_a spatial patterns. It probably has to do with the effect of compaction. The higher the compaction of soils, the lower the total porosity (Hillel, 2004). The drained upper limit, also called field capacity in practice, is expressed in mm to account for the soil thickness. Again, spatial distribution patterns of DUL and EC_a corresponded very well. The higher the DUL value, the higher the EC_a values observed.

Table 3.2 Soil laboratory analysis results for the top soil (0 to 300 mm depth)

Soil property		**V1**	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V9**	**V10**	**V11**	**V12**	**Mean**	**Min**	**Max**	**SD**
Disturbed soil sample																	
Undisturbed soil sample																	
Texture (%)	Silt + Clay	6	8	7	16	2	16	10	11	4	9	14	7	9	2	16	4
	Clay	4	5	6	11	1	13	7	8	3	6	9	5	7	1	13	3
	Silt	2	3	1	5	1	4	2	3	1	3	4	2	3	1	5	1
	Sand	94	93	93	85	98	84	91	89	97	92	87	93	91	84	98	5
Bulk density (g cm^{-3})		1.62	1.42	1.57	1.64	1.49	1.61	1.58	1.71	1.52	1.49	1.57	1.47	1.56	1.42	1.71	0.08
Saturated hydraulic conductivity (mm hr^{-1})		541	528	309	292	259	8	165	9	336	98	83	302	244	8	541	179
Saturation point (%)		33	40	33	31	38	33	32	24	36	39	31	40	34	24	40	5
Total porosity (%)		39	46	41	38	44	39	40	22	43	44	41	44	40	22	46	6
Field aeration capacity (%)		13	27	22	11	20	23	12	9	24	30	20	21	19	9	30	7
Water boundaries (%)	DUL	20	13	10	20	18	10	20	15	12	8	12	19	15	8	20	4
	LL	3	4	3	7	1	7	5	5	2	4	6	3	4	1	7	2
	Water store	17	9	7	13	17	2	15	9	10	4	6	16	10	2	17	5
Soil salts	EC_e (mS m^{-1})	37	23	28	19	21	30	28	34	28	30	19	25	27	19	37	6
	ESP (%)	11	16	12	32	22	8	11	10	11	16	9	17	15	8	32	7
	pH(extract)	7.97	7.96	7.95	7.38	7.81	7.81	7.79	7.78	8	8.02	7.88	7.84	8	7	8	0

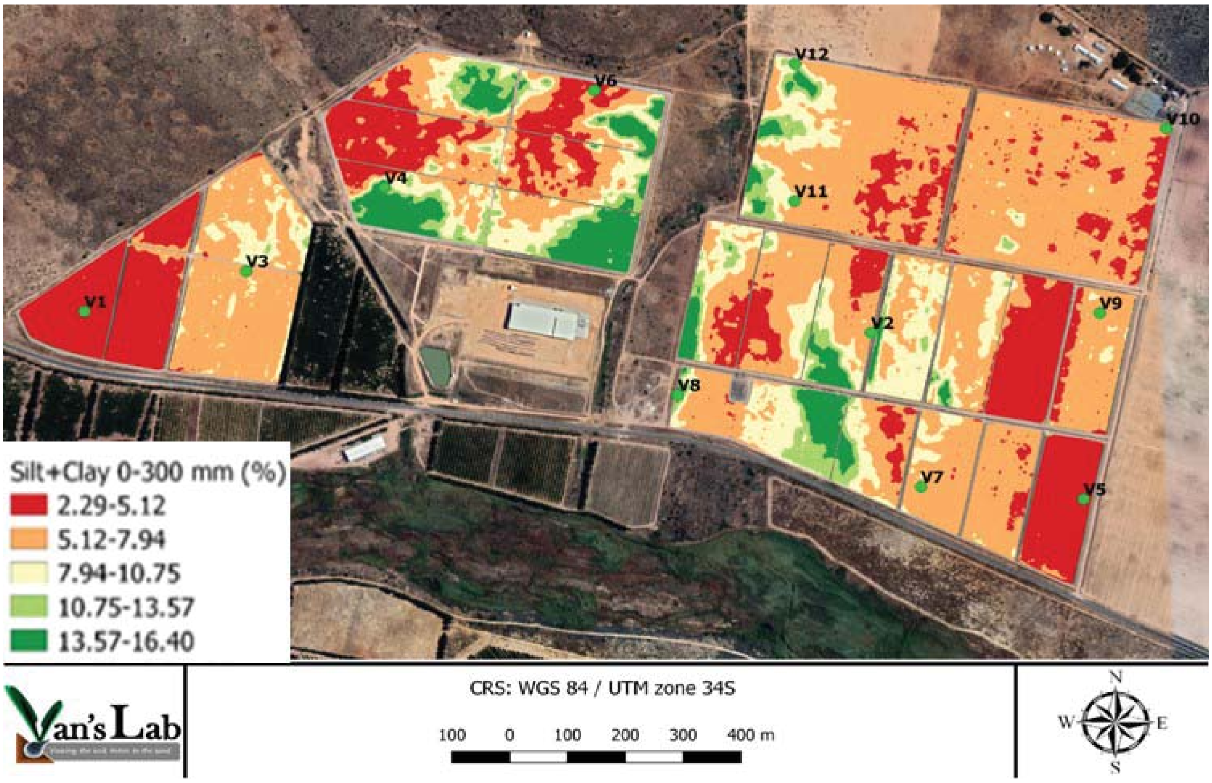


Figure 3.8 Spatial distribution of the silt-plus-clay percentage in the topsoil over the vineyard

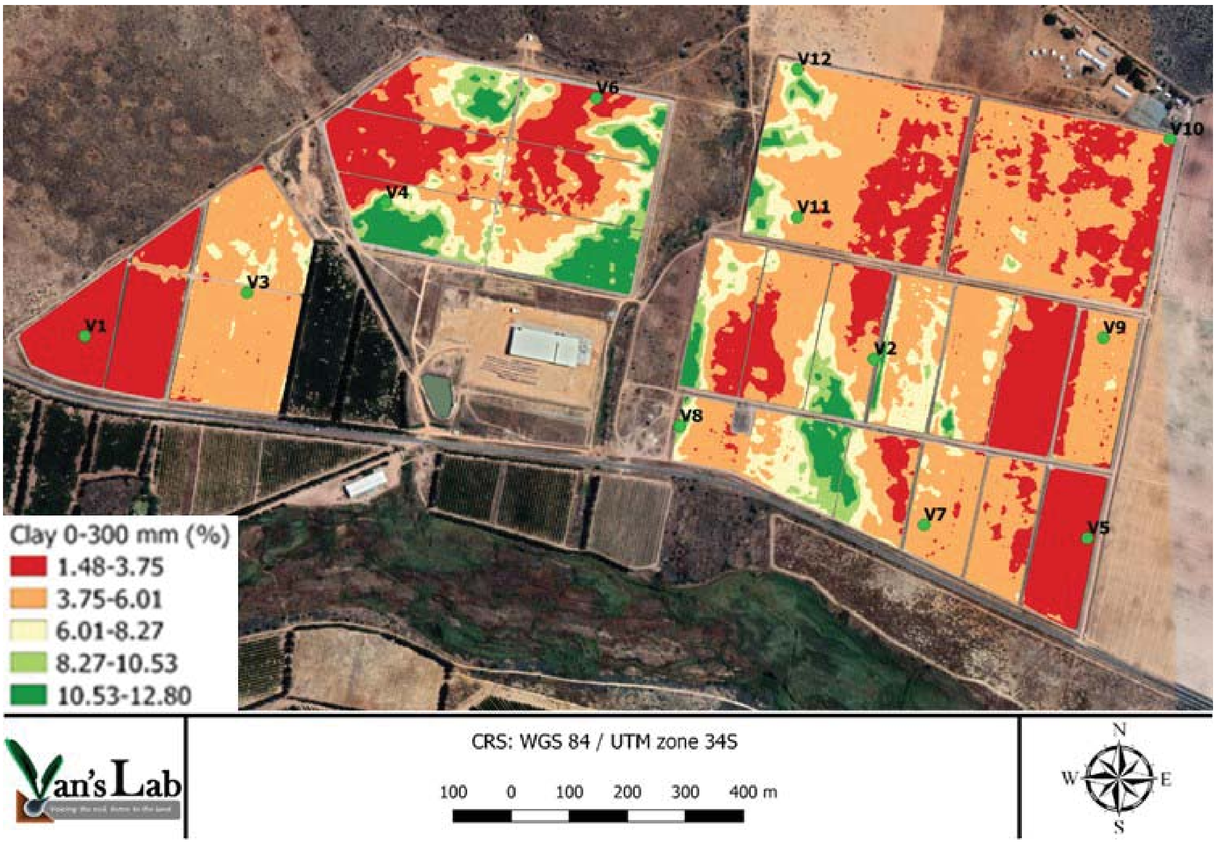


Figure 3.9 Spatial distribution of the clay percentage in the topsoil over the vineyard.

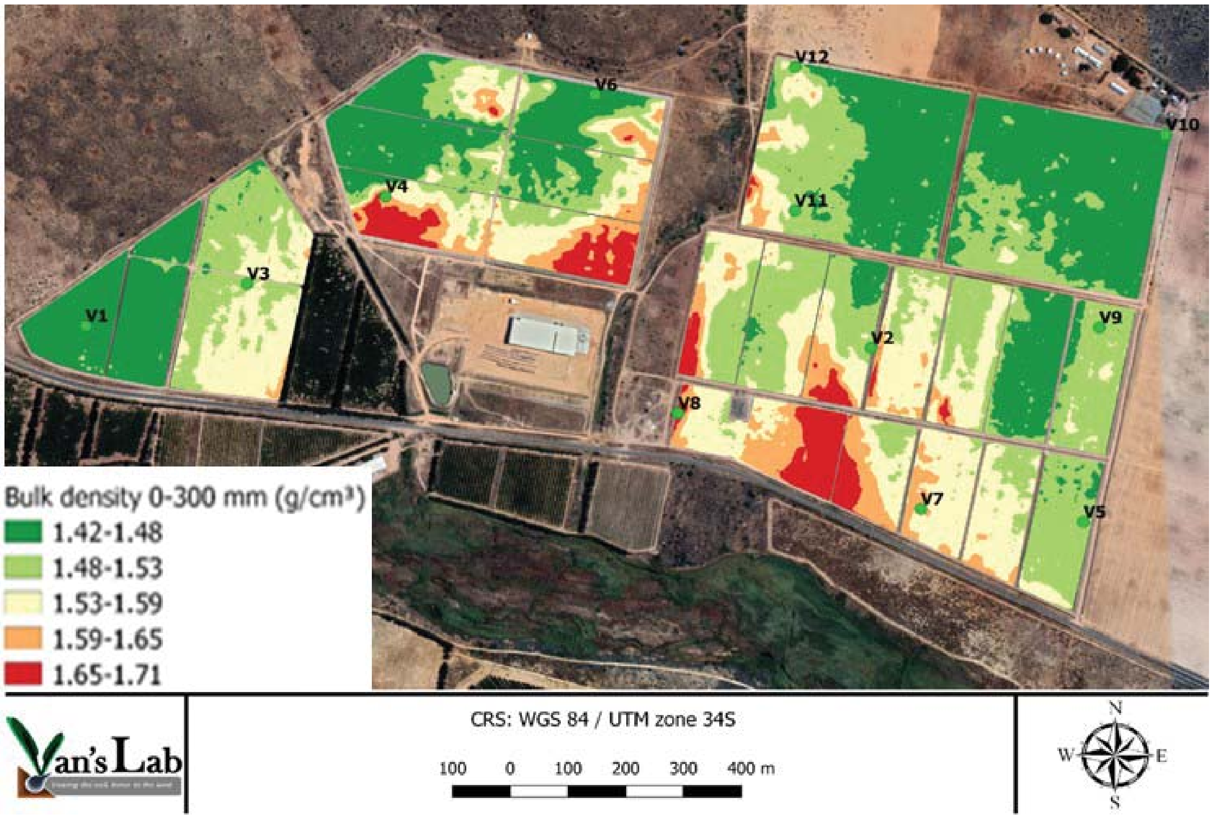


Figure 3.10 Spatial distribution of bulk density (g cm^{-3}) in the topsoil over the vineyard.

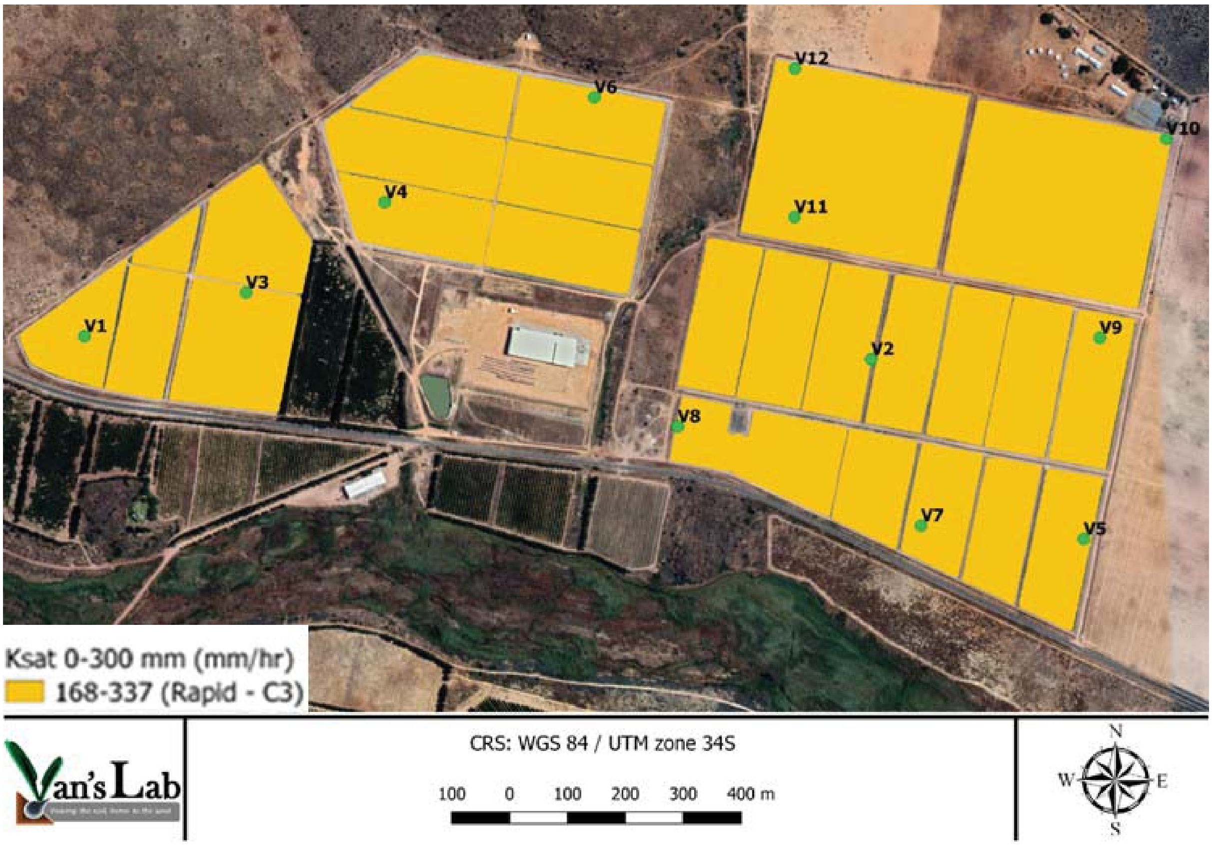


Figure 3.11 Spatial distribution of the saturated hydraulic conductivity (K_{sat}, mm h^{-1}) in the topsoil over the vineyard.

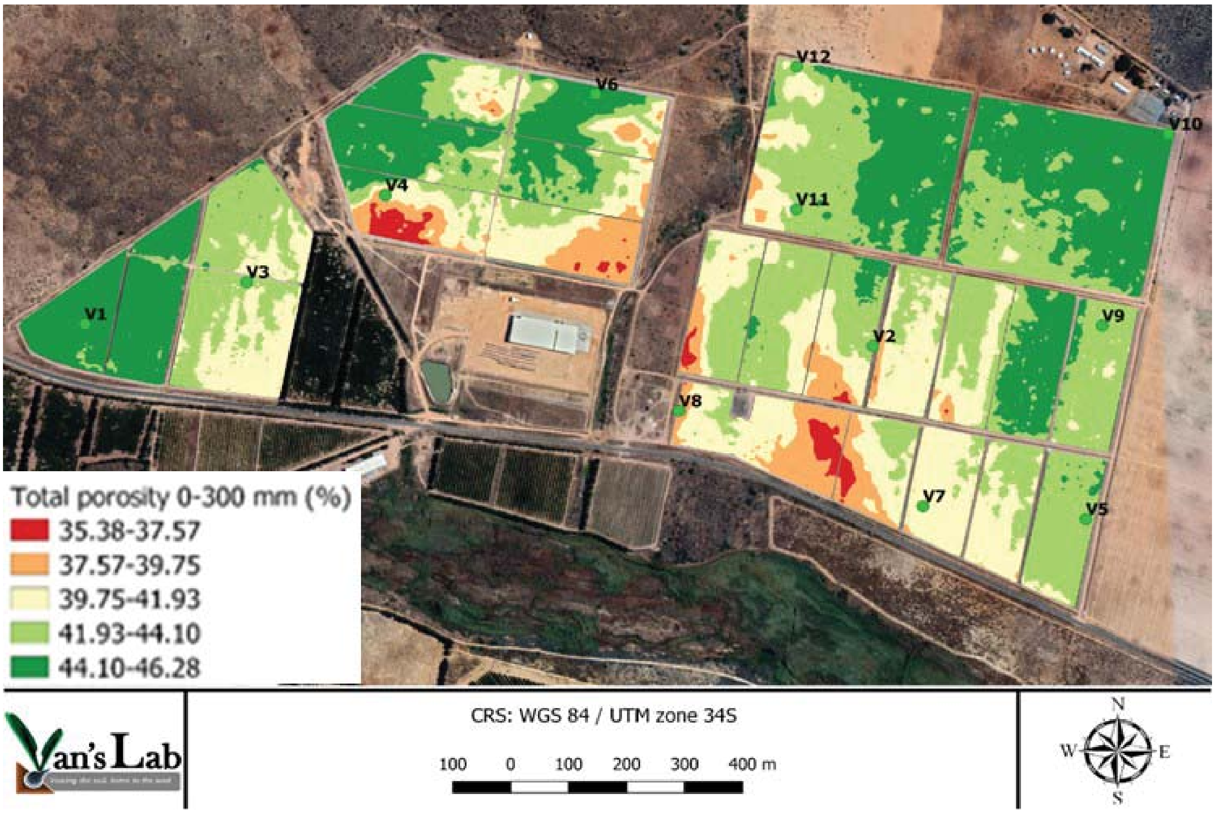


Figure 3.12 Spatial distribution of total porosity (%) in the topsoil over the vineyard.

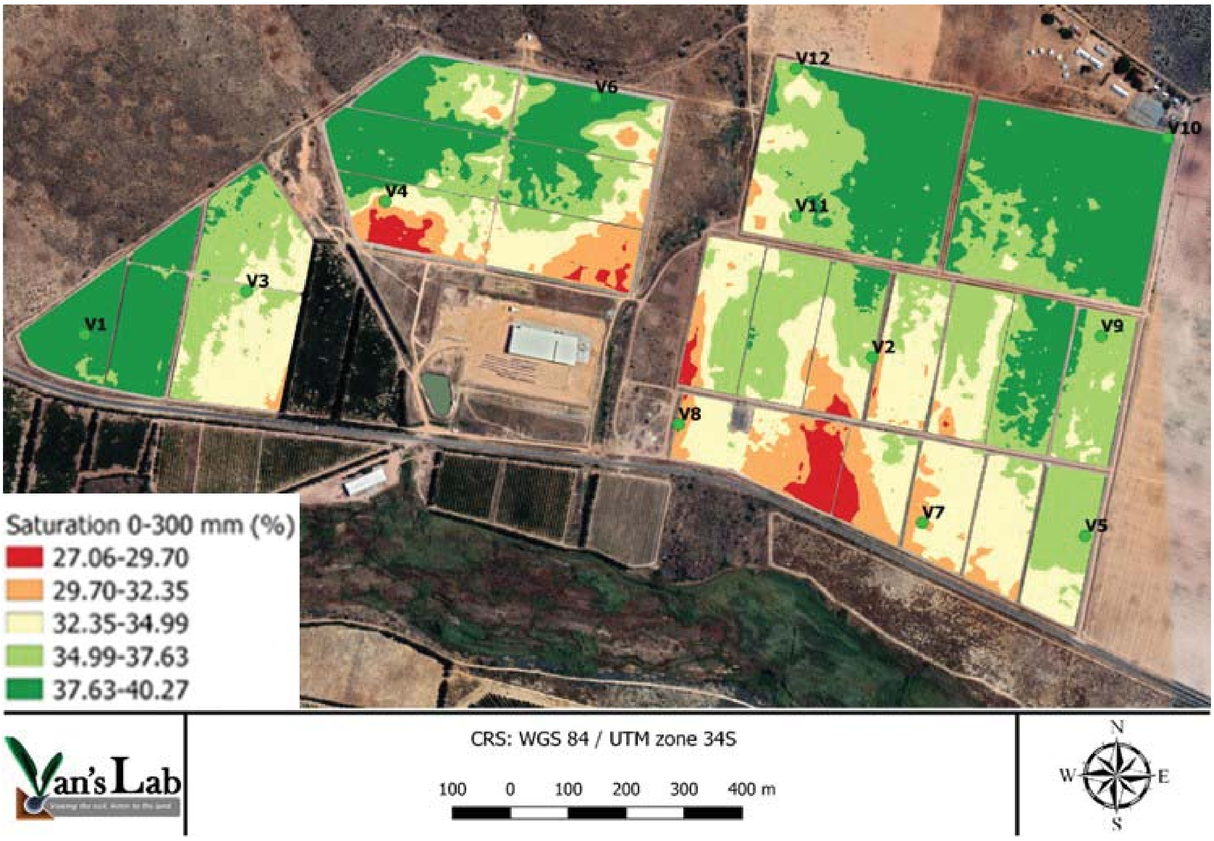


Figure 3.13 Spatial distribution of saturation point (%) in the topsoil over the vineyard.

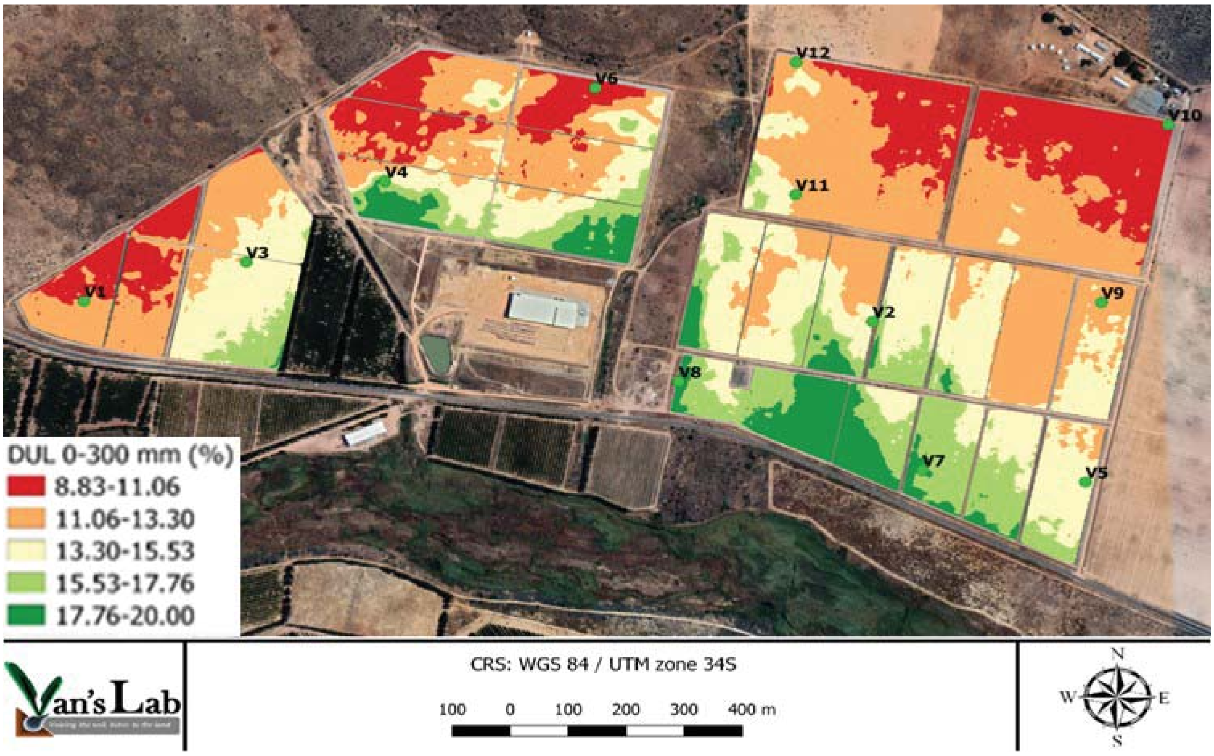


Figure 3.14 Spatial distribution of drained upper limit (DUL, mm) in the topsoil over the vineyard.

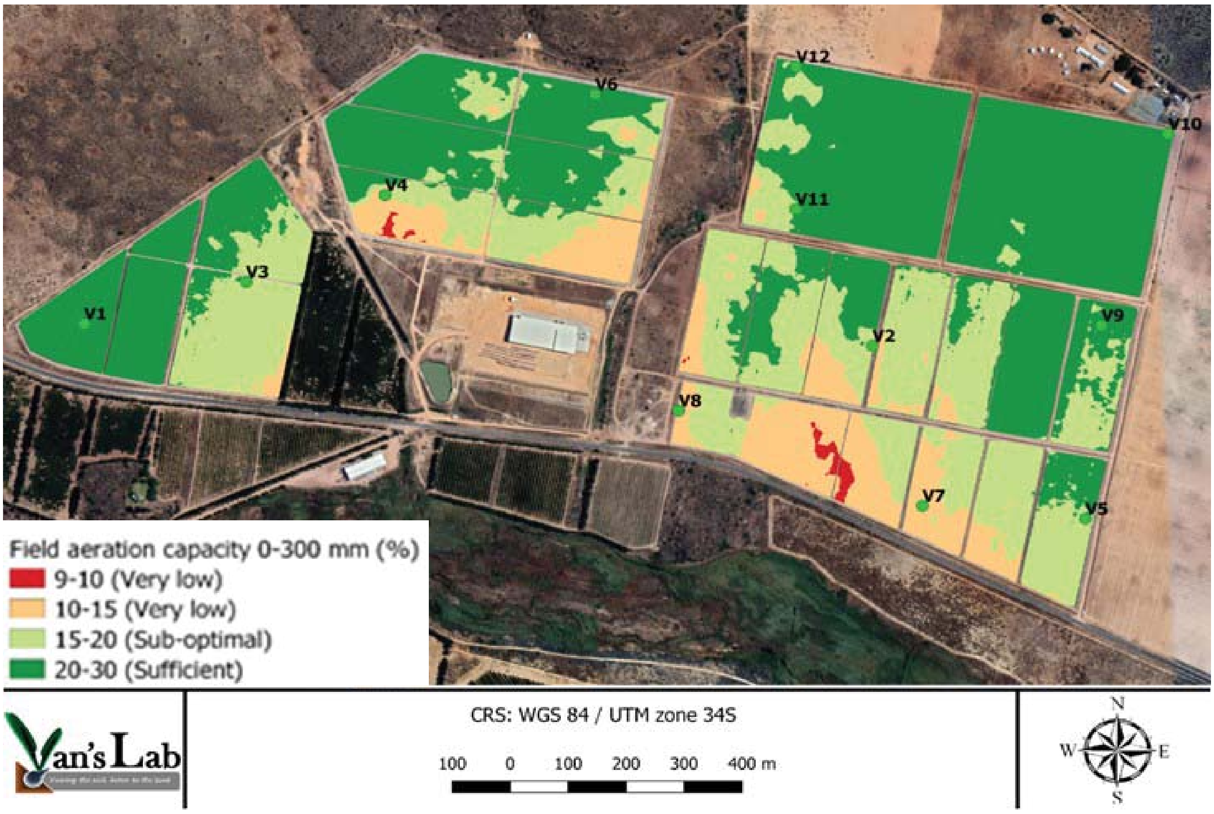


Figure 3.15 Spatial distribution of field aeration capacity (FAC,%) in the topsoil over the vineyard.

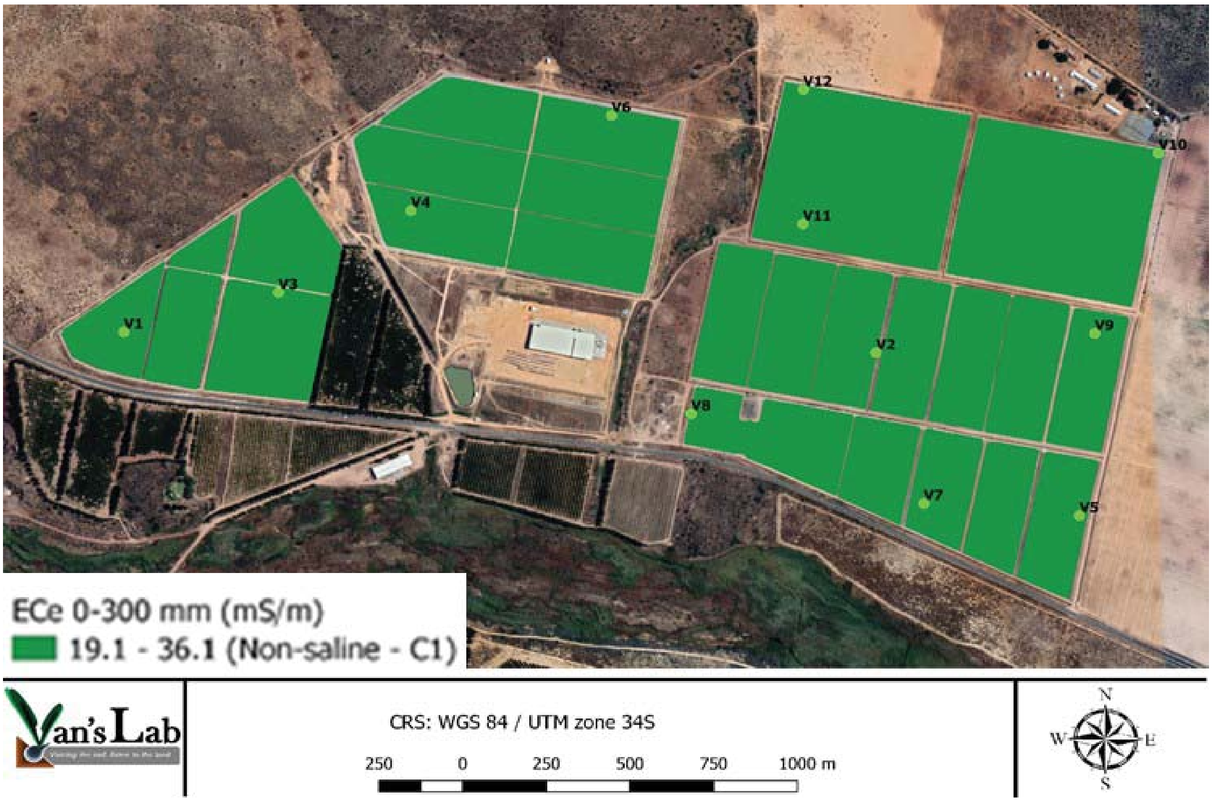


Figure 3.16 Spatial distribution of electrical conductivity (EC_e, mS m^{-1}) in the topsoil over the vineyard.

Figure 3.17 Spatial distribution of exchangeable sodium percentage (ESP, %) in the topsoil over the vineyard.

Table 3.3 Multi-linear regression statistics reflecting on the relationship between the EC_a, elevation and the particular soil property for the topsoil

Soil property	Coefficients			r	p-value
	Intercept	EC_a	Elevation		
Silt + Clay (%)	-1.288	1.064	0.027	0.72	0.08
Clay (%)	-1.662	1.105	0.001	0.73	0.07
BD (g cm^{-3})	0.522	0.092	-0.092	0.80	0.03
K_{sat} (mm hr^{-1})	7.347	0.094	-0.544	0.25	0.82
Saturation point (%)	3.195	-0.154	0.205	0.65	0.19
Field aeration capacity (%)	1.380	-0.424	0.702	0.82	0.02
Total porosity (%)	3.664	-0.106	0.098	0.70	0.13
DUL (%)	4.065	0.268	-0.557	0.71	0.06
EC_e (mS m^{-1})	4.044	0.043	-0.331	0.76	0.05
ESP (%)	-0.333	0.816	0.124	0.77	0.07

The maps of the two soil salt indicators, EC_e (mS m^{-1}) that represents salinity and the exchangeable sodium percentage (ESP, %) that defines sodicity, are depicted in Figures 3.16 and 3.17, respectively. The EC_e of the top soil was below the crop threshold and will not affect the vineyards in any way. However, the ESP is a concern for both the soil and the crop. The ESP at the 12 sampling points ranged from 8 to 32%, with an average of 15%. The spatial distribution of ESP over the vineyard mimics that of EC_a almost perfectly, i.e. a relatively high ESP corresponds with a high EC_a and vice-versa.

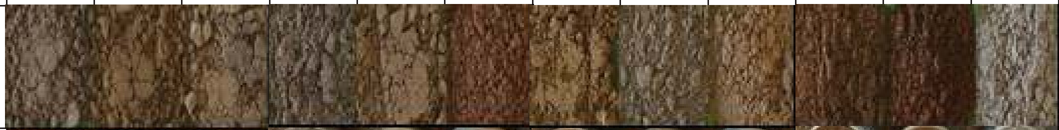
3.3.4.2 Subsoil (300 to 750 mm depth)

Table 3.4 shows the laboratory results on the soil properties of the subsoil measured at the 12 reference points. Statistical parameters of the multiple-linear regression models for each soil attribute is given in Table 3.5. Maps for all measured soil properties for the 300 to 750 mm sampling depth is presented in Figures 3.18 to 3.29.

Internal drainage refers to the flow of water within and through the root zone (Van der Watt and Van Rooyen, 1990). Spatial predictions for K_{sat} was once again poor, so we have to rely on the descriptive statistics in Table 3.5. Average K_{sat} was 233 mm h^{-1} with a standard deviation of 185 mm h^{-1}. This can be classified as rapid and poses a moderate threat to leaching of nutrients.

Spatial accuracy of the clay and clay-plus-silt predictions were good, while bulk density predictions could be classified as moderately accurate. From a soil physical property perspective, the patterns in the clay map, clay-plus-silt map and bulk density map, closely resembles the patterns on the EC_a map. Trends in patterns are similar than described for the topsoil. Higher EC_a values (52.8 to 97.8 mS m^{-1}) correspond to higher silt-plus-clay (11 to 14%), clay (7 to 14%) and bulk densities (1.57 to 1.77 g cm^{-3}). On the other end of the scale, the lower EC_a values correspond well with lower values of the mentioned soil properties.

Table 3.4 Soil laboratory analysis results for the subsoil (300 to 750 mm depth)

Soil property		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	Mean	Min	Max	SD
Disturbed soil sample																	
Undisturbed soil sample																	
Texture (%)	Silt + Clay	13	5	5	22	4	16	9	15	4	10	14	14	11	4	22	6
	Clay	9	4	4	14	3	11	7	10	3	7	11	9	8	3	14	4
	Silt	5	2	1	7	1	5	2	5	1	3	3	5	3	1	7	2
	Sand	88	96	94	78	97	84	91	86	96	92	87	87	90	78	97	6
Bulk density (g cm^{-3})		1.68	1.49	1.62	1.77	1.49	1.63	1.55	1.72	1.52	1.44	1.63	1.5	1.59	1.00	2.00	0.10
K_{sat} (mm hr^{-1})		21	608	330	71	456	302	344	47	268	59	77	215	233	21	608	185
Saturation point (%)		27	40	31	23	39	32	33	22	36	40	33	38	33	22	40	6.14
Total porosity (%)		37	44	39	33	44	38	41	35	43	46	38	43	40	33	46	3.88
Field aeration capacity (%)		15	22	22	9	29	24	20	4	30	32	13	29	21	4	32	8.99
Water boundaries (%)	DUL	13	18	9	14	9	9	13	18	6	8	19	9	12	6	19	4.61
	LL	6	3	3	9	2	7	4	7	2	5	6	6	5	2	9	2
	Water store	7	15	6	0	7	1	9	11	4	3	13	2	7	0	15	5
Soil salts	EC_e (mS m^{-1})	15	17.87	19.84	29.08	21.35	27	21.01	28	16.49	28.58	26.25	22.72	22.75	14.83	29.08	4.97
	ESP (%)	2.92	2.90	2.71	4.40	2.80	3.37	3.15	2.74	2.46	3.18	3.75	4.10	3.21	2.46	4.40	0.60
	pH(extract)	6.30	6.57	6.47	6.37	7.04	6.41	7.04	7.03	6.86	6.73	6.56	6.44	6.65	6.30	7.04	0.28

Spatial predictions of air and water management indicators, i.e. total porosity (%), saturation point (%), field aeration capacity (FAC, %) and drained upper limit (DUL, %), were poor and results should not be used to make spatial interpretations. Instead, considering the descriptive stats in Table 3.4, the averages and standard deviations of these properties were 40±3.9%, 33±6.1%, 21±9% and 12±4.6%, respectively. Of more concern will be the minimum values, since it will show if a particular property is restrictive. Hence, the minimum values are: 33%, 22%, 4% and 6%, respectively. This indicates that there are areas in the field where: (i) hydrophobic characteristics prevail, (ii) aeration is poor, and (iii) water storage is poor.

Although EC_e and ESP values in Table 3.5 are given for the subsoil, these values actually represent both the subsoil and deep subsoil, since the soils were mixed to comply with the farmer's budget. Fortunately, the accuracy of the two soil salt indicator maps (Figure 3.26 for salinity and Figure 3.27 for sodicity) were both good. The EC_e of the subsoil was below 30 mS m^{-1} over the entire field and therefore will not affect the vineyards in any way. Similarly, ESP was below 5% and hence will not affect the hydraulics of the soil. The spatial distribution of ESP over the vineyard mimics that of the EC_a pattern almost perfectly, i.e. a relative high ESP corresponds with a high EC_a and vice-versa.

Table 3.5 Multi-linear regression statistics for the subsoil (300 to 750 mm depth)

	Coefficients				
Soil property	**Intercept**	**EC_a**	**Elevation**	**r**	**p-value**
Silt + Clay (%)	-2.120	1.341	0.144	0.89	0.00
Clay (%)	-2.234	1.283	0.127	0.86	0.01
BD (g cm^{-3})	0.498	0.124	-0.097	0.83	0.02
K_{sat} (mm hr^{-1})	12.015	-1.502	-0.676	0.70	0.10
Saturation point (%)	2.436	0.195	0.146	0.67	0.17
Field aeration capacity (%)	4.337	-0.754	0.161	0.76	0.07
Total porosity (%)	3.474	0.104	-0.001	0.57	0.30
DUL (%)	3.023	0.364	-0.373	0.63	0.21
*EC_e (mS m^{-1})	2.221	0.355	0.052	0.73	0.05
*ESP (%)	0.363	0.422	0.003	0.83	0.03

*represents the average over 300 to 1500 mm soil depth

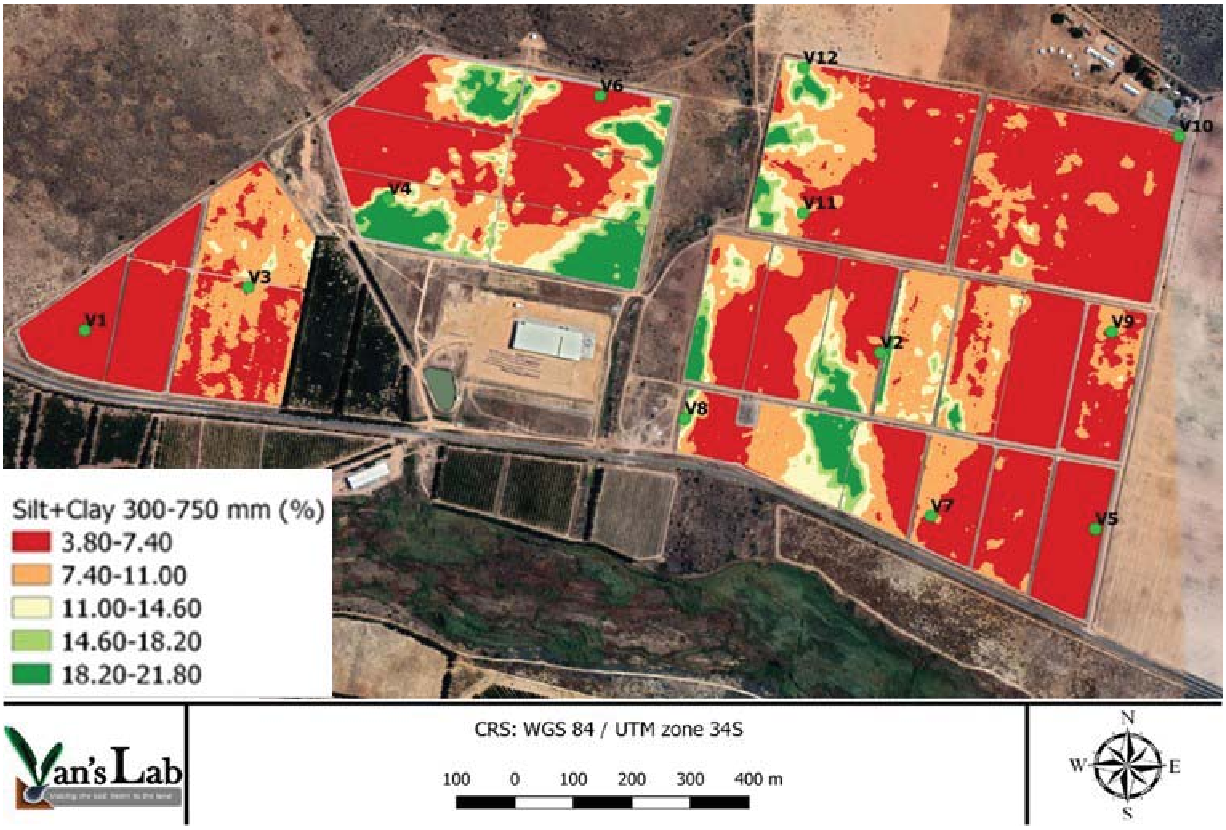


Figure 3.18 Spatial distribution of silt-plus-clay percentage in the subsoil over the vineyard.

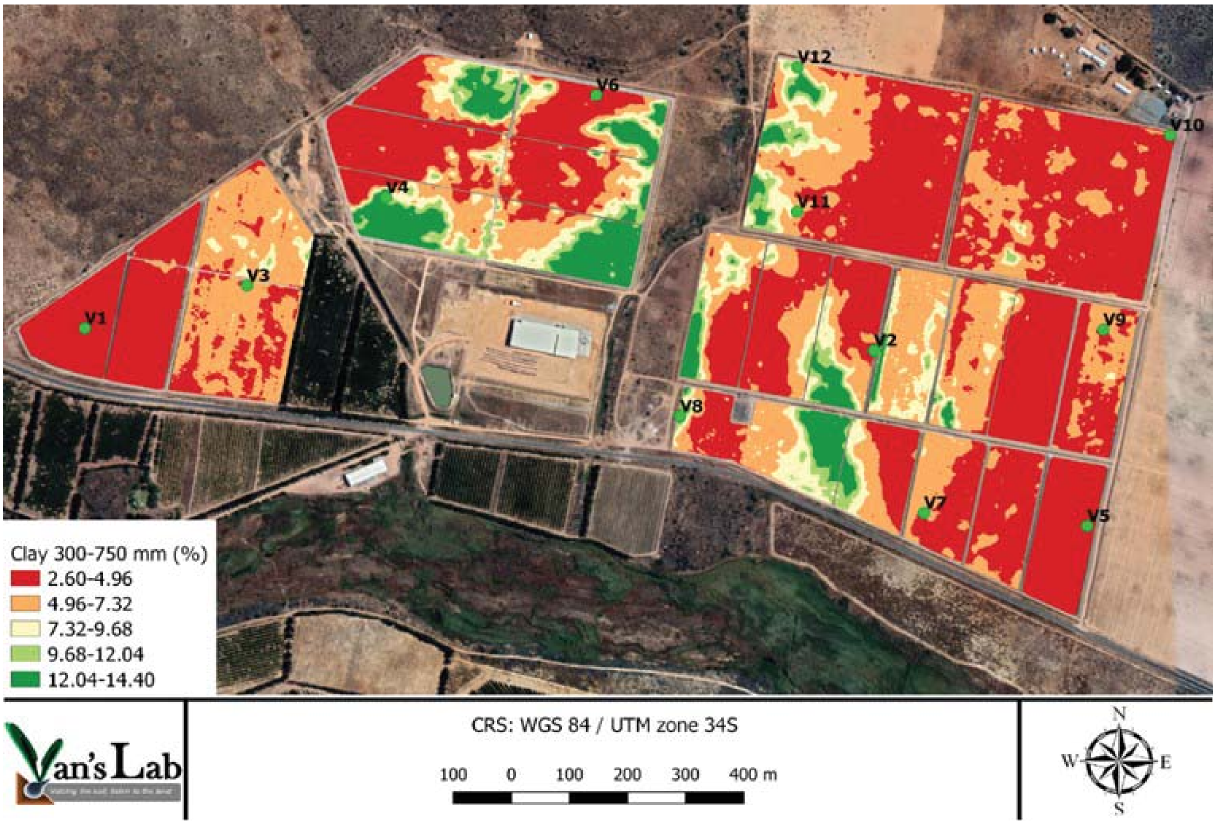


Figure 3.19 Spatial distribution of clay percentage in the subsoil over the vineyard.

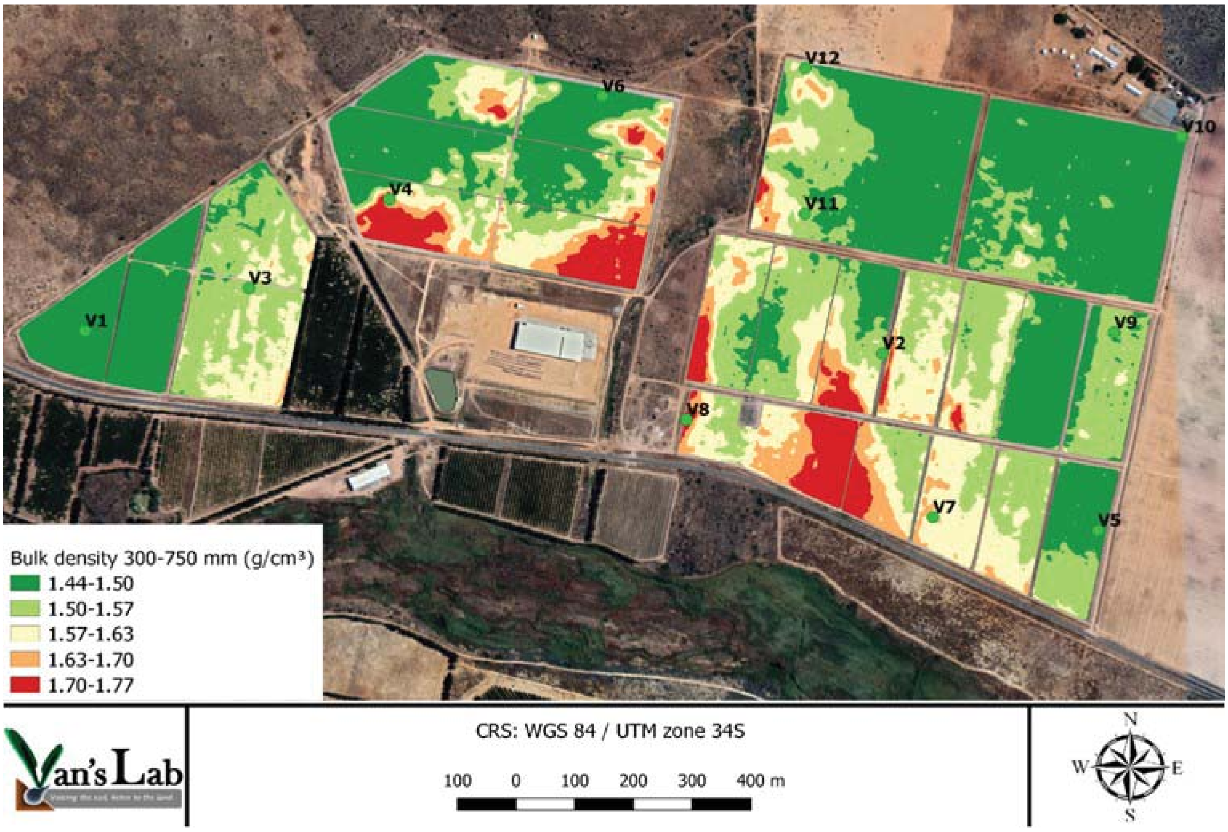


Figure 3.20 Spatial distribution of bulk density (g cm^{-3}) in the subsoil over the vineyard.

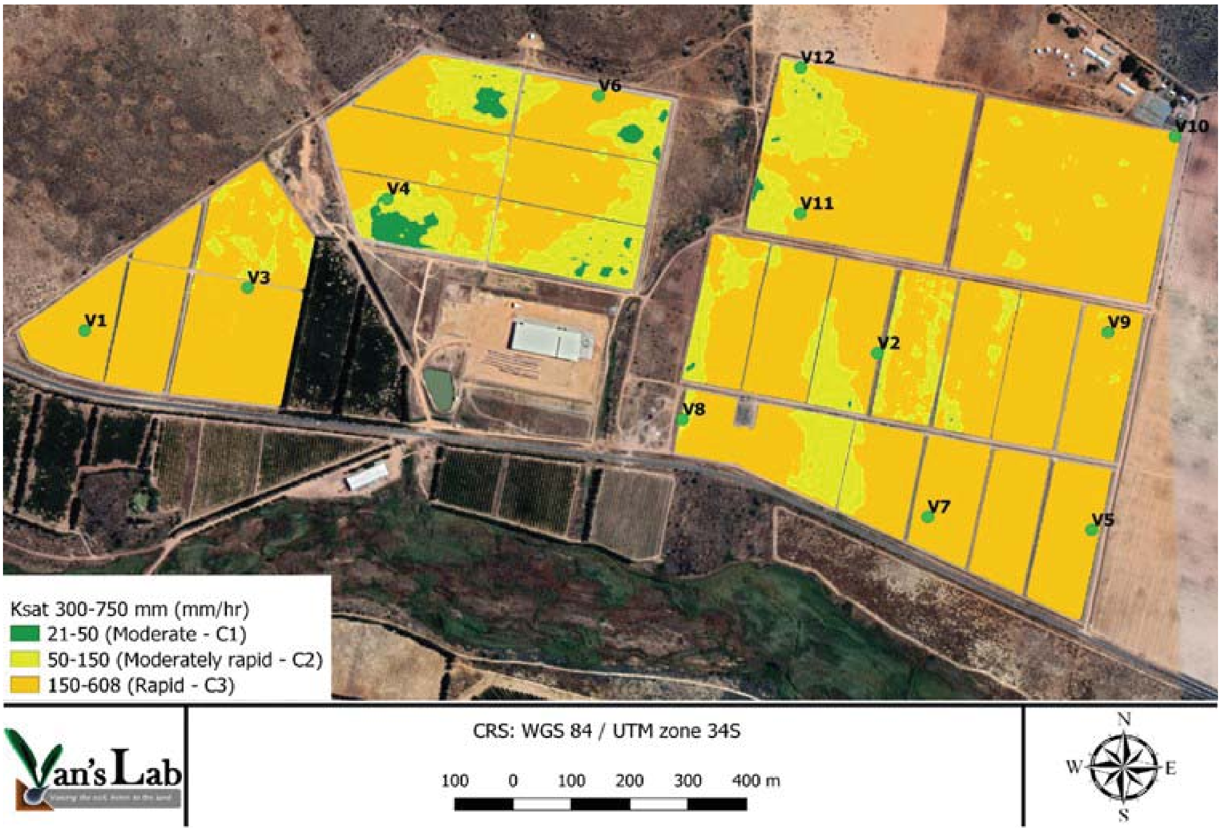


Figure 3.21 Spatial distribution of saturated hydraulic conductivity (K_{sat}, mm h^{-1}) in the subsoil over the vineyard.

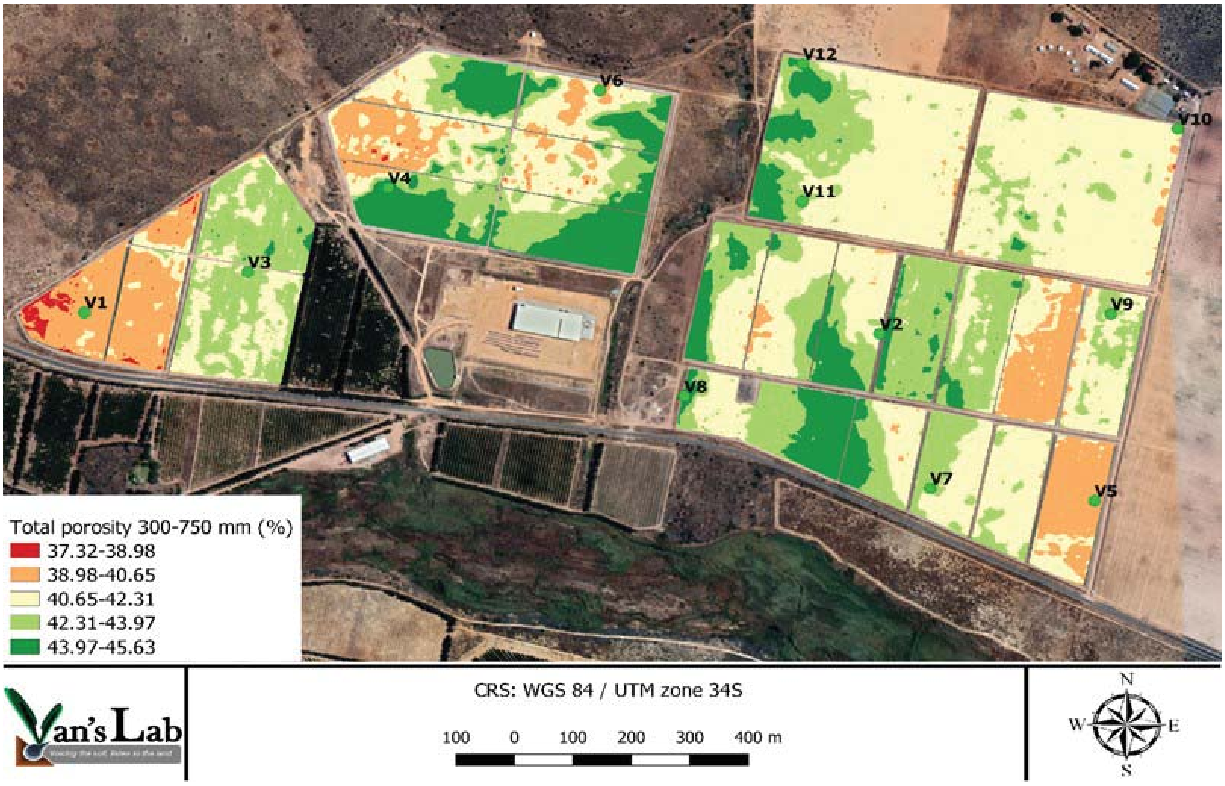


Figure 3.22 Spatial distribution of total porosity (%) in the subsoil over the vineyard.

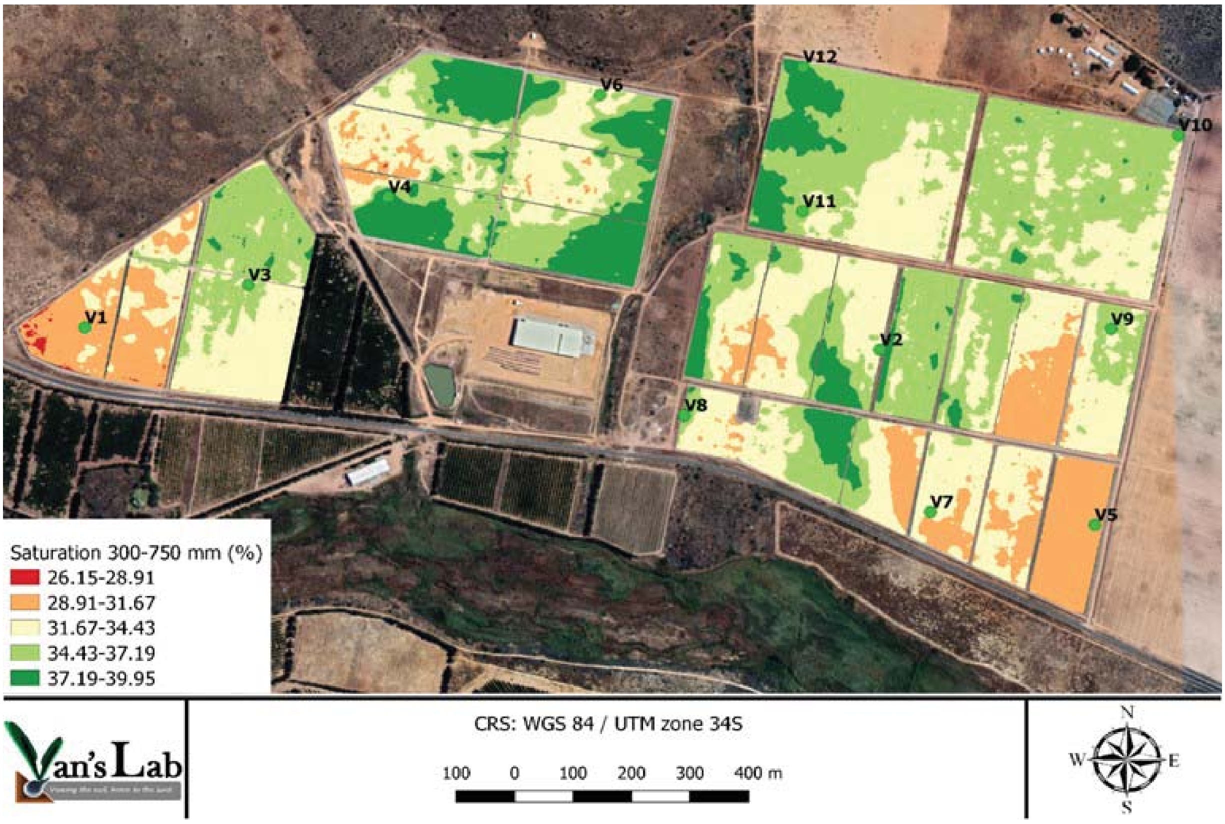


Figure 3.23 Spatial distribution of saturation point (%) in the subsoil over the vineyard.

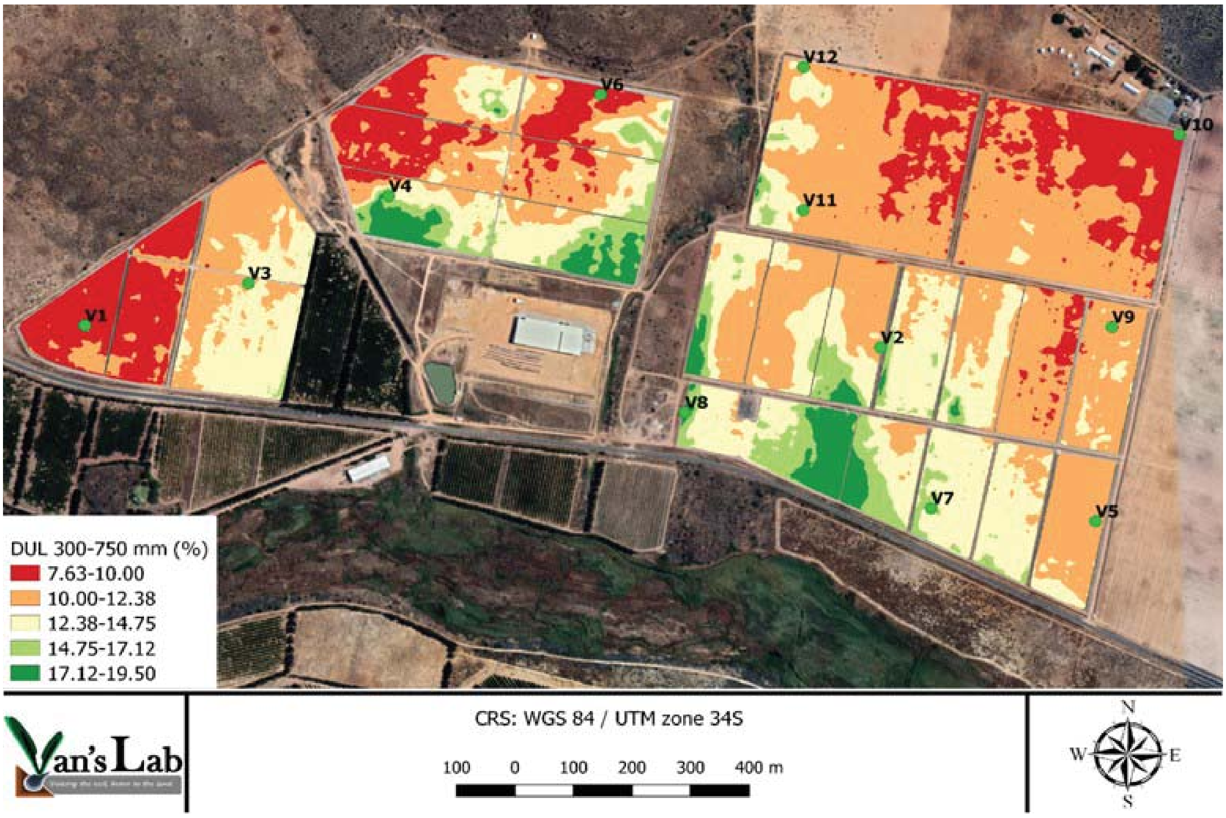


Figure 3.24 Spatial distribution of drained upper limit (DUL, mm) in the subsoil over the vineyard.

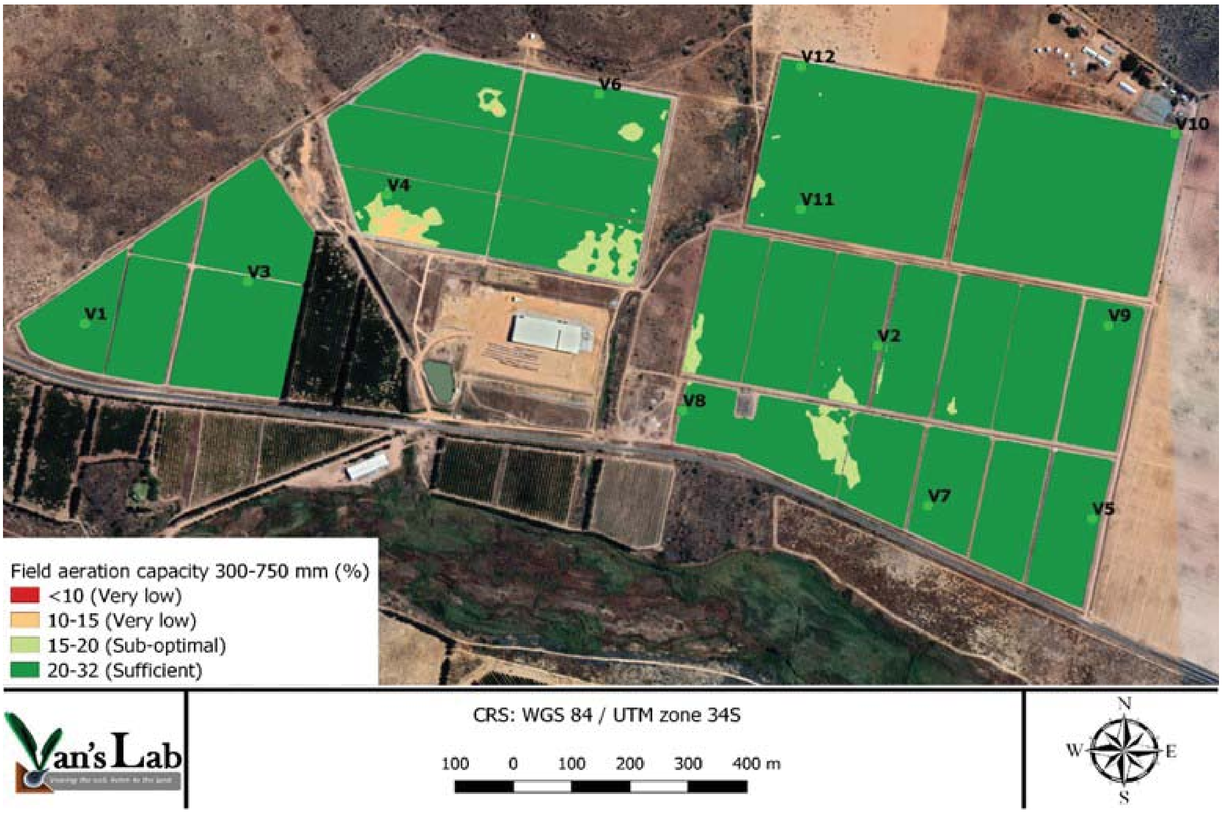


Figure 3.25 Spatial distribution of field aeration capacity (FAC,%) in the subsoil over the vineyard.

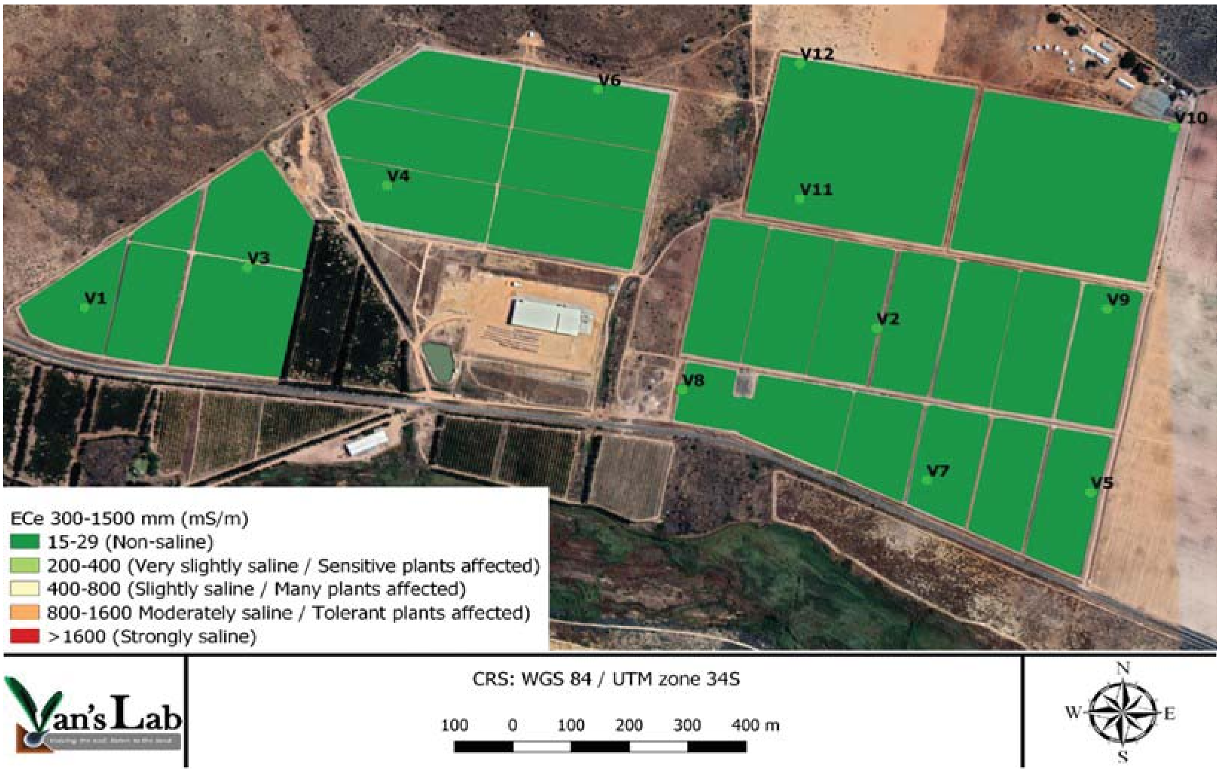


Figure 3.26 Spatial distribution of electrical conductivity (EC_e, mS m^{-1}) in the sub- and deep subsoil (300 to 1500 mm depth) over the vineyard.

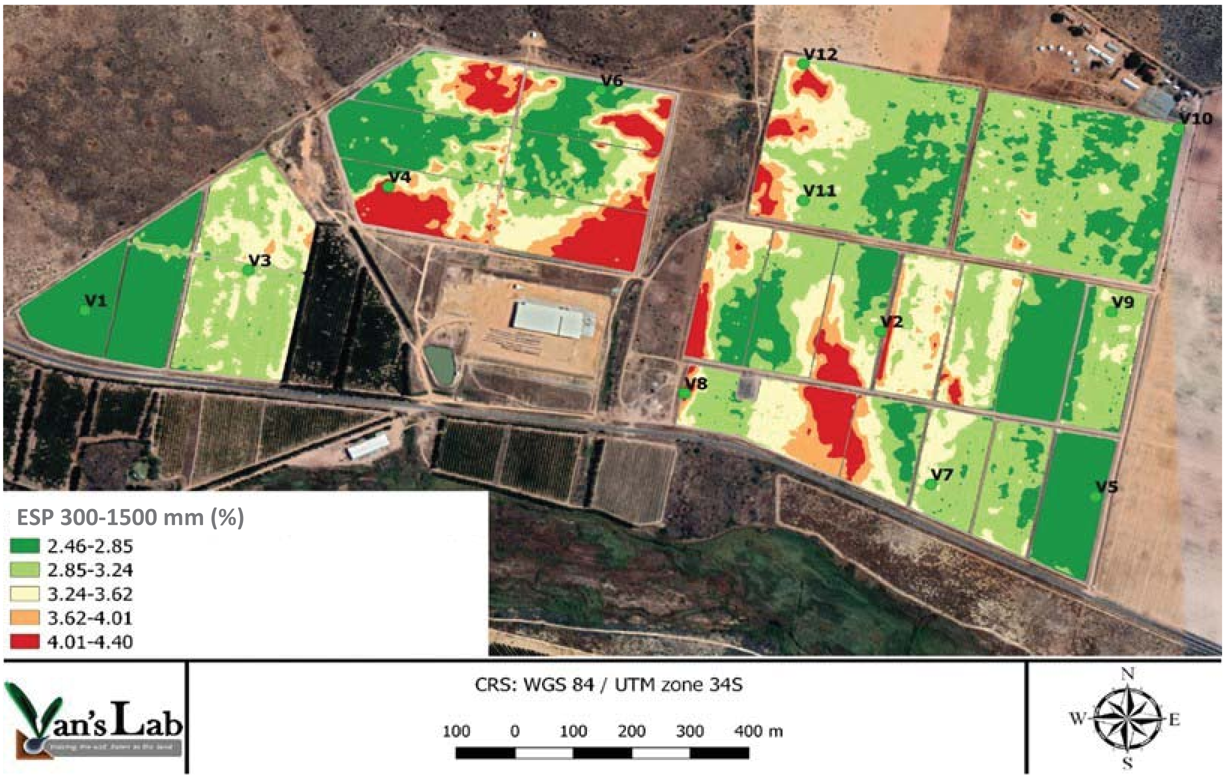


Figure 3.27 Spatial distribution of exchangeable sodium percentage in the sub- and deep subsoil (300 to 1500 mm depth) over the vineyard.

3.3.4.3 Deep subsoil (750 to 1500 mm depth)

At three of the 12 sampling sites, deep subsoil samples could not be taken due to the presence of solid rock. Samples of the rock was taken and the densities determined. Despite the lower number of samples, the r-values of the model predictions were above 71% for all regressions (Table 3.6). Hence, the individual soil property maps are regarded as representative of the spatial distribution of the particular property over the vineyard's deep subsoil.

Of particular interest is the K_{sat} map (Figure 3.31), because it predicts the fate of salt movement in the deep subsoil and hence the sustainability of the vineyard. An important finding is that the spatial patterns on the K_{sat} map reflects on the spatial patterns of EC_a. Areas of slow or impermeable (< 0 to 5 mm h^{-1}) and moderately slow (5 to 15 mm h^{-1}) drainage, represent the areas where water and salts were built-up. On the other hand, areas with drainage above 150 mm h^{-1} (mustard coloured zone on the map), will be prone to nutrient leaching. This is unfortunately a significant portion of the field.

From a soil physical property perspective, the patterns on the silt-plus-clay map (Figure 3.28) and the bulk density map (Figure 3.30), resembles closely the patterns of the EC_a map (Figure 3.2). The high ECa activity zones (yellow, brown and red zones; 52.8 to 97.8 mS m^{-1}) correspond well with: (i) the relatively high silt-plus-clay zone (yellow and green patterns; 15 to 36% clay), and (ii) the higher bulk density zone (yellow, brown and red zone; 1.98 to 2.65 g cm^{-3}). On the other side of the scale, the lower EC_a zones correspond well with lower clay, clay-plus-silt and bulk density zones as indicated on the respective maps.

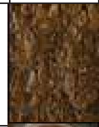
Spatial patterns of the air and water management indicators, i.e. the total porosity (%), saturation point (%), field aeration capacity (FAC, %) and drained upper limit (DUL, %), follow the distinct pattern of the spatial variation of EC_a captured in Figure 3.2.

Table 3.6 Excel multi-linear regression statistics for the 750 to 1500 mm depth

	Coefficients				
Soil property	**Intercept**	**EC_a**	**Elevation**	**r**	**p-value**
Silt + Clay (%)	-0.853	1.796	-0.025	0.91	0.01
Clay (%)	-2.962	1.814	0.025	0.88	0.01
BD (g cm^{-3})	0.708	0.325	-0.197	0.83	0.02
K_{sat} (mm hr^{-1})	8.331	-6.198	1.749	0.93	0.00
Saturation point (%)	4.772	-0.382	-0.168	0.88	0.01
Field aeration capacity (%)	8.027	-1.895	-0.445	0.89	0.01
Total porosity (%)	4.056	-0.356	0.056	0.94	0.00
DUL (%)	-0.331	0.902	0.239	0.89	0.01
*EC_e (mS m^{-1})	2.221	0.355	0.052	0.73	0.05
*ESP (%)	0.363	0.422	0.003	0.83	0.03

*represents the average over 300-1500 mm soil depth

Table 3.7 Soil laboratory analysis results for the deep subsoil (750 to 1500 mm depth)

Soil property		V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	Mean	Min	Max	SD
Disturbed soil sample																	
Undisturbed soil sample					 												
Texture	Silt + Clay (%)	0	6	8	36	4	0	11	0	5	9	24	27	11	0	36	12
	Clay (%)	0	3	5	25	3	0	8	0	4	6	19	19	8	0	25	8
	Silt (%)	0	3	3	11	1	0	3	0	1	3	5	8	3	0	11	3
	Sand%	0	94	92	65	97	0	90	0	96	91	75	75	65	0	97	40
Bulk density (g cm^{-3})		2.65	1.57	1.58	1.89	1.53	2.65	1.65	2.65	1.56	1.57	1.73	1.84	1.91	1.53	2.65	0.46
K_{sat} (mm hr^{-1})		0	392	128	0	528	0	9	0	288	154	46	0	129	0	528	181
Saturation point (%)		0	32	35	22	35	0	31	0	34	26	30	21	22	0	35	14.2
Total porosity (%)		0	41	40	29	42	0	38	0	41	41	35	31	28	0	42	17.5
Field aeration capacity (%)		0	25	29	4	29	0	20	0	27	14	17	3	14	0	29	12.1
Water boundaries (%)	DUL (%)	0	7	7	19	6	0	10	0	7	12	13	18	8	0	19	6.5
	LL (%)	0	3	4	14	2	0	5	0	3	4	10	11	5	0	14	5
	Water store (%)	0	4	3	19	4	0	5	0	4	8	3	7	5	0	19	5
Soil salts	EC_e (mS m^{-1})	15	17.87	19.84	29.08	21.35	27	21.01	28	16.49	28.58	26.25	22.72	22.75	14.83	29.08	4.97
	ESP (%)	2.92	2.90	2.71	4.40	2.80	3.37	3.15	2.74	2.46	3.18	3.75	4.10	3.21	2.46	4.40	0.60
	pH(extract)	6.30	6.57	6.47	6.37	7.04	6.41	7.04	7.03	6.86	6.73	6.56	6.44	6.65	6.30	7.04	0.28

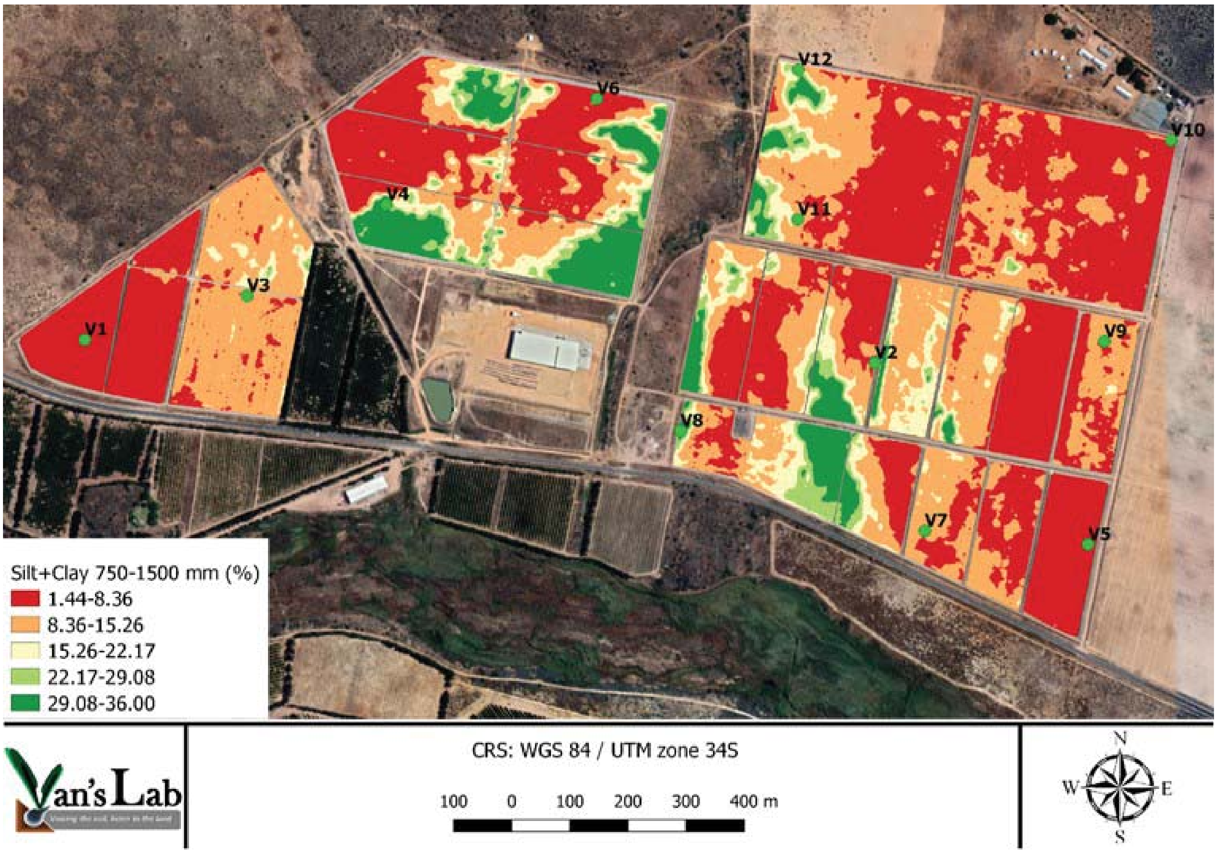


Figure 3.28 Spatial distribution of silt-plus-clay percentage in the deep subsoil over the vineyard.

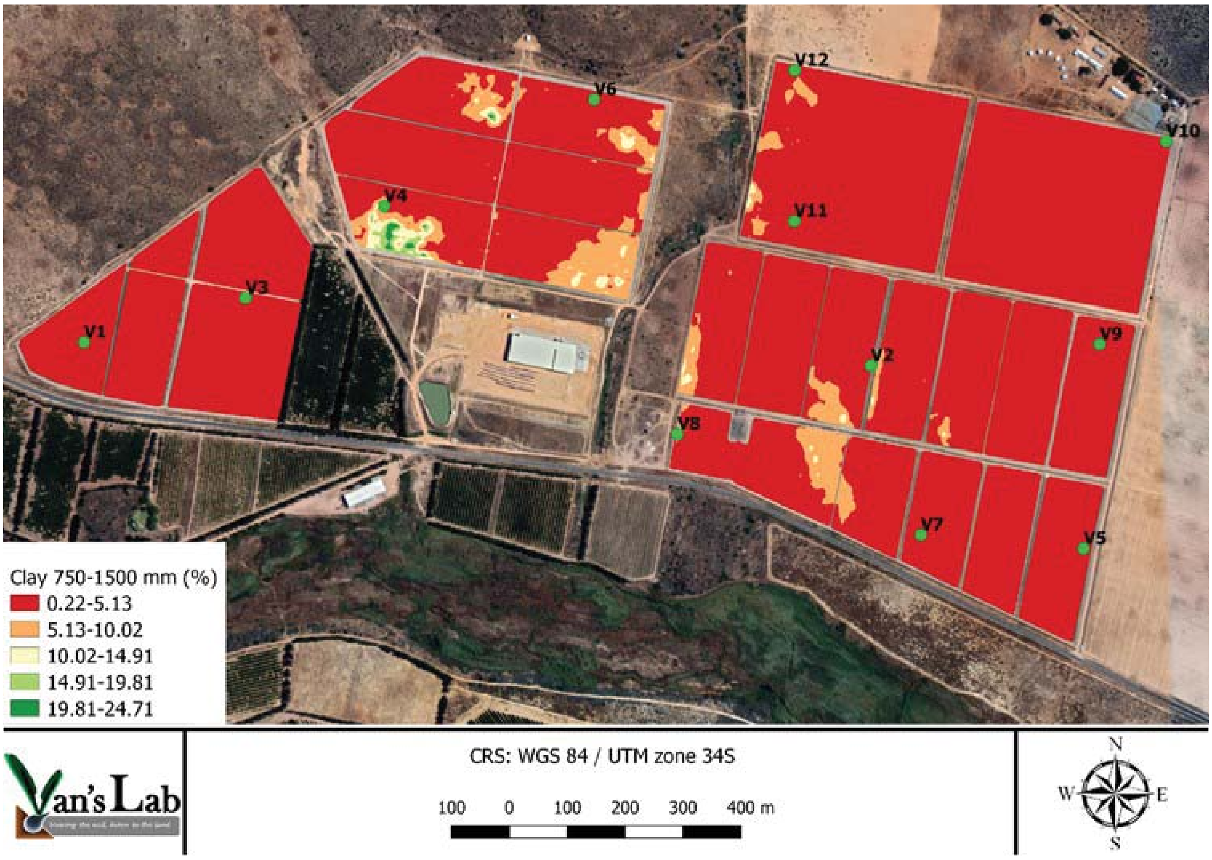


Figure 3.29 Spatial distribution of clay percentage in the deep subsoil over the vineyard.

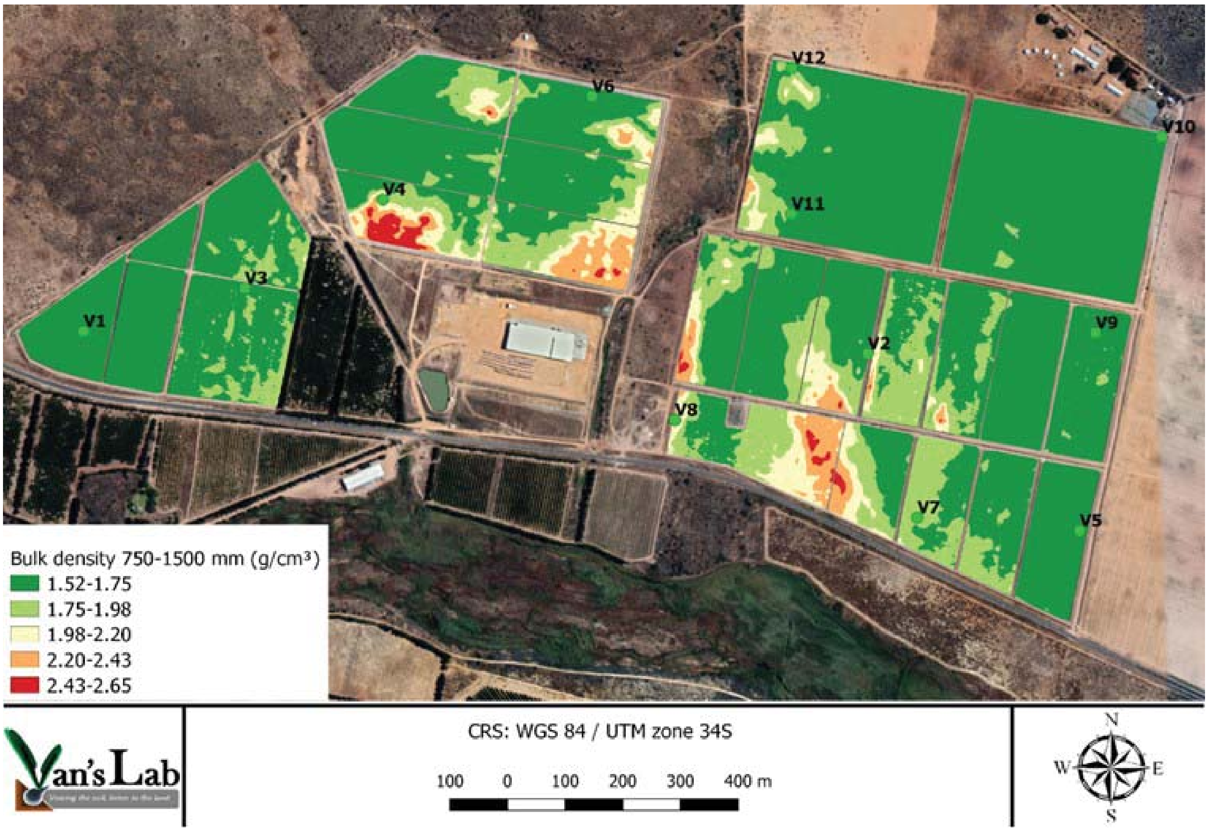


Figure 3.30 Spatial distribution of bulk density (g cm^{-3}) in the deep subsoil over the vineyard.

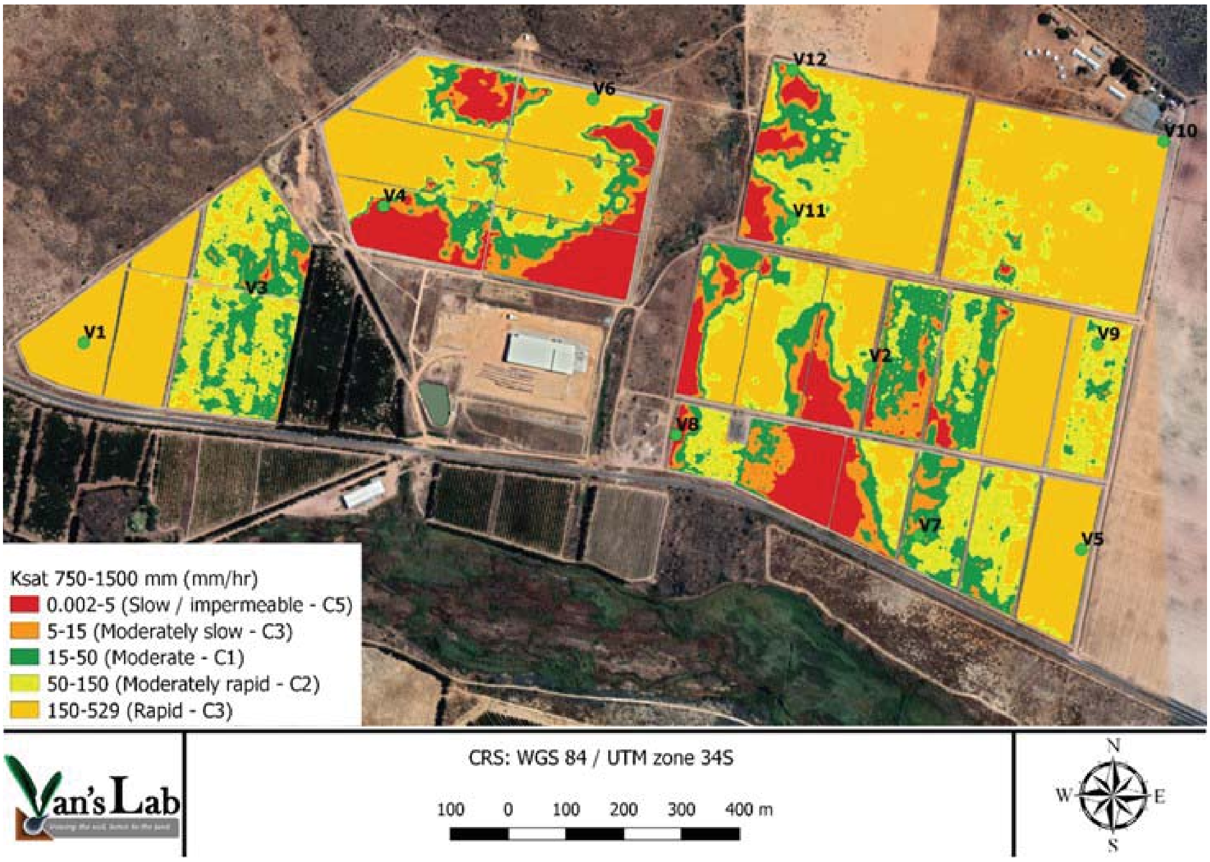


Figure 3.31 Spatial distribution of saturated hydraulic conductivity (K_{sat}, mm h^{-1}) in the deep subsoil over the vineyard.

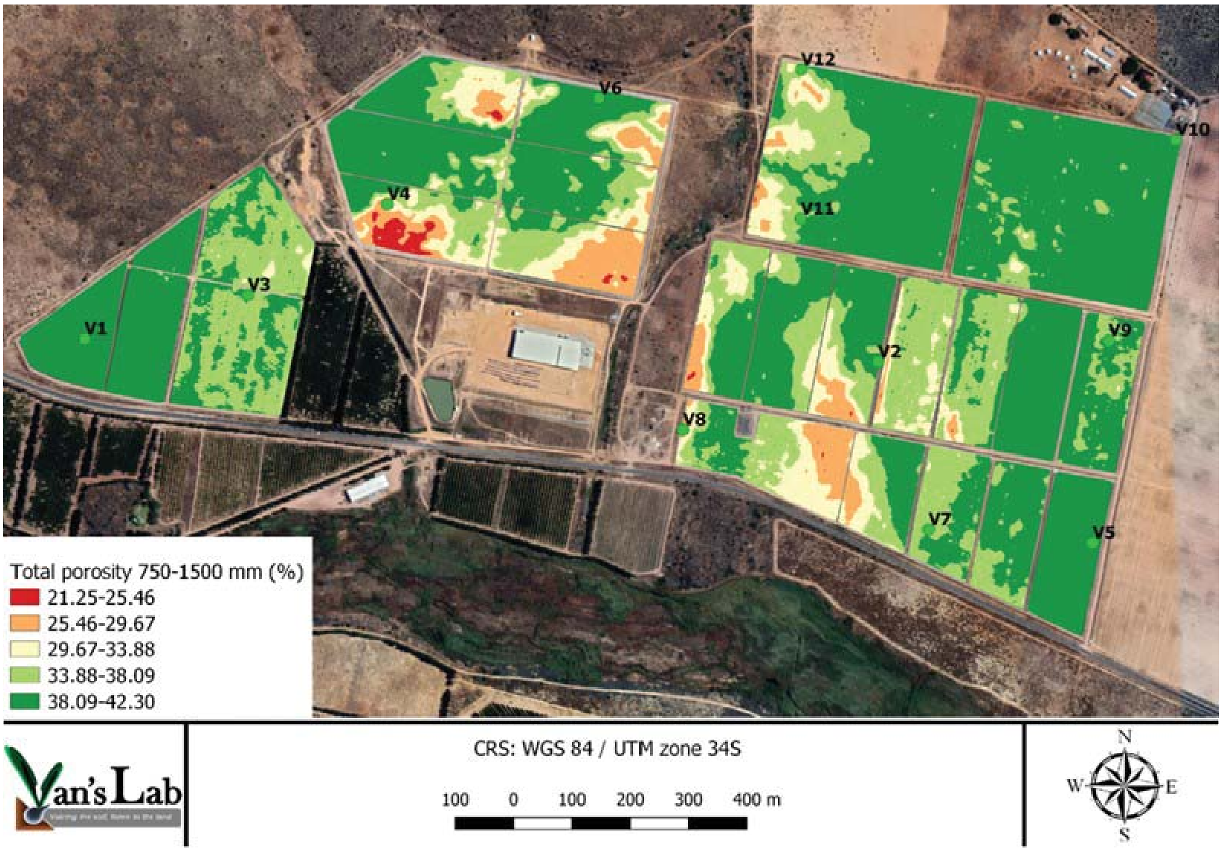


Figure 3.32 Spatial distribution of total porosity (%) in the deep subsoil over the vineyard.

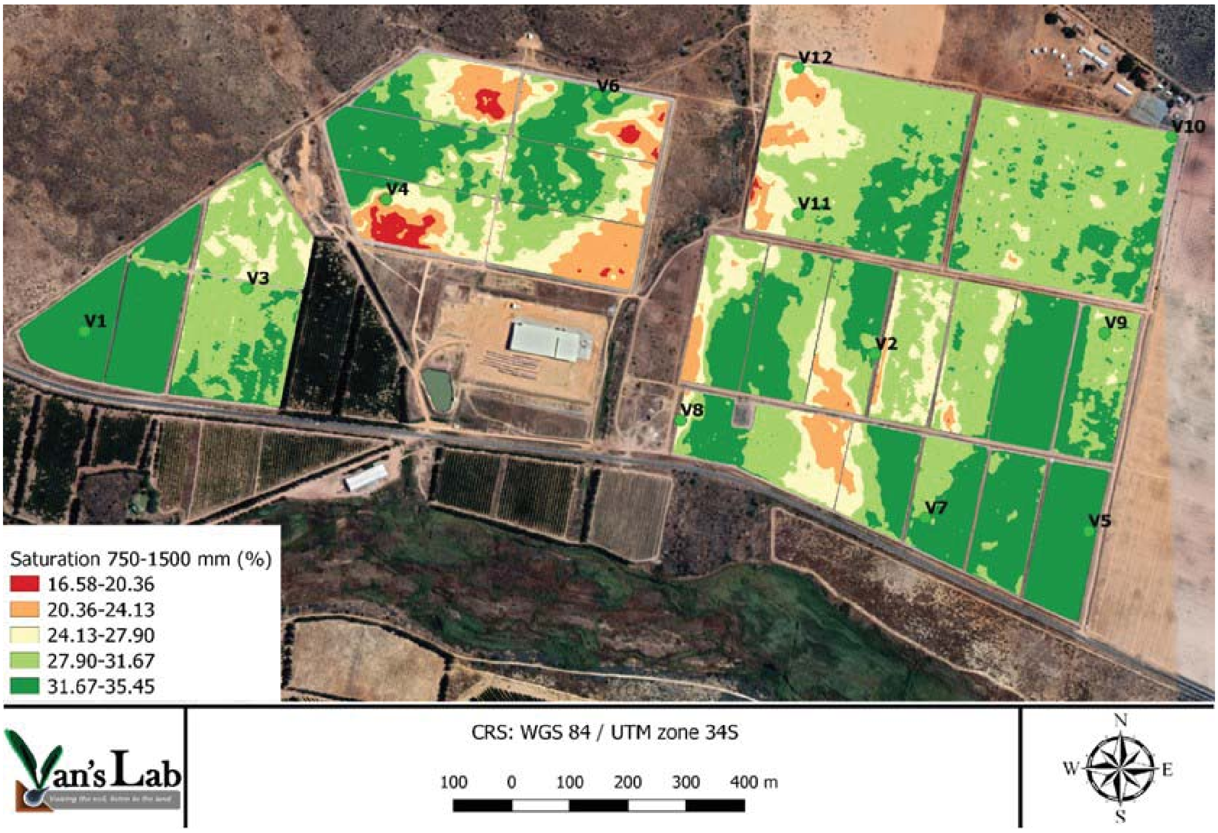


Figure 3.33 Spatial distribution of saturation point (%) in the deep subsoil over the vineyard.

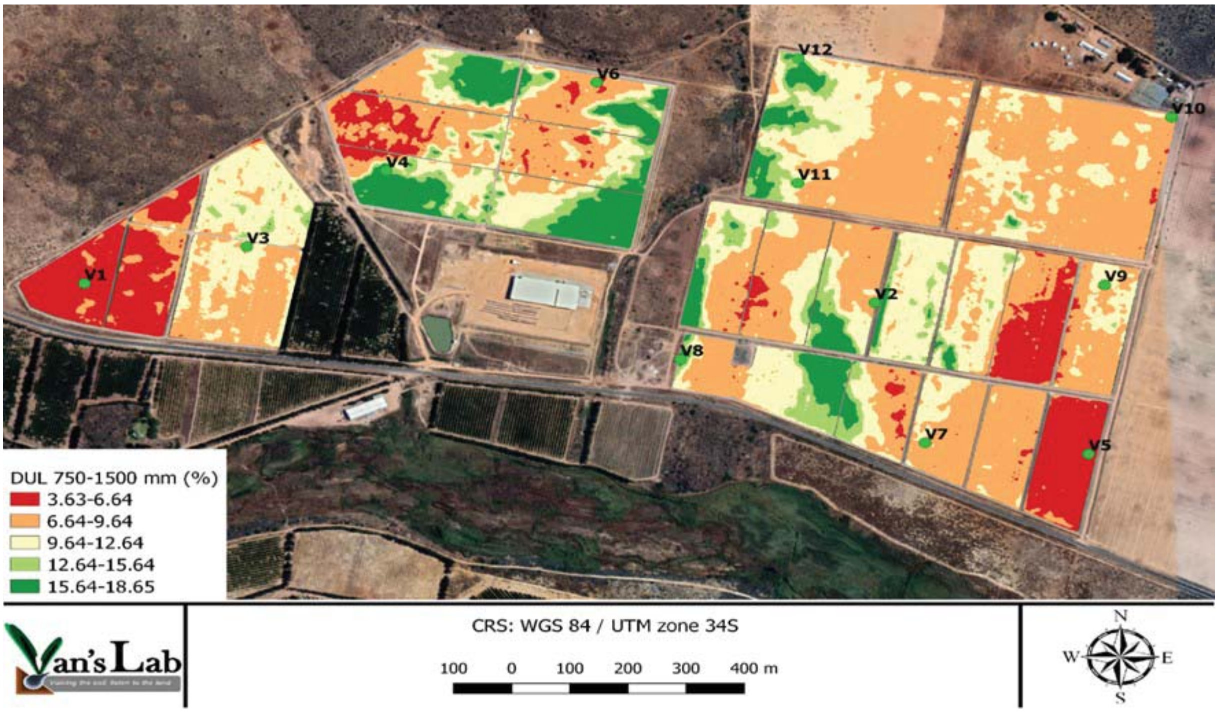


Figure 3.34 Spatial distribution of drained upper limit (DUL, mm) in the deep subsoil over the vineyard.

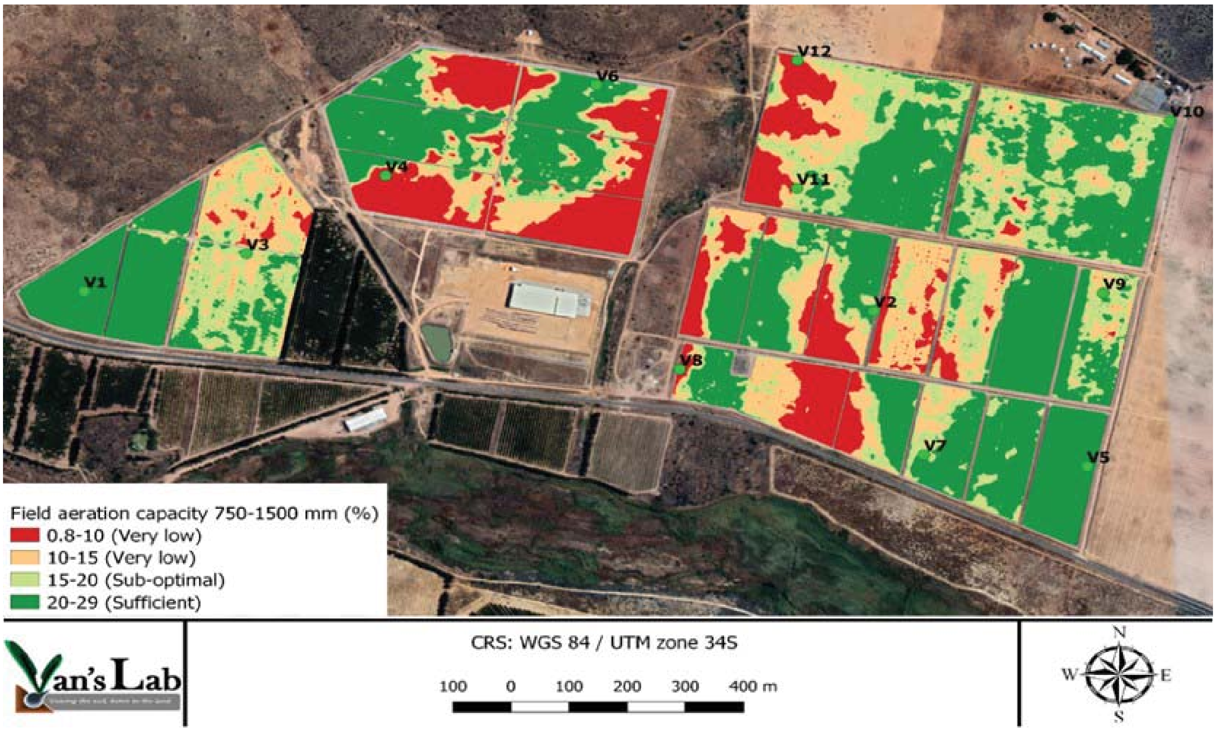


Figure 3.35 Spatial distribution of field aeration capacity (FAC,%) in the deep subsoil over the vineyard.

3.3.5 Soil depth and water storage

Table 3.8 gives the profile depths observed in the field at the 12 reference points. Profile depth ranged from 600 up to 1500 mm. Unfortunately, the results of the multiple regression model to predict profile depth from EC_a and elevation was poor (Table 3.9). Hence, the derived map for profile depths (Figure 3.36) cannot be used for planning purposes.

The profile available water (Table 3.8) ranged from a minimum of 13 mm to maximum of 127 mm at the 12 reference points. On average, the topsoil contributed 31 mm, the subsoil 27 mm and the deep subsoil only 7 mm towards the total profile available water capacity (PAWC). This indicates that the deep subsoil's contribution towards water storage in the profile is almost negligible. The thickness of this layer, as well as its sizeable sand-and-stone or rock fraction are the main contributing factors reducing its water storage capacity. The higher these fractions, the lower a layer's contribution towards the profile's ability to store water for plant uptake.

The spatial distribution of PAWC is depicted in Figure 3.37 and the map is usable to plan irrigation scheduling management.

Table 3.8 Laboratory results for the depth to impermeable layer (profile depth) and water storage between DUL and LL for the different soil layers, as well as profile total

Sampling point	Profile depth (mm)	Water storage (mm)			Plant available water (mm)
		0-300 mm depth	300-750 mm depth	750-1500 mm depth	
V1	790	50	30	0	79
V2	1500	28	68	31	127
V3	1500	20	28	21	69
V4	600	38	14	0	53
V5	1500	51	33	31	115
V6	900	7	6	0	13
V7	1500	46	38	39	123
V8	800	28	51	0	80
V9	1500	29	16	33	77
V10	800	13	13	4	30
V11	1500	17	60	23	99
V12	900	47	11	11	69
Mean	**1149**	**31**	**27**	**7**	**78**
Min	**600**	**7**	**7**	**7**	**13**
Max	**1500**	**51**	**51**	**7**	**127**
SD	**374**	**15**	**17**	**NA**	**35**

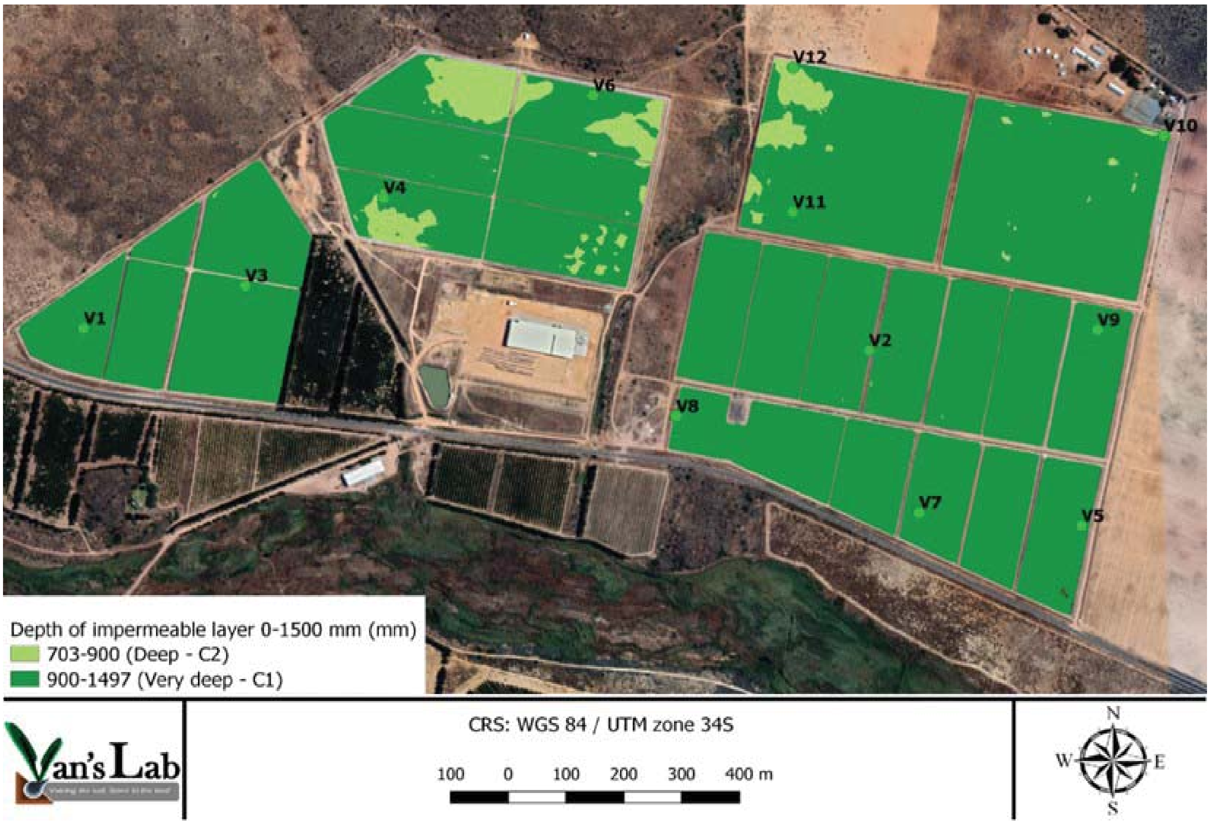


Figure 3.36 Spatial distribution of profile depth (mm) over the vineyard.

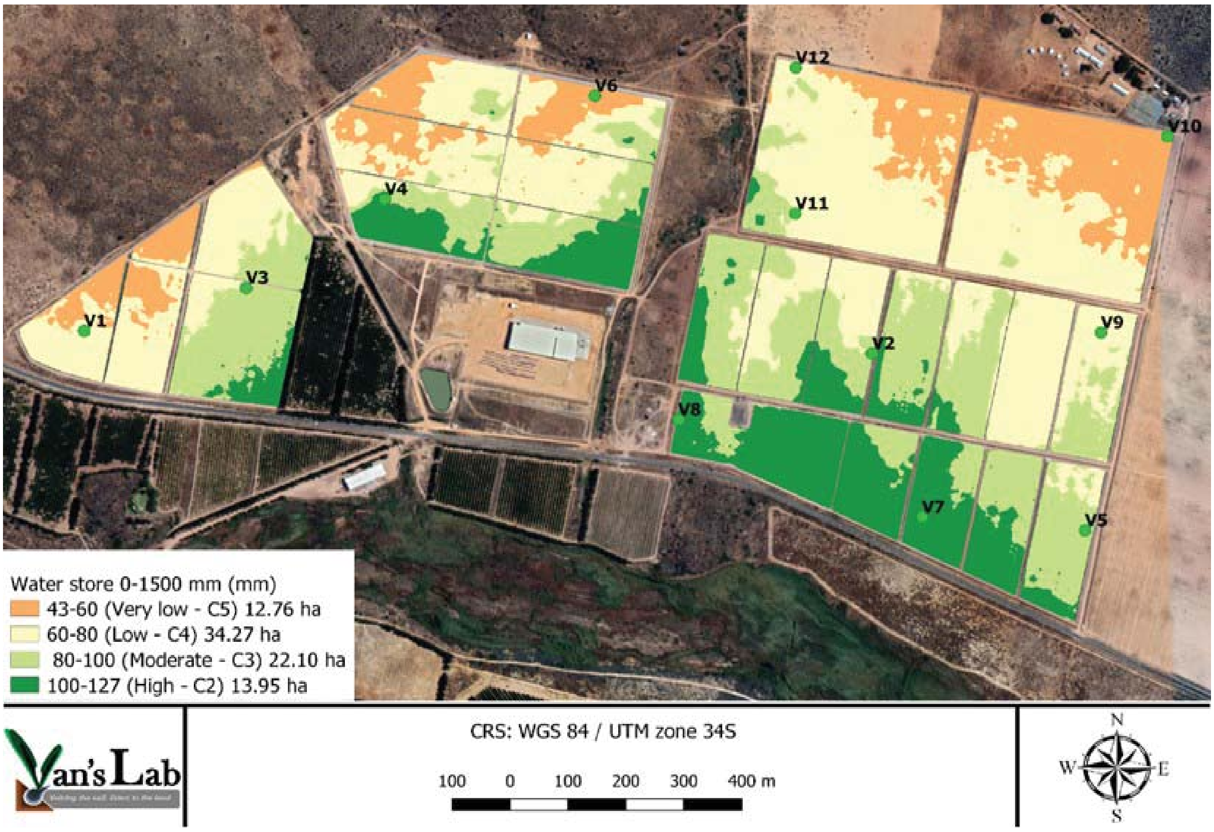


Figure 3.37 Spatial distribution of profile available water capacity (PAWC) or profile water storage (mm) over the vineyard.

Model prediction statistics indicated that the relationship between profile available water capacity and the multi variables, EC_a and elevation, is good (Table 3.9). The water storage map (Figure 3.37) reveals that water storage increased with a decrease in elevation over the field. Near the crest of the field (highest elevation), storage was very low (< 60 mm), followed by the upper midslope with low storage (60 to 80 mm). The lower midslope stored between 80 and 100 mm of water, regarded as moderate, while the lowest part of the field had the highest water storage (100 to 127 mm).

Table 3.9 Excel multi-linear regression statistics for water storage over the profile (0 to 1500 mm)

	Coefficients				
Soil property	**Intercept**	EC_a	**Elevation**	**r**	**p-value**
Profile depth (mm)	-0.853	1.796	-0.025	0.91	0.01
PAWC (%)	-2.962	1.814	0.025	0.88	0.01

3.4 A framework for site-specific assessment of water and salts

A guide was developed to assist in the assessment of water and salts in the root zone of crops. This guide is presented in the form of a matrix framework (Table 3.10). EMI information and inferred soil properties, as highlighted in the results section, were used to demonstrate how this framework can be applied to assess a crop field. The guide focuses on seven soil properties listed in column 1 of the table. Column 2 gives information on the type of measurements used, while Column 3 offers information on the soil depth. Column 4 indicates the severity of the problem, while Column 5 highlights where in the profile the problem is and the magnitude or size of the affected area. Column 6 guides the user in terms of procedures to follow in rectifying the problem.

An example to use the framework: (Remedial procedures described in Appendix B)

i. Soil types: According to a review by Van Huyssteen (2008) and internationally supported by Wilding and Lin (2006), pedology is changing from classification and inventory to a higher level of understanding and quantifying spatially and temporal processes in soils, especially hydrology. This is exactly what is aimed for with this section, the ability to extract information from soil classification descriptions and profile photos at the 12 reference points and to construct a conceptual model of water retention and movement within and beyond the crop field. For example, the red cross in Column 4 indicates severe problems with the soil type in this vineyard. Proof of that can be seen in Appendix A (soil descriptions and photos) and in the diagnostic horizons presented in Table 3.1. In essence, E horizons, signs of wetness, regic sands and lithocutanic characteristics are not desirable features for irrigation soils (Le Roux et al., 2013; Van Rensburg et al., 2020). These soil types belong to irrigability Class 3 or 4, since irrigation will influence hydraulics of the soil significantly and therefore demand high management skills and resources. The E-horizon will influence the water balance of irrigation blocks via lateral flow. Procedure 10 is recommended as remedial action. Quantification of the soil hydrology is dealt with in the next section and specific recommendations will be made to counter the inherent properties of the soil.

ii. Drainage: Four aspects of drainage are assessed, i.e. surface drainage, infiltration, internal drainage and external drainage.

   Surface drainage: The framework indicates that surface drainage requires immediate attention and Procedure 1 (Appendix B) can be used as remedial action. In principle, the farmer should consult an agricultural engineer. The topographical data can be used to redesign the landscape. The problem is highlighted in the terrain analysis presented in Section 3.3.2. The main reason behind the need to redesign the site is the very steep slopes.

Infiltration: The framework indicates that infiltration is a moderate problem. Unfortunately, the spatial prediction of K_{sat} was poor, but the measured values indicated a rapid flow of water. In addition, the ESP map showed that there is a high risk of soil structure degradation and therefore soil crusting will be a reality. Procedure 6 is recommended, i.e. the removal of sodium with the application of gypsum and leaching.

Internal drainage: K_{sat} provides information on the quality of macro-pores, a very important part of soil structure. How are pores connected in each layer? Results indicate a moderate problem. The K_{sat} map was inaccurate and could not be used for planning purposes. The measured average K_{sat} fell into the rapid category, indicating a risk of nutrient leaching. The area that would be most vulnerable is the zone with a clay content lower than 7% (Figure 3.19). Excessive leaching can be controlled through sound irrigation scheduling (Procedure 9).

The presence of E-horizons will lead to lateral flow in subsoil. Procedure 10 is recommended.

External drainage: The assessment is that external drainage poses severe problems. The problems differ between zones.

Firstly, the slow and moderately slow K_{sat} zones: These zones can be further divided into two areas, i.e. the area above 58 masl (m above sea level) elevation and the area below 58 masl elevation. For the area above 58 masl, cutoff drains are recommended (Procedure 10). This is to control lateral water movement between blocks as a result of E-horizons on top of impermeable parent material. This will improve the hydraulics of Sections B and C of the vineyard. The area below 58 masl is a low lying area with depressions, receiving lateral and surface flow from higher elevations. These areas are prone to waterlogging and require artificial drainage (Procedure 4). This should improve Section C further.

Secondly, the zones with rapid K_{sat} values are the result of the sandy texture of the deep subsoil. This affects large areas of Sections A, B and C of the vineyard. The recommendation is to intensify the management of irrigation scheduling (Procedure 7). The principle is to control water applications to ensure that soil water content do not increase above the DUL threshold for normal irrigations, except when leaching strategies are implemented. The data imbedded in Figures 3.14, 3.24 and 3.34 can be used to guide the manager.

iii. Compaction: The impact of compaction is moderate in both the topsoil and subsoil. Nothing can be done about compaction of the deep sub soil, because of the depth and nature of the parent material present. Procedure 5 is recommended for both the topsoil and subsoil.

iv. Salinity: Salinity is not a problem in the vineyard.

v. Sodicity: Sodicity affects soil structure, reducing the quality of the pores, especially meso- and macro pores. The framework suggests severe sodicity problems in the top soil and moderate in the subsoil and deep subsoil. The whole area of the vineyard is affected. It is recommended that sodium be removed using Procedure 6. This procedure is based on the method described in Section 5.3.2. of the level one DSS (Van Rensburg et al. (2020). It was further recommended that the farmer use a variable applicator to apply gypsum over the vineyard.

Table 3.10 Framework for assessment of hydro-physical properties of a crop field, indicating if it demands rectification, the severity of the problem and where to find the information for remedial action [(✘) = severe; (✓) = moderate; (✓) = not affected]

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Soil property	Measurement	Soil layer	➢ Severity	Proof*	Procedure for rectification (Appendix B)
Soil types	Field classification	Horizons with diagnostic E's, signs of wetness and rocks	✘	T3.1; App. 3.1	
Drainage	Saturated hydraulic conductivity (mm hr^{-1}) Signs of wetness from soil classification	Surface drainage	✘	F3.3-3.6	1
		Topsoil (Infiltration)	✓	T3.2; F3.11, F3.9 and F3.17	6
		Subsoil (Internal drainage)	✓	T3.4;F3.21 and F3.19	9 and 10
		Deep subsoil (External drainage)	✘	F3.31	9 and 4
Compaction	Bulk density (g cm^{-3})	Topsoil	✓	F3.10	5
		Subsoil	✓	F3.20	
		Deep subsoil	✘	F3.30	
Salinity	Electrical conductivity (EC_e, mS m^{-1})	Topsoil	✓	F3.16	
		Subsoil	✓	F3.16	
		Deep subsoil	✓	F3.16	
Sodicity	Sodium adsorption ratio or Exchangeable sodium percentage (ESP,%)	Topsoil	✘	F3.17	6
		Sub & deep subsoil	✓	F3.27	
PAWC	Profile available water capacity (mm%)	Whole profile	✘	F3.35; F3.14, F3.24 and F3.34	9 and 7
Aeration	Field aeration capacity (FAC, %)	Topsoil	✓	F3.15	7
		Subsoil	✓	F3.19	7
		Deep subsoil	✓	F3.35	7

*T = Table; F = Figure

vi. PAWC: This reflects on the ability of the profile to store water against gravity. Meso- and micro pores play an important role and again represent soil structure. The framework indicates that PAWC poses challenges regarding irrigation scheduling. The PAWC map indicated that a large area has a capacity below 80 mm, which is a high risk in terms of crop water stress. In order to manage the risk it is recommended that the manager makes use of a commercial irrigation scheduling service provider to help with water management (Procedure 7). The PAWC data can be utilised to find the best location for using soil water probes, while the DUL (Figures 3.14, 3.24 and 3.34) can assist in the calibration of probes.

vii. Aeration: This factor poses moderate problems for respiration processes in the soil. Special attention should be given to areas where FAC is lower than 15%. The map for the deep soil was not accurate, but the clay percentage map can be used to identify affected areas. FAC can be improved by applying Procedure 7.

Note: (i) Although specific agronomic advice on a crop is not part of the level 2 DSS, the advisor should be familiar with the specific crop's requirements with respect to the soil. All perennial crops demand a Class 1 irrigable soil to ensure optimum growth conditions in terms of chemical, physical and biological properties (Irrigation Planning Staff, 1980; Nell, 1991). Any lower class will demand additional resources and management skills (Hensley and Laker, 1980; Dohse et al., 1991). Water quality and quantity are both important factors in the overall analysis (Du Preez et al., 2000; Ehlers et al., 2007; Van Rensburg et al., 2012). (ii) The analysis presented here was restricted to seven specific aspects of the soil, mostly neglected during assessments of crop fields. BCOs are also encouraged to revisit the Level one guide on the nine pointers that elaborate on the broader agronomic aspects in soil salt management. The nine pointers include: quality of irrigation water, suitability of soils for irrigation, irrigation systems, drainage systems, sources of salts, salt thresholds for soils, salt tolerance of crops, monitoring of salts and leaching. If necessary, BCOs should to add some of these aspects to the framework, tailoring it to their clients' needs and circumstances.

3.5 Conclusion

The objective of this chapter was to develop and apply a framework or guide that can be used as a level two decision support for managing soil salts in the root zone of perennial crops. A vineyard of 83 ha was used as a case study. The area was surveyed using a Geonics EM38-MK2 unit mounted on a plastic trailer and towed behind a quad bike equipped with a high resolution GPS. A comprehensive set of results were presented as background for the interpretation of the framework proposed as level two decision support. These results included an EC_a map, terrain assessment, soil descriptions and texture maps, EMI-inferred soil properties for top- sub- and deep subsoils, as well as a soil depth map and profile available water capacity map.

The guide or framework takes the form of a matrix (Table 3.10) that focuses on seven soil properties on the one side (rows) and six columns that provide information on each of the properties, the measurement used, severity of the problem, proof or evidence and what procedure to follow to rectify the problem, if any. The soil properties that were assessed include: soil type, drainage (surface, infiltration, internal and external), compaction, salinity, sodicity, profile available water capacity and aeration of the topsoil, subsoil and deep subsoil. The severity of a particular problem associated with a soil property was derived from norms in literature.

The following conclusions were drawn using the framework for this particular case study: (i) Soil types affect the hydraulics of the vineyard severely; (ii) Slopes are steep and require re-designing to control runoff during rainstorms; (iii) Sodium content of the top layer will cause crusting that will influence infiltration over the whole vineyard; (iv) On the one side there are areas where internal drainage is too high in the top-, sub- and deep subsoil, and on the other side there are areas with slow and moderately slow water flow; (v) External drainage is problematic in high EC_a-activity zones; (vi) salinity is not a problem, while sodicity needs to be addressed over the whole vineyard; (vi) A large area has a PAWC below the 80 mm threshold that poses a real risk to water management. Procedures to rectify the problems were also given in the framework. As a starting point, the framework is targeted at BCOs to be used as part of an upscaling initiative, also called Level Two Decision Support, to advance EMI application in assessment of soil salts in the root zone of perennial crops. This partnership between BCOs, scientists and leading farmers, strives to encourage and empower the irrigation community to continually evaluate and improve on-farm water and salt management through learning, testing and adapting.

CHAPTER 4. PERENNIAL CROPS AS CASE STUDIES FOR SCALING UP SITE-SPECIFIC MANAGEMENT OF WATER AND SALTS

4.1 Introduction

Irrigation water and irrigable soil have essentially reached its maximum level of industrialisation in most countries in the world (Weligamage et al., 2002) and South Africa is not an exception (Le Roux et al., 2007; Van Rensburg et al., 2012). Over the past two decades the World Bank has moved its emphasis away from developing new irrigation schemes towards sustaining and improving productivity of existing crop fields. It has been realised that irrigated agriculture is threatening natural resources and livelihoods, and hence the shift towards projects that focus on rectification of waterlogging and salinity through improved water management (Kijne, 2011). From an environmental perspective, and also important to the World Bank, is the safe discharge of drainage water and ensuring sufficient environmental stream flows.

Given the challenges of water and salt management and the poor socio-economic conditions of the past decade in South Africa, farmers are realising that a wheat-maize cropping system will not sustain Vaalharts, or any other irrigation scheme for that matter, for another 50 years. Hence, land use in the irrigation sector has to change towards high-income crops. Examples of such land use change can be found all over South Africa. In Vaalharts, approximately half of the scheme's total area has been converted from maize-wheat flood irrigated fields into pecan orchards (13 000 to 15 000 ha) (Visser, personal communication[1]). Pressure on global sugar prices and imposed taxes have forced sugarcane growers to look into alternative crops, converting to higher value subtropical crops such as macadamias and bananas (Senekal, personal communication[2]). The wine-industry is not excluded from financial pressures (Jordaan, personal communication[3]). Alternative crops that seem to perform well in traditional wine grape areas in the Western Cape, are table grapes, blueberries, olives and macadamias. The production of lucerne in the summer rainfall region has also been increasing over the past three years, from 1 186 000 tonnes in the 2015/2016 season to 1 376 000 tonnes in 2017/2018 (Agricultural Statistics South Africa, 2018). These land use changes will pose new challenges to natural resources regarding water and salt management, demanding regular monitoring of root zone salinity.

Why apply EMI technology in perennial crops? EMI technology is currently at a stage where site-specific calibration is needed, this means that instruments need to be ground-truthed (Lesch et al., 2000; Corwin and Lesch, 2003; Corwin et al., 2006; Heil and Schmidhalter, 2017). Calibration therefore implies soil sampling and laboratory determination of at least electrical conductivity and dissolved cations using the saturated paste method (Corwin and Lesch, 2005a), which is expensive. Furthermore, EMI surveys require technical specialisation, as well as specialist agronomic and soil laboratory services, and may cost between R550 to R1200 per hectare (Smit, personal communication[4]). The cost-benefit ratio in applying EMI technology is much more favourable for high-income crops, such as grapes, nuts and berries. In addition, many leading and innovative farmers have already shifted towards cultivating perennial crops under irrigation.

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[1] Mr A Visser, 2020. CEO, Golden Peanuts and Treenuts, Hartswater, Northern Cape.
[2] Mr D Senekal, 2019. Senekal Suiker Trust, Mkuze, KwaZulu-Natal.
[3] Mr E Jordaan, 2018. CEO, Hydrawize, Rousenville, Western Cape.
[4] Mr R Smit, 2020. Marketer, Van's Lab, Bloemfontein, Free State.

Most producers of perennial crops make use of advisors (behaviour change officers, BCOs) who support them on a daily basis on the agronomic aspects of water and salt management. The objective of this chapter was to broaden the base and support that is necessary in order to escalate EMI technology application in the irrigated perennial crop sector. Subsequently, eight farming operations was identified as case studies to be used to achieve this goal. Crops used as case studies included lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. These case studies can be presented as real examples to encourage members of crop-specific associations to apply EMI-technology.

4.2 Lucerne

4.2.1 Background, aim and EMI surveying

Lucerne (*Medicago sativa* L.) is the most important forage crop grown in South Africa. Around 10% (150 000 ha) of the total irrigated land is under lucerne production (Fourie, 2017). Approximately 3.7 million tonnes of hay are produced every year on this area, compared to the 0.28 million tonnes of teff, 3 million tonnes of wheat and 9 million tonnes of maize (Fourie, 2017). Lucerne is known for its high water requirement, it typically needs between 800 and 1600 mm of water per growing season (Moot et al., 2012). Water used to irrigate lucerne also transfers salts to the soil.

Extensive research has been done on the effects of salinity stress on vegetative growth of lucerne, including germination, seedling development, plant physiology and shoot biomass (Castroluna et al., 2014; Guo et al., 2016). Poor irrigation water quality may cause foliar injury by the physical wetting of the canopy. The degree of susceptibility to foliar injury depends on leaf characteristics, such as leaf size, the rate of salt absorption through the leaf and the leaf's waxy layer (Maas, 1986). In general, Maas (1986) determined that the upper threshold for sodium and chlorine concentrations, where foliar injury of lucerne occurs from saline sprinkling waters, varies from 10 to 20 mmolc ℓ^{-1}.

Ayers and Westcot (1985), established numerous response curves for crops as affected by increasing irrigation water salinity (EC_i). The response curve for lucerne indicated that the upper threshold is 130 mS m^{-1}. EC_i values beyond this point will linearly reduce yield up to a 100% loss at 1000 mS m^{-1}. In addition, the effect of soil water salinity (EC_e) on relative yield of lucerne is almost similar to the effect of EC_i. The impact of EC_e can be calculated with the Maas and Hoffman (1977) equation (where EC_e is expressed as mS m^{-1}):

$$\text{Relative yield} = 100 - 0.095(EC_e - 200 \text{ mS m}^{-1}) \quad (5.1)$$

Accordingly, lucerne is categorised as medium sensitive to soil water salinity. Fourie (2017) found that the lucerne cultivar 'SA Standard' is more tolerant to soil salinity than what is suggested by the Maas and Hoffman equation. He found that the response of relative yield to EC_e (in mS m^{-1}) is curve-linear and not linear (r^2=0.99):

$$\text{Relative yield} = 5E\text{-}07(EC_e)^2 - 0.001(EC_e) + 1.1332 \quad (5.2)$$

However, Fourie (2017) also found the upper threshold of 200 mS m^{-1}, to be similar to that determined by Maas and Hoffman (1977).

The farm in this case study is located on the banks of the Vaal River in the Northern Province (Figure 4.1a) and was previously owned by a private mining company. The area was mined for diamonds and partly rehabilitated when the farmer bought the property with water rights. Three centre pivots were installed, one of 8.8 ha on the western side and the two 25 ha pivots in the centre of the farm. The rectangular shaped area was earmarked for pecans, while lucerne was established under the pivots. According to the farmer, yields were unsustainably low and he contacted GWK for assistance. GWK officials referred him to Van's Lab, specialising in hydrophysical and chemical surveying of soils. Soil scientists from Van's Lab conducted a reconnaissance soil survey to assess the hydro-physical conditions of the soils on the farm. From this preliminary investigation it was clear the soil hydraulics of the fields were hampered by very high clay content, soft and hard carbonate and possibly salts. Foliar damage by the irrigation water quality was eliminated based on long-term water quality results (Du Preez et al., 2000) for the relevant section in the Lower Vaal River.

An EMI-survey was recommended to characterise spatial distribution of the mentioned soil properties. The farmer accepted the recommendation and the area was surveyed in March 2018 (Figure 4.1a). An additional area on the north-eastern side of the farm was also included in the scan since this was earmarked for a new centre pivot.

4.2.2 Results

Results of the EMI survey to show spatial EC_a variation over the area is presented in Figure 4.1b, while the topographical survey was used to derive a surface drainage map (Figure 4.1c) and infield slope percentage map (Figure 4.1d).

EC_a-inferred soil property maps for the 0 to 300 mm soil layer are depicted in Figure 4.2, these include EC_e (Figure 4.2a), ESP (Figure 4.2b), silt-plus-clay content (Figure 4.2c) and K_{sat} (Figure 4.2d). Figure 4.3 shows the EC_a-inferred soil property maps for the 300 to 750 mm depth, while Figure 4.4 gives the maps for the 750 to 1500 mm soil layer.

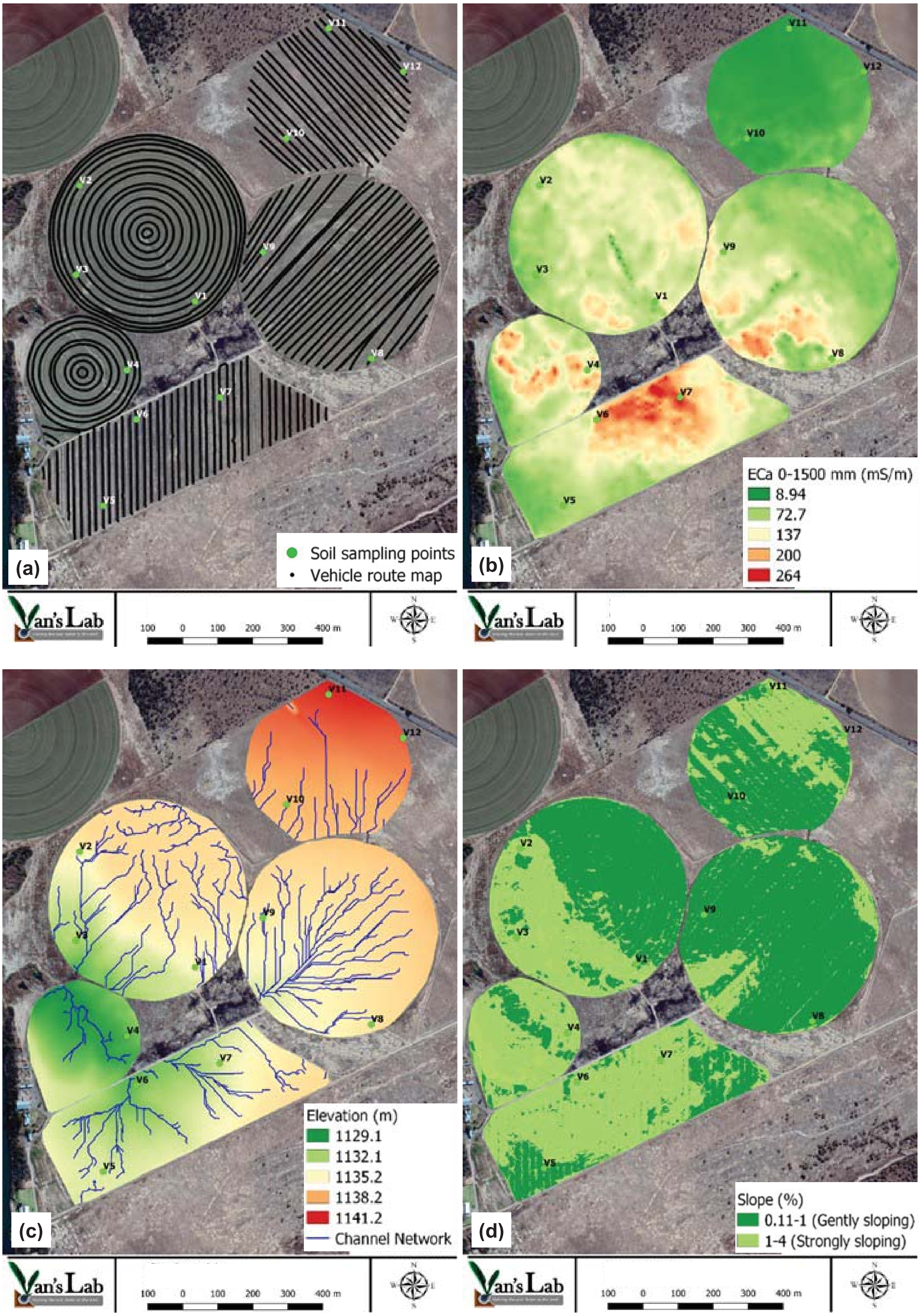

Figure 4.1 Maps of the (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage and (d) slope (%) over the 95.73 ha of lucerne fields.

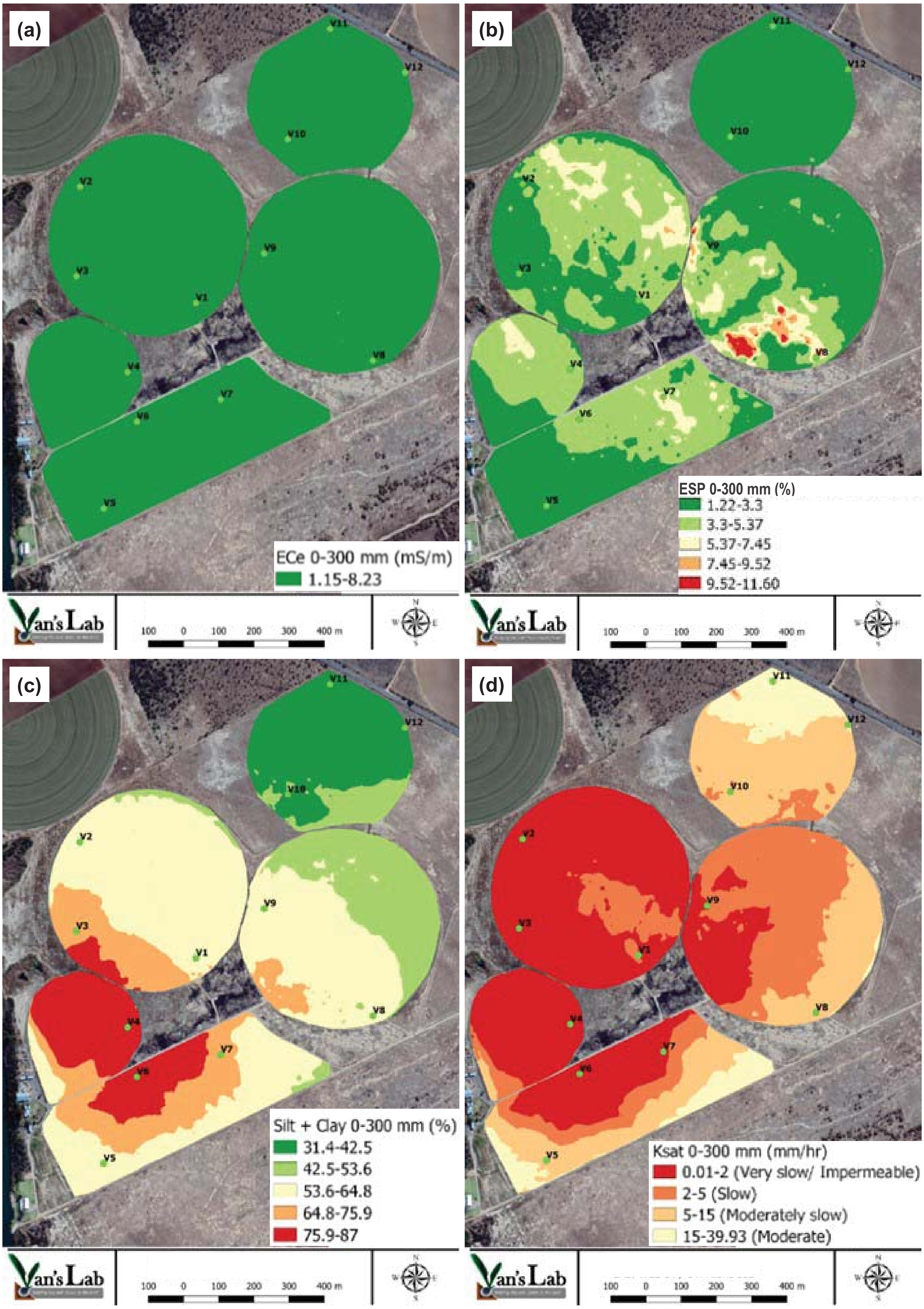

Figure 4.2 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

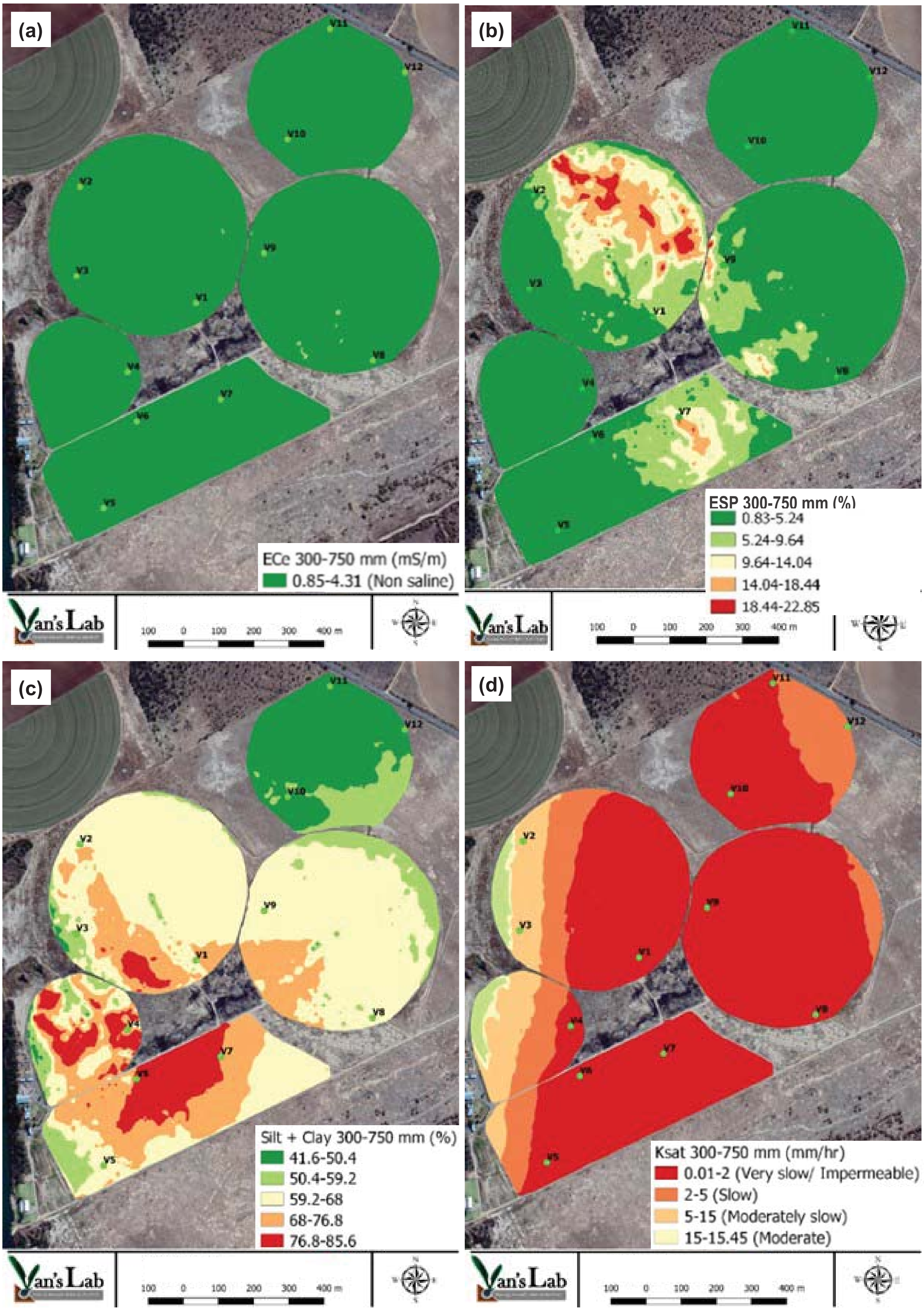

Figure 4.3 EC_a-inferred soil property maps for the 300 to 750 mm layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

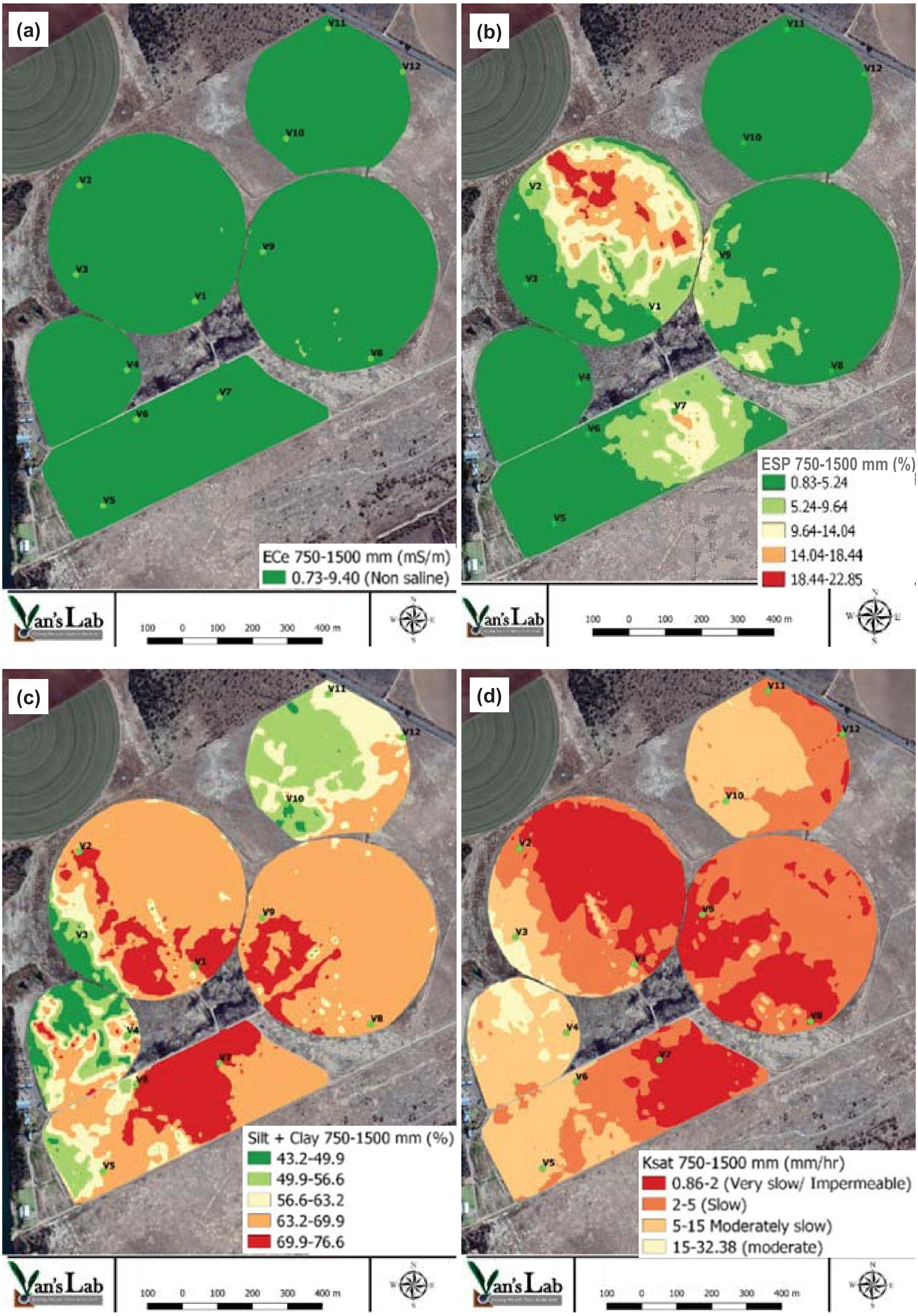

Figure 4.4 EC_a-inferred soil property maps for the 750 to 1500 mm layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

4.2.3 Main findings, recommendations and actions

The results and main findings of the project were discussed with the farmer during a feedback session. The farmer was also revisited in February 2020 to follow up on the outcomes.

i. Topography and soils: The site is situated on a gradual slope with a northern aspect. Soils are mainly clay with bleached and hydromorphic characteristics in both the top- and subsoil due to waterlogging. This is evident from the yellow and grey colours that persist. The soils vary between Rensburg, Arcadia and Addo soil forms with carbonates present in the lower horizon (900 to 1500 mm), further decreasing hydraulic conductivity. A strong relationship between elevation and soil forms were found. Soils on the upper slope have a higher rock content and sandy texture compared to soils at lower elevations. The gradient of the slope encourages interflow of water, silt, clay and soluble carbonates from the upper slope as there is an increase in these properties at lower elevations. Hence, these soils are prone to waterlogging and anaerobic conditions that negatively affect plants roots.

ii. Runoff control: Topographical results suggested that the fields require a proper assessment to control surface runoff. Therefore the case is referred to an agricultural engineer for redesigning the surface drainage system. The surface area of the northern and eastern pivots were landscaped during 2019 and the rest of the area will follow as soon as the lucerne crop has reached its full production cycle.

iii. Infiltration: The infiltration, as expressed by K_{sat} of the top layer, was generally poor, except for the top part of the northern centre pivot. These areas are associated with the high silt-plus-clay zone on the map (green area, Figure 4.2c) and possible dispersion of clay.

iv. Internal drainage: The K_{sat} map of the 300 to 750 mm soil layer indicate that the internal drainage is restricted in the brown and red areas (K_{sat} below 15 mm h^{-1}). Results from the ESP-map suggest that the B-horizon tends to build-up sodium over the whole farm and particularly under the western pivot where ESP-values as high as 33% were measured. The yellow, brown and red areas of the western pivot corresponded well with the low-yielding area pointed out by the farmer. Gypsum was recommended to reclaim the sodium affected field.

v. External drainage: K_{sat} of the 750 to 1500 mm layer was generally low, but slightly better than for the 300 to 750 mm layer, except for the mentioned area with high ESP-values. It is clear from the results that natural drainage is not sufficient to leach sodium and therefore it is recommended that artificial drains be installed. The clay content and K_{sat} data were sent to an agriculture engineer to design site-specific subsurface drains.

vi. Based on the ESP values of the profiles, gypsum application at a rate of 6, 12 and 10 t ha^{-1} was recommended for the northern, western and eastern pivots, respectively. For improving the infiltration and structure of the soil, a total of 12 t ha^{-1} of chicken manure was recommended. The farmer was advised to apply a third of the gypsum and manure two months before establishing the new lucerne fields, a third during spring and the last portion during late summer.

vii. The farmer adopted the manure and gypsum recommendations. During the short visit in February 2020, he revealed that the productivity of the farm improved significantly. He confirmed that the historical yields were on average 1.5 t ha^{-1} per cutting, or 12 t ha^{-1} per annum with 8 cuttings per annum. After the remediation the lucerne yielded on average 4.2 ton ha^{-1} per cutting at the northern pivot, 3.85 t ha^{-1} at the eastern-pivot and 2.4 t ha^{-1} at the western pivot. For eight cuttings per year the estimated yields are 33.6, 30.8 and 19 t ha^{-1} for the pivots, respectively. At the current price of R 2 700 per tonne hay, the survey improved the farmer's financial position significantly.

4.2.4 *Conclusion*

With the EMI survey and directed soil sampling technique it was possible to delineate the salt affected areas in the crop fields. From the results it can be concluded that: (i) salinity was not a problem for both the establish lucerne fields and new fields, and (ii) sodicity posed a real threat to the soil and the crop, especially the B-horizons with high clay content. The high clay-sodium content restricted infiltration, internal drainage and external drainage. The recommended manure and gypsum applications improved the lucerne yields significantly and have taken a mining dump field to a highly productive unit. Hopefully, the farmer will be able to finance the subsurface drainage as recommended in the near future.

4.3 Sugarcane

4.3.1 *Background, aim and EMI surveying*

The sugarcane industry employs 85 000 people directly and a further estimated 350 000 is indirectly employed. Approximately one million people (or 2% of South Africa's population) depend on the sugarcane industry for a living. Annual income for the industry is estimated at more than R14 billion. The industry has a total of 22 949 registered sugarcane growers, farming on 365 000 ha of which approximately 75% is rainfed (SASA, 2019). The remaining 25% under irrigation produces about 43% of the total annual crop (calculated from SASA, 2019).

Sugarcane is grown in the northern parts of the Eastern Cape, KwaZulu-Natal and the most eastern parts of Mpumalanga (Malelane and Komatipoort). Classification of the climate in this region is humid subtropical (Cfa) according to the Köppen-Geiger system (Arnfield, 2020). This means the minimum temperature of the warmest month is greater than or equal to 10°C, and the maximum temperature of the coldest month is less than 18°C but greater than -3°C. The average temperature of the warmest month is 22°C or higher. The annual water requirement (evapotranspiration) for sugarcane ranges from 1100 to 1800 mm depending on the location and climatic conditions (Carr and Knox, 2011). In South Africa rainfall of at least 600 mm per annum is required to produce a crop. The norm, however, is more than 750 mm per annum. Sugarcane in these regions are therefore produced with full irrigation due to insufficient rainfall.

Maud (1959) reported that the occurrence of alkali (sodic) and saline soils was uncommon back then in the sugarcane region of KwaZulu-Natal (KZN) and only two areas of severe alkalisation where known. One being in the Heatonville district, just west of Empangeni, and the other in Nkwaleni, about 40 km west of Empangeni. The Heatonville soils are on Beaufort sediments and the Nkwaleni region are mainly Beaufort derived alluvial soils (Maud, 1959). Soils associated with Beaufort sediments was characterised for the possibility to become sodic (Beater, 1970). Today the occurrence of salt affected soils is much more common. MacVicar and Perfect (1971) reported that 20% of irrigated land in the sugar industry is adversely affected by waterlogging or salinity or both. Applying that 20% value to the area irrigated today, it is estimated that about 21 000 ha under sugarcane is salt affected. It is plausible that the problem could have grown substantially since the 1970's, but no further quantifiable work has been published on salinity and sodicity for the sugarcane industry. Reinders et al. (2016), however, noted that rising water tables is a problem and there is a drastic need for subsurface drainage in large sugarcane irrigation areas of the Pongola Mill supply area. Reasons for the water table problem is not clear, but Jumman (2016) has noted that the poor adoption of objective irrigation scheduling methods in the region is a concern.

Sugarcane is regarded as moderately tolerant to salinity (Richards, 1954; Tanji and Kielen, 2003), but less tolerant to sodicity (Workman et al., 1986; Nelson and Ham, 2000) and the degree of sensitivity varies between varieties and even from crop to crop (Alam et al., 2018). Workman et al. (1986) found that sugarcane yield decreased from 84 t ha^{-1} to 66 t ha^{-1} over a period of 10 years on a saline-sodic soil. However, after the installation of a subsurface drain, the application and incorporation of gypsum and filtercake (an organic by-product from sugarcane mills) followed by leaching, yields improved to 75 t ha^{-1} over the next 10 years.

The EMI survey project of the 66 ha sugarcane plantation, depicted in Figure 4.5a, comprised of a centre pivot irrigated area (half circle) and a dryland area south-west of the centre pivot. The project was earmarked as a pilot for one of the mega sugar companies in South Africa. According to the senior agricultural engineer of the company, large areas on their farms in South Africa and in different countries of Africa are prone to waterlogging and salt accumulation, and demand remediation. The company was in search of solutions for identifying these affected areas, as well as measures to reclaim the soils. Apart from this EMI investigation, the company have also investigated other methods (NDVI images and LiDAR technology) to identify affected areas. The EMI survey was conducted on the 15th of November 2018 using a 15 m transect spacing, resulting in a total of 24 644 EC_a data points, i.e. 1 measuring point per 26.78 m^2.

The aim of this case study was to identify potential areas in the crop field associated with waterlogging and salt accumulation.

4.3.2 Results

Spatial EC_a distribution over the plantation is depicted in Figure 4.5b, while the topographical survey was used to derive a surface drainage map (Figure 4.5c) and infield slope percentage map (Figure 4.5d).

EC_a-inferred soil property maps for the 0 to 300 mm soil layer are depicted in Figure 4.6, these include EC_e (Figure 4.6a), SAR (Figure 4.6b), silt-plus-clay content (Figure 4.6c) and K_{sat} (Figure 4.6d). Figure 4.7 provides the EC_a-inferred soil property maps for the 300 to 750 mm layer, while Figure 4.8 gives the maps for the 750 to 1200 mm soil layer.

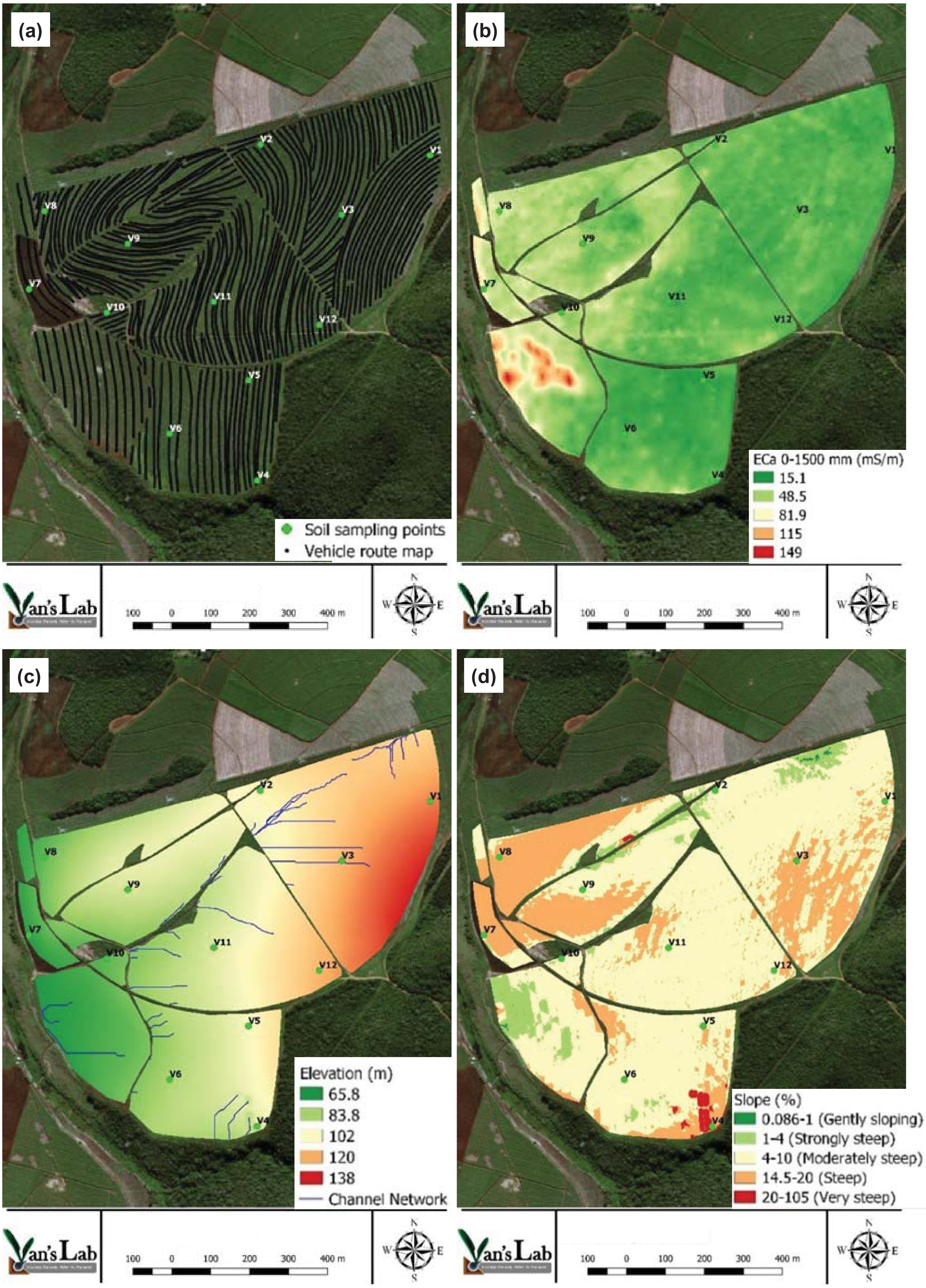

Figure 4.5 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 66 ha sugarcane plantation.

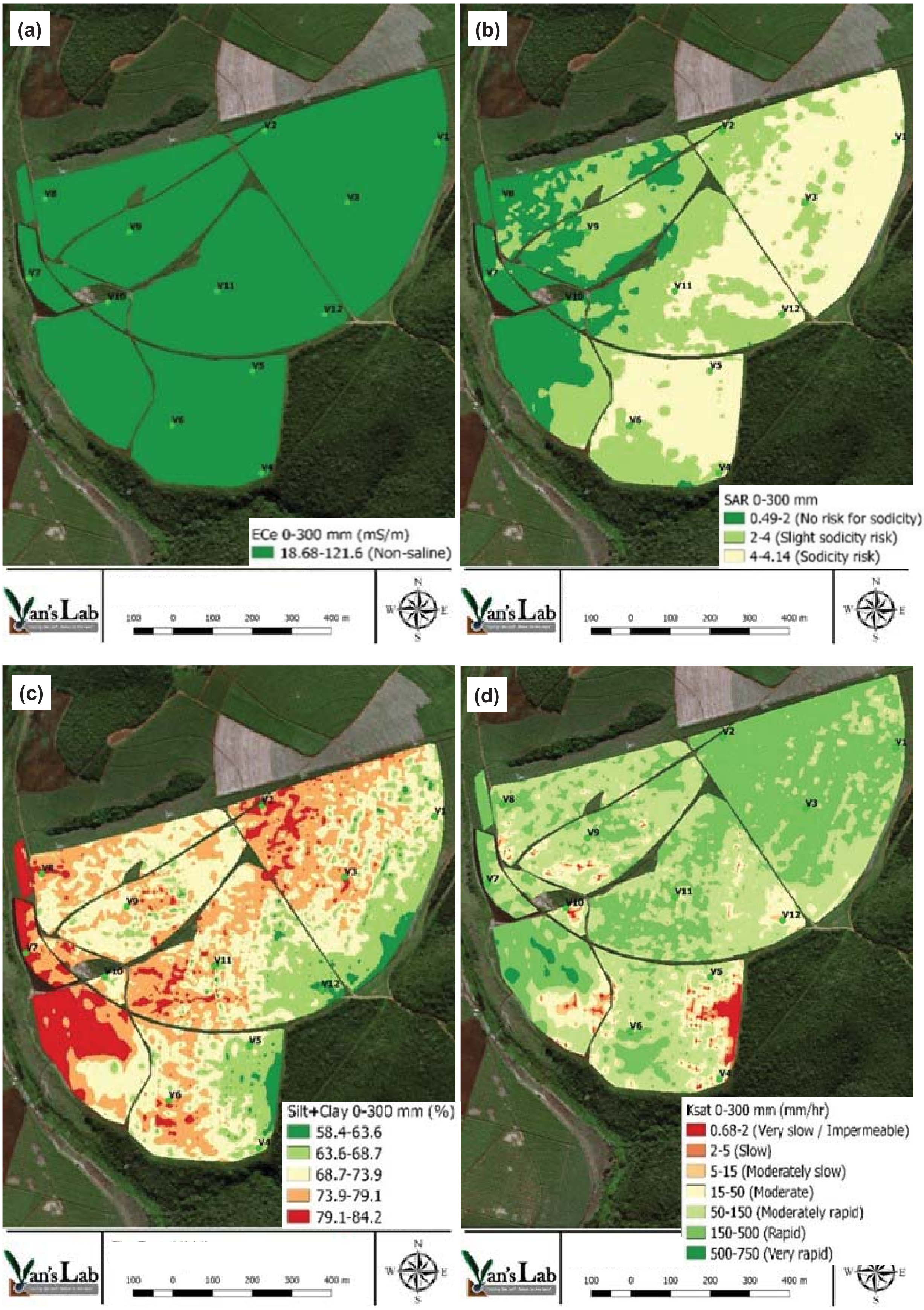

Figure 4.6 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR, (c) silt-plus-clay content (%), and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

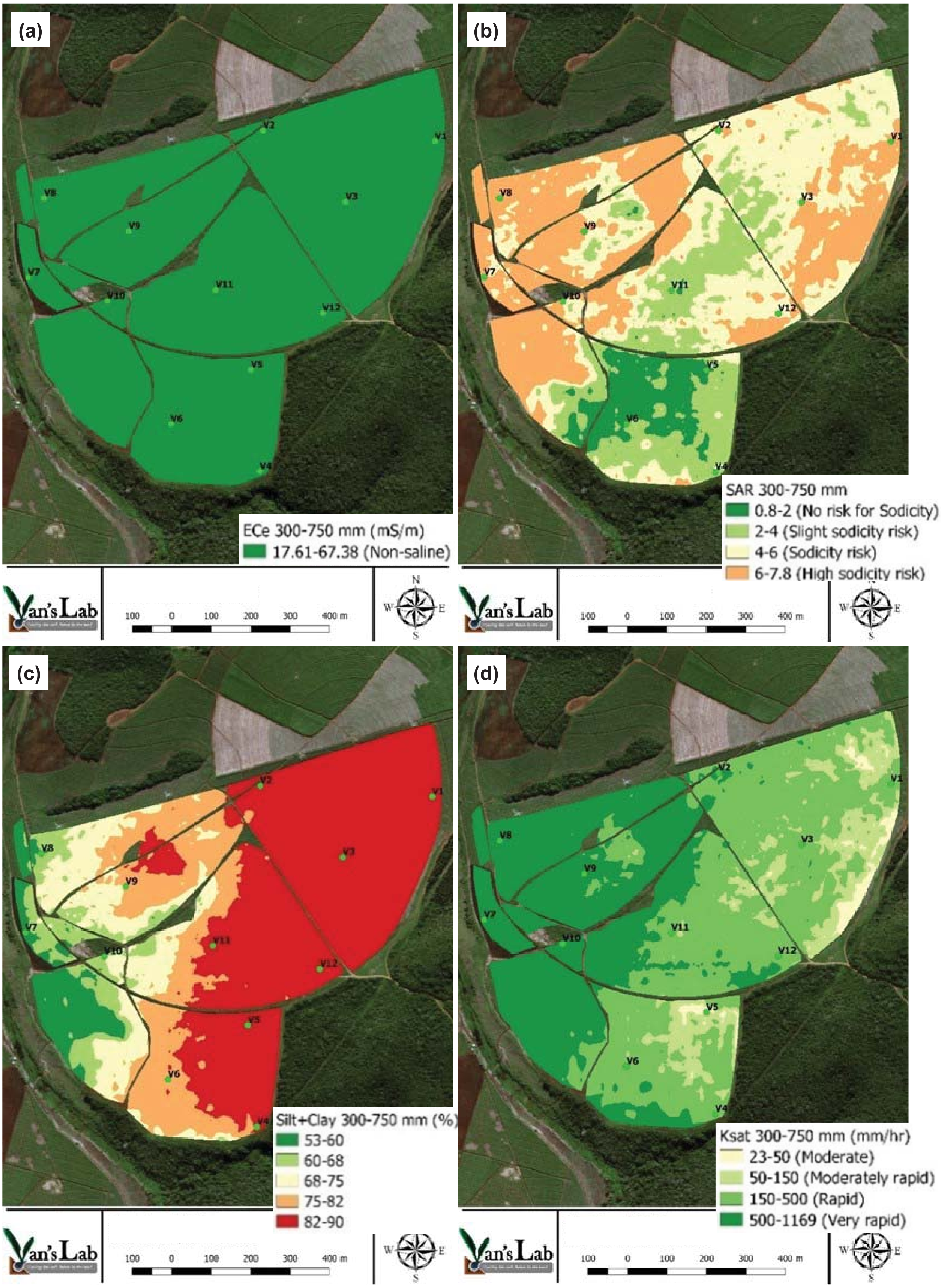

Figure 4.7 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

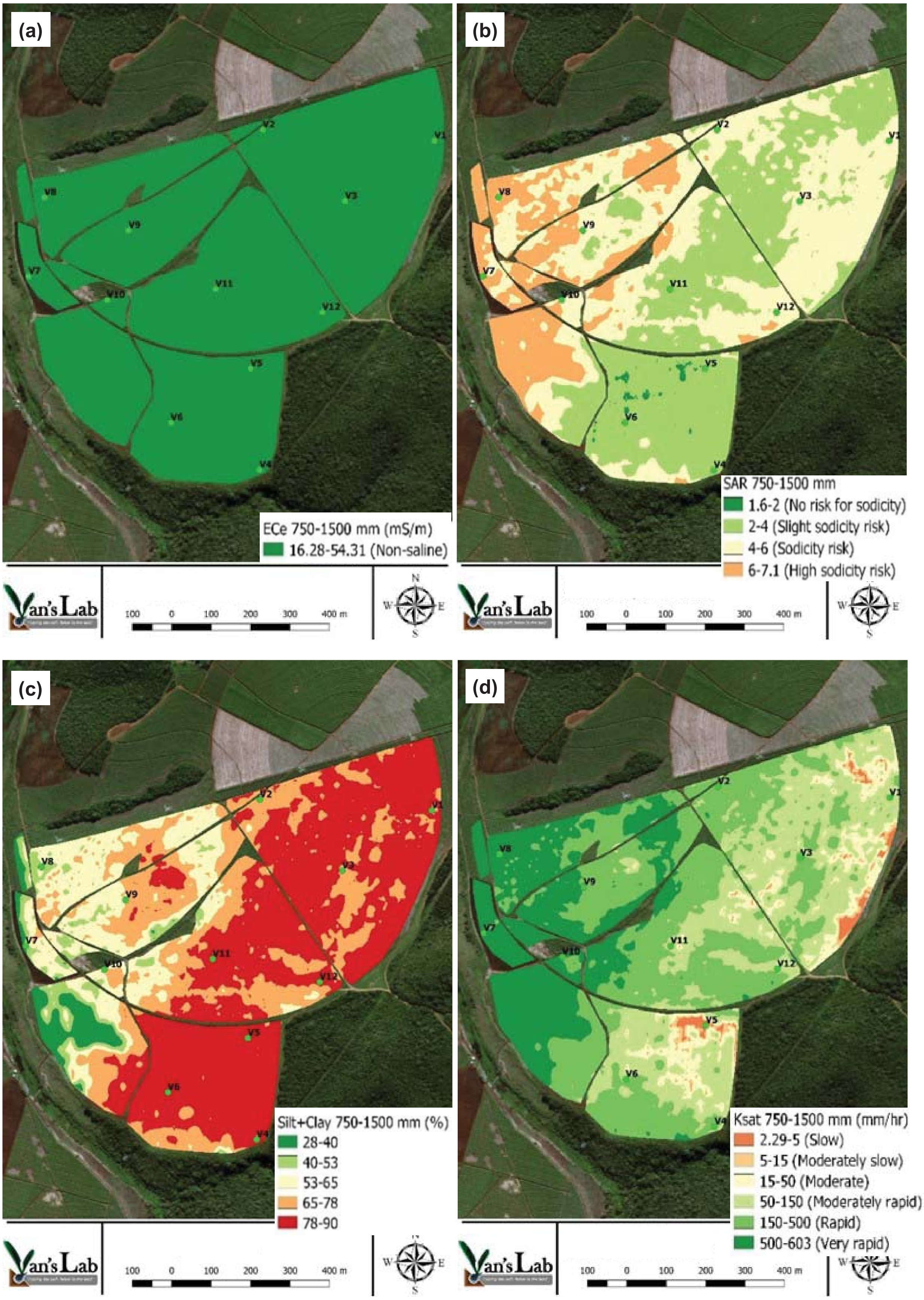

Figure 4.8 EC_a-inferred soil property maps for the 750 to 1200 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR, (c) silt-plus-clay content (%), and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

4.3.3 *Main findings, recommendations and actions*

The results and the following main findings of the project were discussed with the engineers of the company during a feedback session.

i. Topography and soils: There is a site-specific relationship between topography and soils. Soils with an elevation higher than 86 m above sea level (masl), i.e. on the midslope morphological terrain unit, have red structured B-horizons (Shortland form). Soils below 86 masl are associated with either organic (Champagne form) or pedocutanic (Sepane form) horizons. These soils have signs of wetness (hydromorphic) and are prone to waterlogging during high rainfall periods or over-irrigation.

ii. Runoff control: The general slope of the field is 9%, with highest elevation point at 138 masl and the lowest at 65.8 masl over a distance of approximately 800 m. The infield slopes vary greatly with large areas being moderately steep (7 to 10%) to steep (10 to 15%). These results suggest that the field requires a proper assessment to control surface runoff.

iii. Infiltration: Despite the clay soils, infiltration was generally good over the area, except for brown and red zones indicated on the K_{sat} map. These areas are associated with the hydromorphic soils below the 86 masl contour. Areas with slow and very slow infiltration requires at least 10 t ha^{-1} of crop residue incorporation. The rapid and very rapid K_{sat} areas should also be treated with the addition of organic matter in the form of woodchips at a rate of 10 t ha^{-1} or other plant residues, to lower the infiltration and leaching of nutrients.

iv. Internal drainage: Again, despite the high clay content of the 300 to 750 mm layer and large areas with sodicity risk (SAR between 4 and 6) or high sodicity risk (SAR of 6 to 8), the K_{sat} seems to be generally sufficient to leach excess salts to deeper horizons. Hence, the exchange of sodium with calcium is an important recommendation to remove sodium from this layer.

v. External drainage: External drainage is generally good over the field, except for small areas indicated by the brown and red zones on the K_{sat} map of the 300 to 750 mm layer. Artificial drainage should be considered for the slow and moderately slow drainage areas.

vi. Salinity is not a problem over the plantation area. However, there is sound evidence suggesting that sodium salts are building up in the sub and deep subsoil. Parent material of the soils is probably the cause of the high sodium content relative to other basic cations. The fertility report revealed that CEC correlated well with the EC_a values. Hence, three management zones were suggested (data and map not shown). The pH(KCl) values for these zones were on average 4.3, 4.7 and 4.3, respectively. A mixture of calcitic and dolomitic lime was recommended to counter magnesium deficiencies and to increase the pH towards an acceptable value of 5.5. It was argued that calcium will exchange the sodium on the colloidal complex, ready to be leached from the profile.

vii. Actions: The company decided to terminate the engineering section and agricultural operations, probably due to low sugar prices and high taxes they have encountered over the past years. Hence, it was not possible to get feedback on the recommendations.

4.3.4 *Conclusion*

This project was designed as demonstration to agricultural engineers from a sugar company on how valuable EMI technology can be as a tool for sensing salt affected areas in sugarcane plantations. As a test area, they selected one of their plantations comprised of a half-circle pivot and dryland on the lower elevation end of the field. From the topography survey and soil classification results, it was clear that elevation and associated soil forms play a significant role in the movement of water and salts in the field. The EMI-derived soil property maps (clay content, EC_e, SAR and K_{sat}) confirmed areas of very low infiltration, poor internal drainage and poor external drainage. More importantly, EC_e maps showed that salinity was not a threat to the crop. The SAR map illustrated that there was a slight build-up of sodium in the sub soils and deep soils, serving as an early warning system to prevent soil degradation due to dispersion of clays.

Unfortunately, the company apparently terminated their agricultural operations in South Africa, but lessons learnt can still be applied to the broader sugarcane industry. For example, a roadshow was held from 3 to 6 February 2020 to make growers aware of yield losses and soil deterioration due to sodicity. Places where these meetings were conducted and the number of growers who attended were: Malelane (6), Komatipoort (12), Pongola (24), Umfolozi (12) and Empangeni (26). Feedback was also given to co-workers in this project, at Mkuze (4) and at Heatonville (3). It was clear that farmers were unaware of sodicity problems in their soils and a number of farmers contacted SASRI and Van's Lab to assist in the design of salt management plans.

4.4 Olives

4.4.1 Background, aim and EMI surveying

Edible olives and olive oil, comes from a tree that belongs to the family Oleaceae and is classified as *Olea europaea* L. (DAFF, 2010). The olive-farming community in South Africa is a small industry with 170 registered growers, mainly located in the Western Cape (Karoo), Northern Cape (Vaalharts, Prieska and Upington), Eastern Cape (Alicedale), North West (Brits) and Limpopo (Modimolle) provinces (SA Olive, 2020).

From a climate point of view, olive is traditionally grown in areas with a mediterranean-type climate to which it is ideally adapted. Such regions have cool winters, followed by hot dry summers, making irrigation essential. Cool winters are necessary because the crop requires winter chilling to enter a rest phase and initiate flower development, otherwise the tree remains vegetative. Frost is a real risk, especially to young trees, young shoots and inflorescences, and can cause serious yield losses.

For sustainable production of olives, Class 1 and Class 2 soils, as described by Bhattacharjee (1979), is a prerequisite. These soil irrigability classes were slightly adapted for South African conditions (Van Rensburg et al., 2020): Class 1 is defined as highly suitable for irrigation with few or no limitations or preconditions, i.e. the topography is flat, soils have a moderately rapid infiltration capacity (K_{sat}: 50 to 150 mm h^{-1}), internal drainage and external drainage. Soils are deep, medium textured with available water holding capacity of at least 100 to 120 mm over the rooting depth. Class 2 is also suitable for irrigation with slight limitations, such as undulating topography, infiltration, internal drainage and external drainage slightly below or above that of a Class 1 soil. Water holding capacity between 80 and 100 mm over the rooting depth. Production on shallower soils, or soils with water holding capacities below 80 mm will be disappointing, while trees on wet or waterlogged soils are susceptible to asphyxia and root diseases. Soil pH(KCl) should be between 5.5 and 6.5.

Irrigation, usually by means of drippers or micro sprinklers, is a prerequisite for the regular production of high quality fruit (SA Olive, 2020). Although olives are regarded as moderately salt tolerant, saline conditions may reduce fruit weight and oil content, while increasing the moisture content of fruits (Chartzoulakis, 2005). Recent studies suggest that olives can be irrigated with water containing up to

3200 mg ℓ$^{-1}$ of salt (EC_i of 500 mS m^{-1}) producing new growth at leaf sodium levels of 0.4 to 0.5% of dry weight (Chartzoulakis, 2005).

The EMI survey was conducted in September 2018 at a farm in the Western Cape. Some of the trees in the orchards were dying and they also started reducing the canopies of the trees due to insufficient irrigation water and severe drought in the area. The aim of this case study was to identify potential areas in the orchards associated with salt accumulation.

Soils of the 140 ha olive orchards are marginal, dominated by lithocutanic, soft carbonate and hard carbonate subsoils. Due to poor drainage of the soils and restricted depth, trees were planted on ridges. The EMI survey was conducted on the ridges using a 10 m transect spacing (Figure 4.9a). A total of 29 910 EC_a data points were captured, resulting in a density of one measurement per 48.54 m^2. The EC_a data were subsequently used along with a geo-statistical software package for the identification of 24 soil sampling points (V1 to 24).

4.4.2 *Results*

The spatial variation in EC_a is shown in Figure 4.9b, while the topographical survey was used to derive a surface drainage map (Figure 4.9c) and infield slope percentage map (Figure 4.9d). EC_a-inferred soil properties for the 0 to 300 mm soil layer are mapped in Figure 4.10a to d, and include EC_e, SAR, silt-plus-clay content and K_{sat}. Figure 4.11 shows the EC_a-inferred soil property maps for the 300 to 750 mm soil layer.

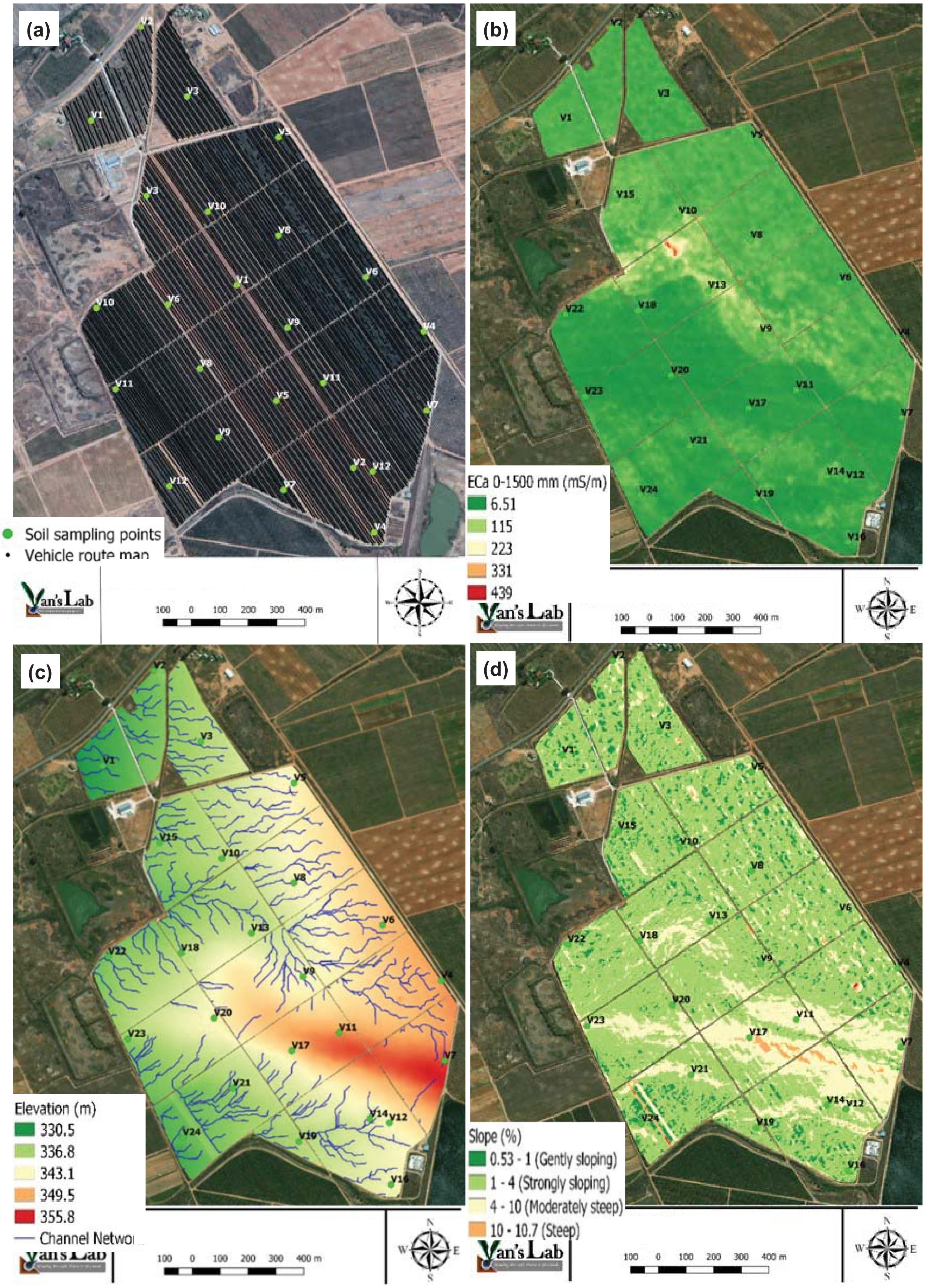

Figure 4.9 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 140 ha olive orchards.

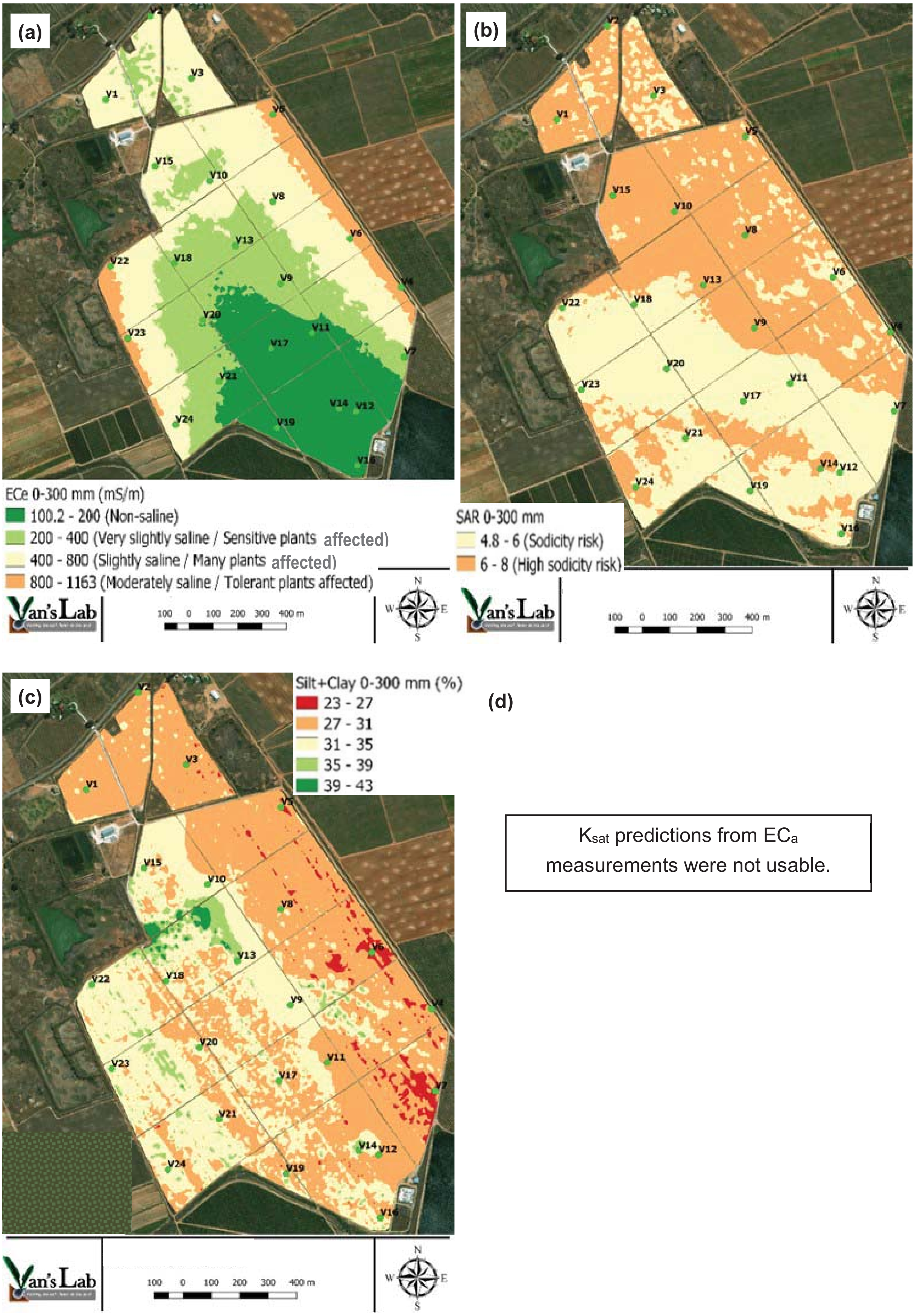

Figure 4.10 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}), over the 140 ha olive orchards.

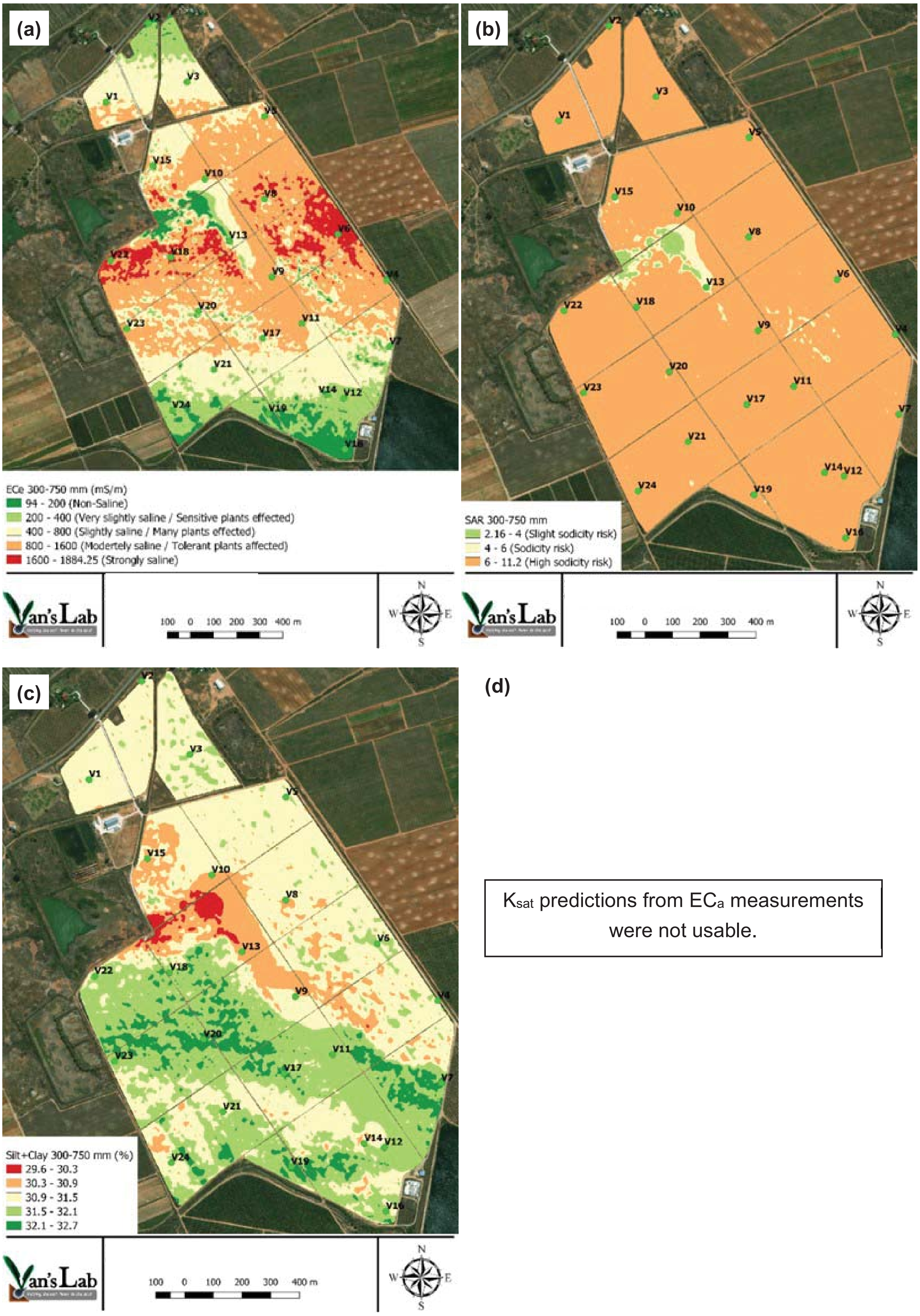

Figure 4.11 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}), over the 140 ha olive orchards.

4.4.3 *Main findings, recommendations and actions*

The results and the following main findings of the project were discussed with the managers and advisors of the farm during a feedback session.

i. Topography and soils: Topography plays an important role in soil formation and micro-climate of this farm as indicated by the infield slope percentage and drainage lines. For example, the hill area has a north and northeast aspect, indicating that the micro-climate will be warmer here than in the rest of the orchards. This information can be used to refine irrigation scheduling practices. Another feature of the hill is that it forms a watershed, directing runoff towards the northwest and southeast along the hill. This also explains the presence of soft carbonate horizons in the areas paralleled with the hill. Soft and hard carbonate formation is an indication of poor drainage of the deeper subsoil resulting in water accumulation and periodic waterlogging. The rest of the surrounding soils are dominated by lithocutanic characteristics. Most soils have signs of wetness in the C-horizon, indicating temporary waterlogging conditions. The stone fraction and sizes vary immensely over the field, making it impossible to map. Stones play an important role in the retention of water and nutrients in the field.

ii. Runoff control: The slope over the area varies from 0.53 to 10%, demanding a thorough assessment concerning runoff control indicated by the surface drainage lines. The slope gradient of the hill area is mainly classed as moderately steep (gradient of 4 to 10%) and is prone to runoff and erosion. Given the accuracy of the topographical data, it is worthwhile to check the efficiency of the current runoff control measures. Current runoff control depends heavily on the fact that the trees are planted on ridges.

iii. Infiltration: A main quality function of the A-horizon is to absorb rainfall and irrigation application and to store the water without inducing waterlogging or excessive leaching. Unfortunately, K_{sat} predictions for the 0 to 300 mm layer was poor and could not be used as a true representation of internal drainage of the A-horizon. Actual K_{sat} measurements obtained from the 24 sampling points indicated that the average final infiltration was 159 mm h^{-1} with huge variation of ± 132 mm h^{-1} over the area. The variation is attributed to the presence of stones that vary irregularly in size and percentage content over the field. Generally, larger stones decrease the hydraulic conductivity, while smaller stones increase it.

iv. Internal drainage: Again, K_{sat} was poorly predicted from EC_a values and actual K_{sat} values was measured at an average of 214 mm h^{-1}, with a standard deviation of 312 mm h^{-1}. Hence, it seems that K_{sat} is not restricted in this layer. Cover crops were recommended between the rows and the crop residue should be placed on the ridges.

v. External drainage: K_{sat} was not measured for the C-horizon, but the micro-morphology of the 750 to 1500 mm depth indicated that signs of wetness are present in almost all the profiles. This is a clear message that external drainage is restricted. It was recommended that clay content and K_{sat} be measured as a requirement for drainage design.

vi. Salinity: Olive is regarded as moderately tolerant to salinity. Unfortunately, the high EC_e in both the topsoil and subsoil layers confirms the build-up of salts. About 40 to 50% of the topsoil is classified as slightly too moderately saline, while about 80% of the subsoil is slightly too strongly saline. According to Chartzoulakis (2009), yield losses of 10% can be expected in the areas that have an EC_e of 380 mS m-^{1}, 25% loss in areas with 550 mS m-^{1}, 50% loss for 840 mS $m^{-1}$and permanent wilting with EC_e above 1400 mS m^{-1}.

vii. Sodicity: From the top and subsoil maps it is clear that large areas in the orchards was affected by sodium salts. Areas were categorised as having a sodic risk (SAR of 4 to 6) or a high sodic risk (SAR of 6 to 11) in both the top and subsoil layers.

viii. Actions: It became apparent from discussion with the managers and advisors that both the quantity and quality of irrigation water was a problem. They had experienced 3 years of drought prior to this survey and did not have sufficient water to meet crop water requirements plus leaching, which explains the build-up of salts in the soils. They were advised to measure EC of the irrigation water and reduce the irrigated area with at least 10%, taking out the marginal areas. The average rainfall is too low (350 mm per annum) for dryland production of the crop. Our concern was the impermeability of the C-horizon, requiring artificial drainage. They invested in continuous soil water sensors to improve daily water management, including leaching.

4.4.4 Conclusion

This case study focuses on salt accumulation in olive orchards located in a semi-arid area of the Western Cape. Prior to the EMI survey, the Western Cape had experienced severe water shortages due to prolonged drought conditions. Canopies of trees were heavily pruned as a measure to reduce crop water requirement. Drought tends to increase the salt content of irrigation water, which then demands additional water for leaching. Other factors that aggravate water and salt management of these orchards are the marginal soils (mainly Glenrosa, Brandvlei and Coega) and undulated topography. From the EC_e maps it was clear that the trees were under water stress due to high salinity and sodicity. Managers were advised to cut down on the irrigated area and to consider the installation of subsurface drains to leach the salts out of the root zone.

4.5 Pecan

4.5.1 Background, aim and EMI surveying

Pecans are tree nuts of the Juglandaceae family, native to North America. Pecan is a deciduous tree and is adapted to grow well in subtropical regions, but also grows well in areas with short, cold winters and long, hot summers (ARC, 2003). They have a distinct seasonal rhythm, good hardiness towards cold, as well as a chilling requirement to initiate uniform bud break (Taylor and Gush, 2007). The fruit require warmth in summer months for maturation, more than 2000 heat units is required to produce good quality nuts. More specifically, the average monthly maximum temperature must exceed 28°C in summer and be lower than 23°C in winter. Average monthly minimum temperature during summer must be higher than 16°C, but lower than 8°C in the winter (Taylor and Gush, 2007). Pecan is the only nut with low chilling requirements (Hassanen and Gabr, 2013). At least 400 hours at or below 7°C is recommended (Anonymous, 2017). These chilling units accumulate during dormancy after the leaves have fallen up until August or September in the Southern Hemisphere (Taylor and Gush, 2007).

Dry conditions in spring and early summer are critical for effective pollination and early nut development. During the greater part of the growing season humidity should not exceed 55% or scab disease may limit production (Alleman and Young, 2006). Only cultivars tolerant to scab should be planted in subtropical areas with very high humidity. The crop uses between 1200 to 1600 mm water annually, hence, rainfall amounts and trends in summer rainfall regions are not satisfactory to provide in the water needs of a pecan orchard (Vermeulen, 2006). It is of paramount importance to make sure that the soil meets the criteria for a Class 1 or Class 2 soil in terms of irrigability (Call et al., 2006; Van Rensburg et al., 2020). Irrigation systems should be installed before planting in order to manage water supply and demand (Carroll, 2015). An acceptable soil pH(H_2O) is between 6.2 and 7 (Upson et al., 2011).

Pecan cultivation is a very popular land-use in the central parts of South Africa. However, the crop demands Class 1 irrigable soils, since it is moderately sensitive to dissolved salts and waterlogging. Therefore, it is important to assess fields for its suitability to cultivate pecans. In the current case study, the farmer obtained land through the Land Reform Program of the Free State Department of Agriculture and Rural Development, and approached Van's Lab for a second opinion on the suitability of the soils for pecans and lucerne (Figure 4.12a).

Three existing centre pivots, located on the northern side of the farm, as well as five crop fields stretching from the centre towards the south-western side of the farm, were included in the survey (Figure 4.12a). Fields under the centre pivots comprises of Tukulu, Etosha, Addo and Brandvlei soil forms and were earmarked for lucerne and cash-crop production. The five fields at the lower elevations were reserved for lucerne and pecan production. Soils in these five field comprises of Tukulu, Etosha, Addo and Augrabies forms.

The aim of this case study was to assess the irrigability of both the centre pivots and the lower lying fields depicted in Figure 4.12a from a salinity and sodicity viewpoint.

The EMI survey was conducted using a 10 m transect spacing (Figure 4.12a). A total of 29 910 EC_a data points were captured, resulting in a density of one measurement per 48.54 m^2. The EC_a data was subsequently used along with a geo-statistical software package for the identification of 12 soil sampling points (V1 to 12).

4.5.2 *Results*

Results on the spatial variation of EC_a are depicted in Figure 4.12b, while the topographical survey was used to derive a surface drainage map (Figure 4.12c) and infield slope percentage map (Figure 4.12d). EC_a-inferred soil property maps for the 0 to 300 mm soil layer are given in Figure 4.13, including EC_e, ESP, silt-plus-clay and K_{sat}. Figure 4.14 displays EC_a soil property maps for the 300 to 750 mm layer, while Figure 4.15 gives the maps for the 750 to 1500 mm soil layer.

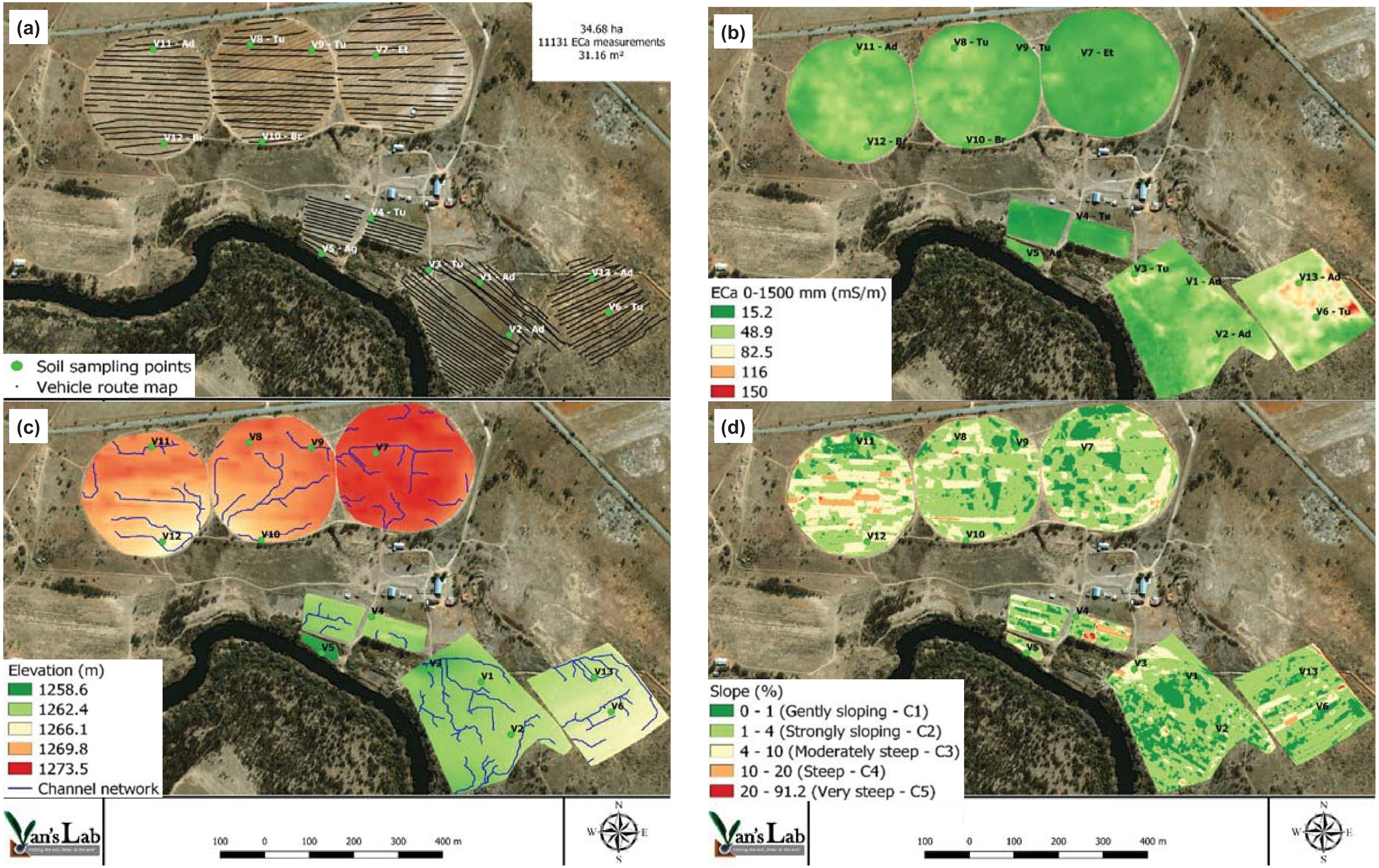

Figure 4.12 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 34.68 ha pecan orchards.

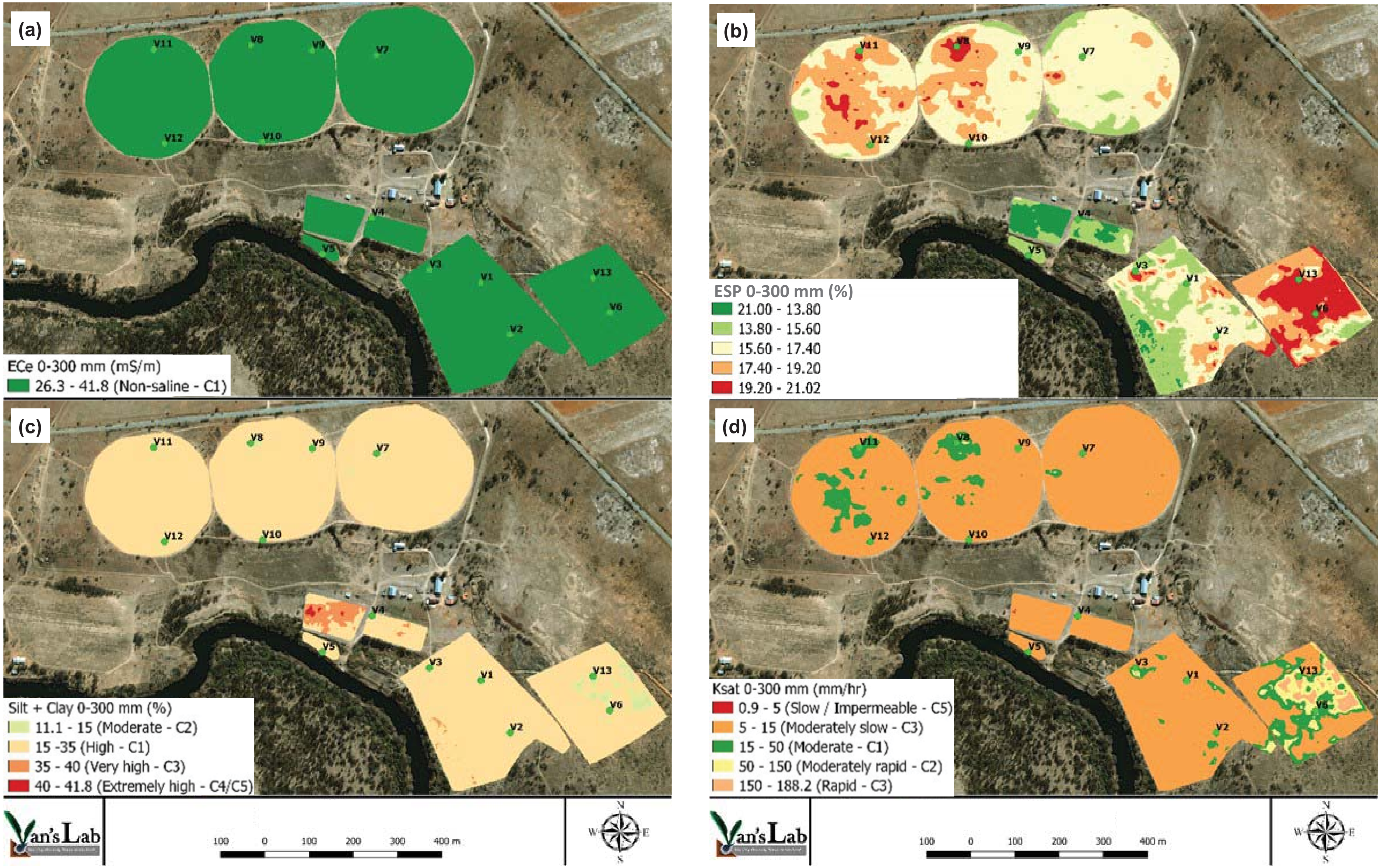

Figure 4.13 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

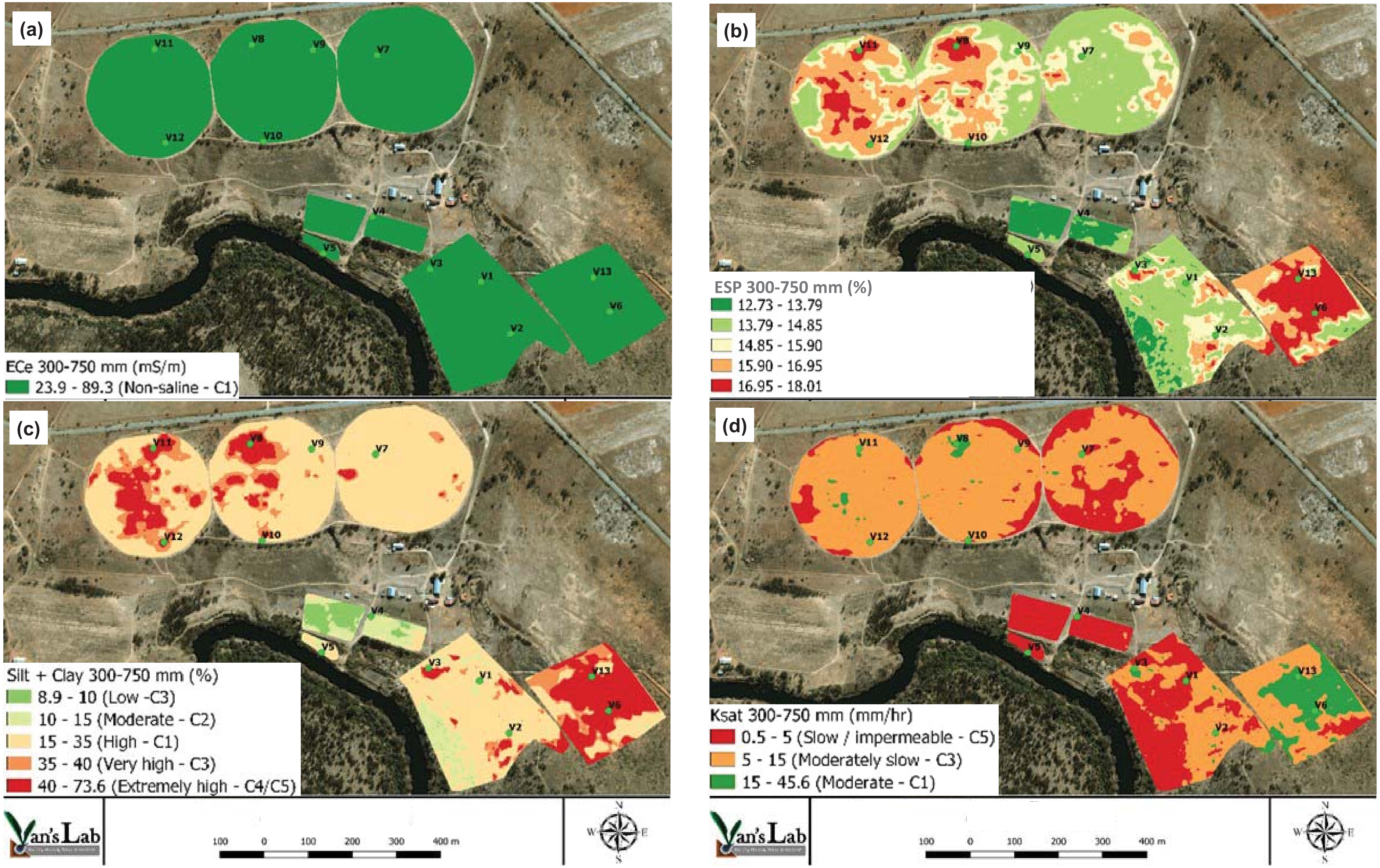

Figure 4.14 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

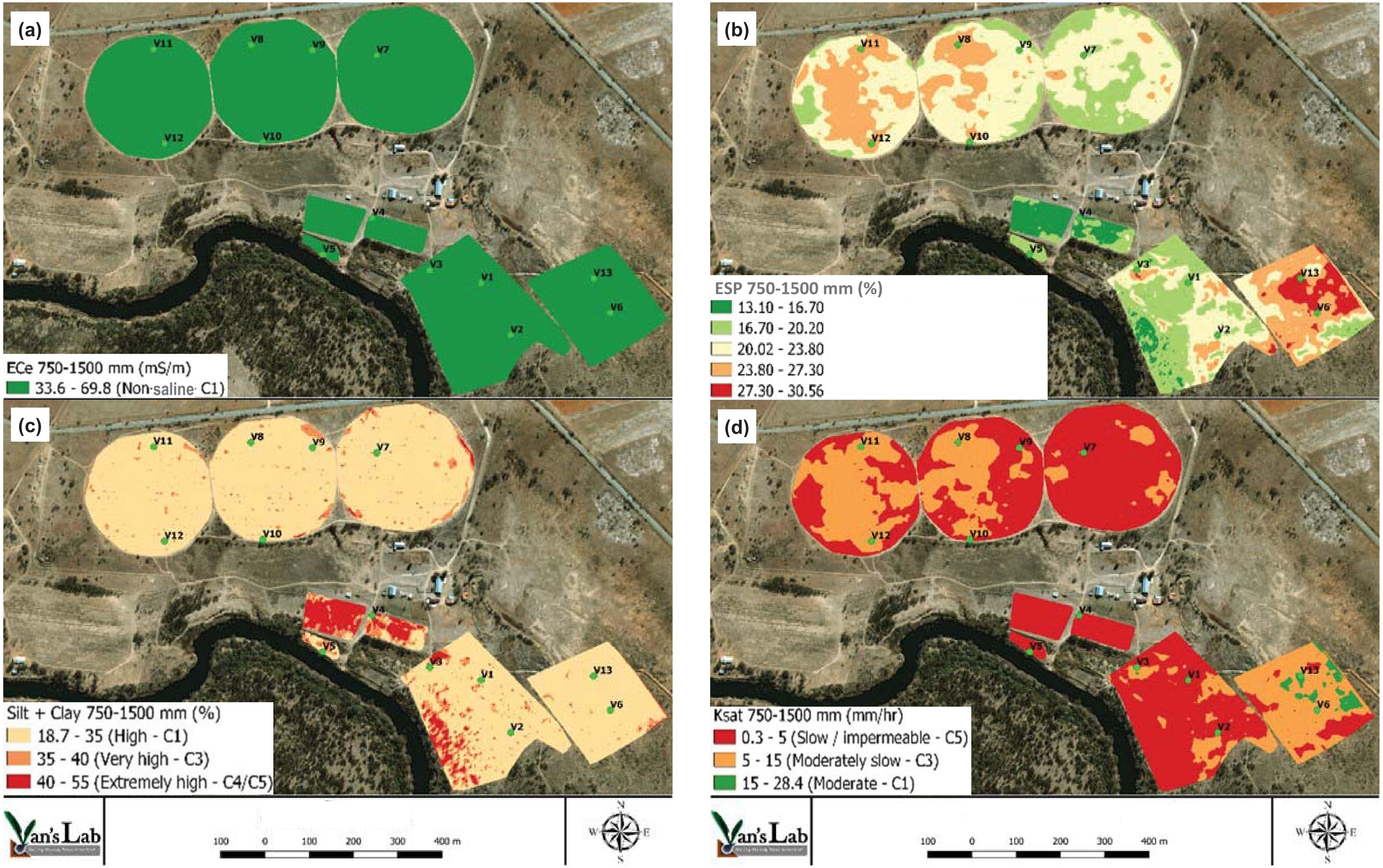

Figure 4.15 EC_a-inferred soil property maps for the 750 to 1500 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

4.5.3 Main findings, recommendations and actions

This case study was a consultation project and permission was granted by the owner to use salinity and sodicity results for research. The farmer received three reports, namely a hydro-physical, a hydro-chemical and a recommendation report. The physical report concentrated on physical aspect relating to water movement and storage in the top-, sub- and deep subsoil. The chemical report focused on chemical and fertiliser remediation from a soils point of view. The recommendation report integrated the physical and chemical properties to solve main problems through specific procedures. The results presented here only highlights the salinity and sodicity related aspects:

i. Topography and soils: For the centre-pivots, depth to soft carbonates decreases from the north to the south over the area, making it less suitable for pecan cultivation due to the influence of the carbonates on fertility, especially the fixation of phosphorus and some micro-elements. The soils in the lower lying area are mainly associated with neocutanic, neocarbonate and soft carbonate (C3 and C4 irrigability classes). These soils pose a waterlogging threat during periods of high rainfall and demands installation of artificial drainage systems.

ii. Runoff control: Only small areas have gentle slopes on the farm, while the rest of the terrain slopes vary between 1 and 20%. The farmer was advised to consult an agricultural engineer for surface runoff design.

iii. Infiltration: K_{sat} of large areas were categorised as moderately slow. This coincides with high ESP that varies between 13 and 21% over the field. Dispersion of clay minerals are probably responsible for the poor final infiltration of the fields. Crop residues at a rate of 10 t ha^{-1} should be incorporated together with gypsum or acidifying reagents, depending on the pH of the soil. Acidifying reagents such as ferrous sulphate and aluminium sulphate are too expensive, therefore sulphur is recommended. The pH of the soil should be checked before a final recommendation is made.

iv. Internal drainage: The internal drainage of the fields is generally slow and moderately slow. Possibly due to the high concentration of sodium in the subsoil as indicated by the ESP map. The application of gypsum or acidifying reagents are recommended, depending on the pH of the soil.

v. External drainage: The deep sub soil (750 to 1500 mm) shows poor drainage as indicated by the K_{sat} map. Again, it seems that a high sodium content caused dispersion of clays. The application of gypsum or acidifying reagents are recommended, depending on the pH of the soil. Sodium needs to be removed from the root zone, and the only way is through the installation of subsurface drains. It is recommended that an agricultural engineer use the hydro-physical information in the report to design a subsurface drainage system.

vi. Salinity: Both pecans and lucerne are regarded as moderately tolerant to soil salinity, hence an EC_e above 200 mS m^{-1} will start to affect growth of the crop. Fortunately, all three soil layers have EC_e values below the threshold and hence salinity does not pose any threat to the production of these crops on these sites.

vii. Sodicity: It was already mentioned that sodium plays a significant role in the reduction of water movement through the entire profile. From the topsoil and subsoil maps it was clear that large areas was affected by sodium. These areas were categorised as having a sodic risk (ESP of 4 to 6%) or a high sodic risk (ESP of 6 to 11%) in both the top and subsoil layers.

viii. Actions: As mentioned this case study is a land reform project with a female owner. The owner relies heavily on her mentor (a neighbouring farmer) for advice and she is dedicated to make this project a success for her family and the Free State Department of Agricultural and Rural Development that granted her the opportunity. The recommendations made to the owner has substantial financial implications and mangers of the Land Reform Project first need to approve activities before it can be applied. Reports were submitted in February 2020 to the Department for further advice on the budget for: (i) landscaping of the surface, preparing ridges to improve runoff and drainage, (ii) installation of subsurface drains underneath the pecans, (iii) application and incorporation of crop residue and gypsum for removal of sodium from the root zone, and (iv) a water and salt management plan to control crop water use and sodicity on a daily basis.

4.5.4 Conclusion

From the EMI and soil physical results it is clear that this land reform initiative presents challenges regarding the sustainability of the irrigation project. It is of utmost importance that the physical and chemical constrains that were exposed through this investigation be rectified, otherwise the project is destined to fail. The main constraints involved, runoff, infiltration, internal drainage and external drainage induced by sodium accumulation over the profile due to the presence of slow permeable soft carbonate and unspecified wet C-horizons. The farmer was advised to consult an agricultural engineer to design surface- and subsurface drainage for the 34 ha field, starting with the area where pecans will be cultivated. These drains will restore water flow and retention in the long run by removing the excess sodium from the fields. Once the drains are in place, chemical amendments and water management can be applied. Leaching is most efficient in the winter when crops are dormant and evapotranspiration is low. This timing also does not coincide with critical periods of nitrogen fertilisation and uptake.

4.6 Walnuts

4.6.1 Background, aim and EMI surveying

Walnut production is a relatively small industry compared to pecans in South Africa, but globally walnuts account for 21.4% of the total tree-nut production of 4 537 732 tonnes forecasted for the 2019/20 season, compared to 2.96% for pecans (INC, 2019). China is the world's largest producer of walnuts, accounting for 50% of the production, followed by the USA with about 33%. Despite the stable walnut market globally, production in South Africa never took off (Kriel, 2020). For example, Rotondo Walnuts Pty Ltd was established by the Industrial Development Corporation in 1999 and is, to date, probably the only company in the country that produces walnuts on a large scale. The company planted about 500 ha walnuts along the Orange River, near Aliwal North, between 2000 and 2008 and harvested about 1200 tonnes in shell by 2019. Rotondo's intention is to escalate production towards 2030/35. (Watkins, personal communication[1]).

The project reported on here, forms part of Rotondo's expansion initiative, aiming to fourfold production by end of 2030/35. The managers contacted Van's Lab for an in-depth investigation regarding the hydro-physical and hydro-chemical properties of the orchards. The first phase of the project included a 101.46 ha area indicated in Figure 4.16a. Long-term rainfall averages at approximately 400 mm per annum, while the crop water requirement ranges from 1200 to 1600 mm per annum when trees are matured. The annual crop water deficit is sourced from the Orange River. Although the Orange River is

[1] Mr P Watkins, General manager Rotondo Walnuts, Rouxville.

renowned for its high-quality water concerning salinity (17 mS m^{-1}) and SAR (0.33), it also contains considerable quantities of silt that may alter the hydraulics of the soil in the long run (Van Rensburg et al., 2012). Soils were surveyed before establishment of trees and comprises of Valsrivier, Augrabies, Oakleaf, Bonnheim, Arcadia and Namib forms.

Walnuts are categorised as ‘sensitive’ to increases in salinity and the crop will experience a 10% yield loss at an EC_e of 230 mS m^{-1}, a 50% loss at 480 mS m^{-1} and a zero yield at 800 mS m^{-1} (Akça et al., 2017). Insufficient water uptake due to increasing osmotic potential in the soil or excessive sodium and chlorine ions in salty soil types, as well as the disruption in ion balance of the plants, are indicated as reasons for a decrease in growth and yield under saline conditions (Lewitt, 1980). A 0.3% chloride, 0.1% sodium and 300 ppm boron content in the leaf tissue are accepted as excessive for walnuts (Akça et al., 2017).

The EMI survey was conducted using an 8 to 10 m transect spacing (Figure 4.16a). A total of 27 294 EC_a data points were captured, resulting in a density of 1 measurement per 27 m^2. The EC_a data were subsequently used along with a geo-statistical software package to identify 20 soil sampling points (V1 to 20). The soils at each of the points were classified and disturbed and undisturbed samples were taken for the topsoil (0 to 300 mm), subsoil (300 to 750 mm) and deep subsoil (750 to 1500 mm).

4.6.2 Results

Results on the spatial variation in EC_a are depicted in Figure 4.16b, while the topographical survey was used to derive a surface drainage map (Figure 4.16c) and infield slope percentage map (Figure 4.16d). Relatively high EC_a activity was observed in the northeast, north, northwest and southeastern parts of the area, while low activity occurred in a broad strip stretching over the area in a south-western direction.

EC_a-inferred soil property maps for the topsoil layer are shown in Figure 4.17, including EC_e, ESP, silt-plus-clay and K_{sat}. Figure 4.18 provides EC_a soil property maps for the subsoil, while Figure 4.19 shows the maps for deep subsoil layer.

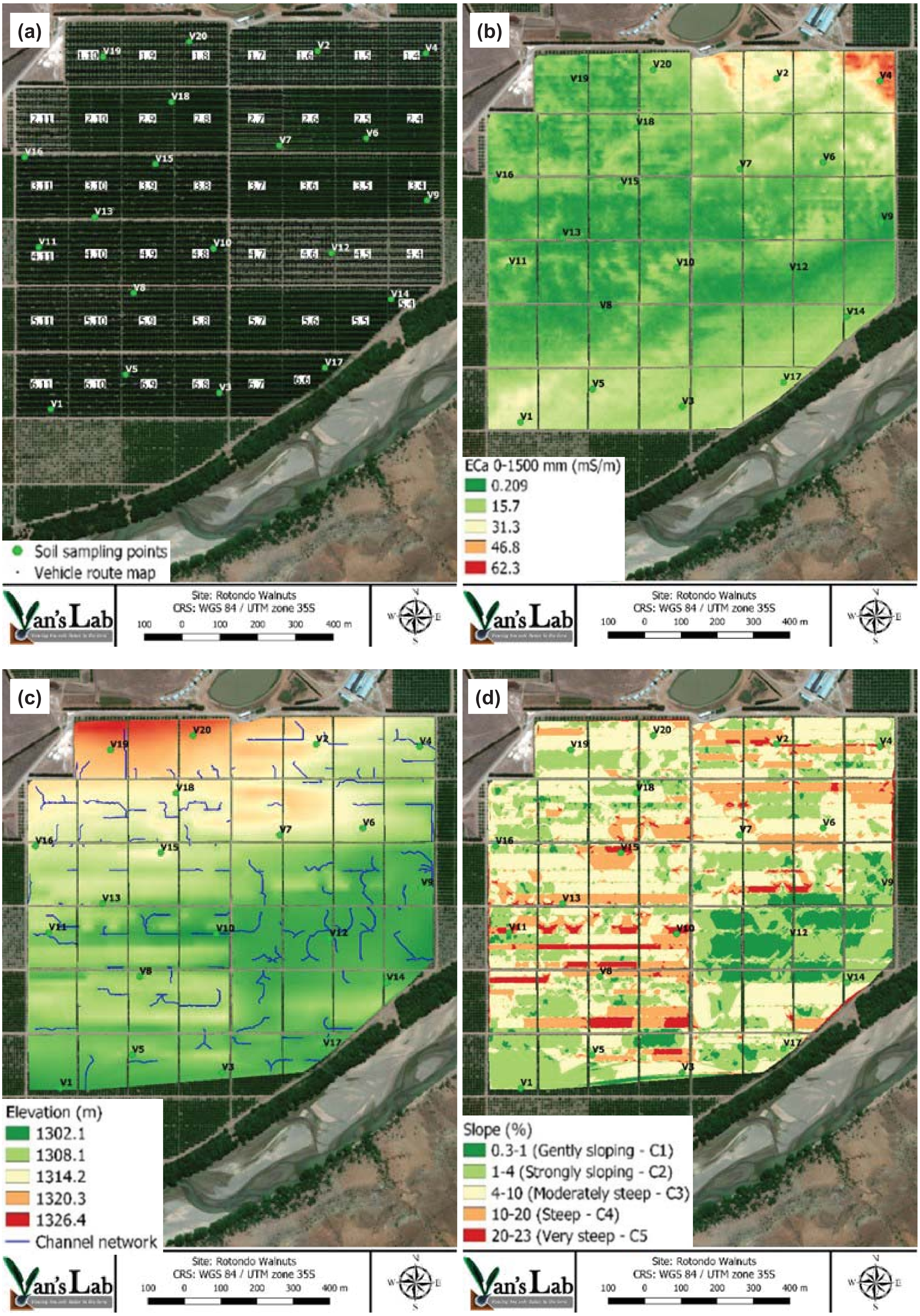

Figure 4.16 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 101.46 ha of walnuts orchards.

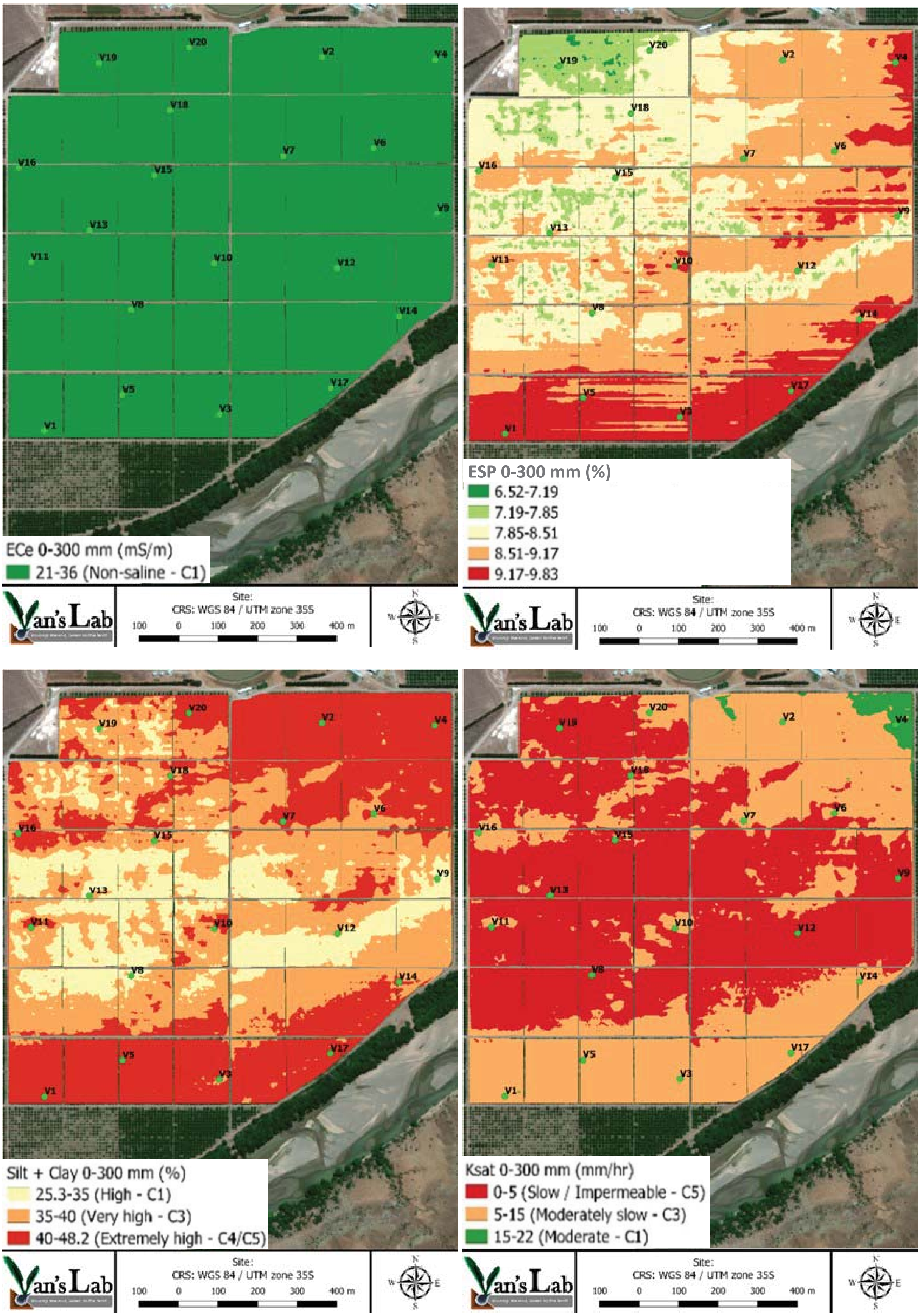

Figure 4.17 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

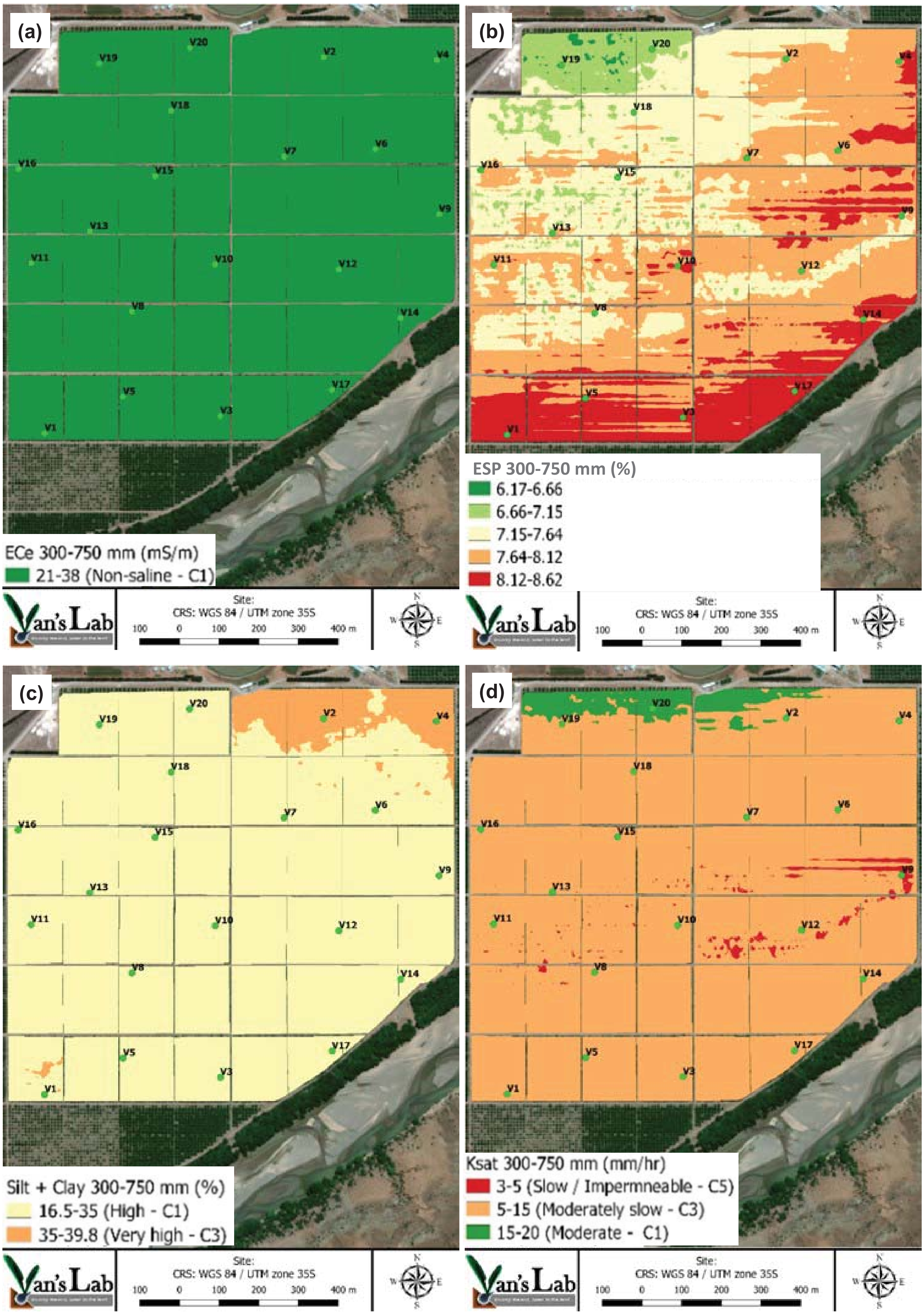

Figure 4.18 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%), (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

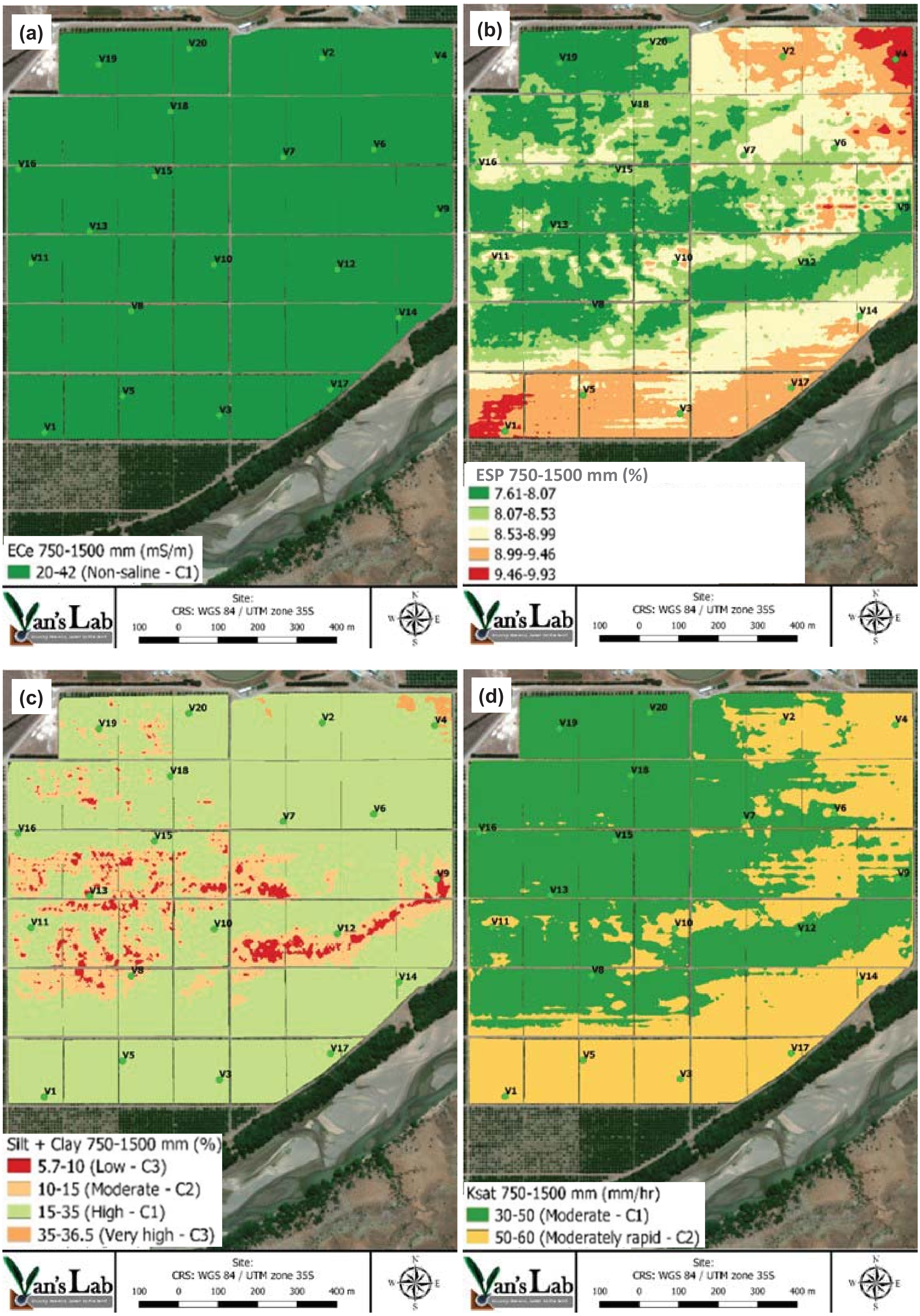

Figure 4.19 EC_a-inferred soil property maps for the 750 to 1500 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%), (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

4.6.3 *Main findings, recommendations and actions*

The following main findings were extracted from the reports to the farm managers:

i. Topography and soils: The topography of the field can be described as undulated, i.e. a wave-like characteristics, with mainly north and south facing hillslopes. Soils will naturally differ over the hillslopes due to the effect of temperature and the building-up of organic matter on cooler south-facing hillslopes, resulting in soils such as Mayo, Inhoek, Rensburg, Tukulu and Oakleaf forms. The gradient of the slopes also encourage interflow of water, silt, clay and cations from the upper slope downwards. Some of the soils in the depressions are therefore prone to waterlogging and anaerobic conditions that negatively affect crop growth.

ii. Runoff control: Due to the undulating topography, infield slopes vary greatly, ranging from 1 to 20% over large areas of the site. There was also visual symptoms of soil erosion present in the orchards, demanding a thorough investigation into runoff-control measures.

iii. Infiltration: The average K_{sat} of the top soil is 13 mm h^{-1}, while the K_{sat} map indicated that a large area of the field has K_{sat} values between 0 and 5 mm h^{-1}. The low K_{sat} can be attributed to the high clay content (26% on average), high silt content (14% on average) and high ESP (8% on average) of the top layer. More than 90% of the area has an ESP of higher than 6%. Dispersion of the silt and clay minerals are probably responsible for the poor final infiltration.

iv. Internal drainage: The internal drainage of the area is generally slow to moderately slow, probably due to the relatively high silt content (12%), clay content (20%) and ESP (8.1%) of the subsoil on average. The ESP map indicated that the entire area had an ESP of 6% and higher. Interesting to note is that the average lime content of the top- (4.8%) and subsoil (5.7%) was high and the EC_e was low. This points to the possibility that carbonates and bicarbonates present in the soil bind with calcium to form calcium carbonate ($CaCO_3$) that precipitates, leaving soluble and adsorbed sodium.

v. External drainage: Unlike the top- and subsoil, the deep subsoil fortunately has sufficient drainage to remove excess salts. This can be attributed to a lower silt (9%) and clay content (16%) on average, compared to the top- and subsoils. However, it is recommended that leaching be monitored at the reference points, since ESP is on average 8.3%.

vi. Salinity: Walnuts are regarded as a crop that is sensitive to salinity. The EC_e values were below 60 mS m^{-1} in all three soil layers. Therefore, it is clear that salinity can be eliminated as a direct factor lowering crop yields. Acidification of the soil or application of gypsum should be carefully managed to keep the EC below the threshold of 200 mS m^{-1}. Corrective measures should be conducted during the winter period when the crop is resting.

vii. Sodicity: As explained, the presence of lime in and low EC_e values probably induced artificially high ESP values. It is recommended that removal of sodium by the crop and the addition of sodium through irrigation water be analysed as a possible causes of sodium accumulation in the soil.

viii. Actions: A meeting was held with the mangers to discuss the hydraulic problems summarised above. Reclamation of the dispersed soils is complicated by the fact that there are areas with free lime and without free lime, according to the 10% HCl test for free lime. However, a $CaCO_3$ analysis revealed that the whole area contains $CaCO_3$. Hence, it was recommended that undisturbed samples be taken at the reference points to conduct laboratory tests on the soil hydraulics using gypsum and sulphur as reclamation agents. The managers agreed to the laboratory test as they have applied lime at a rate of at least 1 t ha^{-1} annually for the past 15 years. The second recommendation refers to the source of sodium that has accumulated in the soil. How is it possible that a high quality water source, such as the Orange River, result in the accumulation of sodium in the soil profile? Is it the sodium content or carbonate content of the irrigation water, low removal of sodium by the crop, or the precipitation of $CaCO_3$ in the soil that cause the problem? The third recommendation was formulated with the aim of addressing the infiltration-runoff dynamics of the top soil. A field experiment was suggested to quantify this relationship on the soils from the 20 reference points. This information can be used to assess the efficiency of the irrigation system. A recommendation was also made that the topography data be used to assess the current surface drainage design to combat erosion. The managers were encouraged to continue with their mulching practice to combat soil erosion by surface water flow.

This case study is an example of a level three decision support system that involves further research for improving the hydraulics of the field and by doing, so optimising the growth conditions of the crop on the short and medium term.

4.6.4 Conclusion

The aim of this case study was to identify site-specific problems related to topography, soil physical and chemical properties that might cause sub-optimum growth conditions in the walnut orchards at this site. Results revealed that the hydraulics of the A and B-horizons are a real concern, aggravated by a combination of factors, including the undulated topography, high silt content and high sodium content that dispersed the colloidal fraction of the soils. The K_{sat} maps of the top- and subsoils provided a sound basis to delineate the problematic areas in the field. Given the spatial information, it was recommended that, firstly, a laboratory experiment should be conducted to select the best commercial product (gypsum or sulphur) and application rates for removing sodium from the soil. The second recommendation was proposed to investigate the origin of the accumulated sodium in the soil. It was also recommended that it would be worthwhile to conduct a field experiment to determine the infiltration-runoff relationships at different irrigation application rates, once the soil hydraulics issues have been resolved,. It was further recommended that an agricultural engineer be approached to assess the surface drainage of the field using the current elevation data.

4.7 Macadamia

4.7.1 Background, aim and EMI surveying

The genus *Macadamia* belongs to the Proteaceae family and only two species, i.e. *M. integrifolia* and *M. tetraphylla*, are of commercial importance (Nagao and Hirae, 1992). Trees take 5 to 12 years to produce nuts and a good tree can produce nuts for 40 years (DAFF, 2012). Macadamias require a hot subtropical climate without much humidity. They flourish at temperatures between 16°C and 25°C, but extended exposure to temperatures above 30°C can harm new growth and cause premature nut shedding during early development. Trees are not frost resistant, but can survive temperatures as low as -3°C. Total production and nut quality is superior when grown at altitudes below 600 m above sea level (Anonymous, 2020). Macadamia branches are brittle and prone to wind damage, hence trees should be protected against wind damage in the first two years and pruned correctly to ensure stronger branch angles (Anonymous, 2020).

Like most perennial crops, macadamias require between 1200 and 1600 mm of water annually, therefore full irrigation in dry areas and supplemental irrigation in the subtropical areas is imperative to obtain high yields with good quality. Macadamia trees flourish in deep, well drained soils with a profile available water capacity between 100 and 120 mm (Class 1 and 2 irrigable soils, Van Rensburg et al., 2020). Trees are tolerant to more acidic soils and a soil pH of 5.0 to 5.5 is ideal.

Macadamia is generally regarded as moderately sensitive to soil salinity (Tanji and Kielen, 2003). The threshold (EC_e) where salinity will start to affect growth is 200 to 300 mS m^{-1} and zero yield is reported at 800 to 1600 mS m^{-1}. Hue and McCall (1989) found no adverse effects when EC of irrigation water was below 300 mS m^{-1}, but above 700 mS m^{-1} growth ceased. Salinisation of the soil also results in an imbalanced nutrient uptake by the crop, especially calcium and the sodium:potassium ratio. A Na:K ratio below 2.5 in leaves indicates the onset of poor growth in macadamia (Nagao and Hirae, 1992).

Macadamia production is a world-class industry worth US$822 million (Anonymous, 2018). South Africa is officially the largest producer and exporter of macadamia nuts in the world, overtaking other top producers, Australia and Hawaii. A reason for this is that South Africa has tripled plantings from 1250 ha in 2013 to 3870 ha in 2016 (SAMAC,2020). Macadamias are mainly grown in Limpopo (near Tzaneen and Levubu), Mpumalanga (Barberton, Nelspruit and Hazyview) and on the north and south coast of KwaZulu-Natal (DAFF, 2012). Nut production in these provinces will probably double in the near future, depending on the performance of orchards of leading farmers who replaced sugarcane with macadamia nuts. The current case study is such an example where sugarcane was replaced by macadamia nuts.

Before establishment of the macadamia orchards in this case study in 2016, sugarcane was cultivated under dryland conditions. The highest point on the terrain is 108 meters above sea level (masl) and the lowest point 50 masl. Rainfall is about 1000 mm per annum. Waterways were also establish to drain the surface water. Soils are mainly grouped as hydromorphic, including Arcadia, Rensburg, Katspruit, Fernwood, Kroonstad, Tukulu and Sepane forms. The crop was planted on ridges to improve drainage. A few lines of subsurface drains were also installed to drain areas that were severely waterlogged. Despite the high-risk soils, the first significant harvest is expected this year and projections look promising. The age of trees in the orchards vary between 1 and 4 years. The success of the crop growth so far was attributed to the low-flow drip irrigation system that was installed and the open-hydroponic fertigation system. However, some areas have been replanted without success.

One of the constrains was that the farmer did not have a drainage-salt-control plan for the field and therefore contacted a drainage company to assist. The company contacted Van's Lab for an EMI-field survey to characterise the salt-affected areas in the crop field. The EMI-survey was conducted from 16 to 20 November 2018 over the 201 ha site (Figure 4.20a). A 10 m transect spacing was used, resulting in a density of one EC_a measurement point per 27 m^2.

4.7.2 Results

The spatial variation of EC_a is depicted in Figure 4.20b, while the topographical survey was used to derive a surface drainage map (Figure 4.20c) and infield slope percentage map (Figure 4.20d).

EC_a-inferred soil property maps for the 0 to 300 mm soil layer are shown in Figure 4.21, including EC_e, SAR, silt-plus-clay and K_{sat}. Figure 4.22 gives the EC_a soil property maps for the 300 to 750 mm layer, while Figure 4.23 provides maps for the 750 to 1500 mm soil layer.

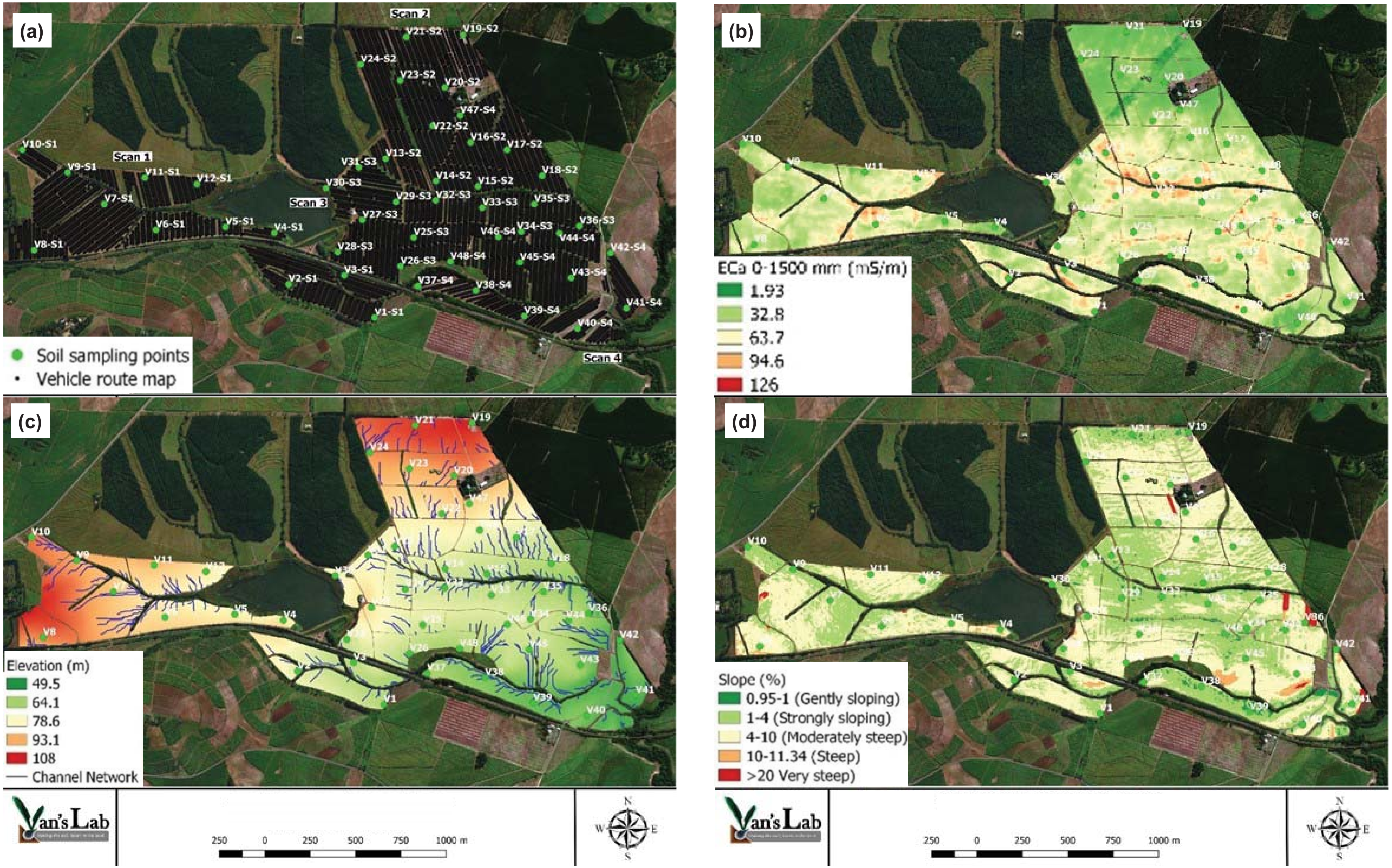

Figure 4.20 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 201 ha macadamia orchards.

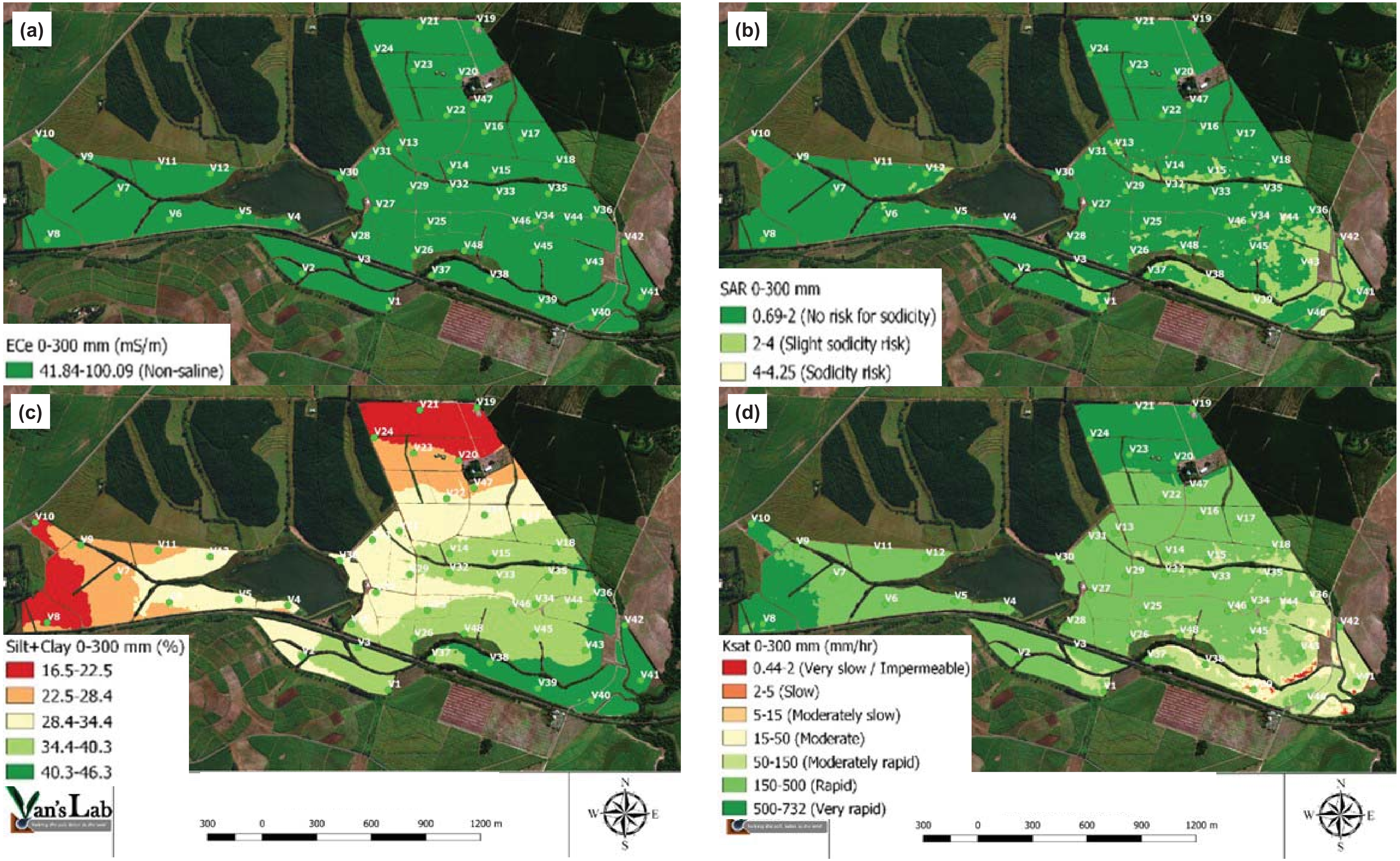

Figure 4.21 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

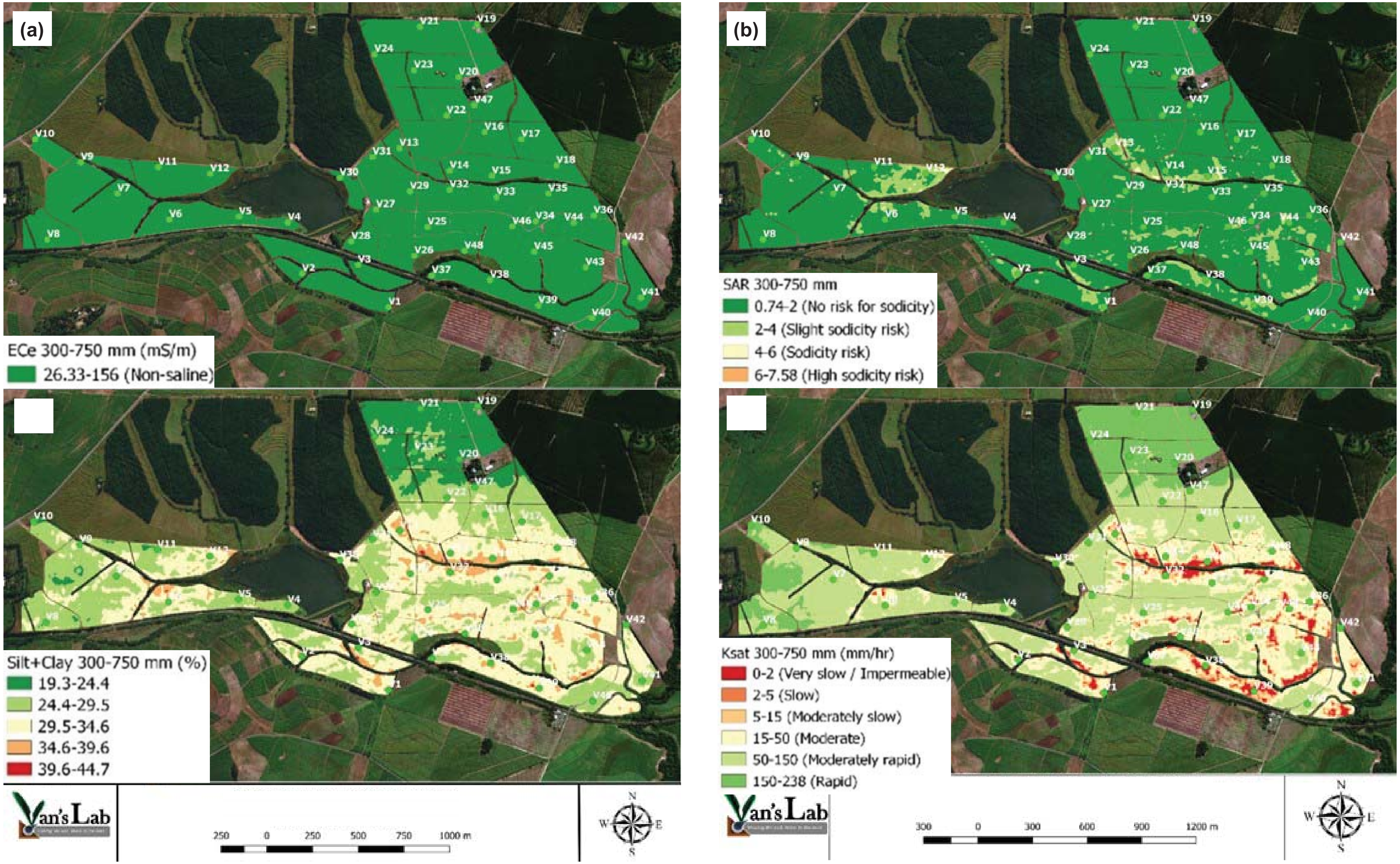

Figure 4.22 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

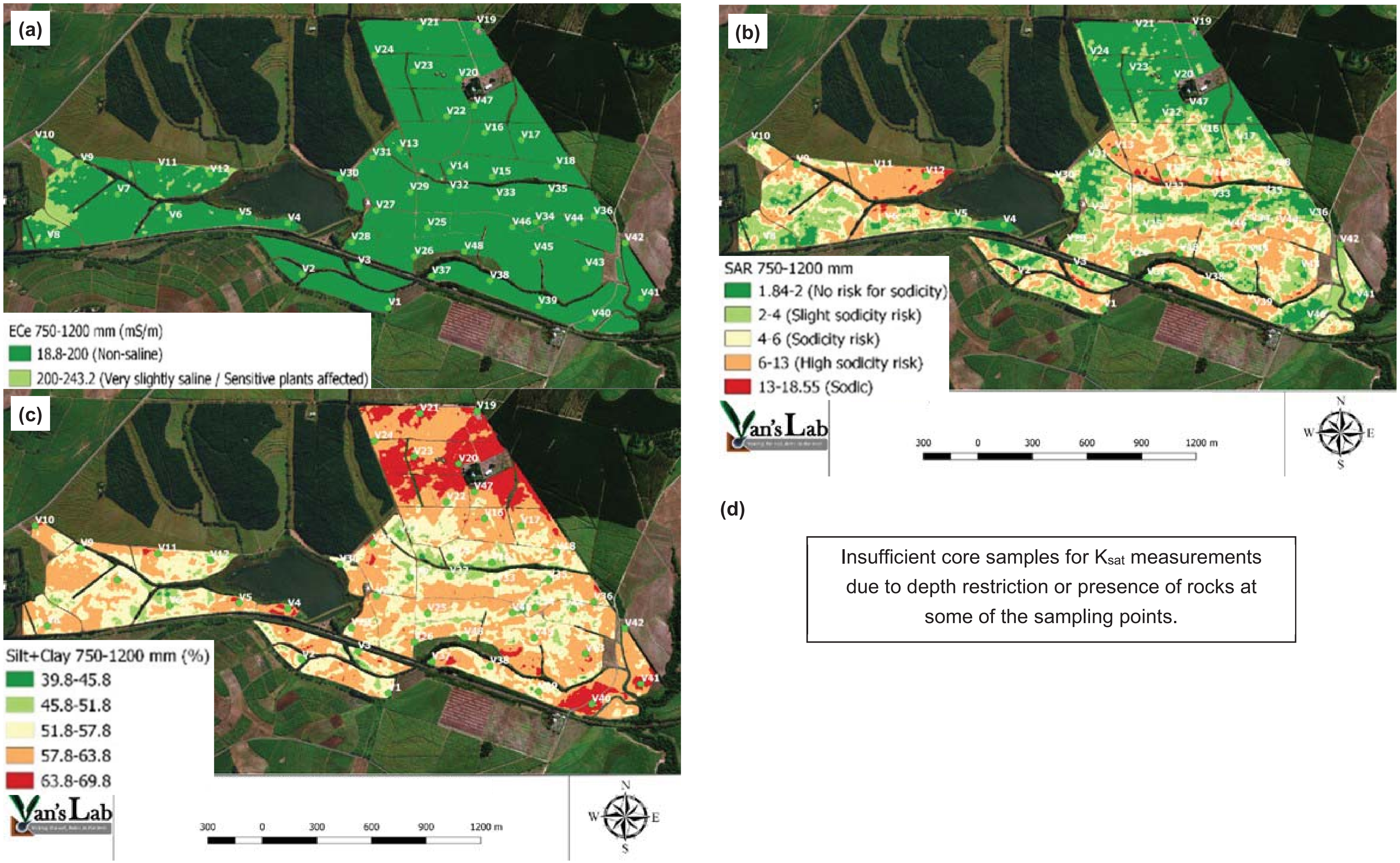

Figure 4.23 EC_a-inferred soil property maps for the 750 to 1200 mm soil layer: (a) EC_e (mS m^{-1}), (b) SAR (c) silt-plus-clay content (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1})

4.7.3 Main findings, recommendations and actions

i. Runoff control: Topographical results suggested that the field requires a proper assessment to control surface runoff. Visual inspection showed areas of waterlogging, confirming the need for runoff control measures.

ii. Infiltration: The infiltration, as expressed by K_{sat} of the topsoil layer, is sufficient for the field, except for the small brown and red areas on the map. These areas are associated with high silt-plus-clay content (Figure 4.21c, green area).

iii. Internal drainage: The K_{sat} map of the subsoil layer indicates that internal drainage is restricted in the brown and red areas (K_{sat} below 15 mm h^{-1}). The SAR map suggests that there is a build-up of sodium salts in the areas with poor infiltration. However, SAR levels are not as high as to induce dispersion of clay particles.

iv. External drainage: It was not possible to measure K_{sat} of the deep subsoil (750 to 1200 mm), but the 48 soil profiles classified in the field suggested that the C-horizons of these profiles have severe signs of wetness, an indication of poor external drainage. The brown and red areas on the deep subsoil SAR map (Figure 4.22b) have SAR values above 6 and up to 18.6. Clay particles start to disperse when SAR rises above 6, especially under low EC_e conditions. Thus, it can be assumed that the mentioned areas on the SAR map require artificial drainage. This area co-inside with the areas indicated by the farm manager where poor growth and replanting of trees occurred.

v. Salinity: The soils generally has a low EC_e, except a small area on the western side of the farm that rose above 200 mS m^{-1} in the deep subsoil.

vi. Sodicity: As mentioned, there are areas where the SAR rose above 6 in the deep subsoil.

Actions: During a meeting between scientists and the farm owners and managers, the EMI technology, soil property measurements and results were explained. Each of the main findings were thoroughly discussed and specific recommendations were made. For example: (i) Surface runoff design: a recommendation was made that the data of the topographical survey be utilised by an agricultural engineer to assess where improvements can be made in the surface-runoff design. (ii) Infiltration: the application of organic matter at a rate of 10 t ha^{-1} per year for 5 years was suggested for the high silt-plus-clay area to improve infiltration. (iii) Removal of sodium from soil: the application of gypsum to remove excess sodium from affected areas. Rates were determined for specific areas and they were encouraged to follow the soil reclamation procedure summarised in Section 5.3.2.1 in the Volume 1 report (Van Rensburg et al., 2020). External drainage: it was recommended that waterlogged and saline areas be reclaimed through the installation of artificial drains. The drain-technology that the company suggested is about a third cheaper than the conventional method. Due to the high cost of drainage and the uncertainty of its efficiency in removing the excess sodium and water, they suggested that a demonstration trail be compiled at three strategic points in the field. If the results are positive then they will drain the rest of the areas. This action falls within the level three DSS category, which demands research and the outcome will determine further actions.

4.7.4 Conclusion

Results of the topographical data, EMI-inferred soil properties were presented to the owners and farm managers and they accepted the report. It was clear that salinity does not affect the soil or crop, although there is a small area on the western side of the farm that needs attention. Our real concern was sodium that has been building-up in the deep subsoil and needs to be removed. A recommendation was made to install drains in designated areas. Seeing that the drain technology is relatively new in South Africa, the owners wanted more clarification on the installation and efficiency thereof. They suggested testing of the drainage technology before any further steps will be taken to reclaim the affected areas. The company agreed to design and conduct a demonstration trail.

4.8 Blueberries

4.8.1 Background, aim and EMI surveying

Blueberry (*Vaccinium* spp.) belongs to the Ericaceae family (sub-family: Vacciniaceae) and was only domesticated in the early 20th century. Many cultivars were bred for a wide range of climates (Ireland and Wilk, 2006). Blueberry is planted in almost every province of South Africa, with the main production areas in the Western Cape (60%), Limpopo (15%), North West (10%) and Gauteng (8%) (SABPA, 2019). The South African blueberry industry is small, but it has grown exponentially over the last few years. Approximately 2000 ha is currently under blueberry production, with a significant portion of the area still in the plant-establishment phase. Production increased from 1 800 t in 2013 to 11 500 t in 2018 (SABPA, 2019). The crop prefers areas without risk of early-season frost damage and soils that are slightly acidic. Blueberries are very sensitive to poor quality irrigation water, with upper limits of 45 to 100 mS m^{-1} for salinity (Ireland and Wilk, 2006: Himelrick and Curtis, 1999). The upper limit for sodium is 46 mg ℓ^{-1}, bicarbonate 92 mg ℓ^{-1}, chloride 70 mg ℓ^{-1} and boron 1 mg ℓ^{-1} (Retamales and Hancock, 2012). Since blueberries are very sensitive to salinity induced stress and waterlogging (Wilk et al., 2009), it requires sound soil and water management practices.

A leading agronomist in the blueberry industry contacted Van's Lab to assist in evaluation of soil conditions of blueberry orchards located in the Western Cape. The 69.8 ha orchards were established in 2007/8. The average annual rainfall of the area is 700 mm, of which a considerable amount will runoff due to very steep slopes. The highest point in the field is 197.2 masl and the lowest point 155.9 masl. As a protection measure against waterlogging, the crop is planted on ridges covered with plastic. Although the plastic will reduce evaporation it will also contribute to runoff. Waterways were establish to drain surface water. Soils are mainly categorised as hydromorphic, including Kroonstad, Fernwood, Longland, Westleigh, Wasbank and Glenrosa forms. The EMI survey was conducted on 15 to 16 July 2019 and the route followed by the mobile unit can be seen in Figure 4.24a. EC_a readings were taken at a density of one measurement per 24 m^2.

Despite the high-risk soils, the field produces a berry yield of about 10 t ha^{-1}, this is about the norm in the industry in an 8-year cycle. This translates into a gross annual income of R800 000, produced at a cost of R443 000 per hectare (SABPA, 2019). The expected net annual income is therefore R357 000 per hectare. The success of the crop was attributed to the low-flow drip irrigation system installed. The aim of this section was to assess soil conditions of the blueberry orchards after 12 years of irrigation, focusing on salinity and sodicity.

4.8.2 Results

Spatial variation in EC_a is depicted in Figure 4.24b, while the topographical survey was used to derive a surface drainage map (Figure 4.24c) and infield slope percentage map (Figure 4.24d). EC_a-inferred soil property maps (EC_e, ESP, silt-plus-clay and K_{sat}) are shown for the topsoil layer (Figure 4.25), subsoil (Figure 4.26) and the deep subsoil layer (Figure 4.27).

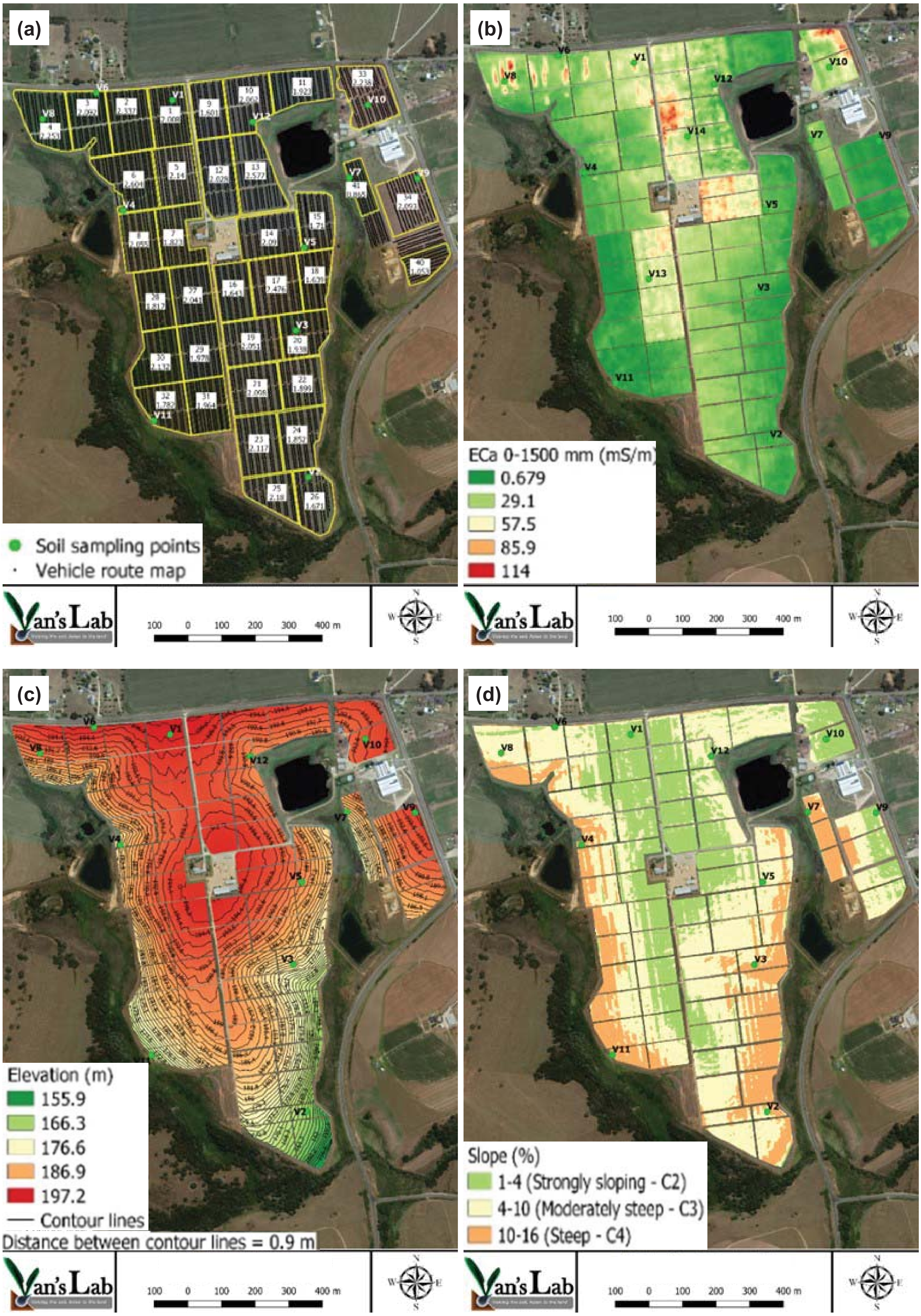

Figure 4.24 Maps of (a) EMI-survey ground route, (b) EC_a spatial variation, (c) surface drainage, and (d) slope (%) over the 69.8 ha blueberry orchards.

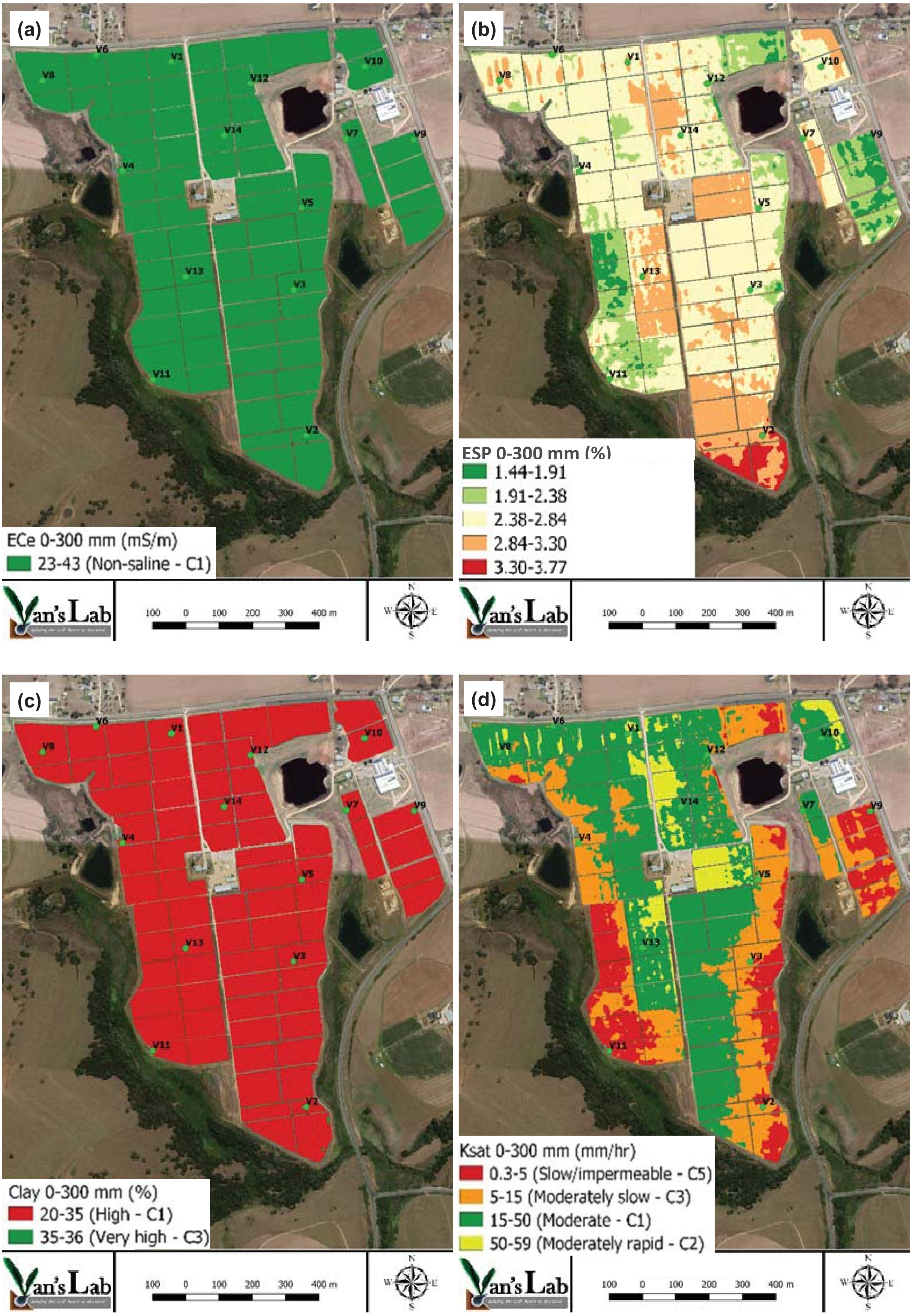

Figure 4.25 EC_a-inferred soil property maps for the 0 to 300 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) clay (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

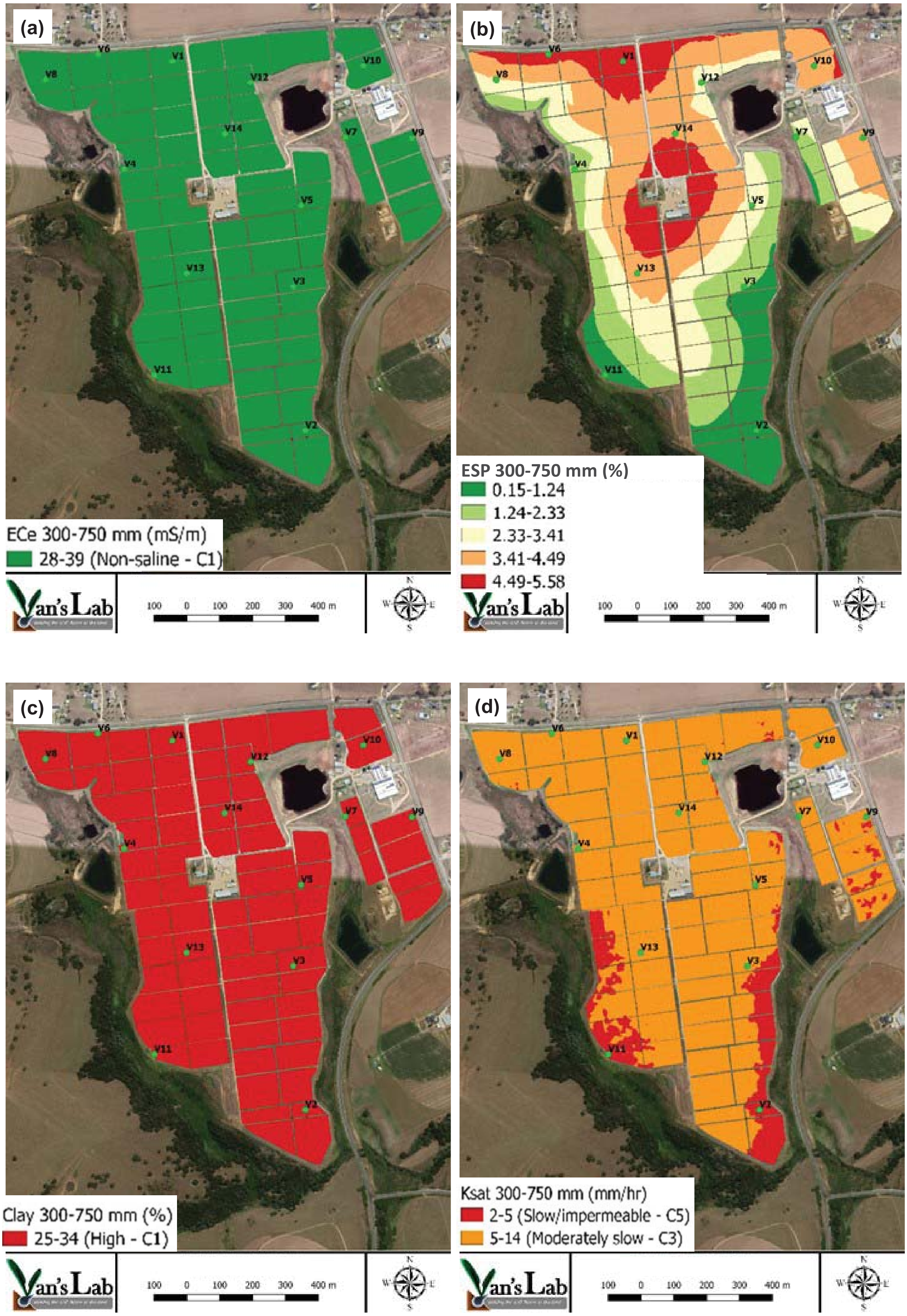

Figure 4.26 EC_a-inferred soil property maps for the 300 to 750 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%) (c) Clay (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

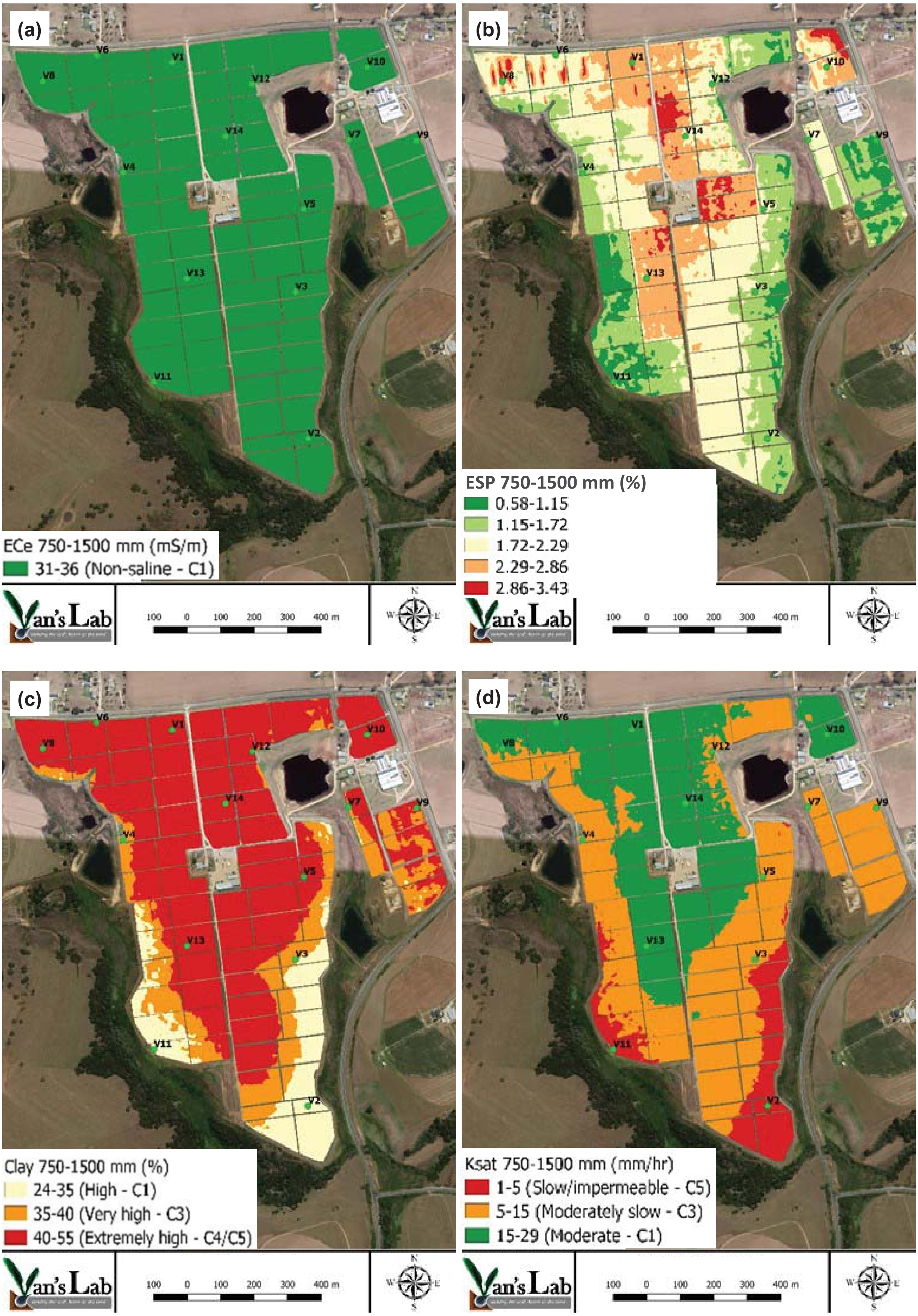

Figure 4.27 EC_a-inferred soil property maps for the 750 to 1500 mm soil layer: (a) EC_e (mS m^{-1}), (b) ESP (%), (c) clay (%) and (d) saturated hydraulic conductivity (K_{sat}, mm h^{-1}).

4.8.3 *Main findings, recommendations and actions*

i. Topography and soils: The site is situated on undulating terrain with a relatively gentle slope at the crest (1 to 4%) and steep slopes at both the eastern and western hillslopes (4 to 16%). The high rainfall (700 mm) and gradient of the slope encourages movement of water, silt, clay and salts vertically in the profile and also laterally. Evidence for this can be found in the average clay content of 16% in the topsoil, 32% in the subsoil and 44% in the deep subsoil. Soils with E-horizons (Kroonstad, Fernwood, Longland and Wasbank) stimulate interflow and pose challenges with respect to water and nutrient management. Plinthic and cutanic soils are a real threat to water management and normally need intervention under irrigation to improve drainage.

ii. Runoff control: Topographical results suggest that the field requires a proper assessment to control surface runoff. Visual inspection showed areas of waterlogging, confirming the need for runoff control measures.

iii. Infiltration: The infiltration, as expressed by K_{sat} of the topsoil, is sufficient on and near the crest area, but moderately slow (5 to 15 mm h^{-1}) and slow (< 5 mm h^{-1}) in the lower part of both the eastern and western hillslopes.

iv. Internal drainage: The K_{sat} map of the 300 to 750 mm soil layer indicates that the internal drainage is restricted in the brown and red zones (K_{sat} below 15 mm h^{-1}). The SAR map suggests that there is a build-up of sodium salts in the areas with poor infiltration. However, SAR levels are not so high as to induce dispersion of clay particles.

v. External drainage: External drainage of the crest seems to be sufficient, but the micromorphology of the soils indicated that soils are subjected to a fluctuating water table. The gradient probably helps with lateral drainage. Drainage of the lower lying areas is poor due to accumulation of clay. ESP is fortunately below 5, this will help to maintain the soil structure.

vi. Salinity: As mentioned earlier, blueberries are very sensitive to salinity and fortunately all EC_e values were below the upper threshold of 40 to 100 mS m^{-1}.

vii. Sodicity: SAR was generally below 4 in the top- and deep subsoil. It was only at the crest area where SAR varied between 5 and 6.

viii. Actions: During a feedback meeting with the owner and his advisors, the EMI technology, soil property measurements and results were explained. Each of the main findings were thoroughly discussed and specific recommendations were made: (i) surface runoff design: a recommendation was made that the data of topographical survey be utilised by an agricultural engineer to assess where improvements can be made in the surface-runoff design; (ii) infiltration: the application of organic matter at a rate of 10 t ha^{-1} per year for 5 years was suggested for the area where infiltration was below 15 mm h^{-1}; (iii) removal of sodium from soil: The application of gypsum was recommended to remove excess sodium from affected areas. Rates were determined for specific areas and they were encouraged to follow the soil reclamation procedure summarised in Section 5.3.2.1 in the level one report of Van Rensburg et al. (2020). The owner asked for the soil property data to be used to write a variable-applicator programme for gypsum and for fertility rectifications (not reported here). (iv) External drainage: In order to manage lateral flow, cut-off drains were recommended between irrigation blocks. It was also recommended that waterlogged areas be reclaimed through the installation of subsurface artificial drains.

4.8.4 *Conclusion*

From the discussion with the owner and his advisors, it was clear that they appreciated the EMI-investigation and the owner requested a survey of the entire blueberry farm. The investigation clearly showed the importance of topography-soil interaction on runoff, infiltration, internal drainage and external drainage. Literature pointed out how sensitive blueberries are towards salinity and sodicity. Fortunately, salinity levels were lower than upper thresholds for the crop, but sodium still needs to be removed through the application of gypsum and leaching. The advisors used EMI soil property data to write a variable-rate applicator programme for gypsum. Specific recommendations were made to overcome topographical and soil restrictions, i.e. cut-off drains between blocks and subsurface drains for waterlogged areas.

CHAPTER 5. CONCLUSIONS, RECOMMENDATIONS AND CONTEXT

5.1 Conclusions

A total of eight case studies were conducted at farmers' fields in order to gain experience with EMI application in real situations regarding water and salt management in irrigated crop fields. In some of the case studies, farmers made use of soil water sensors installed in the top 0.6 to 0.8 m of the soil to manage water. One of the farmers measured EC of the irrigation water to check the fertigation programmes, but no one considered the spatial management of soil salts in the root zone. This was not surprising since most of service providers focus on input requirements of crops, such as fertilisers, seedlings, pesticides and herbicides. On the positive side, there are a few companies that have recently emerged in South Africa specialising in the application of electromagnetic induction (EMI) technology in crop fields.

From literature it can be concluded that EMI technology is globally renowned as a sound method to characterise salinity and sodicity in crop fields. Results from various sources showed that the technology is also useful in assessing other soil properties, such as clay content, sand content, water content, bulk density and cation exchange capacity. The combination of EMI sensors, GPS instruments and computer software have opened opportunities to assess soil salts spatially in crop fields. Protocols for the in situ calibration of instruments have been developed, as well as procedures to identify soil sampling points in the field. Unfortunately, only a few South African researchers have experience in the application of EMI technology in crop fields and they are specialising in different fields of soil science and agronomy.

The first objective for this level two decision support was to illustrate the application of a logic framework, using EMI-derived soil properties, for supporting scientifically sound decisions regarding site-specific assessment of soil salts in the root zone. Specific objectives with the logic framework were: (a) to show salt distribution in the crop field, (b) how it impacts the hydro-physical properties, and (c) to couple site-specific procedures to rectify problematic areas. A case study on a vineyard was used to establish the concept.

To conclude on some of the practical aspects in EMI application the following steps are suggested as a guide for future users of the technology: **Firstly**, the application of EMI technology in practice, means that a crop field should be surveyed with EMI instruments, such as the Geonics EM38-MK2 soil sensor coupled to a GPS, to collect georeferenced apparent electrical conductivity (EC_a) measurement points. The density of EC_a measurement points depends mainly on transect width, which is determined by row width of the crop and affordability of the service. Case studies conducted in this project were surveyed at transect widths that varied between 5 and 20 m, resulting in EC_a measurement density of 1 point per 10 to 40 m^{-2}. The **second step** is to determine the positions of soil sampling points with the ESAP software. In the current project the number of soil sampling points per survey area varied between 12 and 20. The **third step** comprises of: (i) identification of the sampling points in the crop field, (ii) composite sampling of disturbed samples in topsoil (0 to 300 mm), subsoil (300 to 750 mm) and deep subsoil (750 to 1500 mm) for laboratory determination of particle size distribution, electrical conductivity and cations in the saturated paste, (iii) excavating profile pits at the sampling points for soil classification, and (iv) sampling of undisturbed core samples to measure bulk density, saturation point, drained upper limit and saturated hydraulic conductivity. The **fourth step** in the process involves correlation and regression procedures in order to identify the best model to predict a soil property from measured EC_a

data. The **fifth step** entails attribute mapping, i.e. cleaning of data and mapping it into a continuous surface to permit analysis, which is done through geo-statistics. The **sixth step** involves a quality check of data, presentation and interpretation of results, summarising main findings and recommendations. The **last step** in the process is the most important part, and that is to discuss the hydro-physical report with behaviour change officers and the farmer, finding collectively sustainable solutions for soil salt related problems.

As a guideline for the last two steps of the EMI technology application, a framework in the form of a matrix (Table 3.10) was developed and applied using a vineyard as case study. This assessment concentrates on seven soil properties that are often neglected. The properties are listed in the first column of the framework and comprise of soil types, drainage, compaction, salinity, sodicity, profile available water capacity and aeration. Column two gives the methods used to obtain results, while column three directs the user to the three soil layers in the profile, i.e. surface or topsoil (0 to 300 mm), subsoil (300 to 750 mm) and deep subsoil (750 to 1500 mm). The fourth column indicates the severity of a particular soil property. Norms from literature are used to group results into three classes: a red cross indicates severe problems with a particular soil property, a brown tick expresses moderate problems, while a green tick signifies that there is no-problem. Column 5 directs the user to where the results of the soil property can be found in order to confirm the magnitude of the area affected. The last column links site-specific procedures to rectify problematic areas, if possible.

The main challenge, however, is the escalation of EMI technology. It was argued that perennial crops will be the best platform to launch such an initiative as these farmers are in the best financial position to afford such surveys. Hence, the second objective of the project was to target leading farmers in the industry and convince them to apply EMI technology on their farms. Consequently, a further seven case studies on site-specific assessment of water and salts in perennial crops were conducted and presented in Chapter 4. It can be concluded that the logic framework helped in establishing examples for lucerne, sugarcane, olives, pecans, walnuts, macadamias and blueberries. This broadens the base and provides support for scaling up the use of EMI technology to crop-specific associations in the near future. Without exception, the case studies were successful in (a) showing where the salts are in the crop field, (b) showing how this impacts on the hydro-physical soil properties, such as bulk density and water storage in the profile, and (c) coupling site-specific procedures to rectify problematic areas.

Lastly, it can be concluded from our experience that the framework serves as a template for guiding the hydro-physical report, saving time and resulting in a more efficient service. The framework also contributes towards guiding discussions on salt and water management, saving precious time during consultations with farmers.

5.2 Recommendations

Before the onset of this project, EMI technology was largely limited to the research domain and little was done to apply this technology at farm-level to assist in water and salt management. This is at least partly due to the lack of experience in working with EMI technology in South Africa, where only a few individuals had conducted sporadic surveys with EMI in crop fields. EMI-technology has developed significantly over the past decade, with advances in GPS technology, software for identifying sampling points, as well as advances in mapping of soil attributes. Protocols for conducting EMI surveys are also available. All these features have set the table for practical application of EMI technology on farm level.

EMI surveys and the assessment of water and salts in crop fields are expensive. The development of a logic framework for guiding scientists will improve the efficiency of the process. Currently, a full hydro-physical and fertility survey costs between R550 and R1200 per ha, depending on the location, the size of the area to be surveyed and the number of soil samples (Smit, personal communication[1]). This is in line with cost of a detail soil survey and can be recommended to farmers cultivating high-income crops.

According to Thayalakumaran et al. (2007), salt equilibrium in the root zone in response to land-use change takes about 10 to 15 years. This implies that a water and salt survey should be conducted within that time frame. The past decade has witnessed land-use changes from field crops to perennial crops like never before. Farmers are realising that field crops as a sole enterprise, will not be a sustainable solution for the next 50 years. In order to protect crops and soils, as well as to improve land productivity, it is recommended that EMI surveys be conducted once in five years.

The opportunity exists to develop policies that will guide land owners or users of irrigation land towards a higher level of responsibility and accountability in protecting natural resources against water and salt accumulation. EMI technology provides the means to monitor such impacts as demonstrated in the eight case studies presented in this report.

It is important for national food security that arable land subjected to waterlogging and salinity be addressed. Conservatively estimated, about 90 000 ha of South Africa's irrigation soil is salt affected, and this impacts negatively on the livelihoods of farmers across all scales. EMI technology provides a tool that can assist in reducing these affected areas. Use of this technology reflects favourably in light of the World Bank's vision and protocol to prioritise funding for projects that aim to secure and protect irrigated land with the objective of increasing land productivity and livelihoods (Kijne, 2011).

In cases where farmers cannot afford EMI-type services, it is recommended that government provide support to encourage them to conduct such services. A good example is the case study on pecans (Section 4.2.4), where irrigation land was allocated to a farmer as part of a land reform project. After listening to a presentation on EMI application, the farmer requested that an EMI survey be conducted on her farm. The survey showed clearly that the land reform initiative poses challenges regarding the sustainability of the irrigation project. Amongst others, recommendations were made to install surface- and subsurface drains, which the farmer cannot afford currently. The case study was submitted to the provincial government for further funding, since the project is destined to fail without implementation of the recommended improvements.

In terms of scaling up the application of EMI technology on farm level, it is recommended that training be provided to BCOs, since they play a decisive role in dissemination of information to farmers. The relationship between scientists on the one side (scientist), farmers on the other side (applicator) and behavior change officers (BCO) on the base line, forming an equilateral triangle, is imperative to accelerate this initiative. It is important that the partnership in this relationship is equal and not be skewed towards isosceles or scalene triangle shapes where one side or partner dominates the other. This partnership advocates for a more sustainable irrigation sector attempting to empower farmers and encourage them to continually evaluate and improve on-farm water and salt management through learning, testing and adapting (Kijne, 2011).

[1] Mr R Smit. Marketer, Van's Lab, Bloemfontein, Free State.

The socio-economic survey conducted amongst irrigation farmers in South Africa (Van Rensburg et al., 2020; Barnard et al., 2020), revealed that farmers perceive the benefits of salinity management to outweigh the costs. However, they were also of opinion that the effort to implement salt management interventions is not necessarily worth the benefit gained. So, hard and clever work is required to bridge the mindset of applicators and to package EMI-information. It is recommended that demonstration trails on land reclamation be conducted at leading farmers' fields. A good example is the macadamia case study where the farmer insisted that demonstration trails be conducted in some of the affected areas to show the efficiency of the latest subsurface drain technology.

Lastly, case studies on reclamation of sodic soils in South Africa are scarce and such proof is needed to convince farmers to apply recommended procedures. So we need to test our recommendations in a practical way.

5.3 Context

In the overarching project, three WRC reports, Volumes 1 to 3, were delivered with the theme "On-farm water and salt management guidelines for irrigated crops". The goal was to cater for farmers on all scales of operation, whether they are producing food for their families, for the country or for international communities. Volume 1 reports on the basic methods and procedures for monitoring of root zone salinity. It is written as a level one decision support guideline (Van Rensburg et al., 2020). This information is in the domain of the public and any farmer, manager, advisor or behaviour change officer (extensionist) has access to the information.

Volume 2 was aimed towards the expansion of EMI technology application for site specific management of water and salts, i.e. precision agriculture. EMI surveys are expensive and it was argued that leading farmers in the perennial crop sector will be ideal for introducing EMI technology to co-farmers, once they have adopted the technology. Volume 2 discusses the application of EMI technology in eight case studies where a framework was developed as a guide or level two decision support on EMI technology exchange to farmers.

Volume 3 reflects on EMI research (upscaling) conducted on selected irrigation farms in the Northern Cape, Free State, Eastern Cape and KwaZulu-Natal. This is to achieve a deeper understanding of salt-related problems and their medium to long-term management. This type of DSS is on a research level and is aimed at serving the science community, although mega-farmers, cooperatives and companies may also benefit from it in the medium to long-term. In this case, salinity models like SWAMP are used to make medium to long-term estimations of salt effects on land productivity.

REFERENCES

ABRO, I.P., YADAV, J.S.P. and MASSOUD, F.I. (1988). Salt-affected soils and their management. FAO Soils Bulletin No. 39. FAO, Rome, Italy.

AGRICULTURAL STATISTICS SOUTH AFRICA (2018). Department of Rural Development and Land Reform South Africa. Available from http://www.ruraldevelopment.gov.za/

AKÇA, Y., ŞIMŞEK, H., ÜNLÜKARA, A., MURADOĞLU, F. and ÇEKIÇ, Ç. (2017). Effects of salt and water stress on walnut of the leaf nutrient accumulation. *J. Int. Sci. Publ.: Agric. Food* **5** 535-541.

ALAM, K.S., ISLAM, M.S., HOSSAIN, G.M.A. and ALAM, K.M. (2018). Screening salinity tolerant sugarcane varieties considering yield, quality and economic parameters in southern region of Bangladesh. *Eco-friendly Agril. J.* **11** (03) 38-42.

ALLEMAN, L. and YOUNG, B. (2006). Fruit and nut production in KwaZulu-Natal. KwaZulu-Natal Department of Agriculture and Environmental Affairs, KZN Agri-Report N/A/2006/24.

AMEZKETA, E. (2007). Soil salinity assessment using directed soil sampling from a geophysical survey with electromagnetic technology: a case study. *Span. J. Agric. Res.* **5** (1) 91-101.

ANONYMOUS (2017). Pecan growing information page. Australian Pecan Growers Association http://www.pecangrowers.org.au/pages/pecan_growing.html

ANONYMOUS (2018). The macadamia. https://themacadamia.co.za/2018/03/25/macadamias-2018-overview

ANONYMOUS (2020). Top tips to grow the best quality macadamia nuts. Retrieved on 24/02/2020 from https://www.agriorbit.com/top-tips-to-grow-the-best-quality-macadamia-nuts/

ARC-ITSC (2003). Cultivate subtropical crops. Agricultural Research Council, Institute of Tropical and Subtropical Crops, South Africa.

ARNFIELD, A.J. (2020). Köppen climate classification. Encyclopaedia Brittanica Inc. Retrieved from https://www.britannica.com/science/Koppen-climate-classification.

AYERS, R.S. and WESTCOT, D.W. (1985). Water quality for agriculture. FAO Irrigation and Drainage Paper No. 29. FAO, Rome, Italy.

BARNARD, J.H., VAN RENSBURG, L.D., BENNIE, A.T.P. and DU PREEZ, C.C. (2017). Water and salt balances of two shallow groundwater cropping systems using subjective and objective irrigation scheduling. *Water SA* **43** (2) 581-594.

BARNARD, J.H., VAN RENSBURG, L.D., VAN ANTWERPEN, R., VAN HEERDEN, P.S., JUMMAN, A., STEENEKAMP, D., GROVÉ, B., DU PREEZ, C.C. (2020) On-farm water and salt management guidelines for irrigated crops: Level three decision support. WRC Report No. TT 847/3/21. Water Research Commission, Pretoria, South Africa.

BEATER, B.E. (1970). Soil series of the Natal sugar belt. The South African Sugar Association, Durban.

BENNIE, A.T.P., COETZEE, M.J. and VAN ANTWERPEN, R. (1988). Water balance model for irrigation based on soil profile water supply rate and crop water requirements. WRC Report No. 144/1/88. Water Research Commission, Pretoria, South Africa.

BHATTACHARJEE, J.C. (1979). Land evaluation criteria for India. World Soil Resources Report No. 50. FAO, Rome, Italy.

BURT, R. (2014). Soil survey field and laboratory methods manual. Soil survey investigations. Report No. 51 version 2.0. Kellogg Soil Survey Laboratory, United States Department of Agriculture, Lincoln, Nebraska.

CALL, R.E., GIBSON, R. and KILBY, M.W. (2006). Pecan production guidelines for small orchards and home yards. Report AZ1400. University of Arizona Cooperative Extention, Tucson, USA.

CARR, M.K.V and KNOX, J.W. (2011). The water relations and irrigation requirements of sugarcane (*Saccharum officinarum*): A review. *Exp. Agric.* **47** (1) 1-25.

CARROLL, B. (2016). Starting pecan trees. Oklahoma Cooperative Extension, Fact Sheet HLA-6207. Oklahoma State University, Stilwater, USA.

CASTROLUNA, A., RUIZ, O.M., QUIROGA, A.M. and PEDRANZANI, H.E. (2014). Effects of salinity and drought stress on germination, biomass and growth in three varieties of *Medicago sativa* L. *Avances en Investigación Agropecuaria* **18** 39-50.

CHARTZOULAKIS, K.S. (2005). Salinity and olive: Growth, salt tolerance, photosynthesis and yield. *Agric. Water Manage*. **78** 108-121.

CORWIN, D.L. and LESCH, S.M. (2003). Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agron. J.* **95** 455-471.

CORWIN, D.L. and LESCH, S.M. (2005a). Apparent soil electrical conductivity measurements in agriculture. *Comput. Electron. Agric.* **46** 11-43.

CORWIN, D.L. and LESCH, S.M. (2005b). Characterizing soil spatial variability with apparent soil electrical conductivity. I Survey protocols. *Comput. Electron. Agric.* **46** 103-133.

CORWIN, D.L. and SCUDIERO, E. (2016). Field-scale apparent soil electrical conductivity. In: S Logsdon (ed.), Methods of Soil Analysis: Volume 1. Soil Science Society of America, Madison, USA.

CORWIN, D.L., LESCH, S.M., OSTER, J.D. and KAFFKA, S. (2006). Monitoring management-induced spatio-temporal changes in soil quality through soil sampling directed by apparent electrical conductivity. *Geoderma* **131** 369-387.

DAFF (2010). Olive production guideline. Department of Agriculture, Forestry and Fisheries. South Africa.

DAFF (2012). A profile of the South African macadamia nuts market value chain. Department of Agriculture, Forestry and Fisheries. South Africa.

DAMI, I., BORDELON, B., FERREE, D.C., BROWN, M., ELLIS, M.A., WILLIAM, R.N.D. and OOHAN, D. (2005). Midwest grape production guide. Bulletin 919. Ohio State University Extension, USA.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (1996). South African Water Quality Guidelines (2nd edn). Volume 4: Agricultural Use: Irrigation. Pretoria, South Africa.

DOHSE, T., SCHOEMAN, J.L. and TURNER, D.P. (1991). Changing aspects to the assessment of land suitability for irrigation planning. Proceedings Southern African Irrigation Symposium, Durban, June 1991. SABI, Pretoria.

DOOLITTLE, J.A. and BREVIK, E.C. (2014). The use of electromagnetic induction techniques in soils studies. *Geoderma* **223-225** 33-45.

DU PREEZ, C.C., STRYDOM, M.G., LE ROUX, P.A.L., PRETORIUS, J.P., VAN RENSBURG, L.D. and BENNIE, A.T.P. (2000). Effect of water quality on irrigation farming along the lower Vaal River: The influences on soils and crops. WRC Report No. 740/1/100. Water Research Commission, Pretoria, South Africa.

EHLERS, L., BARNARD, J.H., DIKGWATLHE, S.B., VAN RENSBURG, L.D., CERONIO, G.M., DU PREEZ, C.C. and BENNIE, A.T.P. (2007). Effect of irrigation and water table salinity on the growth and water use of selected crops. WRC Report No. 1359/1/07. Water Research Commission, Pretoria, South Africa.

FOURIE, K.L. (2017). Evaluation of salinity and irrigation guidelines for lucerne. MSc Agric thesis, University of the Free State, Bloemfontein, South Africa.

GARCIA, M. and MEDINA, E. (2013). Effects of salt stress on salt accumulation in roots and leaves of two sugarcane genotypes differing in salinity tolerance. *Trop. Agric.* **51** 15-22.

GRISSO, R.B., ALLEY, M., McCLELLAN, P., BRANN, D. and DONOHUE, S. (2009). Precision farming: A comprehensive approach. Virginia Cooperative Extention, Publication 442-500. Virginia State University, USA.

GUO, P., HONGXU, W., WANJUN, Z. and BAO, Y. (2016). Physiological responses of alfalfa to high level salt stress: Root ion flux and stomatal characteristics. *Int. J. Agric. Biol.* **18** 125-133.

HANSON, B., GRATTAN, S. and FULTON, A. (2006). Agricultural salinity and drainage. Water Management Series, Publication 3375. University of California, Davis, USA.

HANQUET, B., FRANKINET, M., PAREZ, V. and DESTAIN, M.F. (2002). Mapping within-field soil variability for precision agriculture using electromagnetic induction. Paper number 02-PA-004, Proceedings of AgEng, Budapest 2002. Scientific Society of Mechanical Engineering.

HASSANEN, S.A. and GABR, M.F. (2013). In vitro rooting of pecan (*Carya illinoensis*). *World Appl. Sci J.* **21** (3) 315-319.

HEIL, K. and SCHMIDHALTER, U. (2017). The application of EM38: Determination of soil parameters, selection of soil sampling points and use in agriculture and archaeology. *Sensors* **17** (11) 1-44.

HENSLEY, M. and LAKER, M.C. (1980). A proposed integrated procedure for the identification, delineation, evaluation and planning of irrigable land. Proceedings of the 9th National Congress, Soil Science Society of South Africa, Durban. Technical Communication No. 174.

HENSLEY, M., BENNIE, A.T.P., VAN RENSBURG, L.D. and BOTHA, J.J. (2011). Review of 'plant available water' aspects of water use efficiency under irrigated and dryland conditions. *Water SA* **37** (5) 771-779.

HEROLD, C.E. and BAILEY, A.K. (1996). Long term salt balance of the Vaalharts Irrigation Scheme. WRC Report 420/1/96. Water Research Commission, Pretoria, South Africa.

HILLEL, D. (2004). Introduction to environmental soil physics. Elsevier Academic Press, Amsterdam, Netherlands.

HIMELRICK, D. and CURTIS, L.M. (1999). Commercial blueberries. Alabama Cooperative Extension Service Publication No. ARN-663. Alabama State University, USA.

HUE, N.V. and McCALL, W.W. (1989). Soil salinity and the growth of macadamia seedlings. *J. Plant Nutr.* **12** (4) 449-464.

HUTH, N. and POULTON, P. (2002). An electromagnetic induction method for monitoring variation in soil moisture in agroforestry systems. *Austr. J. Soil Res.* **45** 63-72.

INC (2019). 2019/2020 dried fruit production estimated. International Nut and Dried Fruit Council. Fruit Growers News, 15 Nov 2019. Retrieved from https://fruitgrowersnews.com/news/2019-2020-dried-fruit-production-estimated/

IRELAND, G. and WILK, P. (2006). Blueberry production in northern NSW. Primefact 195. NSW Department of Primary Industries, Australia.

IRRIGATION PLANNING STAFF (1980). A method of evaluating land for irrigation development. Proceedings of the 9th National Congress, Soil Science Society of South Africa, Durban. Technical Communication No. 174.

ISLA, R., ARAGUES, R. and ROY, A. (2003). Spatial variability of salt affected soils in the middle Ebro valley(Spain) and implications in plant breeding for increase of plant productivity. *Euphytica* **134** 325-334.

JUMMAN, A. (2016). Using system dynamics to explore the poor uptake of irrigation scheduling technologies in a commercial sugarcane community in South Africa. Unpublished PhD thesis, University of KwaZulu-Natal, South Africa.

JURY, W.A., GARDNER, W.R. and GARDNER, W.H. (1991). Soil Physics, 5th edn. John Wiley and Sons, New York, USA.

KARGAS, G., CHATZIGIAKOUMIS, I., KOLLIAS, A., SPILIOTIS, D. and KERKIDES, P. (2018). An investigation of the relationship between the electrical conductivity of the soil saturated paste extract EC_e with the respective values of the mass soil/water ratios 1:1 and 1:5 ($EC_{1:1}$ and $EC_{1:5}$). The 3rd international conference on "Insights on the Water-Energy-Food nexus", Greece, 27-30 June 2018. Proceedings **2** 661.

KIJNE, J.W. (2011). Teaching irrigation science and water management: accepting professional diversity. *Irrig. Sci.* **29** 1-10.

KLUTE, A. and DIRKSEN, C. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. In: A Klute (ed.), Methods of soil analysis, 2nd edn. Part 1: Physical and mineralogical methods. Soil Science Society of America Book Series: 5. pp 687-734.

KRIEL, G. (2020). South African Nuts: Walnuts. Retrieved from http://southafrica.co.za/walnuts.html.

KUNDHANDLE, G., GROENEWALD, D.C., BAIPHETHI, M.N., VILJOEN, M.F., BOTHA, J.J., VAN RENSBURG, L.D. and ANDERSON, J.J. (2004). Socio-economic study on water conservation techniques in semi-arid areas. WRC report no. 1267/1/04. Water Research Commission, Pretoria, South Africa.

KUTÍLEK, M. and JENDELE, L. (2008). The structural porosity in soil hydraulic functions – a review. *Soil Water Res.* **3** (Special Issue 1) S7-S20.

LAL, R. and SHUKLA, M.K. (2004). Principles of soil physics. CRC Press, Boca Raton, USA.

LANYON, D. (2011). Salinity management interpretation guide. Arris Pty Ltd./Grape and Wine Research and Development Corporation, Adelaide, Australia.

LE ROUX, P.A.L., DU PLESISS, M.J., TURNER, D.P., VAN DER WAALS, J. and BOOYSEN, H.B. (2013). Field book for the classification of South African soils. South African Soil Surveyors Organisation.

LE ROUX, P.A.L., DU PREEZ, C.C., STRYDOM, M.G., VAN RENSBURG, L.D. and BENNIE, A.T.P. (2007). Effect of irrigation on soil salinity profiles along the Lower Vaal River, South Africa. *Water SA* **33** 473-477.

LESCH, S.M., CORWIN, D.L. and ROBINSON, D.A. (2005). Apparent soil electrical conductivity mapping as an agricultural management tool in arid zone soils. *Comput. Electron. Agric.* **46** 351-378.

LESCH, S.M., RHOADES, J.D. and CORWIN, D.L. (2000). ESAP-95 version 2.01R – User manual and tutorial guide. USDA Research Report No. 146. United States Department of Agriculture, George E. Brown Jr. Salinity Laboratory, Riverside, California, USA.

LEWITT, J. (1980). Responses of plants to environmental stress. Academic Press, New York, USA.

MAAS, E.V. (1986). Salt tolerance of plants. *Appl. Agric. Res.* **1** 12-26.

MAAS, E.V. and HOFFMAN, G. (1977). Crop salt tolerance – current assessment. *J. Irrig. Drain. Div. Am. Soc. Civ. Eng.* **103** 115-134.

MACVICAR, C.N. and PERFECT, G.A. (1971). The soils of the Eastern Transvaal sugar industry. *Proc. S. Afr. Sug. Technol. Ass.* **45** 189-195.

MAUD, R.R. (1959). The occurrence of two alkali soils in Zululand. *Proc. Annual Cong. S. Afr. Sugar Tech. Ass.* **33** 138-144.

MENGISTU, A.G., VAN RENSBURG, L.D. and MAVIMBELA, S. (2018). Characterisation of the soil pore system in relation to its hydraulic functions in two South African aeolian soil groups. *S. Afr. J. Plant Soil.* **36** 107-116.

MENGISTU, A.G., VAN RENSBURG, L.D. and MAVIMBELA, S.W. (2017). The effect of soil water and temperature on thermal properties of two soils developed from aeolian sands in South Africa. *Catena* **158** 184-193.

MOHLOTSANE, P.M., OWUSU-SEKYERE, E., JORDAAN, H., BARNARD, J.H. and VAN RENSBURG, L.D. (2018). Water footprint accounting along the wheat-bread value chain: Implications for sustainable and productive water use benchmarks. *Water* **10** 1167. (16 pp).

MOLDEN, D., OWEIS, T., STEDUTO, P., BINDRABAN, P., HANJRA, M.S. and KIJNE, J.W. (2009). Improving agricultural water productivity: between optimism and pessimism. *Agric. Water Manage.* **97** 528-535

MOOT, D., TEIXEIRA, E. and BROWN, H. (2012). Alfalfa. In: P Steduto, TC Hsiao, E Fereres, and D Raes (eds). Crop yield response to water. FAO Irrigating and Drainage Paper No. 66

NAGAO, M.A. and HIRAE, H.H. (1992). Macadamia: Cultivation and physiology. *Crit. Rev. Plant Sci.* **10** (5) 441-470

NAIDOO, S., VAN ANTWERPEN, R. and PAMMENTER, N. (2004). Quantifying the effects of soil salinity on the physiology of three South African sugarcane varieties. *Proc. S. Afr. Sug. Technol. Ass.* **78** 313-330.

NELL, J.P. (1991). Besproeibaarheid van gestruktuurde gronde. MSc Agric verhandeling. Universiteit van die Oranje Vrystaat, Bloemfontein, Suid-Afrika.

NELSON, P. and HAM, G. (2000). Exploring the response of sugarcane to sodic and saline conditions through natural variation in the field. *Field Crops Res.* **66** 245-255.

NIMMO, J. (2004). Porosity and pore size distribution. In: D Hillel (ed.), Encyclopaedia of soils in the environment. Academic Press, New York, USA. pp 295-303.

NON-AFFILIATED SOIL ANALYSIS WORK COMMITTEE (1990). Handbook of standard soil testing methods for advisory purposes. Soil Science Society of South Africa, Pretoria, South Africa.

PAGLIAI, M. and VIGNOZZI, N. (2002). The soil pore system as an indicator of soil quality. *Adv. GeoEcol.* **35** 69-80.

PATTEN, K.I., NEUENDORFF, E., NIMR, G., HABY, V. and WRIGHT, G. (1989). Cultural practices to reduce salinity/sodium damage of rabbiteye blueberry plants (*Vaccinium ashei* Reade). *Acta Hortic.* **241** 207-212.

POGNANT, D., CANONE, D., PREVIATI, M. and FERRARIS, S. (2013). Using EM equipment to verify the presence of seepage losses in irrigation canals. *Procedia Environ. Sci.* **19** 836-845.

REINDERS, F., OOSTHUIZEN, H., SENZANJE, A., SMITHERS, J., VAN DER MERWE, R., VAN DER STOEP, I. and VAN RENSBURG, L.D. (2016). Development of technical and financial norms and standards for drainage of irrigated lands. WRC Report No. 2026/2/15, Volume 2. Water Research Commission, Pretoria, South Africa.

RETAMALES, J.B. and HANCOCK, J.F. (2012). Blueberries. CABI, USA.

RICHARDS, L.A. (1954). Saline and alkali soils: Diagnosis and Improvement. USDA Agriculture Research Service Handbook 60.

SABPA (2019). Berries ZA: Reports and Statistics. South African Berry Producers Association. https://www.berriesza.co.za/reports-statistics/

SA OLIVE (2020). Olive growing. South African Olive Industry Association. https://www.saolive.co.za/olive-growing/.

SAMAC (2020). An overview of the South African macadamia industry. Macadamias South Africa NPC. https://www.samac.org.za/industry-overview/

SASA (2019). South African sugar industry directory 2019/2020. https://www.sasugarindustrydirectory.co.za/static/SASA%20ID%202019-20%20web-57bf7440b199cbfeece5defc209c77ca.pdf

SCHOENHOLTZ, S.H., VAN MIEGROET, H. and BURGER, J.A. (2000). A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *For. Ecol. Manage.* **138** 335-356.

SHONGWE, N. and WAHOME, P. (2014). Effects of salinity stress on vegetative growth of chrysanthemum (*Dendranthema glandiflora* Kitam). *UNISWA Res. J. Agric.* **15** 19-27.

SIBSON, R. (1981). A brief description of natural neighbor interpolation. In: V Barnett (ed.), Interpolating multivariate data. John Wiley and Sons, New York, USA. pp 21-36.

SMETTEM, K. and SMITH, R.E. (2002). Field measurements of infiltration parameter. In: E Smith (ed.), Infiltration theory for hydrological applications. Water Resource Monograph 15. American Geophysical Union, Washington, USA. pp 135-157

SOIL CLASSIFICATION WORKING GROUP (1991). Soil classification: A taxonomic system for South Africa. Department of Agricultural Development, South Africa.

SOIL SCIENCE DIVISION STAFF (2017). Soil survey manual. USDA Handbook No. 18.

STEENEKAMP, D. (2019). Sampling and extraction methods for soil inorganic nitrogen determination to calibrate the EM38 in irrigated fields. MSc Agric thesis. University of the Free State, Bloemfontein, South Africa.

STREUTKER, A. (1977), The dependence of permanent crop production on efficient irrigation and drainage at the Vaalharts Government Water Scheme. *Water SA* **3** 90-103.

SUDDUTH, K.A., KITCHEN, N.R., WIEBOLD, W.J., BATCHELOR, W.D., BOLLERO, G.A., BULLOCK, D.G., CLAY, D.E., PALM, H.L. PIERCE, F.J. SCHULER, R.T. and THELEN, K.D. (2005). Relating apparent electrical conductivity to soil properties across the north-central USA. *Comput. Electron. Agric.* **46** 263-283.

TANJI, K.K. and KIELEN, N.C. (2003). Agricultural drainage water management in arid and semi-arid areas. FAO Irrigation and Drainage Paper No. 61. FAO, Rome, Italy.

TAYLOR, N. and GUSH, M. (2007). The water use of fruit trees and orchard crops in South Africa – a knowledge review. WRC Project K5/1770. Water Research Commission, Pretoria, South Africa.

THAYALAKUMARAN, T., BETHUNE, M.G. and MCMAHON, T.A. (2007). Achieving a salt balance – Should it be a management objective? *Agric. Water Manage.* **92** 1-12.

UNITED STATES SALINITY LABORATORY STAFF (1954). Diagnosis and improvement of saline and alkali soils. LA Richards (ed.), USDA Handbook No. 60.

UPSON, S., ROHLA, C., LOCKE, J. and SPRINGER, J. (2011). Pecan production: Establishing and managing an improved variety pecan enterprise in the southern Great Plains. The Samuel Roberts Noble foundation agricultural division. NF-HO-12-01.

URDANOZ, V., AMEZKETA, E., CLAVERIA, I., OCHOA, V. and ARAGUES, R. (2008). Mobile and geo-referenced electromagnetic sensors and applications for salinity assessment. *Span. J. Agric. Res.* **6** (3) 469-478.

USDA-NRCS (2019). Saturated hydraulic conductivity in relation to soil texture. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr10/tr/?cid=nrcs144p2_074846.

VAN DER WATT, H.V.H. and VAN ROOYEN, T.H. (1990). A glossary of soil science. The Soil Science Society of South Africa, Pretoria, South Africa.

VAN HUYSSTEEN, C.W. (2008). A review of advances in hydropedology for application in South Africa. *S. Afr. J. Plant Soil* **25** (4) 245-254

VAN RENSBURG, L.D., BARNARD, J.H., BENNIE, A.T.P., SPARROW, J.B. and DU PREEZ, C.C. (2012). Managing salinity associated with irrigation at Orange-Riet and Vaalharts irrigation schemes. WRC Report No. 1647/1/12. Water Research Commission, Pretoria, South Africa.

VAN RENSBURG, L.D., VAN HEERDEN, P., VAN ANTWERPEN, R., JUMMAN, A., STEENEKAMP, D., NELL, P., DU PLESSIS, H.M. and BARNARD, J.H. (2020). On-farm water and salt management guidelines for irrigated crops: Level one decision support system. WRC Report No. TT 847/1/21. Water Research Commission, Pretoria, South Africa.

VERMEULEN, J. (2006). Pekanneute – suksesvolle alternatief op Vaalharts. Senwester, Desember 2006, 12-14.

WALKER, R. (2010). Managing salinity in the vineyard. Growing winegrapes 2010, Factsheet.

WALWORTH, J.L. (2011). Salinity management and soil amendments for southwestern pecan orchards. Arizona Cooperative Extention, Publication No. AZ1411-2011. University of Arizona, Tucson, USA.

WARRENCE, N.J., BRAUDER, J. and PEARSON, K. (2002). Basics of salinity and sodicity effects on soil physical properties. Department of Land Resources and Environmental Sciences, Montana State University, USA.

WELIGAMAGE, P., BARKER, R., HUSSAIN, I., AMARASINGHE, U. and SAMAD, M. (2002). World irrigation and water statistics 2002: with a guide to data sources. International Water Management Institute (IWMI), Colombo, Sri Lanka.

WIENHOLD, B.J. and DORAN, J.W. (2008). Apparent electrical conductivity for delineating spatial variability in soil properties. In: BJ Allred, JJ Daniels and MR Ehsani (eds), Handbook of agricultural geophysics. CRC Press (Taylor and Francis Group), Boca Raton, USA.

WILDING, L.P. and LIN, H. (2006). Advancing the frontiers of soil science towards a geoscience. *Geoderma* **131** 257-274.

WILK, P., CARRUTHERS, G., MANSFIELD, C. and HOOD, V. (2009). Irrigation and moisture monitoring in blueberries. Primefact 827. NSW Department of Primary Industries, Australia.

WOOD, W.W. (2008). Soil salinization is like cancer, a slow and certain white death. University of Michigan USA.

WORKMAN, M., SCOTT, P.M. and NIXON, D.J. (1986). A review of the management and amelioration of saline/sodic soils at Mhlume (Swaziland) Sugar Company. *Proc. S. Afr. Sug. Technol. Ass.* **60** 162-167.

APPENDIX A. SOIL DESCRIPTION OF 12 PROFILES (V1 TO V12)

Figure A1 Soil profile of reference point V1.

Table A1 Soil classification for profile V1

Soil form: Cartref				
Horizon		1	2	3
Abbreviation		Ap	B1	B2
Master horizons		Orthic A	E-horizon grey	Lithocutanic hard
Thickness (cm)		30	35	15
Colour (wet)		Brown grey	Light grey	Light grey
Transition of horizons		Diffuse (>100 mm)	Diffuse (>100 mm)	
Structure	Type	Apedal	Apedal	Subangular blocky
	Grade			Weak
	Size/Class			Fine (Block <10 mm)
Compaction		No	No	No
Sand fraction		Medium	Medium	Medium
Signs of wetness		Present	Present	Present
Cutans		Absent	Absent	Absent
Mottles		None	None	None
Concretions		None	None	None
Consistency		Loose	Loose	Loose
Free lime		None	Slightly	Slightly
Rock	Abundance	None	Few (<10%)	Abundant (>20%)
	Size		2-25 mm	2-25 mm
	Type		Other	Other
Root abundance		Moderate	Few	Few
Rooting depth (cm)				65
Depth to impermeable layer (cm)				80

Figure A2 Soil profile of reference point V2.

Table A2 Soil classification for profile V2

Soil form: Constantia				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	E-horizon grey	Yellow apedal B
Thickness (cm)		35	35	30
Colour (wet)		Brown grey	Light grey	Yellow
Transition of horizons		Diffuse (>100 mm)	Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Subangular blocky	Structureless (Single grained non-coherent)
	Grade	Weak	Weak	Structureless (Single grained)
	Size/Class	Fine (Block <10 mm)	Fine (Block <10 mm)	
Compaction		No	No	No
Sand fraction		Coarse	Medium	Medium
Signs of wetness		Present	Present	Present
Cutans		Absent	Absent	Absent
Mottles	Abundance	None	Few (<2%)	None
	Size		Fine (<5 mm)	
	Contrast		Faint	
	Colour		Black (organic matter)	
Concretions		None	None	None
Consistency		Loose	Loose	Loose
Free lime		Slightly	Slightly	None
Rock		None	None	None
Root abundance		Moderate	Moderate	Few
Rooting depth (cm)				125
Depth to impermeable layer (cm)				150

Figure A3 Soil profile of reference point V3.

Table A3 Soil classification for profile V3

Soil form: Fernwood			
Horizon		1	2
Abbreviation		A	B1
Master horizons		Orthic A	E-horizon grey
Thickness (cm)		35	85
Colour (wet)		Dark grey	Light grey
Transition of horizons		Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)
	Grade	Weak	Structureless (Single grained)
	Size/Class	Fine (Block <10 mm)	
Compaction		No	No
Sand fraction		Medium	Medium
Signs of wetness		Present	Present
Cutans		Absent	Absent
Mottles		None	None
Concretions		None	None
Consistency		Loose	Loose
Free lime		None	None
Rock		None	None
Root abundance		Abundant	Moderate
Rooting depth (cm)			135
Depth to impermeable layer (cm)			150

Figure A4 Soil profile of reference point V4.

Table A4 Soil classification for profile V4

Soil form: Tukulu				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	Neocutanic	Unspecified wet
Thickness (cm)		30	45	35
Colour (wet)		Light grey	Brown grey	Brown grey
Transition of horizons		Diffuse (>100 mm)		
Structure	Type	Subangular blocky	Subangular blocky	Subangular blocky
	Grade	Weak	Moderate	Strong
	Size/Class	Fine (Block <10 mm)	Medium (Block 10-25 mm)	Medium (Block 10-25 mm)
Compaction		No	No	No
Sand fraction		Medium	Fine	Fine
Signs of wetness		Present	Present	Present
Cutans		Absent	Present	Present
Mottles	Abundance		Few (<2%)	Common (2-20%)
	Size		Fine (<5 mm)	Fine (<5 mm)
	Contrast		Clear	Prominent
	Colour		Yellow	Yellow
Concretions		None	None	None
Consistency		Loose	Loose to slightly hard	Loose to slightly hard
Free lime		Slightly	None	None
Rock		None	None	None
Root abundance		Moderate	Few	Few
Rooting depth (cm)				110
Depth to impermeable layer (cm)				150

Figure A5 Soil profile of reference point V5.

Table A5 Soil classification for profile V5

Soil Form: Fernwood			
Horizon		1	2
Abbreviation		A	B1
Master horizons		Orthic A	E-horizon yellow
Thickness (cm)		20	70
Colour (wet)		Brown grey	Yellow
Transition of horizons		Diffuse (>100 mm)	
Structure	Type	Granular	Structureless (Single grained non-coherent)
	Grade	Weak	Structureless (Single grained)
	Size/Class	Very fine	Structureless (Single grained
Compaction		No	No
Sand fraction		Medium	Medium
Signs of wetness		Present	Present
Cutans		Absent	Absent
Mottles	Abundance	None	Few (<2%)
	Size		Fine (<5 mm)
	Contrast		Clear
	Colour		Black (organic matter)
Concretions		None	None
Consistency		Loose	Loose
Free lime		None	None
Rock		None	None
Root abundance		Abundant	Moderate
Rooting depth (cm)			125
Depth to impermeable layer (cm)			150

Figure A6 Soil profile of reference point V6.

Table A6 Soil classification for profile V6

Soil form: Garies				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	Red apedal B	Dorbank
Thickness (cm)		30	45	5
Colour (wet)		Red brown	Red	
Transition of horizons		Diffuse (>100 mm)		
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)	Structureless (Massive rock controlled)
	Grade	Weak	Structureless (Single grained)	Structureless (Massive)
	Size/Class	Fine (Block <10 mm)		
Compaction		No	No	No
Sand fraction		Medium	Medium	Medium
Signs of wetness		Present	Present	
Cutans		Absent	Absent	
Mottles		None	None	
Concretions		None	None	None
Consistency		Loose	Loose	Hard
Free lime		None	None	None
Rock	Abundance	None	Few (<10%)	Abundant (>20%)
	Size		2-25 mm	>100 mm
	Type		Other	Other
Root abundance		Abundant	Moderate	None
Rooting depth (cm)				82
Depth to impermeable layer (cm)				90

Figure A7 Soil profile of reference point V7.

Table A7 Soil classification for profile V7

Soil form: Clovelly				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	Yellow apedal B	Unspecified
Thickness (cm)		35	45	25
Colour (wet)		Yellow	Yellow	Yellow
Transition of horizons		Diffuse (>100 mm)	Diffuse (>100 mm)	
Structure	Type	Structureless (Single grained non-coherent)	Structureless (Single grained non-coherent)	Structureless (Single grained non-coherent)
	Grade	Structureless (Single grained)	Structureless (Single grained)	Structureless (Single grained)
	Size/Class	None	None	None
Compaction		No	No	No
Sand fraction		Medium	Medium	Medium
Signs of wetness		Present	Present	Present
Cutans		Absent	Absent	Absent
Mottles	Abundance	None	Few (<2%)	Few (<2%)
	Size		Fine (<5 mm)	Fine (<5 mm)
	Contrast		Faint	Faint
	Colour		Black (organic matter)	Black (organic matter)
Concretions		None	None	None
Consistency		Loose	Loose	Loose
Free lime		None	None	None
Rock		None	None	None
Root abundance		Moderate	Moderate	Few
Rooting depth (cm)				130
Depth to impermeable layer (cm)				150

Figure A8 Soil profile of reference point V8.

Table A8 Soil classification for profile V8

Soil form: Cartref				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	E-horizon grey	Lithocutanic hard
Thickness (cm)		35	40	20
Colour (wet)		Brown grey	Light grey	Light grey
Transition of horizons		Clear (25-100 mm)	Clear (25-100 mm)	
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)	Structureless (Massive rock controlled)
	Grade	Weak	Structureless (Single grained)	Structureless (Massive)
	Size/Class	Fine (Block <10 mm)		
Compaction		No	No	No
Sand fraction		Medium	Medium	Medium
Signs of wetness		Present	Present	Present
Cutans		Absent	Absent	Absent
Mottles	Abundance	None	Few (<2%)	None
	Size		Fine (<5 mm)	
	Contrast		Faint	
	Colour		Black (organic matter)	
Concretions		None	None	None
Consistency		Loose	Loose	Hard
Free lime		Slightly	Slightly	Slightly
Rock	Abundance	Few (<10%)	Few (<10%)	Common (2-20%)
	Size	2-25 mm	2-25 mm	25-100 mm
	Type	Other	Other	Other
Root abundance		Moderate	Few	None
Rooting depth (cm)				80
Depth to impermeable layer (cm)				85

Figure A9 Soil profile of reference point V9.

Table A9 Soil classification for profile V9

Soil form: Fernwood			
Horizon		1	2
Abbreviation		A	B1
Master horizons		Orthic A	E-horizon yellow
Thickness (cm)		35	95
Colour (wet)		Dark grey	Yellow
Transition of horizons		Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Structureless(Single grained non-coherent)
	Grade	Weak	Structureless (Single grained)
	Size/Class	Fine (Block <10 mm)	
Compaction		No	No
Sand fraction		Fine	Fine
Signs of wetness		Present	Present
Cutans		Absent	Absent
Mottles	Abundance	None	Common (2-20%)
	Size		Fine (<5 mm)
	Contrast		Prominent
	Colour		Grey
Concretions		None	None
Consistency		Loose	Loose
Free lime		None	None
Rock		None	None
Root abundance		Abundant	Moderate
Rooting depth (cm)			120
Depth to impermeable layer (cm)			150

Figure A10 Soil profile of reference point V10.

Table A10 Soil classification for profile V10

Soil form: Namib			
Horizon		1	2
Abbreviation		A	B1
Master horizons		Orthic A	Regic sand
Thickness (cm)		35	85
Colour (wet)		Dark brown	Light brown
Transition of horizons		Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)
	Grade	Weak	Structureless (Single grained)
	Size/Class	Fine (Block <10 mm)	
Compaction		No	No
Sand fraction		Fine	Fine
Signs of wetness		Absent	Present
Cutans		Absent	Absent
Mottles	Abundance	None	Few (<2%)
	Size		Fine (<5 mm)
	Contrast		Clear
	Colour		Grey
Concretions		None	None
Consistency		Loose	Loose
Free lime		None	None
Rock		None	None
Root abundance		Moderate	Few
Rooting depth (cm)			128
Depth to impermeable layer (cm)			150

Figure A11 Soil profile of reference point V11.

Table A11 Soil classification for profile V11

Soil form: Bloemdal				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	Red apedal B	Unspecified wet
Thickness (cm)		35	40	30
Colour (wet)		Red brown	Red brown	Red brown
Transition of horizons		Diffuse (>100 mm)	Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)	Structureless (Single grained non-coherent)
	Grade	Weak	Structureless (Single grained)	Structureless (Single grained)
	Size/Class	Fine (Block <10 mm)		
Compaction		No	No	No
Sand fraction		Medium	Medium	Fine
Signs of wetness		Absent	Present	Present
Cutans		Absent	Absent	Absent
Mottles		None	None	None
Concretions		None	None	Abundant (>50%)
Consistency		Loose	Loose	Loose to slightly hard
Free lime		None	None	None
Rock		None	None	None
Root abundance		Moderate	Moderate	Few
Rooting depth (cm)				122
Depth to impermeable layer (cm)				150

Figure A12 Soil profile of reference point V12.

Table A12 Soil classification for profile V12

Soil form: Kroonstad				
Horizon		1	2	3
Abbreviation		A	B1	B2
Master horizons		Orthic A	E-horizon grey	Gley cutanic
Thickness (cm)		35	50	30
Colour (wet)		Dark grey	Light grey	Light grey
Transition of horizons		Diffuse (>100 mm)	Diffuse (>100 mm)	
Structure	Type	Subangular blocky	Structureless (Single grained non-coherent)	Subangular blocky
	Grade	Weak	Structureless (Single grained)	Moderate
	Size/Class	Fine (Block <10 mm)		Medium (Block 10-25 mm)
Compaction		No	No	No
Sand fraction		Medium	Medium	Fine
Signs of wetness		Present	Present	Present
Cutans		Absent	Absent	Present
Mottles	Abundance	Few (<2%)	Few (<2%)	Common (2-20%)
	Size	Fine (<5 mm)	Fine (<5 mm)	Medium (5-15 mm)
	Contrast	Clear	Clear	Prominent
	Colour	Black (organic matter)	Yellow	Yellow
Concretions		None	None	None
Consistency		Loose	Loose	Slightly hard
Free lime		None	None	None
Rock		None	None	None
Root abundance		Moderate	Few	None
Rooting depth (cm)				90
Depth to impermeable layer (cm)				150

APPENDIX B. RECLAMATION PROCEDURE DESCRIPTIONS

Procedure 1: Rectification of excessive surface runoff

The topographical information in this report is sufficient for designing surface drains (contours). Agricultural engineers are trained to design surface drains.

Procedure 2: Rectification of poor infiltration

This is a soil structure problem. Can be corrected through cultivation and the addition of crop residue to improve structure of the topsoil. The K_{sat} map of the 0 to 300 mm depth can be used to identify areas of poor infiltration. Apply crop residue at a rate of 10 t ha^{-1} and mix thoroughly with topsoil – use a mould board plough if the problem is severe, otherwise use a chisel plough to create macro-pores.

Procedure 3: Rectification of poor internal drainage

If compaction is present only in the topsoil, use a chisel plough to rectify compaction. If the subsoil is compacted use deep ripping and traffic control for rectifying drainage problems in the subsurface. K_{sat} maps of the top- and subsoil layers can be used for identifying problematic areas. Make sure that the implement penetrates the restrictive layer. Open the profile after the first run of the ripper and inspect the actual depth of disturbance.

Procedure 4: Rectification of poor external drainage

This problem can be rectified through the design and installation artificial subsurface drains. The soil hydraulics data in the report is available to define the areas requiring installation of artificial drains. The type of drains, size of pipes and spacing is an engineering speciality and therefore demands special attention. Consult an agricultural engineer.

Procedure 5: Rectification of soil physical compaction

Top soil: chisel ploughing

Sub soil: deep ripping – Make sure that the shaft penetrates deep enough to break the compacted layer.

Note: Plough and disc implements are notorious for compacting and pulverising soils. As a precaution to prevent compaction, make sure the soil water content is at an optimum level when tillage operations are performed. The optimum water content for soil tillage operations (plough and disc, **not** rip) is near the Drained Upper Limit (DUL). Rip (subsoiling) or chisel operations should be performed when soil is at the dryer end of the scale, i.e. near the Lower Limit (LL).

Procedure 6: Rectification of sodic soils (Swartbrak).

i. Irrigation water should be analysed to determine its quality and whether it can be used for leaching in the procedure for sodium removal from the topsoil (0 to 300 mm).
ii. It is of utmost importance to make sure that the applied water infiltrates. Sodium in soils tends to reduce infiltration. In bare fields, broadcast at least 10 t ha^{-1} of crop residue.

iii. Broadcast the recommended quantity of gypsum (calculated from ESP), but do not apply more than 5 t ha^{-1} per year. If wind is a problem, spray 15 ℓ ha^{-1} of molasses meal after the application of gypsum, otherwise use granular gypsum.

iv. Mix the organic matter and gypsum thoroughly with the soil (mould board plough).

v. Apply irrigation water at a rate of 0.5 mm water per mm soil depth. The effective rooting depth can be taken as 1000 mm. Hence, a total of 500 mm (irrigation plus rain) is needed to leach sodium salts beyond the rooting depth.

vi. About 6 months after leaching, soil samples should be taken and analysed for extractable sodium concentration to monitor the reclamation process. The reason for monitoring the progress is because some sodic soils contain soluble sodium carbonate that also needs to be neutralised with the gypsum. The original sampling points can be used to measure salinity and sodicity at the different depths. Coordinates of sampling points are provided in hydro-physical report.

Note: The process of sodium removal is based on the principle that the excess adsorbed sodium (Na^+) on the exchange complex is displaced by calcium ions (Ca^{++}) and that the Na^+ is then leached from the soil. The process is complicated by the fact that the flow of water through sodic soils is drastically reduced by dispersion and swelling clay that block soil pores during wetting, this complicates the washing in of Ca^{++} and washing out of Na^+.

Procedure 7: Rectification and management of poor aeration

Soil water probes should be installed that continuously measure soil water. Soil structure will be modified, hence new core samples should be taken to measure the soil water boundaries. This will help to schedule irrigations. Contact water management specialists that provide continuous measuring technology.

Procedure 8: Topography – considerations on aspect features

The aspect results in the hydro-physical report should be used to assist in the selection of crops and cultivars that are suited to the soil temperature. Hillslopes that are north-facing will represent warmer soils, while southern facing hillslopes have cooler soils. Similarly, east-facing and west-facing hillslopes will also differ, receiving morning sun and late afternoon sun, respectively. Water use of plants and growth will also be different on the different hillslopes due to prevailing energy balances.

Procedure 9: Controlling of leaching in sandy soils

The problem with sandy soils is its high saturated hydraulic conductivity and poor nutrient retention due to lack of colloids (clay and organic particles). The addition of organic matter will help with both water retention and nutrient retention. The addition of crop residue will also improve problems related to rapid or slow infiltration. Crop residues should be applied at a rate of 10 t ha^{-1} in the first year, followed by 3 t ha^{-1} for the next five years.

Procedure 10: Controlling of lateral movement in soils

Establish the relationship between E-horizons and topography. In orchards, cut-off drains should be installed between blocks to control undesired flow of water from one block to the other. Contact an agricultural engineer for professional advice.