Soil health and quality concept in agricultural extension and soil science. An assessment of topsoil conditions in a long-term vineyard soil management trial in Robertson, South Africa

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Submitted in partial fulfilment for the degree

Master of Science (Agriculture)

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a l·NJŎK 2011

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part, submitted it at any university for a degree.

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Signature

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Name in full

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Date

Acknowledgments

In the process of this study, a number of role players have been fundamental in the completion of this project. Recognizing support of institutions and individuals for their confidence in my abilities, requires a sincere word of thanks.

My research supervisor, Dr. Andrei Rozanov for sharing your knowledge, time, patience and enthusiasm on the subject I insisted on researching. My research co-supervisor, Dr. Eduard Hoffman for all the encouragement and knowledge you have offered.

Dr. Keith du Plessis for his research guidance and remaining positive and excited about the project. Thank you for eagerly arranging funding for this project and all the additional logistical matters.

The Agricultural Research Council Infruitec-Nietvoorbij and Wine-tech for financial and technical support and assistance, in particular Dr. Johan Fourie. Ms Marde Booyse for assistance with statistical analysis.

All the staff of the Soil Science department for their "open door"policy and encouragement. Lecturing staff, for the supportive manner in which you all shared interest in my studies and career as a whole. Nigel Robertson for your *assistance* in the field and in the department laboratory.

Central Analytical Facility staff in the soil science department, in particular Matt Gordon, Esme Spicer and Herschel Achilles for assistance with chemical analysis and providing assistance at any given time.

Western Cape Department of Agriculture, Cape Institute for Agricultural Training, and *Elsenburg College,* for assistance in covering a portion of tuition costs. Colleagues in the Basic Sciences faculty.

My immediate family, William, Suzie, William-John and Tania Mathys, for believing in my abilities and for your patience and support during the past few years. Words surpass my gratitude. My sister and housemate, Tania Mathys, for your care and humour on a daily basis. Thanks my Melina

The Mathys and Zimri and Kunnie familes. In particular Prof. Julian Kunnie, for the encouragement and dreaming about my career on my behalf at times.

All my dearest friends for your support, wisdom, love, assistance and respect during this exploratory journey.

My fellow soil science colleague and sisters Meryl Mandy Awkes and Constance-Marie Hugo. Thank you for your support and sharing your brilliance.

The Almighty God for granting me this opportunity, providing the strength for completion and love for your creation.

Abstract

The natural resource condition or *health* has been accepted as a valuable indicator of sustainable land use. The assessment of soil health (quality) has become a valuable tool in determining the sustainability of land management systems. This work aims to evaluate the sustainability of soil management practices in agricultural extension for vineyards in Robertson, South Africa based, on the current approach of the concept of soil health and soil quality, as well as to briefly explore the present reservations regarding the definition of the concept. The soil management treatments include a mechanical weed control, chemical weed control, annual addition of straw mulch, annual cover crop and perennial cover crop. The objective of study is to (i) identify suitable soil health (quality) indicators for vineyards in the study area; (ii) analyze the soil health (quality) indicators for different soil management treatments; (iii) evaluate the effect of various soil management treatments on the overall soil functionality, by comparing measured indicators to the soil property threshold values, for optimal vine growth; iv) establish a more consistent understanding and use of the terms *health* and *quality,* as understood and used in the general science community, with particular reference to the public health system. The soil physical, chemical and biological properties which were selected as indicators of soil health (quality) based on specific criteria similar to previous work done on the concept. The properties selected include soil texture, gravimetric water content, bulk density, soil aeration, water aggregate stability, soil pH, EC, available N,P,K , soil organic matter content, soil microbial biomass, potential mineralizable nitrogen and soil respiration. The study makes use of methods of analysis previously used for soil health and soil quality assessments, as well as soil analytical methods as accepted by experienced soil scientist within the study area. The soil was sampled on three separate events to depths of 0-200 mm for initial characterization of soil and 0-50 mm to compare soil health (quality) *Between* tracks and *In* tracks of treatment plots. The values obtained for each property were compared with the optimum for vineyards and ranked accordingly. The treatment that resulted in the most desirable soil health (quality) was the straw mulch and perennial cover crop treatments.

Opsomming

Die toestand of gesondheid van natuurlike hulpbronne is aanvaar as `n waardevolle aanduiding van volhoubare grondgebruik. Die assessering van grond gesondheid (kwaliteit) is 'n waardevolle hulpmiddel in die bepaling van die volhoubaarheid van grond bestuur stelsels. Hierdie werkstuk poog om die volhoubaarheid van grond bestuurs praktyke te evalueer vir wingerde in Robertson, Suid-Afrika wat baseer is op die huidige benadering van grond gesondheid en kwaliteit. Die tesis dek ook die huidige onsekerhede oor die konsep en definisies van terme wat gebruik word in die konsep. Die grond bestuur praktyke sluit in 'n meganiese onkruidbeheer, chemiese onkruidbeheer, jaarlikse toevoeging van `n strooi deklaag, jaarlikse en meerjarige dekgewas dekgewasse. Die doel van die studie was om (i) die geskikte grond gesondheid (kwaliteit) indikators vir wingerde in die studie area te identifiseer, (ii) die grond gesondheid (kwaliteit) indikators vir verskillende bogrond bestuur praktyke te identifiseer; (iii) die effek van verskillende grond bestuur praktyke op die algehele grond funksies te evalueer, deur dit te vergelyk met die gemete indikators vir drempelwaardes vir optimale wingerd groei; iv) 'n meer konsekwente begrip en gebruik van die terme “gesondheid” en “kwaliteit” vas te stel, soos dit verstaan en gebruik word in die algemene wetenskaplike gemeenskap, met spesifieke verwysing na die openbare gesondheidsisteem. Die grond fisiese, chemiese en biologiese eienskappe wat as indikators van grond gesondheid (kwaliteit) geselekteer was, word gebaseer op spesifieke kriteria soortgelyk aan dié wat in vorige werk op die konsep gedoen was. Die eienskappe wat geselekteer is sluit in grondtekstuur, gravimetriese waterinhoud, bulk digtheid, grond deurlugting, totalle water stabiliteit, grond pH, electriese geleiding, toeganklike N, P, K, grond organiese materiaal inhoud, grond mikrobiese massa, potensiële mineraliseerbare stikstof en grond respirasie. Die studie maak gebruik van analitiese metodes wat voorheen gebruik was vir grond gesondheid en kwaliteit, sowel as die grond analitiese metodes soos gebruik deur ervare grondkundiges binne die studie gebied. Die grondmonsters was geneem op drie afsonderlike geleenthede oor dieptes van 0-200 mm vir die aanvanklike karakterisering van grond en 0-50 mm, om grond gesondheid (kwaliteit) *Tussen*

trekkerspore en *In* trekkerspore van die persele te vergelyk. Die waardes verkry vir elke eienskap was vergelyk met die optimum vir wingerde en verdeel volgens kwaliteit. Die behandeling wat die mees optimale grond gesondheid (kwaliteit) getoon het, was die strooi deklaag en meerjarige dekgewas behandelings.

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Glossary of Terms

Function:	A service, role, or task that meets objectives for sustaining life and fulfilling humanity's needs and is performed by soil or an ecosystem
Indicator:	An object that indicates the state or level of something; a device providing specific information on the state or condition of something, in particular
Minimum dataset:	The smallest set of soil properties that can be used to characterize or measure soil quality. The MDS will vary based on the intended land use, soil type, and climate
Pedotransfer Function:	A mathematical function that relates soil characteristics and properties with one another for use in the evaluation of soil quality.
Quality:	A quantitative or qualitative measure used to estimate functional capacity. Indicators should be adequately sensitive to change, accurately reflect the processes or biophysical mechanisms relevant to the function of interest, and be cost effective and relatively easy and practical to measure. Soil quality indicators are often categorized into biological, chemical, and physical indicators
Sustainable use:	Ensuring that resources are used within their capacity for renewal, maintaining and enhancing the ecological integrity of

	natural systems, and minimising or avoiding risks that will lead to irreversible damage
Threshold value:	A specific value or range of a soil property or indicator that is required to ensure that a soil process or function is not restricted or adversely influenced. This term is synonymous with the terms critical values, reference values, baseline values or trigger values, in soil quality assessment.

1 Introduction

Sustainable land use has become ever more important due to the recent focus of sustainable use of all natural resources. The draft Sustainable Utilization of Agricultural Resources Bill (2003), defines sustainable utilisation as "*the utilisation of natural agricultural resources for the production of food and other produce to enhance food security in an environmentally sound way, without compromising the ability of future generations to meet their own needs*." Agricultural resources include the soil, water and vegetation occurring on agricultural land, excluding weeds and invader plants (NDA, 2003).

The assessment of soil health has become a valuable tool in determining the sustainability of land management systems (Karlen et al., 1997). Soil health being "*the continued capacity of a soil to function as a vital living system within ecosystem and land use boundaries, to sustain biological productivity, to promote the quality of air and water environments, and to maintain plant, animal and human health*" (Doran and Safley, 1997). The terms soil health and soil quality are often used synonymously in previous work done, (Larson and Pierce, 1994; Karlen, Andrews and Doran, 2001; Doran, 2002; Scholter, Dilly and Munch, 2003) with preference to the term soil quality by scientists and soil health by producers (Romig, Garlynd, Harris and McSweeney, 1995).

In agriculture, excellent soil health (quality) relates to the maintenance of high productivity without significant soil or environmental degradation (Singer and Ewing, 2000). Soil health (quality) can thus not be determined without the assessment of the soils individual properties responsible for specific function, i.e. the quality of the soil for a specific purpose.

The soil functions can be summarised as follows, i) sustaining biological activity, diversity, and productivity; ii) regulating and partitioning of water and solute flow; iii) filtering, buffering, degrading, immobilizing, and detoxifying organic and inorganic materials, including industrial and municipal by-products and atmospheric deposition; iv) storing and cycling nutrients and other elements within the earth's biosphere; and v) providing support

for socioeconomic structures and protection for archaeological treasures associated with human habitation (Karlen et al.,., 1997).

The soils functions, be it ecological or linked to human activity, are defined by the inherent soil properties. The chemical, physical and biological components of soil are dependent on the soil forming factors (climate, time, parent material, topography, potential biota). The response of a soil system to certain practices and activities is unique to the factors under which the soil was formed and currently occurs.

In the search for identifying suitable measurable indicators for soil health (quality), certain soil properties, which can be used as indicators of soil health (quality), are evaluated for their usefulness for a specific soil-crop-climate location. The purpose of an indicator is to provide a value on a scale of measurements derived from a series of observed properties; that can reveal changes as a function of time and thus, also an evaluation of sustainability (Karlen, D.L., Stott, D.E. 1994).

Since soil functioning is subject to the soil forming factors and current land use, the selection of soil health (quality) indicators, must be identified for a specific soil-crop-climate scenario. This needs to be done in order to assess the soil health (quality), which therefore provides a measure of the degree of sustainable land use.

The soil health concept has not been accepted by all soil scientists or soil researchers (Letey; Sojka; Upchurch; Cassel; Olson; Payne; Petrie; Price; Reginato; Scott; Smethurst and Triplett, 2003). The criticisms regarding soil health (quality) concept include, "*premature acceptance of an incomplete formulated and largely untested paradigm*; *the concept has not yet been thoroughly analytically challenged*; *assessments have been drawn from a relatively narrow crop production and ecological perspective to positively or negatively weight soil quality assessment factors"* (Sojka and Upchurch, 1999).

Further weaknesses identified in the concept include having a dysfunctional definition; being a flawed approach to quantification; and failure to integrate simultaneous functions. Letey *et al.,* (2003) has summarised the limitations as follows:

a) There is no standard to which soil quality indicators can be compared,
b) The functional relationships between soil quality and soil quality indicators cannot always be established empirically,
c) There is confusion and contradiction as to which soil quality index values can be compared (assuming a reliable soil quality index can be determined),
d) The soil quality paradigm does not address water quality issues,
e) No consideration is given to crop specificity although crops differ in their response to many soil attributes.

For this reason the concept requires further exploration to address the weaknesses identified by the broader soil science community. The intention of this study is not to address all the limitations as highlighted by Letey *et al.,* (2003), but is considered in the conclusion chapter of this work.

The objective of the study is to (i) identify suitable soil quality indicators for vineyards in the Robertson area; (ii) analyze the soil quality indicators for different soil management practices; (iii) evaluate the effect of various soil management practices on the overall soil functionality, by comparing measured indicators to the soil property threshold values, for optimal vine growth; iv) establish a more consistent understanding and use of the terms *health* and *quality,* as understood and used in the general science community, with particular reference to the public health system.

In the light of the limitations identified above for the soil health and quality concept, this work aims to *evaluate the soil health conditions of vineyards under different soil management practices, in Robertson, South Africa based on the current approach of the concept of soil health and soil quality and briefly explore the present reservations regarding the definition of the concept*.

Since no standardized methods of analysis for soil health (quality) are presently available, the study utilizes the methods of analysis previously used for soil health and soil quality assessments and analytical methods used by experienced soil scientist within the study. The standardization of specific methods of analysis, do not fall within the scope of this study, but may be a potential research area to be considered for future soil health(quality) assessment.

Ideally, soil health (quality) assessments are done in relation to the ability of the soil to fulfil its functions. In the case of vineyards, the soil function must ensure optimal plant growth and optimal crop yields. This study only views the soil health (quality) with respect to specific threshold values of soil properties as defined for optimal crop (vine) growth. A comparison of soil quality in relation to crop yields serves as area for future research as yield potential of specific soil properties may differ with particular cultivars. The cultivar used in this study is Chardonnay/Richter 99. The soil requirements for optimal vine growth, as defined by the ARC-Infruitec/Nietvoorbij, will be used as the threshold value for each of the indicators discussed.

The chapters in this dissertation include a literature study on the soil health (quality) concept to provide background information on the concept and cover the various approaches taken to assessing soil health (quality). The approach taken in this study is also explained in a subsection of an abovementioned chapter, along with the experimental design and soil sampling description. This chapter is followed by the assessment of the soil health (quality) indicators in three separate chapters for soil physical, chemical and biological indicators. Each of these indicator chapters consists of subsections of a brief introduction of the selected indicators; a description of the methods used in the analysis; results and discussion; and a summary and conclusion. The final chapter takes a look at an alternative approach to understanding the soil health (quality) with the focus of defining the terms *health* and *quality* separately instead of using these terms interchangeably. Certain appropriate definitions and concepts are borrowed from the public health system and compared to that of agricultural systems.

2 Selection of indicators of soil quality

2.1 Introduction

There have been numerous soil properties which have been proposed as indicators of soil quality (Larson and Pierce, 1991; Doran and Parkin, 1994; Sparling, 2006; Gugino, Idowu, Schindelbeck, van Es, Wolfe, Moebius, Thies, and Abawi, 2007.), selected based on a set of criteria (Doran et al., 1996) or on a set of management goals associated with soil functions (Andrews, Karlen and Cambardella, 2004). The set of properties selected are collectively referred to as a minimum data set (MDS) of soil indicators used to monitor changes in soil health (quality). The minimum dataset of indicators was first proposed by Larson and Pierce (1991) and later adjusted by others (Gregorich, Carter, Angers, Monreal and Ellert 1994; Doran and Parkin, 1994; Clara Ines Nicholls, Miguel A. Altieri, Andre Dezanet, Marcos Lana, Diogo Feistauer and Maykol Ouriques, 2004; Gugino *et al.,* 2007) to be related to specific management goals (Table 1).

The MDS must include soil attributes in which quantitative attributes can be measured over a short time span and to be useful for land use and management decisions. MDS do not usually encompass all relevant properties for a region, but includes only those properties relevant to soil types, farming systems, and land uses of the area being evaluated (USDA, NRCS and Soil Quality Institute, 2001).

The MDS components are selected on a basis of ease of measurement, reproducibility, and to the extent they represent key variables that control soil quality. Larson and Pierce (1994) also suggest that the type of measurement and the measurement procedure should be standardized within a geographic region.

Soil properties, which are too costly or difficult to measure, but are desirable in a MDS can be predicted from other more easily measurable properties, using pedo transferable functions (PTF).

For practical purposes (for use by both scientists and producers) a set of basic suitability criteria has been suggested for the selection of indicators (Doran et al., 1996). The indicator need to:

1. Encompass ecosystem processes and relate to process-orientated modelling.
2. Integrate soil physical, chemical, and biological properties and processes.
3. Be accessible to many users and applicable to field conditions.
4. Be sensitive to variations in management and climate. The indicators should be sensitive enough to reflect the influence of management and climate over long-term in soil quality, but not be too sensitive as to be influenced by changes in short-term weather patterns.
5. Where possible, be elements of existing soil data bases.

Using the MDS approach as a starting point in the screening of indicators, a list of basic soil properties have further been developed by Doran and Parkin (1996), which meet requirements of previously mentioned criteria as well as consideration of a holistic interpretation of indicators with respect to the ecosystem that they are part of.

Table 1. Example of a minimum data set of physical, chemical and biological indicators for screening the quality and health of soil (after Doran and Parkin, 1994 and Larson and Pierce, 1994).

Indicators of soil health (quality)	**Relationship to soil health (quality) and function (rationale as a priority measurement)**
	Physical
Texture	Retention and transport of water and chemicals; Modelling use, soil erosion and variable estimate
Depth of soil, topsoil and rooting	Estimate of productivity potential and erosion; normalizes landscape geographic variability
Bulk density	Potential for leaching, productivity, and erosivity; ρ_b needed to adjust analysis to volumetric basis
Water holding capacity	Related to water retention, transport, and erosivity; available H_2O:

(water retention characteristics.)	calculate from soil bulk density, texture, and OM
	Chemical
Soil Organic Matter (OM) (total organic C and N)	Defines soil fertility, stability, and erosion extent; use in process models and for site normalization
pH	Defines biological and chemical activity thresholds; essential to process modelling
Electrical conductivity	Defines plant and microbial activity thresholds
Extractable N, P, and K	Plant available nutrients and potential for N loss; productivity and environmental indicators
	Biological
Microbial biomass C and N	Microbial catalytic potential and repository for C and N; modelling: Early warning of management effect on OM
Potentially mineralizable N (anaerobic incubation)	Soil productivity and N supplying potential; process modelling; (surrogate indicator of biomass)
Soil respiration, water content, and temperature	Microbial activity measure (in some cases plants); process modelling; estimate of biomass activity

The interpretation of any of the indicators (apart from the soil biological, physical and chemical attributes and their ecological relevance) holds little value. With respect to evaluation of soil health or quality, such an approach can be misleading (Doran et al., 1996).

Soil properties, which are less readily available, are estimated from properties which are relatively more easily measureable may be estimated by means of pedotransfer functions (Baker, 2007).

The majority of the work done in the development of pedotransfer functions has been conducted in Europe and the United States (Tomasella and Hodnett, 2004; Wösten and Nemes, 2004; Rawls, 2004). Problems regarding the accuracy of results obtained from these functions in alternate locations such as sub-Saharan Africa, have brought about the need for evaluation of the accuracy of pedotransfer functions in predicting soil properties (Young, Gowing, Hatibu, Mahoo and Payton, 1999).

An important principle associated with using the soil quality concept as an assessment tool, is that any framework or indexing procedure must recognize both *inherent* and *dynamic* soil properties and processes (Karlen, Andrews and Doran, 2001). *Inherent* properties are those determined by the basic soil forming factors: parent material, climate, time, topography and vegetation. This explains why soils with differences due to forming factors have different absolute capabilities and cannot be compared in a significant way to soil health (quality). *Dynamic* properties reflect changes associated with current or past land use and anthropogenic management decisions, and can thus be measured to compare different practices on similar soils (Karlen et al., 2001).

Comparison measurements over time for different soil management situations (of soils with equivalent inherent soil quality) provide the conceptual linkage between soil quality, environmental quality (soil, water and air quality), and agricultural sustainability (Karlen et al., 2001). The conceptual linkage provides support for the use of soil quality assessment as a tool for quantifying the overall effects associated with a specific set of management practices on specific soil resources (Karlen et al., 2001).

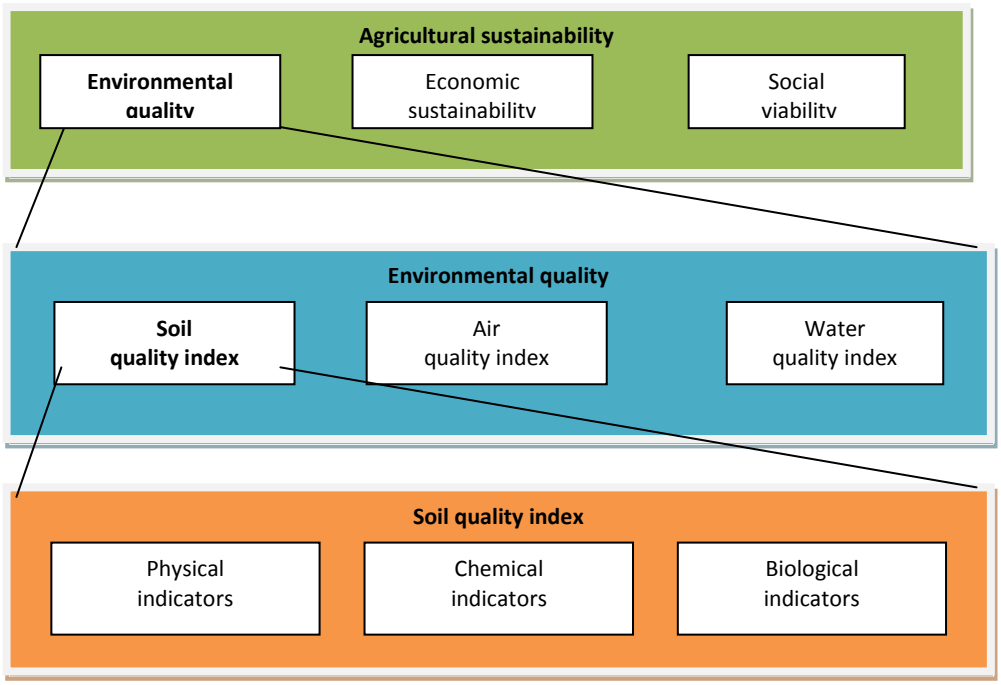
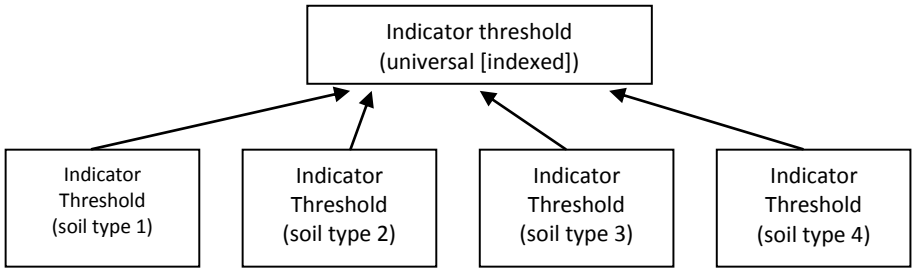


Figure 1. Hierarchy of agricultural indices showing soil quality as one of the critical foundations for assessing sustainable land management (Andrews et al.,., 2002)

With the common knowledge on soil functions, properties (including indicator thresholds) and knowledge derived from the studies on the effects of specific management tools, the potential outcome can be management thresholds. These thresholds refer to the most severe disturbance any management may incur without inducing significant changes towards unsustainable conditions.

Using soil acidity as an example, soil pH is a soil quality indicator for which a threshold can be established. The rate of liming (e.g. kg $CaCO_3$/ha/year) required to maintain the pH at the prescribed level, represents the management threshold (Karlen et al., 2004). This approach is illustrated in Figure 2.

a)



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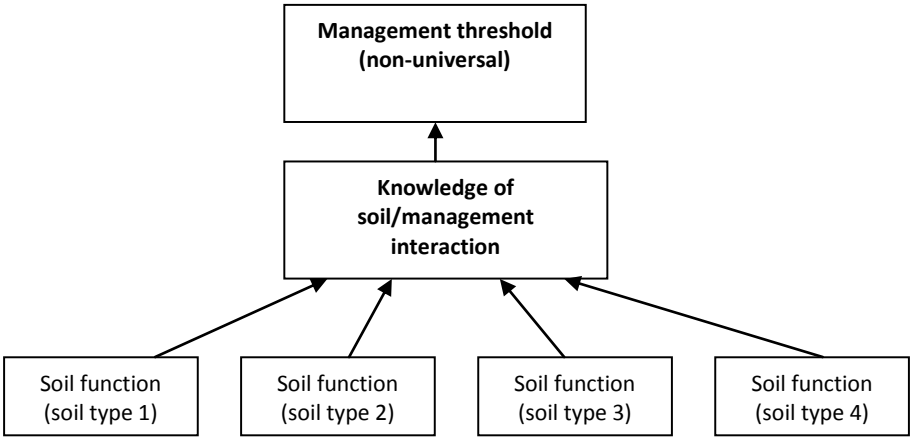


Figure 2. Schematic illustration of the a) 'indicator threshold' approach typically applied in soil quality studies and b) the suggested 'management threshold' approach (Karlen et al.,., 2004).

An alternative approach to assessing the sustainability of natural resource management systems which makes use of a site-specific selection of the indicators, was suggested by Lopez-Ridaura et al.,. (1999) and was adapted by Govaerts et al., (2006), (Figure 4) to assess soil health (quality) for a long-term tillage, residue management and rotation trial for wheat (Triticum aestivum) and maize (Zae mays L.). In this approach, the limiting factors for the prevailing agro-ecological conditions are listed, followed by the measurements of the indicators related to the limiting factors. The indicators significantly influenced by the specific management are then retained as possible candidates to be included in the actual minimum data set.

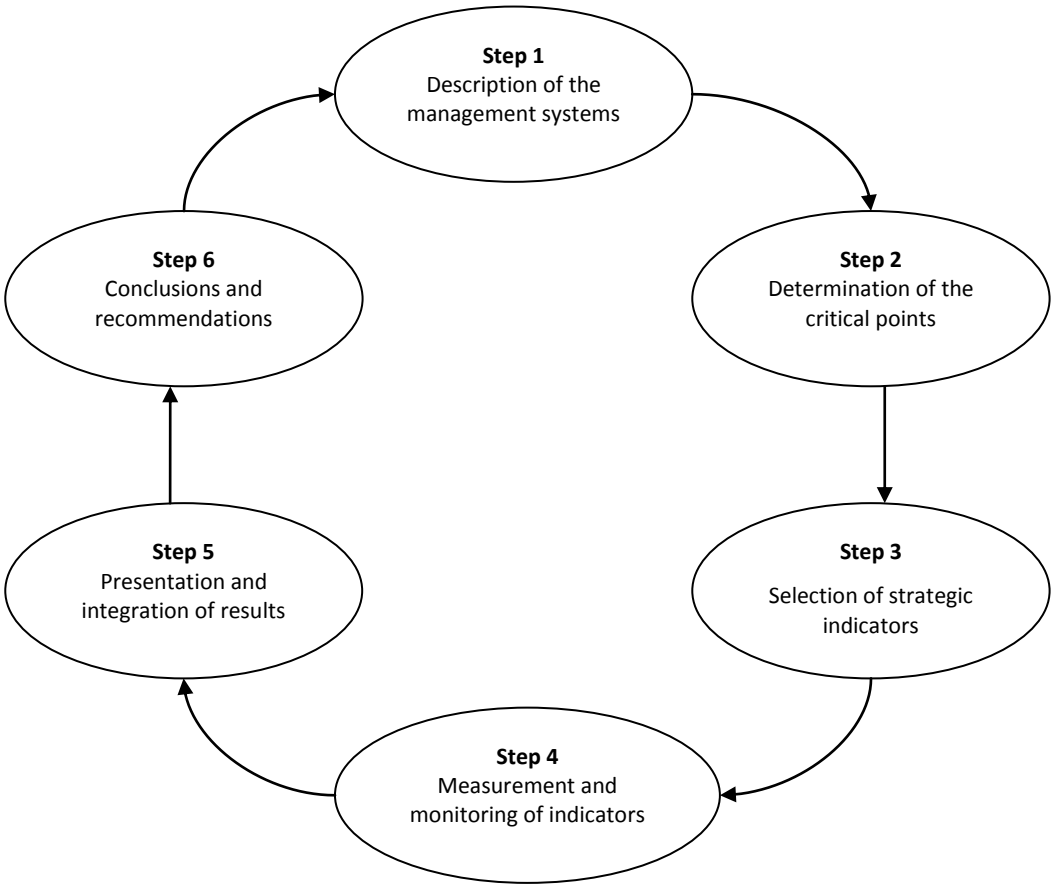


Figure 3. The framework for assessing the sustainability of natural resource management systems evaluation cycle (Lopez-Ridaura et al.,., 1999).

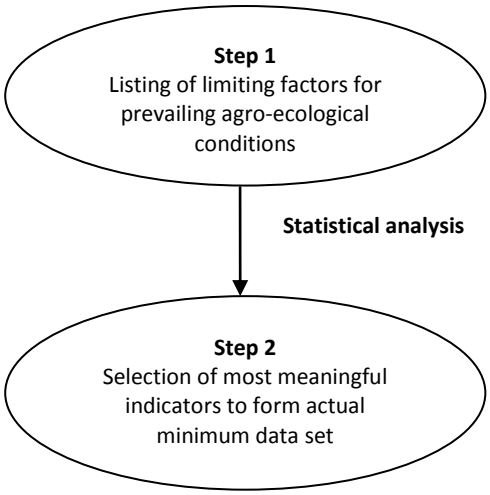


Figure 4. The framework for assessing soil health (quality) of natural source management systems evaluation cycle (adapted from Govaerts et al.,., 2006).

The approaches discussed thus far generally use an ecological framework to evaluate soil quality based on the following sequence: functions, process, properties, properties indicators, and methodology as indicated in Table 2 and Table 3.

Table 2. Sequential framework to evaluate soil quality for thespecific purpose or fitness of use (Carter, 2002)

Sequence steps	Sequential framework	Questions implied by the framework
1	Purpose	What will the soil be used for?
2	Functions	What specific role is being asked of the soil?
3	Processes	What key soil processes support each function?
4	Properties or attributes	What are the critical soil properties for each process? What are their critical or threshold levels?
5	Indicators, surrogates, or pedotransfer function	When the attribute is difficult to measure or not available, which indirect or related property or properties can be used in its place?
6	Methodology standardization	What methods are available to measure the attribute? Technical rules and protocols for soil sampling, handling, storage, analysis, and interpretation of data.

Table 3. Sequential framework to evaluate soil quality for specific purpose or fitness of use (Carter, 2002)

Sequence steps	Sequential framework	Rain-fed cropping systems in a winter rainfall region
1	Purpose	Crop production
2	Functions	Regulating and partitioning of water and solute flow
3	Processes	Water infiltration, nutrient cycling
4	Properties or attributes	What are the critical soil properties for each process? What are their critical or threshold levels?
5	Indicators, surrogates, or pedotransfer function	Infiltration rates; SOM;
6	Methodology standardization	What methods are available to measure the attribute? Technical rules and protocols for soil sampling, handling, storage, analysis, and interpretation of data.

At present, there is no consensus amongst soil scientists on what a MDS for soil quality should contain, but the approach suggested by Doran et al., 1996, has been used as a starting point in most work done on soil quality. For the assessment of soil quality in agricultural systems, the focal point is managing the system to enhance production, while not degrading soils and the environment (Gregorich, 2006). The selection of the properties suitable as indicators of soil quality for the study was based on the selection criteria suggested by Doran *et al.,* 1996. The above mentioned approach has been used to select indicators for the intended study (Table 4).

2.2 Experimental design

The trial was set up in a Chardonnay/Richter 99 vineyard in November 1992 at the Agricultural Research Council Infruitec-Nietvoorbij Research farm near Robertson. The town of Robertson (33˚50'S, 19˚54'E) is situated in the Breede River Valley region of the Western Cape, South Africa (Figure 5). Robertson is within a semi-arid climatic region with high temperatures in summer and cooler temperatures in winter than the Mediterranean climate of the Western Cape (Bonnardot , Carey and Strydom, 2000). The mean annual rainfall amounts to 278mm, of which most rainfall events occur during winter. The soil cover treatments were established between vines that were spaced 1.5 m in the row and 2.75 m

between rows (Fourie, 2010). The experiment was a completely randomised design, with five treatments replicated four times.

a)

b)

Figure 5. a) Location map of study area in Robertson, South Africa. b) ARC Robertson Experimental farm

The treatments included: i) no cover crop, post-emergence chemical control of a 1 m wide strip in the vine row and mechanical control in the work row from just before grapevine bud break (end of August 2010) to just before harvest (end of January 2010); ii) no cover crop, full surface post-emergence chemical control from the end of August to the end of January; iii) full surface straw mulch packed out annually approximately two weeks after grapevine bud break at a density of 8 tons/ha; iv) annual cover crop: crop rotation triticale (100 kg.ha^{-1}) and grazing vetch (50 kg.ha^{-1}), 2 yr/specie. Sprayed with a herbicide before bloom, and v) perennial cover crop: permanent perennial rye grass (14 kg.ha^{-1}) chemical weed control on the ridges.

a) 

b) 

c) 

d) 

e)

Figure 6. Weed control treatments, a) mechanical weed control; b) chemical weed control; c) straw mulch weed control; d) annual cover crop and e) perennial cover crop.

2.3 Soil sampling

The soil was obtained from Agricultural Research Council's Experimental farm near Robertson (33°49'44.51"S, 19°53'9.28"E). Soils were sampled on three occasions (February 2009, July 2009 and May 2010) for analysis during the study. Soil classification was also conducted in June 2010 on five soil $1m^3$ profile pits excavated a day prior to the field classification. The dominant soil forms identified within the study site is the Augrabies form. Full soil classification description can be found in APPENDIX IV.

For the first set of samples, a selection of 20 soils was used for the initial characterization of the study site. Composite samples of the topsoil for each sampling location were made in order to identify possible changes in soil properties which may have occurred as a result of the different soil management treatment. Sampling was done to 200 mm depth at all 20 locations.

For the second set of samples, the sampling depth of 50 mm was used in order to evaluate the soil quality of the pedoderm, as defined by Fey and Mills (2004), in comparison to that of the traditional sample of the plough depth of 0-200 mm. The pedoderm is a "*thin layer of soil at the interface with the atmosphere, a few millimetres to centimetres thick, within which certain properties exhibit a marked vertical change in expression sometimes not readily detected through field observation" (Fey and Mills, 2004)*.

The properties that were found to be different relative to the bulk of the surface horizon typically include the organic matter content, plant nutrients, microbial activity and aggregate stability (Fey and Mills, 2004; Fey and Mills, 2005).

In addition to refining the analysis to the pedoderm for the various treatments, pedoderm samples were also taken *between* the tracks and *in* tracks for each soil management treatment. A total of 80 samples were collected to a depth of 50 mm.

Figure 7. Soil surface of treatment plots prior to sampling for bulk density

A third set of soil samples were collected solely for the assessment of biological properties. Biological soil properties are sensitive to seasonal changes, thus the sampling time for

assessment of biological soil properties is recommended to be taken in late autumn or early spring and at the end of cropping season (Stenberg, 1999). The sampling for biological properties was done after routine agricultural operations as to not influence the microbiota (Stenberg, 1999).

2.4 Statistical procedures

The experimental design was a randomised block design with 5 treatments randomly allocated in 4 blocks. Analyses of variance were performed on the data obtained using SAS (SAS, 1990) to identify differences between treatments. Student's t-test of least significant difference was calculated at the 5% and 10% significance level to identify differences between treatment means. The Shapiro-Wilk test was performed to test for non-normality (Shapiro and Wilk, 1965). The statistics was conducted by the Agrimetry division of the Agricultural Research Council- Infruitec.

2.5 Study Overview

The following framework (Figure 8) for assessing the sustainability of natural resource management systems in terms of soil quality as defined by Lopez-Ridaura *et al.,.* (1999), has been used in this study. The figure below summarizes the approach taken in the assessment of the soil resource sustainability of the various soil management treatments.

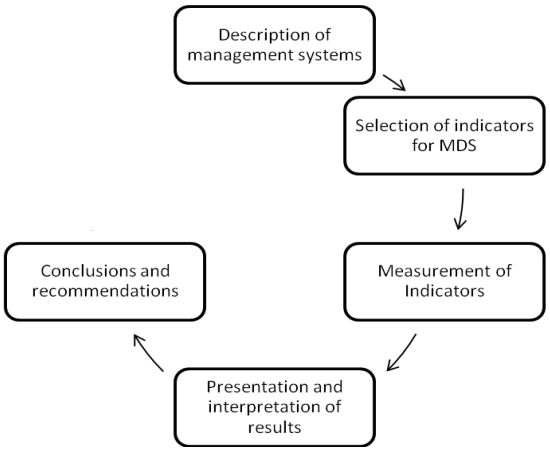


Figure 8. The framework for assessing the sustainability of soil management systems for the study

Table 4. Selection criteria for soil quality indicators from soil properties (adapted from Doran *et al.,* 1996 and Gugino *et al.,* 2007)

Indicator needs	**Soil properties previously used in SQ assessments**														
	Soil texture	Bulk density and	Aeration	Hydraulic conductivity	Gravimetric water content	Aggregate stability	Surface hardness	Subsurface hardness	Soil pH	Electrical Conductivity	Extractable N,P,K	Organic Matter Content	Soil Microbial Biomass	Potential Mineralizable N	Soil Respiration
Be accessible to many users and applicable to field conditions	✓	✓	?	?	✓	✓	✓	✓	✓	✓	✓	✓	?	?	?
Be sensitive to variations in management and climate.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Relevant to soil processes and functions	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Where possible, be components of existing soil data bases.	✓	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	?	?	?
Consistency and reproducibility	✓	✓	?	?	✓	✓	✓	✓	✓	✓	✓	✓	?	?	?
Ease and cost of sampling	✓	✓	?	?	✓	?	✓	✓	✓	✓	✓	✓	?	?	?
Cost of analysis	✓	✓	?	?	✓	?	?	?	✓	✓	✓	✓	✓	✓	✓

✓ **certain (yes)**

? uncertain,

Possibly determine using pedotransfer function

Potential indicator

Appropriate indicator

3 Selected soil physical properties

3.1 Introduction

For the present study, physical soil quality indicators were selected based on the same criteria used to select the chemical and biological indicators of soil quality. The following indicators will be discussed briefly namely: soil texture, soil water content, bulk density and aggregate stability. These indicators were part of numerous minimum datasets used in assessing and monitoring soil quality (Stenberg, 1999; Andrews, Mitchell, Karlen, Hartz, Horwath, Pettygrove, Scow and Munk, 2002).

3.1.1 Soil Texture

Soil texture is of great importance in determining the general characteristics of soil (Lyon, Buckman and Bradym 1955). The relative proportions of the various size factions of soil seldom changes in time in an undisturbed environment. Texture contributes to the soils inherent quality and cannot be changed through soil management (Gugino *et al.,* 2007).

Since the experimental trial site has had various soil cover crop practices, the possibility of textural changes needs to be assessed. Quantifying the changes in soil texture indicates the magnitude of the decline in soil quality (Leys, 2006). Texture is also useful in indirectly determining other parameters which are not easily determined by means of pedotransfer functions, such as the soils hydraulic characteristics (Nemes and Rawls, 2004). In most cases texture is used as an indicator of soil quality under various soil-crop-climate scenarios (Doran *et al.,* 1994; Karlen *et al.,* 2001; Bielders, Michels and Bationol, 2002; Gugin *et al.,* 2007). Texture is linked to the retention and transport of water and chemicals essential for the biological productivity function of soil thus also an important parameter in soil quality (Doran and Parkin, 1994; Larson and Pierce, 1994; Karlen *et al.,* 2001).

3.1.2 Soil Water Content

Water is vital to all the phases of plant growth with all the metabolic processes in the plant dependant of the availability of water (Hausenbuiller, 1975). One of the obvious effects of water shortage in plant growth is seen in the reduction in plant elongation and slowed growth (Hausenbuiller, 1975). The amount of water in soil may be expressed as volumetric water content, Θ_v, and as gravimetric water content, Θ_g (Jury and Horton, 2004). The determination of the soil water is often required as part of the determination of other soil properties, such as bulk density (Blake and Hatge, 1986), microbial biomass and soil respiration (Jacinthe and Lal, 2006) and thus remains an important soil physical property to measure.

3.1.3 Bulk Density

Bulk density, is known as the mass (weight) of a unit volume of dry soil is (Lyon *et al.,* 1952). Soil cultivation largely influences bulk density by either increasing the volume of soil or by diminishing it. When the bulk density of soil is altered, the functioning of soil in terms of regulating and portioning of water is also affected (Karlen *et al.,* 2001). From bulk density, important soil properties such as soil aeration can be calculated, especially useful for

Bulk densities of clay, clay loam, and silt loam surface soil may range from 1.00-1.6 $g.cm^3$, for sands and sandy loams varying from 1.2-1.8 $g.cm^{-3}$(Lyon *et al.,* 1955). As soil compact, naturally or due to human impact, the bulk density of soil increases. The effect of the various soil cover crop treatments on bulk density is often measured to determine the impact practices may have on soil quality (Bielders *et al.,* 2002; McDowell, Drewry and Paton, 2004; Chatterjee and Lal, 2009).

3.1.4 Aggregate stability

Aggregation is the process of cementing together of several soil particles into secondary units referred to as peds or aggregates (van der Watt and van Rooyen, 1995). Water stable aggregates (which do not disintegrate easily) are of particular importance to soil structure (van der Watt and van Rooyen, 1995). Aggregates are also important in soil due to their role

in water infiltration, moisture content, drainage, aeration, microbial activities and root penetration (Allison, 1973). Aggregation of soil particles may occur as a result of various soil processes or due to soil faunal activities (faunal secretions assisting with the binding of soil particles to larger aggregates). Organic matter and clay also assist with the formation of soil aggregates and high contents of these properties, are frequently associated with dominant water stable aggregates. If the soil aggregates lack stability upon wetting, dispersion occurs and the aggregates slake and cause clogging of soil pores (Jastrow and Miller, 1991).

In soil quality assessment, determining the amount of water stable aggregates has also been part of numerous studies especially those related to cultivation practices. Since the experiment was initially set up to evaluate the effects of different soil management practices on vineyards, aggregate stability as a physical indicator, should be particularly useful for this soil quality assessment.

3.2 Materials and Methods

3.2.1 Soil texture

The relative proportions of various particle sizes of soil namely sand, loamy sand, sandy loam and sandy clay loam and are further subdivided classes according to the relative percentages of course, medium and fine sand (Soil Classification Working Group, 1991). The particle size distribution of a soil defines the proportions of the various particle sizes the soil contains (Gee and Bauder, 1986). The method used to determine the particle fractionation consist of pre-treatment of soil to destruct the soil aggregates by chemical treatment to remove binding substances such as carbonates, organic matter, iron oxides and siliceous cementing agents (Gee and Bauder, 1986). Following the pre-treatment, the soil is dispersed by means of hexametaphoshate and the various size fractions of the suspension extracted at time intervals, which are calculated from Stokes' equation for the sedimentation of spherical particles (Gee and Bauder, 1986). The complete description of the method and the raw data can be found in APPENDIX I.

3.2.2 Soil Water Content

In order to determine the gravimetric water content of a particular soil sample, the water mass must be determined by drying the soil to constant weight and measuring the soil sample mass after and before drying. The water mass (or weight) is the difference between the weights of the wet and oven dry samples. The criterion for a dry soil sample is the soil sample that has been dried to constant weight in oven at temperature at 105^{o}C. The complete method can be found in the Appendix section of this document. The soil water content was determined for the 0-50 mm soil composites and calculated using the moist weight and oven dried weight (FSSA, 2007).

$$(g.g^{-1}) = \frac{(\text{weight of moist soil} - \text{weight of oven dry soil})}{\text{weight of oven dry soil}} \qquad \textbf{Equation 1}$$

3.2.3 Bulk Density

In field, the bulk density is determined by means of the core method (Blake and Hartge, 1986). This is done by driving a cylinder of known volume ($V_{cylinder}$) into the soil and thereby obtaining a core of natural soil. The soil is then weighed and dried and the amount of water and dry soil (m_{dry}) is determined. By dividing the mass of dry soil by the volume of cylinder, a number for bulk density (ρ_b) is obtained (Lyon *et al.,* 1955). The complete method can be found in the Appendix section of this document.

$$\text{Soil bulk density } \mathbf{(g.cm^{-3})} = \frac{\textbf{oven dry weight of soil (g)}}{\textbf{volume of soil (cm}^{3}\textbf{)}} \qquad \textbf{Equation 2}$$

The relative bulk density (RBD) was calculated relative to the lower limit of the threshold value (Carter, 2006) for optimal root and plant growth.

$$\textbf{Relative bulk density} = \frac{\textbf{measured bulk density (g.cm}^{-3}\textbf{)}}{\textbf{1.5 g.cm}^{-3}} \times \mathbf{100} \qquad \textbf{Equation 3}$$

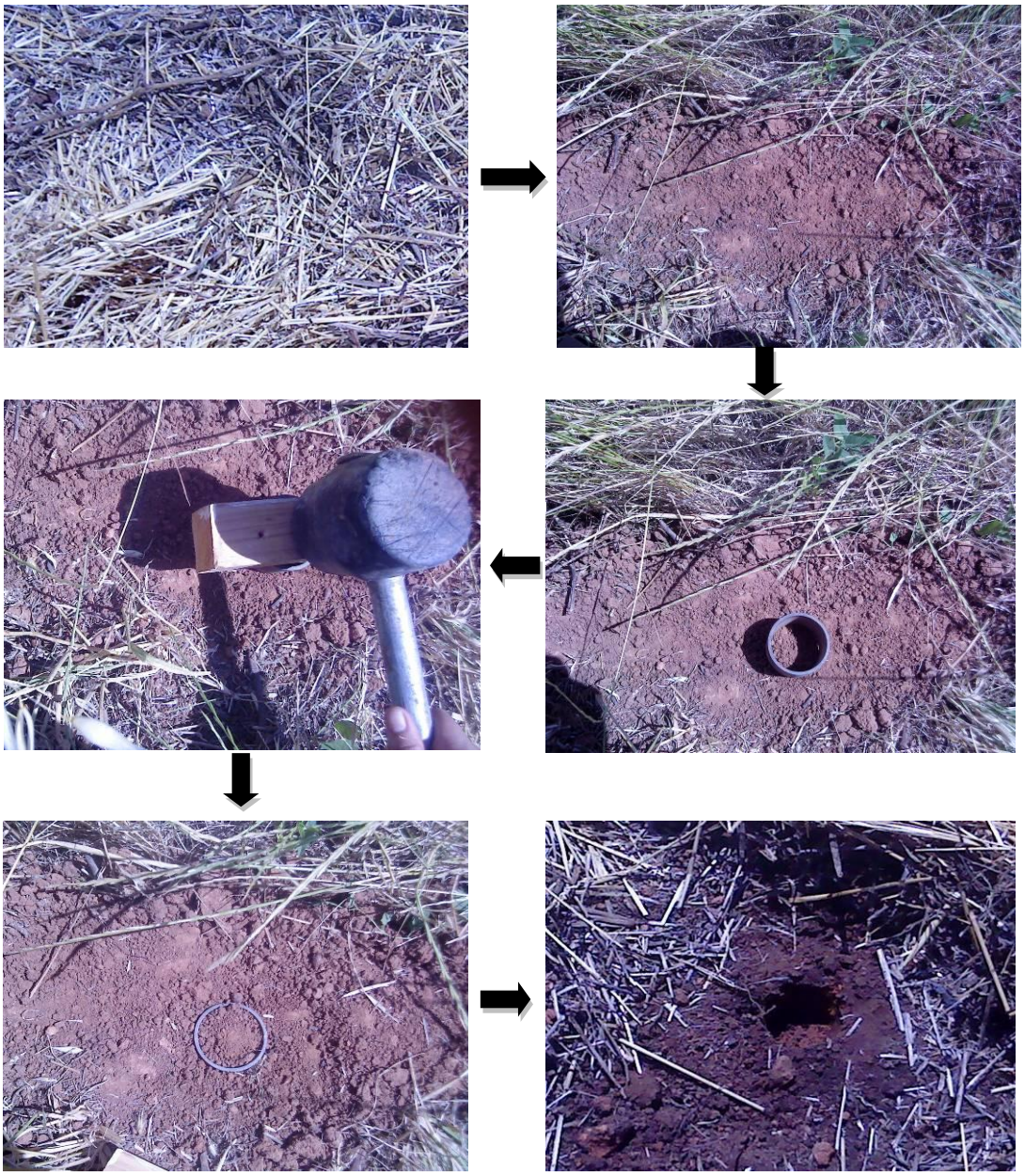


Figure 9. Soil sampling for core bulk density determination

3.2.4 Aggregate stability

The water aggregate stability was determined by wet-sieving of the 0-50 mm soil composite for each treatment, *Between* tracks and *In* tracks. The method is based on the mass of soil aggregates remaining on a sieve fraction, following cycles of wet sieving (Herrick, Whitford,

de Soyza, Van Zee, Havstad, Seybold and Walton, 2001) comparing the different aggregate fractions remaining after wet sieving, with the dry aggregate fractions.
A total of ten sets (one sample per treatment and position) and of samples were used for this analysis. The same set of samples that were used for particle size distribution (soil texture) was used in the water aggregate stability analysis.

The wet sieving consisted of rinsing 10 g of air-dried sample of soil with distilled water through a nest of three sieves (> 2 mm, 0.25-2,0 mm, and 0.106-0.25 mm). The portions remaining in the respective sieves were then quantitatively transferred to porcelain evaporative dishes and dried at 105˚C overnight.

The results obtained from the method used in the study are limited to comparing the particle size percentages of water stable aggregates (WSA) with that of the dry sieved aggregates. The water stable aggregates were calculated as follows:

$$\textbf{Percentage Water stable aggregates} = \frac{\text{mass of aggregates in fraction (g)}}{\text{initial sample mass(g)}} \times 100 \qquad \textbf{Equation 4}$$

The ratio of water stable aggregates to dry-sieved aggregates (DA) and the ratio of water stable aggregates to the texture analysis fractions (TAF) were calculated as follows:

$$\textbf{Aggregate stability ratio} = \frac{\text{water stable aggregates of fraction } \boldsymbol{a} \text{ (\%)}}{\text{dry-sieved aggregates of fraction } \boldsymbol{a} \text{ (\%)}} \qquad \textbf{Equation 5}$$

Where ***a*** denotes the specific particle fraction (>2 mm, 0.25-2,0 mm, and 0.106-0.25 mm) obtained from particle size analysis.

3.3 Results and Discussion

When using soil health (quality) as an assessment tool for evaluating sustainability and ecosystem response, it is essential to recognize that (1) spatial and temporal scales are critical, and (2) soil quality depends on both inherent and dynamic properties and processes.

The difficulty in interpreting indicators relates mostly to scale. Thus being able to determine which soil quality indicators will provide the most useful measurements, and how large the differences must be, to have statistical significance, or to be mechanistically or functionally meaningful (Karlen *et al.,* 2001) is fundamental but challenging. This hurdle is overcome by the use of indices and thresholds defined by desired management goals or functions that the soil needs to perform.

Thresholds are defined as points at which stimuli provoke significant response or the levels of environmental indicators beyond which a system undergoes significant changes; (FAO, 1993). The preferred use of indicator thresholds instead of baseline, benchmarks or references, often used in literature on soil quality indicators, is encouraged because of the terms association with resilience (Schønning, Elmholt and Christensen, 2004; Lal, 2006). The threshold values used to denote boundaries between sustainable and unsustainable indicator values, are specific to the soil use intended. The main quality concern for agricultural soils, is how to identify sustainable management practices (Schønning *et al.,* 2004). Past evaluations of the management practices have focused the evaluation of the soil properties on the indentification of the impact of the practices on crop productivity (Bielders *et al.,* 2002; Fourie, Agenbag and Louw, 2007; Chatterjee and Lal, 2009).

Concerning crop production, indicator threshold values may be obtained from soil characteristics required for optimum crop growth as well as from historic soil data of a specific location. Comparing measured indicator values to threshold values provide a means of recommending whether or not a specific practice is sustainable (Schønning *et al.,* 2004). Crop growth requirements for vineyards are defined by the threshold values selected for the physical indicators measured. All the statistical data can be found in APPENDIX IV.

3.3.1 Soil texture

Since soil texture is an inherent property of the soil, the determination thereof was only done on a few treatment plots for use of characterization of the soil. With the dominant soil texture being sandy clay loam (Table 5).

Table 5. Soil particle size determination for 0-50 mm soil composites

Treatment Name	Position	Textural class
Mechanical	*Between tracks*	Sandy clay loam
Mechanical	*In tracks*	Sandy loam
Chemical	*Between tracks*	Sandy loam
Chemical	*In tracks*	Sandy clay loam
Straw mulch	*Between tracks*	Sandy clay loam
Straw mulch	*In tracks*	Loam
Annual cover crop	*Between tracks*	Sandy loam
Annual cover crop	*In tracks*	Sandy loam
Perennial cover crop	*Between tracks*	Sandy clay loam
Perennial cover crop	*In tracks*	Sandy clay loam

3.3.2 Soil Water Content

The water content obtained for the various treatments are given in Table 6:

Table 6. Gravimetric water content of 0-50 mm soil composites *Between* tracks and *In* tracks

Treatment Name	Position	Gravimetric water content (g/g, %)	t-test *
Mechanical	*Between tracks*	3.90	b
Mechanical	*In tracks*	4.41	a b
Chemical	*Between tracks*	4.95	a b
Chemical	*In tracks*	3.94	b
Straw mulch	*Between tracks*	6.34	a
Straw mulch	*In tracks*	6.10	a b
Annual cover crop	*Between tracks*	4.25	a b
Annual cover crop	*In tracks*	4.80	a b
Perennial cover crop	*Between tracks*	3.80	b
Perennial cover crop	*In tracks*	4.99	a b

* Means with the same letter are not significantly different. Data differ significantly at the 5% level.

Statistically, the straw mulch treatment had significantly higher water content between tracks. The variations in water content in *Between* tracks and *In* tracks within the treatments were not significantly different. A common pattern observed in the data was the higher water content *In* tracks than *Between* tracks for the cover crop treatments. A possible reason for this could be the regular occurrence of traffic in these plots due to usual field operations needed by cover crops in comparison to the straw mulch treatment. For the same reason, the straw mulch treatments soil water content *Between* tracks and *In* tracks are relatively the same due to the limited traffic and tillage taking place in these plots and as a result, the *In* track position is not as defined and sunken, as in the case of the cover crop treatments.

The chemical treatments had higher soil water contents *Between* tracks than *In* tracks. In a study conducted by Ferreroa, Usowicz and Lipiec (2005) on the impacts of tractor traffic on vineyard soil properties, no differences in terms of soil water content were found for tilled soils verses the soils with a permanent cover which was contrary to what was found in this study. The reason for this could be the sample depth used for the analysis. In this study, the sample depth of 0-50 mm, allowed for the analysis of soil properties within the pedoderm, which is often different from the bulk top soil horizon. It is known that pedodermal expression is maximal under conservation practices and minimal under conventional cultivation practices (Fey and Mills, 2004). The higher water content observed *Between* tracks in the chemical treatments is attributed to the ease with which water penetrates cultivated soils, in comparison to the cover crop treatments in which surface crust feature was more pronounced.

3.3.3 Bulk Density

Bulk density affects plant growth due to its effect on soil strength and soil porosity (Chang, 2002). High soil densities have a direct effect on vine performance due to the effect it has on the distribution, and functional capacity of the root system to extract water and nutrients from the soil (Lanyon, Cass and Hansen, 2004). The technique used to determine bulk density core method as recommended in the Cornell Soil Health Manual (Gugino, et al.,

2008) produced results which were not near the norm for the Robertson area (1.4-1.7 $g.cm^{-3}$) and obtained in unpublished data for a study conducted by the ARC (Hoffman, 2011).

The dryland cultivated vineyard soils in this semi-arid area were not suited for use of the core method for determining bulk density. Soils in this area are prone to surface crusting and this too was observed during soil sampling. The surface crust varied between 3-5 mm thick and the removal of the surface crust is recommended (Hoffman, 2011) if the soil core technique is to be used. In this case, an adjustment to the core volume was made in order to account for the effect of the soil crust. Due to the high variation obtained during measurement, the clod method is recommended for future bulk density determinations for soils in the semi-arid area. The revised values calculated for the bulk density is listed in Table 8.

Table 7. Bulk density values obtained from core method of Soil Health Manual and Revised bulk density

Treatment Name	Soil Health Manual Method Bulk density ($g.cm^{-3}$)	Revised Bulk density ($g.cm^{-3}$)
Mechanical	0.95	1.19
Chemical	1.11	1.39
Straw mulch	1.33	1.66
Annual cover crop	1.11	1.66
Perennial cover crop	1.06	1.39

Overall, the bulk density was significantly higher *In* tracks than *Between* tracks (Statistics shown in APPENDIX IV). This was expected, due to the pressure exerted on the soil by the tractor tyre in the tracks. The critical bulk density for root growth varies with different textures and for sandy clay loam soil, the threshold values for root growth for different soil types were measured by Morris and Lowery (1988). The bulk density values, for the various plot treatments and positions, in comparison to the threshold value, is given in Table 88.

Table 8. Critical bulk density values for root growth for different soil textures (adapted from Morris and Lowery, 1988)

Treatment Name	Position	Textural class	Revised Bulk density ($g.cm^{-3}$)	Threshold Bulk density ($g.cm^{-3}$)	t Grouping*
Mechanical	*Between tracks*	Sandy clay loam	1.19	1.55-1.75	*d*
Mechanical	*In tracks*	Sandy loam	1.62	1.55-1.75	*a*
Chemical	*Between tracks*	Sandy loam	1.39	1.55-1.75	*c*
Chemical	*In tracks*	Sandy clay loam	1.42	1.55-1.75	*bc*
Straw mulch	*Between tracks*	Sandy clay loam	1.66	1.55-1.75	*a*
Straw mulch	*In tracks*	Loam	1.57	1.45-1.60	*ba*
Annual cover crop	*Between tracks*	Sandy loam	1.66	1.55-1.75	*c*
Annual cover crop	*In tracks*	Sandy loam	1.57	1.55-1.75	*ba*
Perennial cover crop	*Between tracks*	Sandy clay loam	1.39	1.55-1.75	*dc*
Perennial cover crop	*In tracks*	Sandy clay loam	1.56	1.55-1.75	*bc*

* Means with the same letter are not significantly different. Data differ significantly at the 5% level.

The relative bulk density (RBD) can be calculated relative to this threshold values in order to rate the bulk density in relation to the root and plant growth. If the relative bulk density is less than 80%, it is considered to be within the low range, 82-87% the optimum range and greater than 90%, within a high range which is generally associated with soil conditions that inhibit root growth (Carter, 2006).

Table 9. Bulk density and relative bulk density of *Between* tracks and *In* tracks

Treatment Name	Position	Bulk density ($g.cm^{-3}$)	Relative Bulk density (%)
Mechanical	*Between tracks*	1.19	68.00
Mechanical	*In tracks*	1.62	92.57
Chemical	*Between tracks*	1.39	79.43
Chemical	*In tracks*	1.42	81.14
Straw mulch	*Between tracks*	1.66	94.86
Straw mulch	*In tracks*	1.57	89.71
Annual cover crop	*Between tracks*	1.66	94.86
Annual cover crop	*In tracks*	1.57	89.71
Perennial cover crop	*Between tracks*	1.39	79.43
Perennial cover crop	*In tracks*	1.56	89.14

In terms of the threshold values for bulk density as defined by Carter (2006) and that of Morris *et al.,* (1988) In tracks of the mechanical and the straw mulch treatment and Between tracks of the annual cover crops, the relative bulk densities (above 90%) are generally associated with soil conditions that inhibit root growth (Table 8).

Statistically, the straw mulch treatment had the highest bulk density in comparison to the other treatments. This occurrence is expected, since the soil has not been tilled for 18years with annual layering of straw for mulching. At this stage, it is worth mentioning that the straw plots were most difficult to sample soil from. Results in Table 8 show t grouping which demonstrates that the effect of treatments is mainly pronounced in the sections between the tracks. Tracks complicate the experiment and seem to have a greater influence than the treatment itself.

3.3.4 Aggregate stability

Aggregate stability or soil structural stability is a measure of the ability of the soil aggregates to resist change in response to the application of stress. General methods for aggregate stability are based on the ratio in fragment sizes before and after the application of a specific stress (Diaz-Zorita, Grove and Perfect, 2002). The measurements made under induced saturated conditions (*applied stress*), provides a measure of the minimum stability that soil has (Pojasok and Kay, 1990).

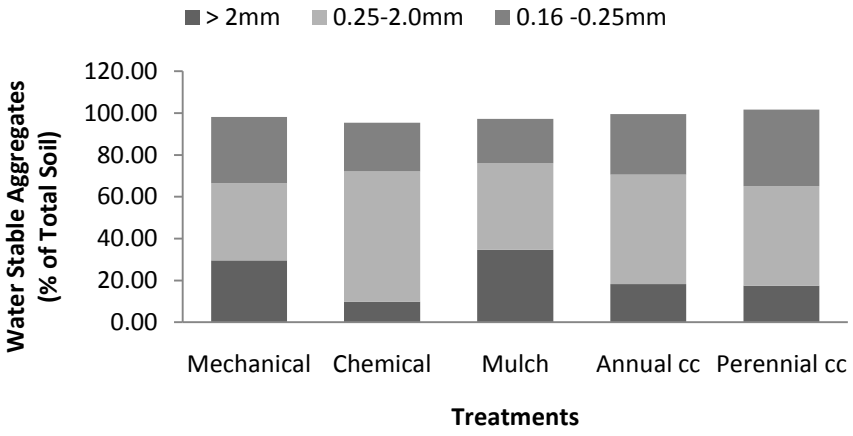


Figure 10. Water stable aggregates of soil management treatments

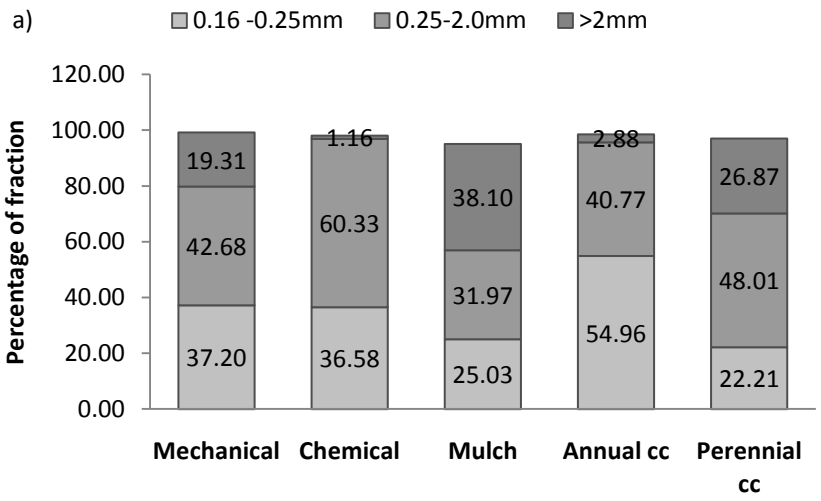


Figure 11a. Water stable aggregates *In* tracks of soil management treatments

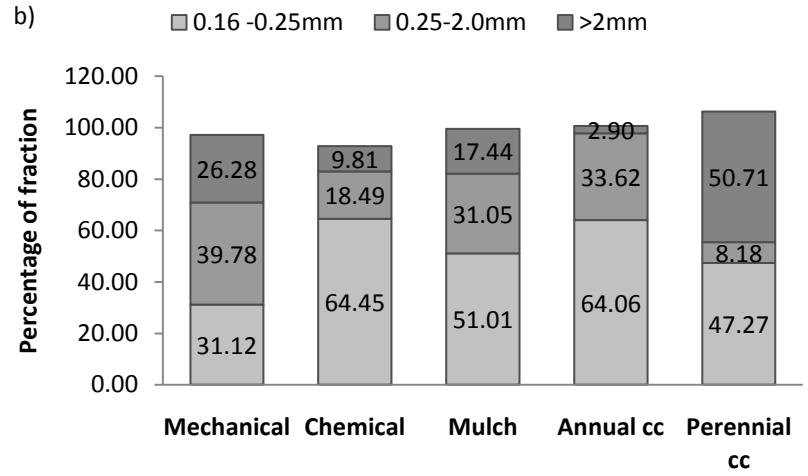


Figure 12b. Water stable aggregates *Between* tracks of soil management treatments

The ratio of WSA to DA calculated can be used as measure of indicating the structural stability of the soils under the various soil management treatments (Table 9). The ratio of WSA to texture analysis fractions (TAF) was also calculated and is given in Table 11.

Table 10. Ratio of WSA to DA for soil management treatment plots

Treatment Name	0.106 - 0.250 mm	0.25- 2.00 mm	>2.00 mm
Mechanical	3.55	1.26	0.46
Chemical	2.03	1.68	0.20
Straw mulch	31.56	6.61	0.37
Annual cover crop	54.76	8.97	0.20
Perennial cover crop	11.60	1.47	0.27

Table 11. Ratio of WSA to TAF for soil management plots

Treatment Name	0.106 - .250 mm	0.25- 2.00 mm	>2.00 mm
Mechanical	0.44	1.32	0.96
Chemical	0.32	2.31	0.29
Straw mulch	0.30	1.40	0.61
Annual cover crop	0.40	1.96	0.38
Perennial cover crop	0.54	1.45	0.29

From the ratios calculated, the treatment with the highest percentage of the largest particle fraction (>2 mm fraction) can be considered to have more water stable aggregates than treatments with lower percentages for that specific particle fraction.

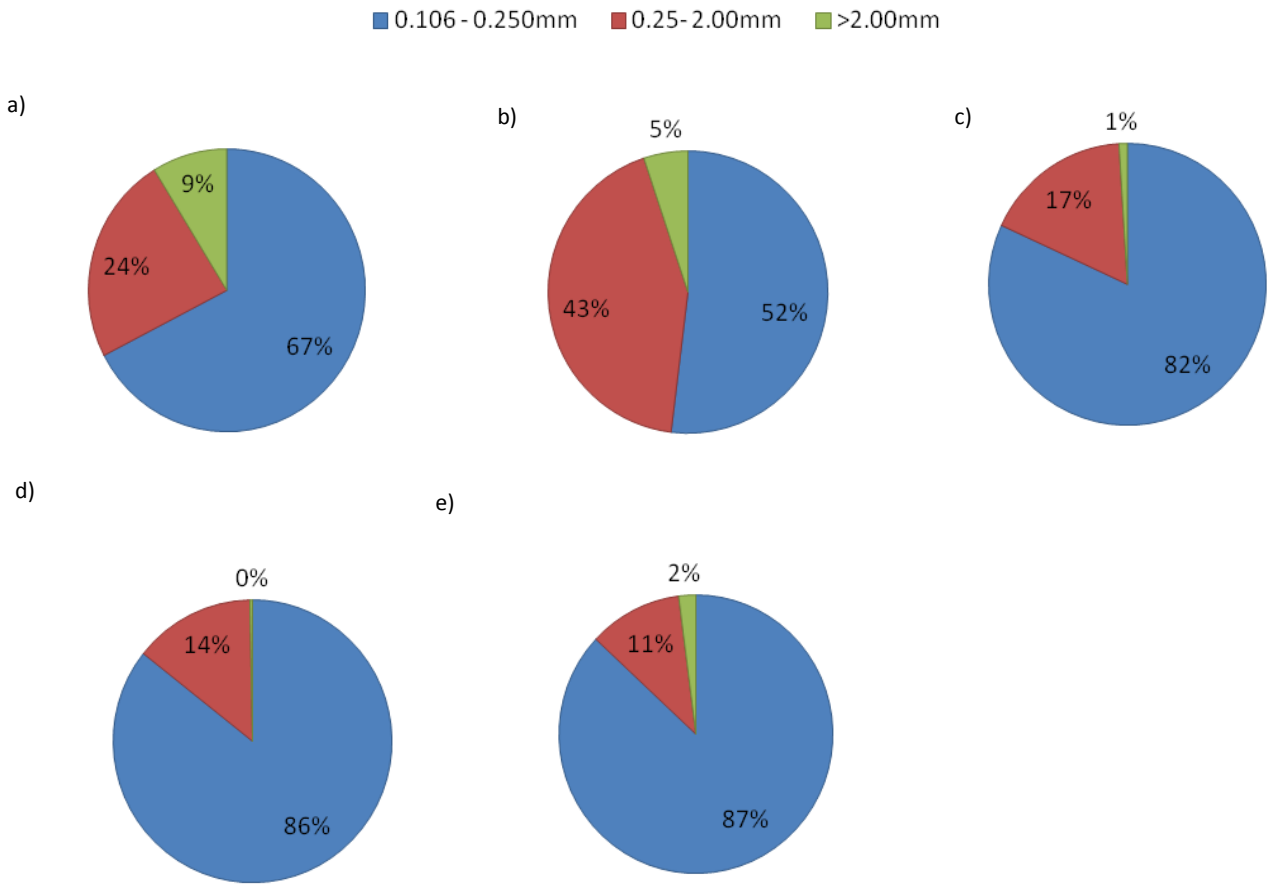


Figure 13. WSA:DA for treatments, a) mechanical weed control; b) chemical weed control; c) straw mulch weed control; d) annual cover crop and e) perennial cover crop.

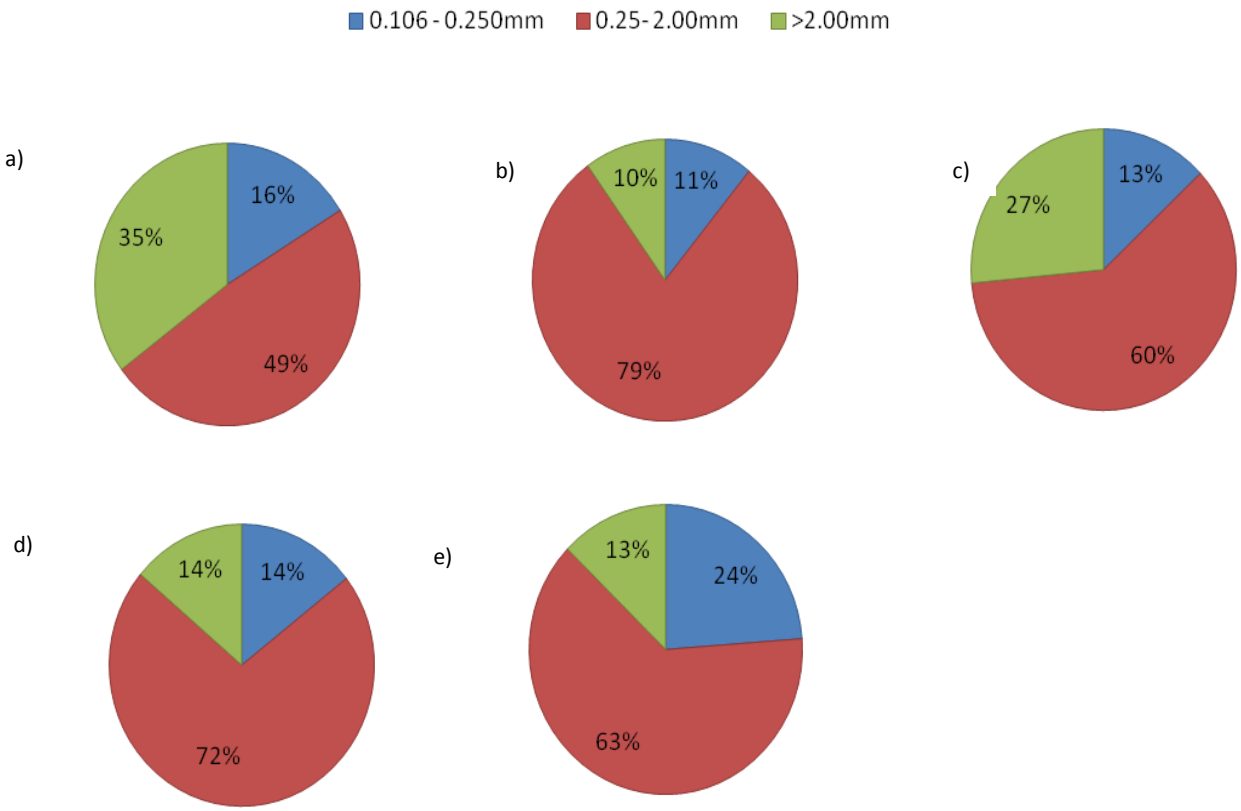


Figure 14. WSA:TAF for treatments, a) mechanical weed control; b) chemical weed control; c) straw mulch weed control; d) annual cover crop and e) perennial cover crop.

From the results above, the treatments yielding the largest ratio of stable aggregates >2 mm are the mechanical and straw mulch treatments. The same conclusion can be drawn from the ratio of water stable aggregates to dry aggregates as well as the ratio of water stable aggregates to texture analysis fractions. The better structural stability in the mechanical and straw mulch treatment plots, could be related to the organic matter content of the soils. Organic matter content plays an important role in aggregation of soil particles. Since the straw mulch treatment plots have the highest organic matter content in comparison to the remainder of the treatment plots, the ratio of water stable aggregates was expected to be larger. The presence of earthworms is also a contributing factor to the higher structural stability. In an earthworm study conducted on the site by Maboeta (2010), the earthworms (adults, juveniles and cocoons) were most abundant in the straw mulch treatment plots.

Figure 15. Earthworm casts and earthworms in plots of perennial cover crop treatment plots observed during second sampling occasion (July, 2009).

The presence of termites is also a contributing to aggregation. Termites bring large quantities of clay sized particles from the subsurface to the surface and in the process the clay particles are glued together by the fluid excreted by the termites (Duiker, 2002). The mechanical treatment plot was the only plot that tested positive (effervescences in 10% solution of HCl) for the presence of a "*heuweltjie*" within the plot.

Figure 16. Soil surface of mechanical treatment plot was the only plot which tested positive for the presence of a "*heuweltjie*"

The larger ratio of water stable aggregates despite lower organic matter content could be the due to the presence of termites. In addition to the contribution of the termite secretion to aggregation, the concentration and type of cations present also play a role in aggregation. The presence and concentration of divalent cations also contribute to aggregation, with calcium having the stronger ability than magnesium to flocculate clays (Duiker, 2002). The calcium concentration of the mechanical plot was also the highest (Table 12) of the treatment plots and thus the contribution of calcium concentration to aggregation is plausible.

Table 12. Exchangeable cations for the 0-50 mm soil composites

	Exchangeable cations (cmol(+)/kg)			
Treatment Name	**Ca**	**Mg**	**Na**	**K**
Mechanical	15.80	4.26	0.45	1.23
Chemical	14.46	4.39	0.45	1.30
Straw mulch	14.29	5.73	0.45	1.28
Annual cover crop	10.99	4.63	0.51	1.13
Perennial cover crop	11.61	5.31	0.49	1.51

3.4 Summary and conclusions

Soil quality assessment is increasingly becoming a valuable tool in determining sustainability of soil management practices (Larson and Pierce, 1991; Doran and Parkin, 1994; Sparling, 2006; Gugino, Idowu, Schindelbeck, van Es, Wolfe, Moebius, Thies, and Abawi, 2007.).

Studies identifying minimum datasets of soil properties for specific soil-crop-climate conditions have been conducted in order to monitor changes in soil quality (Santana, Fernandes, Ivo and Costa, 2009).

In this study, the soil quality of the pedoderm was characterised by analyzing the selected soil quality indicators and comparing the indicator values with the optimum value required for optimum crop (vine) growth.

The indicators analyzed were soil texture; soil water content; bulk density and aggregate stability. None of the treatments had limiting physical properties for vine growth. In terms of soil quality, none of the physical conditions created by the treatments resulted in unfavourable soil conditions or quality for crop growth.

4. Selected soil chemical properties

4.1. Introduction

For the study, chemical soil quality indicators were selected based on the same criteria used to select the biological and physical indicators of soil quality. The minimum data set selection criteria includes i) measurements need to be applicable to field conditions; ii) soil property sensitivity to variations in management and climate; iii) relevance to soil processes and functions; iv) where possible, be components of existing soil data bases; v) measurements of property should consistent and reproducible; vi) measurements should by relatively easy and vii) sampling and analysis should be economical (Doran and Parkin,1994).

The selected indicators, are based on the above mentioned criteria, as part of the minimum data set for the study, namely, soil pH; electrical conductivity; exchangeable cations; and soil organic matter content. These indicators were part of numerous minimum datasets used for assessing and monitoring soil quality (Steenberg, 1999; Andrews *et al*., 2002).

4.1.1. Soil pH

Soil reaction (pH) is an important aspect of soil agricultural potential. Chemical reactions in the soil control the nutrient availability and are largely influenced by the soil pH (Barber, 1995). Soil pH is used to indicate the chemical status of soil since it affects numerous vital biological processes (Hausenbuiller, 1978). For this reason, soil pH is one of the properties most frequently measured in order to predict the availability of plant nutrients. The process of mineral dissolution and cation exchange capacity are dependent on pH (Heil and Sposito, 1997), and thus measurment of the soil pH is useful for estimation of the abovementioned properties. In crop production, adjusting the soil pH is common practice in creating an optimum growth environment for the desired crop (Hausenbuiller, 1978). The research into adjusting soil pH has been done widely for most crops, with a common starting point being the measurement of the soil pH in water. Consequently, soil pH data is part of most

minimum data sets as it is usually part of historic data for crop production areas. The ease of measurements also supports the use of soil pH as a suitable indicator of soil quality.

4.1.2. Electrical conductivity

The presence and relative concentration of certain salts in soils impact soil physical properties. Due to the effect of soil salt concentration on plant osmotic potential, soil salinity remains an important property to use when assessing soil production potential (Berstein, 1975; Munns, 1993; Zhu, 2001). Soil salt concentration also defines plant growth thresholds and microbial activity thresholds (Doran and Parkin, 1994 and Larson and Pierce, 1994). The ease of measurements also supports the use of the property as a suitable indicator of soil quality

4.1.3. Extractable Nitrogen(N), Phosphorous(P) and Potassium(K)

Soil fertility is the capacity of a soil to supply nutrients in amounts, forms and proportions at a desirable rate to plants to ensure optimum plant growth (Hausenbuiller, 1975). Soil is considered fertile if it has the capacity to satisfy the nutrient requirement of plants (Hausenbuiller, 1975). The fertility of a soil is measured directly in terms of the amount and availability of ions essential in plant nutrition. Assessing the quantity of plant available nutrients in the soil (*soil fertility*) is done by analyzing an extract of soil obtained by adding chemical extractants (Dala and Subba Roa, 2006). Of the sixteen essential plant nutrients, only plant available nitrogen, phosphorous and extractable potassium are considered for soil quality assessment (Gregorich, 2002).

4.1.4. Organic Matter

Soil consists of a mineral fraction and an organic matter fraction which constitutes 5-10% of the soil (Gregorich, Carter, Doran, Pankhurst and Dwyer, 1997). Soil organic matter is the fraction of the soil which ranges from, undecaying plant and animal tissue through temporary products of decomposition to fairly stable amorphous humus (van der Watt and van Rooyen, 1995). Soil organic matter is composed of an active fraction and a stable humus fraction. The active fraction consist of living organisms (*bacteria; actinomycetes; yeast;*

algae; protozoa; nematodes, fauna and fungi) and a readily decomposable soil organic matter fraction (Gregorich et al., 1997).

As soil organic matter is closely related to other soil quality indicators such as aggregate stability, water holding capacity and cation exchange capacity, it is considered as one of the most important indicators of soil quality (Larson and Pierce, 1991 and Doran and Parkin, 1994; Christensen and Johnston, 1997; Hussain, Olson, Wander and Karlen, 1999; Schoenholtz, Miegroet and Burger, 2000). Soil organic matter is also a source of plant nutrients that are released into plant available forms through decomposition by microorganisms (Heil and Sposito, 1997). In relation to soil functionality, soil organic matter defines the soil fertility, stability, and the extent of erosion (Doran et al., 1994, Larson et al., 1994).

The comparison of changes in the masses of organic carbon and organic nitrogen may not provide an adequate measure of the important changes in soil organic matter content that may occur, but is considered as a coarse measure of soil quality (Gregorich et al., 1997). The good correlation between soil organic matter to other desirable soil attributes, such as high levels of microbial biomass and good soil structure, makes the measurement of soil organic matter important in soil quality assessment (Gregorich et al., 1997).

4.2. Materials and Methods

For the analysis of the soil chemical properties, composite samples of the topsoil for each of the treatments were made in order to identify possible changes in soil properties which may have occurred as a result of the different soil management practices. Sampling was done to 200 mm depth at all 20 plots within the study area.

The second set of sampling was done in order to compare differences between soil properties in the pedoderm as well as *between* tracks and *in* tracks for the soil management treatments. A total of 80 samples were collected to a depth of 50 mm.

4.2.1. Soil pH

The soil pH was measured after 10 g of 2 mm fraction of air dried soil was shaken with 50 ml of distilled water and the tip of a glass electrode inserted in the supernatant of the solution (Thomas, 1996).

4.2.2. Electrical conductivity (EC)

The soil electrical conductivity was measured after 10 g of 2 mm fraction of air dried soil was shaken with 50 ml of distilled water and the tip of a conductivity meter was inserted in the supernatant of the solution (Rhoades, 1996).

4.2.3. Extractable Potassium

The cations, including potassium, were extracted using a 1 M ammonium acetate extract at pH 7 (Tan, 1996).

4.2.4. Extractable Phosphorous

The available phosphorous was extracted by means of the Bray 2 method (Kuo, 1996).

4.2.5. Soil Organic Carbon and Nitrogen

Organic carbon and nitrogen was determined by dry combustion total C and N by complete combustion using a Eurovector Euro EA Elemental Analyzer. Stock amounts of C and N were calculated from the bulk density and sample depth (Lee et al., 2009) as illustrated below.

$$\textbf{Stock C (kg.ha}^{-1}\textbf{)} = \%C \times \rho_b\ (kg.m^{-3}) \times 0.05m \qquad \textbf{Equation 6}$$

4.2.6. Soil Organic Matter (SOM) content

The soil organic matter content was initially determined by loss on ignition, which yielded values that did not correspond with the estimated value, calculated from the organic carbon content (Conradie, 1994). For this reason, the organic matter content which was determined from the organic carbon percentage determined from complete dry combustion. The calculation is presented below.

$$\textbf{\%SOM} = 1.72 \times \%\ C \qquad \textbf{Equation 7}$$

4.3. Results and Discussion

The monitoring of the soil quality indicators is conducted in such a manner to identify trends in quantitative indicators of the soil. Establishing whether or not the various management practices are successful or whether management changes should be recommended is also an objective of several soil quality assessments (NRCS, 2004). Identifying what is considered as high or low values for a specific soil property for a specific land use, is imperative when interpreting the measured soil properties (Sparling, 2002).

Identifying defined targets in soil quality assessment for the various soil properties, are under discussion (Sparling, 2002). Nevertheless, the identification of what constitutes high, or low target value desirable for each particular soil and land use, is needed in order to interpret the numeric values (Sparling, 2002). These desirable (optimum) values were obtained from the crop requirements for the area under study. Each indicator is interpreted by comparing the obtained value with the optimum value for the specific land use. In this case, the land use is vineyards with five different soil management treatments.

The soil nutrient requirements for the vineyard, as defined by the ARC Infruitec-Nietvoorbij, will be used as the desired value for each of the indicators discussed.

The following sets of results were obtained for the chemical indicators as selected for the soil quality assessment. The results from the statistical analysis are discussed below and the data is listed in APPENDIX IV.

4.3.1. Soil pH

The soil pH was measured to determine the acidity or alkalinity of the soil. The treatment data is presented in the table and figures below.

Table 13. Average soil pH (H_2O) of 0-50 mm soil depth between tracks vs. in tracks

Treatment Name	Position	Depth 0-50 mm	t Grouping *
Mechanical	*Between tracks*	7.75	b a
Mechanical	*In tracks*	7.76	a
Chemical	*Between tracks*	7.5	b a c
Chemical	*In tracks*	7.35	b d c
Straw mulch	*Between tracks*	7.8	a
Straw mulch	*In tracks*	7.25	e d c
Annual cover crop	*Between tracks*	6.88	e
Annual cover crop	*In tracks*	7.03	e d
Perennial cover crop	*Between tracks*	7.11	e d c
Perennial cover crop	*In tracks*	7.17	e d c

* Means with the same letter are not significantly different. Data differ significantly at the 5% level.

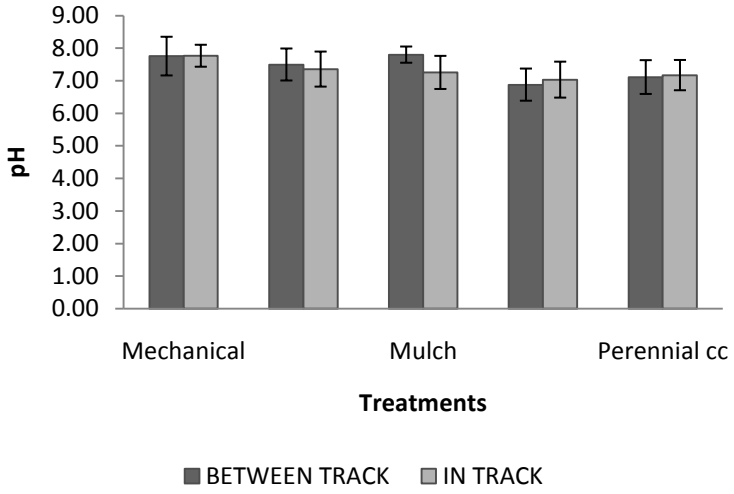


Figure 17. Average soil pH (H_2O) of 0-50 mm soil depth *Between* tracks vs. *In* tracks

Table 14. Soil pH(H_2O) of 0-50 mm vs. 0-200 mm soil composite

	sample depth ***pH (H_2O)***	
Treatment Name	**0-50 mm**	**0-200 mm**
Mechanical	7.76 a	8.56 a
Chemical	7.42 ab	8.32 b
Straw mulch	7.52 ab	8.52 a
Annual cover crop	6.95 b	8.07 a
Perennial cover crop	7.14 b	8.26 b

Means with the same letter are not significantly different. Data differ significantly at the 5% level.

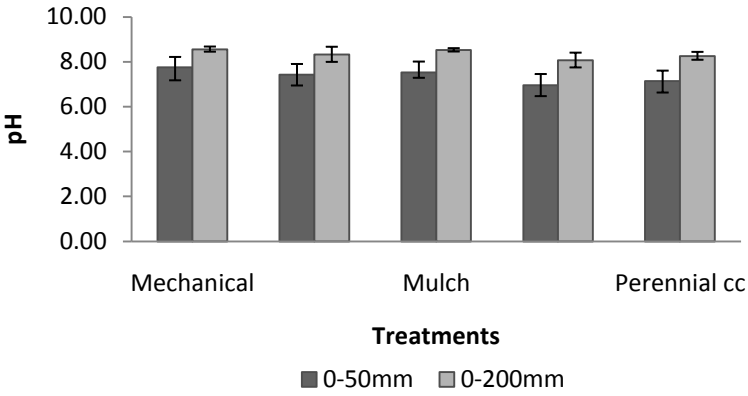


Figure 18. Soil pH of 0-50 mm vs. 0-200 mm soil composite

From the figures above, it is clear that no major differences exist between treatments in terms of soil pH. The differences in soil pH that do occur, relates to soil depth, with the pH increasing by at least 1 unit from 0-50m to 0-200 mm soil depth. No treatment or position differences $p>0.05$ were found (APPENDIX IV). The t-test reveals significant differences between the treatment means for mechanical vs. annual and perennial cover crops. The chemical and straw mulch treatments show statistically insignificant differences from other treatments.

Furthermore, these pH values indicate high base saturation in all plots that supports the exclusion of base saturation from the MDS in this case, as part of soil quality assessments.

4.3.2. Electrical conductivity (EC)

The results obtained from the analysis of the 0-50 mm soil fraction as well as the 0-200 mm soil composite. Below is a graphical representation of the two sampling positions and soil depths.

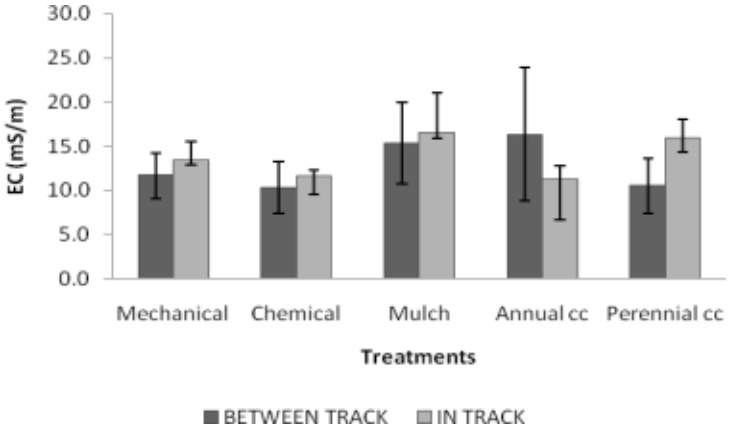


Figure 19. EC_e of 0-50 mm sample *Between* tracks and ***In*** tracks

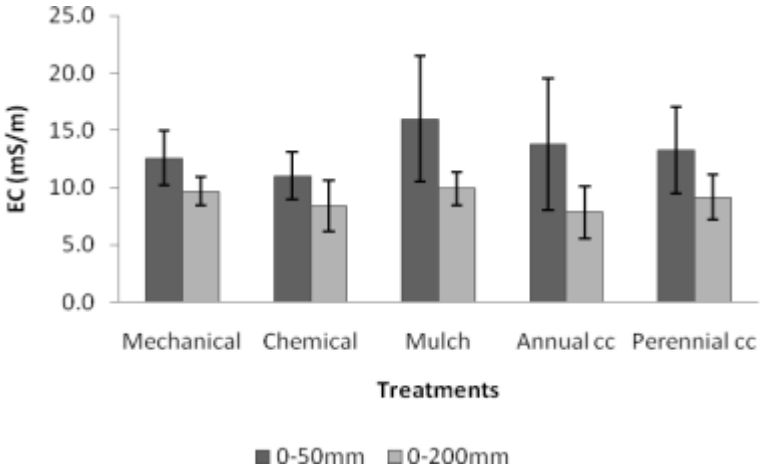


Figure 20. Average soil EC of 0-50 mm vs. 0-200 mm soil depth

At the 0-200 mm soil depth, no significant differences was found between most of the treatments. At the 0-50 mm soil depth, only the straw mulch treatment had significantly higher EC than the chemical treatment. In most of the treatments, the EC was higher *In* track than *Between* tracks, but this variation was not statistically significant. The possible reason for the higher salt content *In* tracks, could be due to salts accumulating in micro-depressions of tracks as well as poor infiltration occurring in tracks due to surface crusts that were observed during soil sampling (Figure 22 and Figure 22).

a) b)

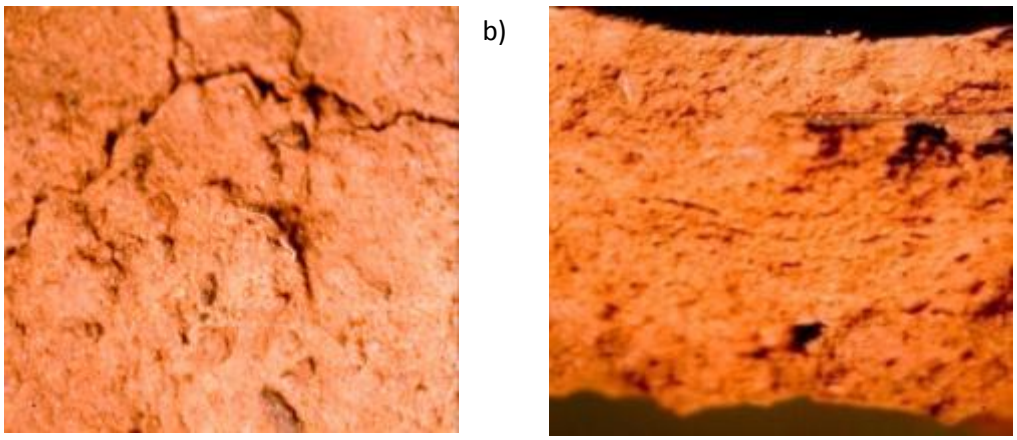


Figure 21. Soil surface crusts (3 x magnification). a) mechanical treatment plot(top view); b) cross section of soil crust from mechanical treatment

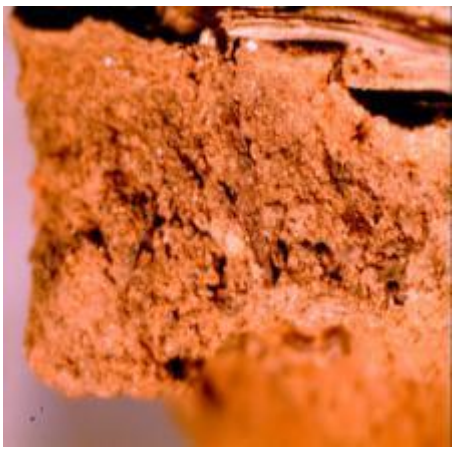
a)  b) 

Figure 22. Soil surface crusts (3 x magnification) cross section of a) straw mulch treatment plot; b) perennial cover crop treatment

The 0-50 mm soil composites in all treatments exhibit higher EC values in comparison to the 0-200 mm soil composites. Most of the salt accumulation occurs at the soil surface and thus less depth averaging (0-50 mm) reveals more distinct differences between treatments.

This observation corresponds with that found in other studies where the pedoderm soil properties are compared to that of the bulk top soil horizon (Karlen, Wollenhaupt, Erbach , Berry, Swan, Eash and Jordahl, 1994; Fey and Mills, 2004).

The annual cover crop treatment had an EC which was higher *Between* tracks in comparison to *In* tracks. The annual cover crop treatment bucks the general trend and is difficult to interpret.

Soil salinity is an important factor when considering the soil's suitability for specific crop production. Vineyards are relatively resistant to saline condition below 400 $mS.m^{-1}$(Richards, 1954) and thus the differences found, in terms of electrical conductivity, should not impact on crop yield.

4.3.3. Extractable N, P and K

For each of the plant macro nutrients evaluated, concentration norms as determined by the ARC-Infruitec/Nietvoorbij and that of the Fertilizer Society of South Africa (FSSA) were used to compare the obtained value with the desired value for vineyards. The data obtained from the analysis is listed in APPENDIX II. The nitrogen percentage and the bulk density were used to calculate the stock amounts (Lee, Hopmans, Rolston, Baer and Six, 2009) of nitrogen (Figure 23).

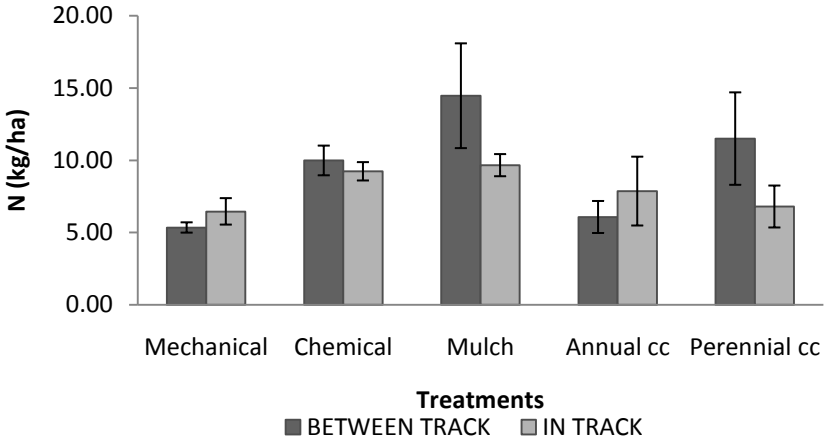


Figure 23. Nitrogen stock (kg.ha^{-1}) *Between* tracks vs. *In* tracks (0-50 mm)

The treatments were all fertilized with 14 kg.ha^{-1} of limestone ammonium nitrate (LAN) during seedbed preparation, as well as with 14 kg.ha^{-1} at the two to four leaf phenological stage of the cover crops. The other treatments received 14 kg.ha^{-1} by means of broadcasting (Fourie, 2010). The nitrogen fertilization norm of 20-40 kg N.ha^{-1} is recommended for wine grapes in a dryland-supplementary irrigated area, for ideal growth vigour to obtain a production yield of 10-15 ton.ha^{-1} (Conradie, 1994).

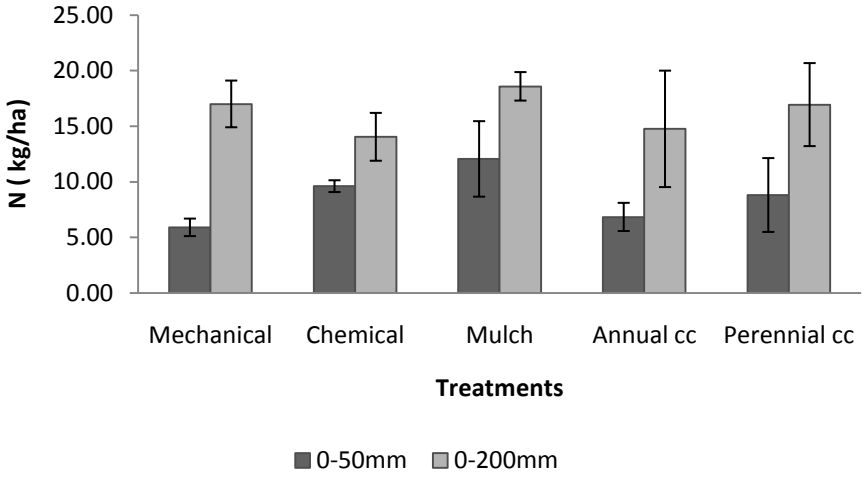


Figure 24. Nitrogen content of 0-50 mm and 0-200 mm soil

The nitrogen content was generally higher in the straw mulch treatment in comparison to the other treatments for the 0-50 mm and the 0-200 mm soil composites but this difference was not statistically significant due high variance of EC values. Under no-till practices, increases in nutrient concentration in the pedoderm in comparison to bulk top soil nutrient concentration is common (Karlen *et al.*, 1994) and the same trend was found in this study.

Phosphorous (P) application for vines is done more as a phosphorous deficiency precaution, rather than a phosphorous requirement. This is done since the P requirement for vines is relatively low (0.7 $kg.ton^{-1}$) in comparison to other plant nutrients (N requirement for vines amounts to 4kg N. ton-1). Soils, which have clay contents greater than 15% (as in with these soils), require a phosphorous content of 30 $mg.kg^{-1}$ for viticultural soils (Conradie, 1994).

Phosphorous content was only analyzed for the 0-200 mm soil composites of the five treatments and not assessed for between tracks and in tracks of the various treatments. The straw mulch treatment exhibited the highest P concentration but not significantly different from the other treatments. Generally all sample plots had P concentration values above the crop requirement level (Figure 25).

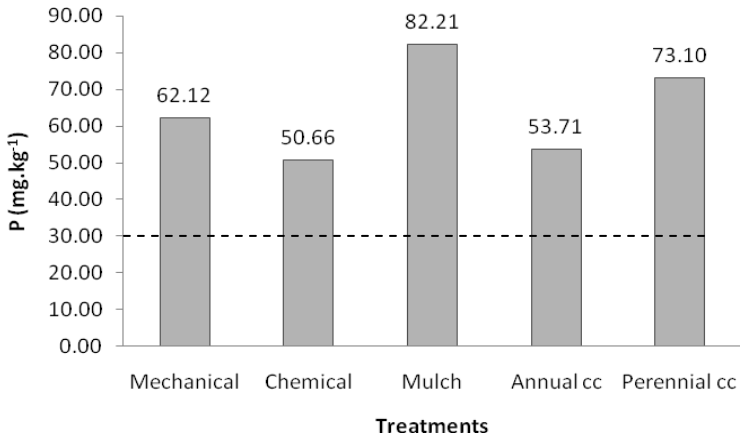


Figure 25. Phosphorus concentration of 0-200 mm soil composites relative to the P requirement (--) for vineyards

In soils with an exchangeable potassium concentration above 5 $cmol_c.kg^{-1}$, as with the soils for the study area (Table 16), the norm for potassium fertilizer is 80-100 mg.kg-1 (Conradie, 1994). The recommendation was made specifically for the viticultural dark coloured, structured, alluvial, clay loam soils of the Breede River Valley (Conradie, 1994). The potassium content of the soil depths measured both had concentrations above the requirement for wine grapes (Table 15).

Where potassium levels are higher than 120 $mg.kg^{-1}$, no potassium should be applied on soils (Conradie, 1994).

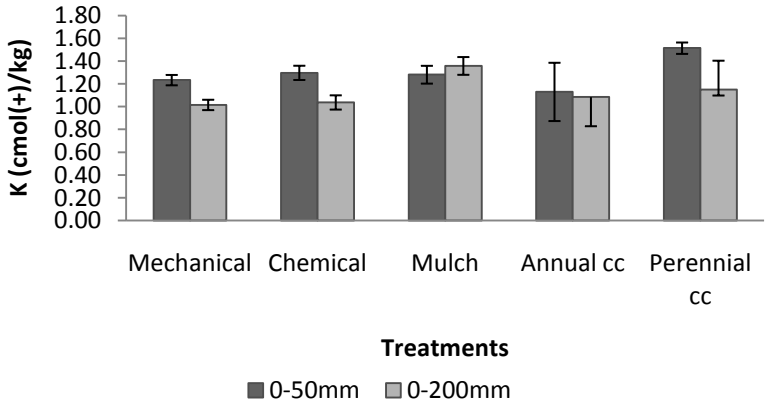


Figure 26. Potassium concentration of 0-50 mm and 0-200 mm soil composites

The potassium concentration for the 0-200 mm soil depth of the straw mulch, annual cover crop and the perennial cover crop treatments is significantly different from each other, with the perennial cover crop exhibiting the highest K concentration. The chemical and mechanical treatments showed mixed statistically insignificant results (Table 14).

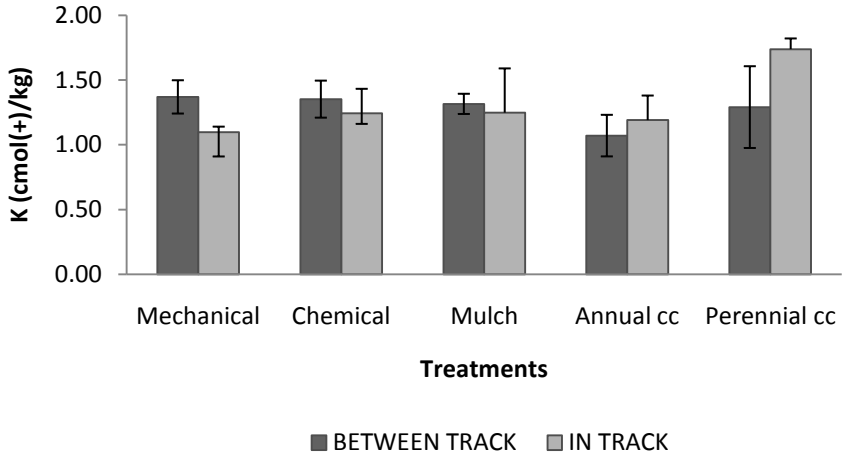


Figure 27. Potassium concentration *Between* tracks vs. *In* tracks

Table 15. Extractable N, P and K for 0-200 mm soil composites

Treatment name	N %	P mg.kg^{-1}	K mg.kg^{-1}
Mechanical	0.08 *a*	62.12 *a*	481.00 *c b*
Chemical	0.06 *a*	50.66 *a*	496.00 *c b*
Straw mulch	0.07 *a*	82.21 *a*	499.50 *a*
Annual cover crop	0.06 *a*	53.71 *a*	440.63 *c*
Perennial cover crop	0.08 *a*	73.10 *a*	590.25 *b*

Means with the same letter are not significantly different. Data differ significantly at the 5% level.

Table 16. Exchangeable cations of 0-50 mm and 0-200 mm soil composites

	Ca ($cmol_c.kg^{-1}$)		Mg ($cmol_c.kg^{-1}$)		Na ($cmol_c.kg^{-1}$)		K ($cmol_c.kg^{-1}$)	
Treatment Name	0-50 mm	0-200 mm	0-50 mm	0-200 mm	0-50 mm	0-200 mm	0-50 mm	0-200 mm
Mechanical	15.80	12.14	4.26	2.63	0.45	0.27	1.23	1.02
Chemical	14.46	9.80	4.39	2.84	0.45	0.25	1.30	1.04
Straw mulch	14.29	10.47	5.73	3.13	0.45	0.23	1.28	1.36
Annual cover crop	10.99	6.92	4.63	2.81	0.51	0.29	1.13	1.08
Perennial cover crop	11.61	8.72	5.31	2.84	0.49	0.26	1.51	1.15

Table 17. Exchangeable cations *Between* tracks vs. *In* tracks (0-50 mm)

	Exchangeable cations ($cmol_c.kg^{-1}$)									
Treatment Name	**Ca**		**Mg**		**Na**		**K**		**ESP (%)**	
	Between tracks	**In tracks**	**Between tracks**	**In tracks**	**Between tracks**	**In tracks**	**Between tracks**	**In tracks**	**Between tracks**	**In tracks**
Mechanical	15.00	16.61	3.96	4.57	0.40	0.50	1.37	1.10	1.86	2.14
Chemical	14.02	14.90	4.14	4.64	0.38	0.51	1.35	1.24	1.81	2.29
Straw mulch	13.05	15.52	5.09	6.37	0.39	0.51	1.31	1.25	1.85	2.06
Annual cover crop	10.30	11.68	4.42	4.83	0.45	0.57	1.07	1.19	2.56	2.89
Perennial cover crop	10.72	12.50	4.71	5.92	0.46	0.51	1.29	1.74	2.37	2.19

The Exchangeable Sodium Percentage (ESP), was calculated to determine to what extent, the soils sodicity would be influenced at the pedoderm. As observed with the EC measurements, the ESP values were generally higher *In* tracks than *Between* tracks (Table 17). The perennial cover crop treatment plot was the exception, where the ESP value was higher *Between* tracks. The reason for this is not clear, since the measured sodium value In tracks was found to be higher than the sodium level Between tracks. Soils with ESP values below 5% are also not considered sodic and therefore, the use of ESP should only be considered under these conditions. ESP values, above 15% are regarded as critical due to the effect of sodium on the

soil physical properties (Murphy, 2002). The ESP values for the various treatment plots are the range of 1.81-2.89%. The dominant exchangeable cation in the treatment plots is calcium as clearly seen in Table 17.

4.3.4. Organic Matter

The results obtained from the analysis of the 0-50 mm soil fraction as well as the 0-200 mm soil composites can be found in APPENDIX II. The organic matter content is used, in addition to the clay content, as a broad guideline in nitrogen fertilizer recommendations (Conradie, 1994). Heavy soils (>6% clay), as in the case of the 0-50 mm fraction of the study area (where the percentage carbon > 0.9%) no nitrogen fertilizer is required for young vines (Conradie, 1994). For soils with a carbon content of 1%, the total nitrogen concentration amounts to approximately 770 $mg.kg^{-1}$ (Conradie, 1994).

Table 18. Organic matter content for 0-50 mm and 0-200 mm soil composites

	sample depth OM%	
Treatment Name	**0-50 mm**	**0-200 mm**
Mechanical	2.33	1.69
Chemical	3.40	1.27
Straw mulch	3.29	1.29
Annual cover crop	2.34	1.33
Perennial cover crop	3.12	1.46

Data did not differ significantly at the 5% level.

Although the mechanical and annual cover crop treatment seemingly show lower OM% means, but these differences are not statistically significant (APPENDIX IV). The percentage of soil organic matter in the 0-50 mm and 0-200 mm soil depths of the five treatments did not differ significantly. The *In* tracks and *Between* track means for the various treatment showed significant differences within treatments (Table 18). Vehicle movement seems to have had a greater effect than the treatment itself.

Table 19. Organic matter content *Between* tracks vs. *In* tracks (0-50 mm)

	OM %	
Treatment Name	**Between tracks**	**In tracks**
Mechanical	2.41	2.25
Chemical	3.72	3.08
Straw mulch	4.11	2.47
Annual cover crop	2.22	2.46
Perennial cover crop	3.85	2.39

Data did not differ significantly at the 5% level.

The worth of determining organic carbon content in soils extends to prediction of soil physical properties such an aggregation, water holding capacity (FSSA, 2007) and aeration (Conradie, 1994). The latter can be determined from the carbon:nitrogen ratio in soils, where a well aerated soil has normally has a C:N of 13 (Conradie, 1994). The C:N values are shown in **Table 20**. The C:N in the 0-50 mm and 0-200 mm soil depths of the five treatments did not differ significantly. The C:N for *Between* tracks and *In* tracks also did not differ significantly.

Table 20. Carbon Nitrogen (C:N) ratio of 0-50 mm and 0-200 mm soil composites

	sample depth C:N	
Treatment Name	**0-50 mm**	**0-200 mm**
Mechanical	12.78	12.48
Chemical	11.52	12.10
Straw mulch	10.83	10.32
Annual cover crop	11.98	13.15
Perennial cover crop	12.10	11.26

Data did not differ significantly at the 5% level.

The variations amongst treatments, in terms of stock OM amounts, are observed to be more apparent in the 0-50 mm than in the 0-200 mm soil composites (Figure 28). With the straw mulch treatment yielding the highest stock OM content with the 0-50 mm soil depth.

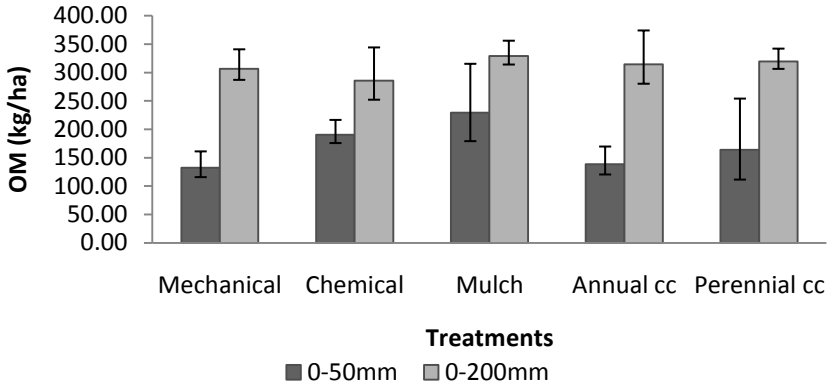


Figure 28. Organic matter content of 0-50 mm and 0-200 mm soil composites

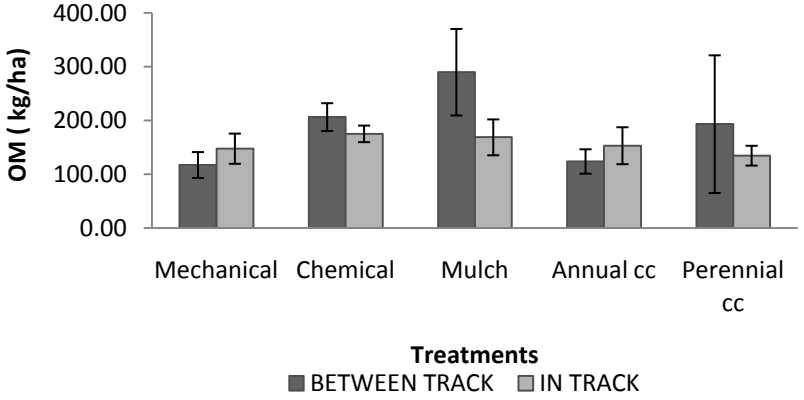


Figure 29. Organic matter content *Between* tracks vs. *In* tracks

The importance of noting such variation is of value when considering a range of soil management treatments potential for soil carbon sequestration. The rationale behind soil

carbon sequestration is that an increase of soil organic carbon content, presumably contributes to the reduction in atmospheric carbon dioxide (Ringuis, 2002).

A study examining the soil carbon sequestration opportunities and challenges for developing countries in sub-Saharan Africa, highlights the improving agricultural practices and land-use management to increase the agricultural productivity and sequester soil carbon (Ringuis, 2002). Being able to account for the gains of soil organic matter resulting from a specific land use is paramount. The use of smaller sampling increments (pedoderm) provides more pronounced evidence of the influence of the land use management on soil carbon. The difference seen in the soil management treatments of this study is an example of this.

The stock values obtained by a study conducted by Mills and Cowling (2010) on below ground carbon stocks in landscapes of South Africa, observed that soil carbon stocks also decrease substantially with soil depth.

Knowledge of the SOC stock values found in other studies within South Africa is useful, since threshold values for organic matter content were not available at the time of this study. In the study of Mills and Cowling (2002), old agricultural land, intact and degraded *Spekboom thicket* had been found to have SOC stocks in the range of ±5-10 ton.ha^{-1} for the 0-100mm soil depth. This range was obtained from graph illustrating soil carbon (ton.ha^{-1}) in the published works of this study (Mills and Cowling, 2010). The SOC obtained in this study for the 0-50 mm soil depth at most yielded SOC of 0.13 ton.ha^{-1}.

Table 21. Soil Organic Carbon Stock values for soil management treatments

Treatment Name	SOC kg.ha^{-1}	SOC ton.ha^{-1}
Mechanical	76.96	0.08
Chemical	110.88	0.11
Mulch	133.25	0.13
Annual cover crop	80.49	0.08
Perennial cover crop	95.26	0.10

4.4. Summary and conclusions

Soil quality assessments, consists of monitoring of soil properties useful as indicators of soil quality. The selected soil properties, referred to as indicators, are measured and compared to values required for optimum crop production. If the measured values for the various indicators fall out of range of the required optimum, production management interventions are recommended to improve the soil quality or overall soil condition for the specific production system.

The optimum pH $_{(H2O)}$ for vineyards range between pH 6-7 (FSSA, 2007), where the treatments pH range from 6.88 to 7.8. This range is suitable for most crops, though slightly alkaline (FSSA, 2007).

The electrical conductivity of the treatments is also within a range that is not harmful to vineyards. The differences observed amongst treatments in terms of the EC, were mostly accounted for by the differences in terms of water holding capacity brought about by the higher organic material accumulation of the straw mulch treatment. As a result, more dissolved salts are present due to the water held by organic matter. It needs to be emphasized that the average EC of the straw mulch treatment is way below the threshold value for viticultural soils.

Nitrogen is applied annually in the form of 50 $kg.ha^{-1}$ LAN, irrespective of vine vigour, to ensure optimum production of dry material. As mentioned earlier, the phosphorous content required for optimal vineyard growth is relatively low. The measured P content in the mechanical, straw mulch and perennial cover crop treatments are double the norm for viticultural soils. Regarding the potassium levels in the various treatments, where potassium levels are higher than 120 $mg.kg^{-1}$, no production management intervention is required.

Organic matter content is not a direct requirement for crop production and at present no norms are available for optimum organic content levels for viticultural soils. The organic matter content as an indicator remains an essential component in the minimum data set due to the direct effects OM content have on overall functionality. Monitoring the

accumulation of organic matter in soil due to agricultural practices is beneficial to providing evidence of carbon being sequestered as a result of certain practices.

Generally, the chemical indicators of soil quality measured require no management intervention to obtain optimum soil quality conditions for optimal vine growth. No noticeable differences were found within the treatments in terms of the measured indicators, verses the desired optimum value for the respective indicator.

The study also paid special attention to possible differences in soil quality, which could be the result of agricultural traffic (this includes any form of compaction induced by traffic on the treatment plots). It is widely known that vehicle traffic has direct impacts on soil physical properties such as reducing pore space and increasing the bulk density of soils (Raper, 2004). With the regard to soil chemical properties, the chemical indicators, N and OM content was generally higher *In* tracks than *Between* tracks. The exchange cations measured (Ca, Mg, Na and K) all had higher values for *Between* tracks than *In* tracks. The accumulation of these nutrients *In* tracks could be as a result of the impact of agricultural vehicle traffic, which causes compaction, thus restricting the amount of possible movement of these nutrients deeper in the soil horizon. This occurrence is also more prevalent within the pedoderm of conservation soil management type where pedodermal expression is known to be maximal (Fey and Mills, 2005).

5. Selected soil biological properties

5.1. Introduction

For the present study, biological soil quality indicators were selected based on the same criteria used to select the chemical and physical indicators of soil quality. The following indicators will briefly be discussed namely: soil microbial biomass (SMB), potential mineralizable nitrogen (PMN), soil respiration, soil fauna and soil microbial diversity. These indicators have been part of numerous minimum datasets used for assessing and monitoring soil quality (Stenberg, 1999; Andrews et al., 2002).

5.1.1 Soil Microbial Biomass (SMB)

The microbial biomass the living component of the soil. Microbial biomass includes bacteria, fungi, soil microfauna and algae and accounts for 1-3% of organic carbon (Gregorich *et al*., 1997).

Microbial biomass is significant as it plays a key role in the soil with controlling the conversion of organic matter into plant nutrients. SMB also influences the storage of carbon through immobilization (Gregorich *et al*., 1997). Since SMB is regarded as the most active pool and dynamic pool of soil organic matter, due to the role it plays in immobilization and mineralization processes, the changes in SMB can be considered as an "early warning" signal changing soil conditions (Bloem *et al*., 2006). Soil microbial biomass responds quickly to changes in soil processes resulting from changes in soil management and has thus been part of most minimum data sets for soil quality assessment (Stenberg, 1999; Andrews *et al.,* 2002)

Soil microbial biomass may be determined by a variety of methods which, at this stage, have not yet been standardized for soil quality assessment. Direct methods of measuring SMB consists of counting the colony forming units of microbes on soil dilution series using the most probable number or direct microscopic counting methods (Turco *et al*., 1994; Islam and

Wright, 2006). Indirect methods include assessing SMB by using biochemical, chemical and physical principles for the determination of cell constituents such as carbon, nitrogen, phosphorous, sulphur, adenosine triphosphate and phospholipids of microbes (Islam and Wright, 2006). Common methods of extraction of these constituents with their respective advantages and disadvantages have been summarized in Table 22.

Indirect methods are more commonly used than direct methods due to the rapid, simple and precise measurements of SMB conducted in past studies. The chloroform fumigation incubation has been used as a reference for the calibrations and correlation for other methods (Islam and Wright, 2006). The microwave soil extraction method has in recent studies on SMB (Islam and Weil, 1998; Sparling *et al*.,, 1998; Montgomery *et al*., 2000) been used due to the simplicity, rapidity, and precision of the method (Islam and Wright, 2006). For the present study, the microwave soil extraction method (Islam and Weil, 1998) modified by Wang et al., (2001) will be used for determination of SMB.

5.1.2 Potential Mineralizable Nitrogen (PMN)

Nitrogen availability is one of the major determinants in soil fertility. Predicting the amount and timing of nitrogen mineralization (*N availability)* in soil is of importance since improper use of N fertilizers could result in environmental pollution problems (Duxbury and Nkambule, 1994). Nitrogen mineralization is measured as the net flux of inorganic nitrogen and immobilization by soil organisms. The mineralizable nitrogen is typically measured in laboratory incubations of soil (Gregorich *et al*., 1997). The organisms, the physical, the chemical, the climatic environment, and the quality of plant residue affect the mineralization of organic material in terrestrial ecosystems (Gregorich *et al*., 1997). Since moisture and temperature constraints that occur in the field are removed in laboratory incubations, the measurements obtained for mineralizable nitrogen, represent the maximum potential rates that only rarely occur in the field (Gregorich *et al*., 1994). Nonetheless, mineralizable nitrogen is considered an important aspect of soil quality due to the usefulness thereof in determining the capacity of soil organic matter to supply inorganic nitrogen to the crop (Gregorich *et al*., 1994).

Table 22. Advantages and Disadvantages of Microbial Biomass Measurement Methods (adapted from Islam and Wright, 2006)

Method	Advantage	Disadvantage
Chloroform ($CHCl_3$) Fumigation Incubation and Extraction methods	Both CFI and CEF methods yield good estimates of SMB	$CHCl_3$ is a biohazard. CFI method is affected by high organic matter content, organic amendments, low pH, and soil waterlogged conditions. Time-consuming and involves several steps
Microwave (MW) Irradiation Incubation and Extraction method	rapid, precise, safe and reliable very economical	
Rehydration Method	simple procedure for SMB determination that does not use hazardous chemicals	Prolonged air-drying of soil often releases non biomass C, a portion of the SMB may be insensitive to air-drying.
Freeze-Dried Soil Extraction Method	precise, reliable, and safe	Requires trained personnel and sophisticated equipment.
Adenosine Triphosphate Extraction Method		SMB measurement is often uncertain because of storage conditions, season of collection. low and irregular recovery, and weak correlation to SMB
Phospholipid Fatty Acids Extraction Method	Extracts are easily analyzed to identify	Time-consuming, complex, and expensive method
Substrate-Induced Respiration (SIR) Method	fast method to measure SMB,	May often overestimate by measuring the glucose responsive active portion of the SMB. Requires a Gas Chromatography to measure evolved CO_2.
UV Spectroscopic Method	rapid and inexpensive method	Process uses $CHCl_3$. The results are often compromised by soil colloidal interferences and electrolyte precipitation.

5.1.3 Soil Respiration

Soil respiration has traditionally been used as a measure of soil biological activity (Jacinthe and Lal, 2006). Soil microorganisms oxidize organic materials with the generation of energy and production of carbon dioxide (Jacinthe and Lal, 2006). In terms of soil quality, soil respiration has been used as an indicator of quality and fertility, especially with regard to the effect of soil management practices on soil microbial activity (Haney *et al*., 2008). Soil respiration rate is measured as the volume of CO_2 released (or O_2 consumed) per unit soil volume per unit time (White, 2006).

Various methods for measuring soil respiration exist. These methods include the alkali absorption method (A-A-method) whereby the CO_2, evolved in a closed chamber, is absorbed in a caustic soda solution; the open flow infra-red gas analyzer method whereby ambient air flows through a chamber and the CO_2 flux is calculated from the concentration difference between in-let and outlet-air (Bekku *et al*., 1996).

Other determinations make use of a closed chamber whereby CO_2 is periodically sampled and the CO_2 concentration in the chamber measured (Bekku *et al*., 1996). Another type of closed chamber in which the air is circulated from the gas analyzer and returned to the chamber is known as the dynamic closed chamber method (Bekku *et al.,* 1996). It was found by Bekku *et al.,* (1996) and others (Jacinthe *et al*., 2006) that the infra-red gas analyzer method, closed chamber method and dynamic closed chamber method were more suitable for soil respiration measurement, than the alkali absorption method which overestimated the actual respiration values in comparison with the other methods. More recently, a comparison of the chemical titration method; infra-red gas analysis or gas chromatograph; and the Solvita gel system for soil CO_2 analysis was performed in order to identify suitable methods for laboratory determination of soil CO_2 respiration (Haney *et al.,* 2008). The results obtained from the comparative study indicated that the methods compared well with each other (Haney *et al*., 2008). Aspects highlighted from the study indicate that the chemical titration method pose environmental concern regarding the disposal of chemicals

used during the chemical titration (Haney *et al.,* 2008). The Sovita gel kit measurements proved to be a simple and rapid means of quantifying soil microbial activity (Haney *et al.,* 2008). With regard to the present study, the Solvita gel kit was too costly for the large sample numbers intended for this specific study. The use of gas chromatography as a detector of the CO_2 concentration, has also been used in previous investigations of soil microbial activity. (Macfadyen, 1970; Nakayama, 1990; Mondini *et al*., 2010). Soil respiration, in this case, is assumed to be equal to the change in CO_2 concentration over the incubation period minus the CO_2 concentration in the atmosphere (Zimmermann and Frey, 2002).The ease of measurement and cost effectiveness was the main criteria for use of the specific method.

5.1.4 Soil Fauna

Soil fauna consist of organisms classified according to their size *in width* as microfauna (100 µm), mesofauna (100-2000 µm) and macrofauna (>2000 µm) (Gregorich *et al.,* 1994). Of the major functional properties of soils, in which soil fauna is directly involved in, is the disappearance, decomposition, and release of nutrients from crop and animal residues (Gregorich et al.,1994). The development of biopores and the mixing of organic and mineral soil components by soil fauna, are also directly related to the major functional properties of soil (Gregorich et al., 1994).

The soil faunal populations are greatly affected by soil moisture, temperature and availability of food (Lavelle, 1988; Bardget and Cook, 1998; Mikola, Bardgett and Hedlund, 2002). Soil and crop management may also affect the composition and abundance of soil faunal communities (Mikola et al., 2002). With regard to soil fertility, soil fauna plays an important role in the structure of soils and therefore the determination of the abundance, diversity, or activity is thought useful as an indicator of soil quality (Gregorich et al., 1994).

Earthworms are considered of the most important soil fauna in terms of biomass and activity. Soil properties such as structure and chemistry are known to be substantially influenced by earthworms' activity (Chaoui, Zibilske and Ohno, 2002). Earthworms are

involved in soil processes such as organic matter decomposition (Römbkea, Jänscha and Didden, 2005). The use of earthworms as indicators of soil quality is widely used in soil quality assessments due to the influences earthworm activity and abundance have on major soil properties (VandenBygaart, Fox, Fallow and Protz, 2000; Chaoui *et al*., 2002, Römbkea *et al*., 2005).

The soil micro-anthropod, earthworm abundance and diversity was investigated as part of broader the Soil Health project run by the Agricultural Research Council, Infruitec Nietvoorbij. More detail with regard to results obtained during their investigation will be mentioned in the Results and Discussion chapter.

5.3. Materials and Methods

The samples were sealed and stored at 8˚C until analysis was conducted. The various treatment samples were analyzed for soil microbial biomass, potential mineralizable nitrogen and soil respiration.

5.2.1 Soil Microbial Biomass (SMB)

Soil microbial biomass as determined by an adapted method of the microwave irradiation-microbial biomass carbon method (Islam and Weil, 1998) with field moist samples (equivalent to 10 g dry weight). Soils were irradiated twice at 600 W for 70 sec and temperature of the samples measured. The temperature of irradiated samples ranged from 70-86°C. The irradiated samples along with non-irradiated (control) samples were then incubated for 10 days at room temperature. Following the incubation period, samples were quantitatively transferred to 500 ml beakers with distilled water and water was removed by evaporating the sample on a water bath. Dried samples were then milled and carbon and nitrogen determined by dry combustion with an elemental analyzer (Eurovector).

5.2.2 Potential Mineralizable Nitrogen (PMN)

Potential mineralizable nitrogen as determined by incubating soil samples and the amount of ammonium produced in that period was used to indicate the capacity for nitrogen

mineralization (Gugino *et al*., 2007). Air dried samples were sieved and two 8 g soil samples were weighed into 50 ml bottles. To one bottle, 40 mL of 2 M KCl was added and shaken on a mechanical shaker for 1 hour, filtered and the soil extracts were analyzed for ammonium concentration. To the second bottle, 10 ml of distilled water was added, then hand shaken and incubated for 7 days at 30°C. After the incubation period, 30 mL of 2.67M KCl was added to the second bottle and shaken for 1hour on the mechanical shaker, filtered and the soil extracts were analyzed for ammonium concentration.

5.2.3 Soil Respiration (SR)

Soil respiration was determined by incubating field moist samples (equivalent to 10g dw) in 50ml bottles sealed for a period of incubated for 7days at 30°C. Following the incubation period, the headspace in the sample bottle was collected using a syringe. The headspace samples collected was then analyzed by for CO_2, C_2H_4 and O_2 by means of gas chromatography.

5.2.4 Soil Fauna

The following analysis was conducted as part of the broader soil health project of the ARC. Soil composites were sampled using a auger to a depth of 75 mm. This was done since the micro-arthropods mainly occupy the top soil. The samples were taken to the laboratory and microarthropods were extracted with the Berlese-Tullgren extraction chamber. The organisms were later sorted into different orders and families, depending on the extent of identification possible with the use of current keys (ARC Report, 2009). In addition to the micro-anthropods being analysed, an earthworm count was conducted for the study site (Maboeta, 2009).

5.4. Results and discussion

The monitoring of the soil quality indicators is conducted in such a manner to identify trends in quantitative indicators of the soil. Establishing whether or not the various management practices are successful or whether additional management changes should be recommended, is also an objective of soil quality assessments (NRCS, 2004). Identifying

what is considered as high or low values for a specific soil property for a specific land use, is imperative when interpreting the measured soil properties (Sparling, 2002). Identifying defined targets in soil quality assessment for the various soil properties, are under discussion (Sparling, 2002). Nevertheless, the identification of what constitutes high, of low target values desirable for each particular soil and land use, is needed in order to interpret the numeric values (Sparling, 2002). These desirable (optimum) values were obtained from the crop requirements for the area under study. Each of the indicators is interpreted by comparing the obtained value, with the optimum value for the specific land use. Soil biological properties have received little attention in past studies and thus no historical data is available for the properties measured. Critical limits for these indicators will be interpreted in terms of the indicators ability sustain favourable conditions in the soil for optimal crop growth. The results from the statistical analysis are discussed below and the data is listed in APPENDIX IV.

5.2.5 Soil Microbial Biomass (SMB)

The soil microbial biomass was measured in order to indicate change in terms of biological activity and is considered to be a rapidly changing and highly dynamic characteristic of soil.

Analysis was conducted for each position (*Between* tracks and *In* tracks) per treatment replication, resulting in a total of 40 samples. The results presented in the study were obtained by removing all negative yielding samples (where the initial value was higher than that of the incubated value) from the specific batch and calculating an average value of the replication per treatment. Stock amounts of soil microbial biomass were also calculated using the bulk density and sample depth (Table 23). The results obtained from the analysis are presented graphically and the raw data can be found in APPENDIX III.

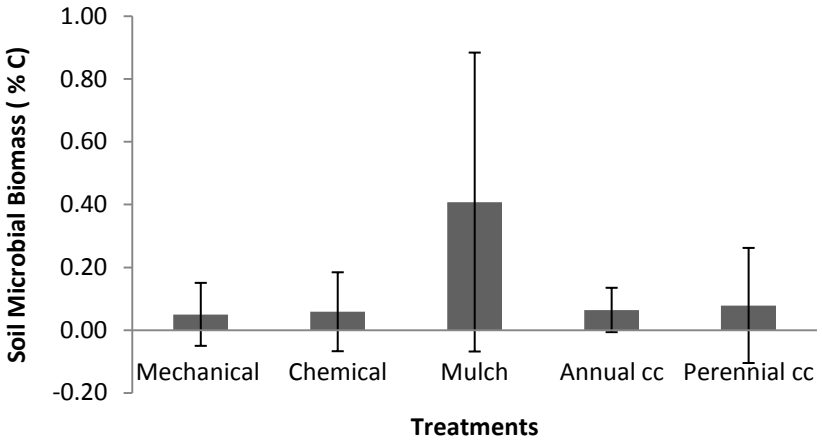


Figure 30. Soil microbial biomass per soil management treatment

Table 23. Stock soil microbial biomass per soil management treatment

Treatment Name	Soil Microbial Biomass (kg C.ha^{-1})
Mechanical	2.74
Chemical	3.28
Straw mulch	26.13
Annual cover crop	3.78
Perennial cover crop	4.28

Overall the straw mulch treatment yielded the highest soil microbial biomass followed by the perennial cover crop treatment. This result was expected since the straw mulch treatment has the highest organic matter content and the nature of the treatment is the annual additional of organic material in the form of straw. Comparisons *Between* tracks and *In* tracks were not possible since only a few of treatment samples yielded positive results for the analysis conducted. The statistical analysis included the negative values obtained from the method used and revealed no significant differences between treatments or sampling position (*Between* or *In* tracks).

5.2.6 Potential Mineralizable Nitrogen (PMN)

The soil nitrogen mineralization potential is defined as the quantity of soil organic nitrogen that is susceptible to mineralization (Standford, Carter and Smith, 1974). Analysis was conducted for each position (*Between* tracks and *In* tracks) per treatment replication, resulting in a total of 40 samples.

The results presented in the study were obtained by removing all negative yielding samples (where the initial value was higher than that of the incubated value) from the specific batch and calculating an average value of the replication per treatment. The results obtained from the analysis are presented graphically and the raw data can be found in APPENDIX III.

Shown in the figures below are values of PMN estimated from the concentration of ammonium mineralized during the short-term (7days) incubation.

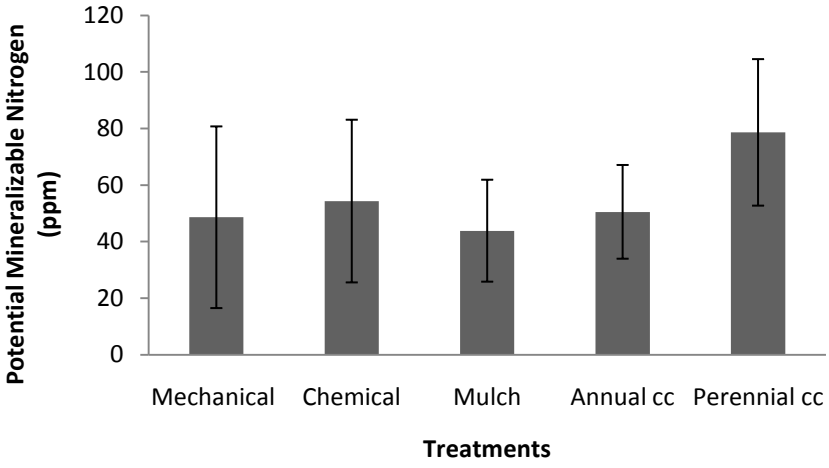


Figure 31. Average potential mineralizable nitrogen (ppm) for soil management treatments

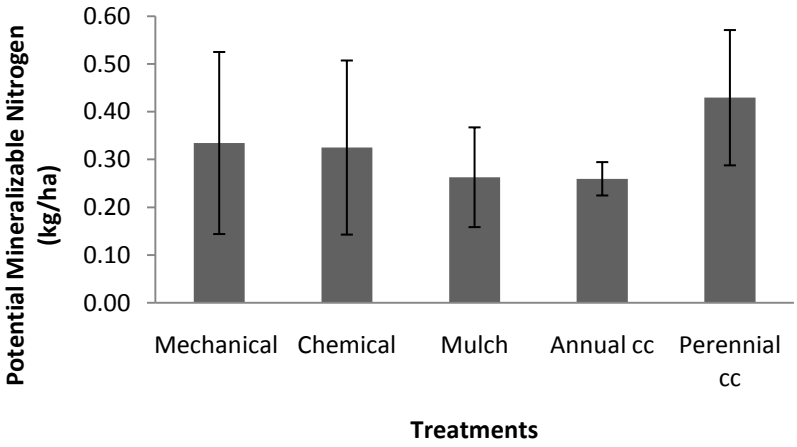


Figure 32. Average potential mineralizable nitrogen (kg.ha^{-1}) for soil management treatments.

The statistical analysis included the negative values (ppm) obtained revealed no significant differences between treatments or sampling position (*Between* or *In* tracks).

Using the stock amount of nitrogen, instead of the ppm values, in comparing the PMN of the various treatments provides a means of evaluating the PMN with that of the organic nitrogen determined as part of the chemical indicators.

PMN is determined in order to evaluate the capacity of soil organic matter to supply inorganic nitrogen to the crop. The C:N in organic matter determines whether immobilization or mineralization is likely to occur. A C:N ratio of 25 to 30 is considered a critical point for either immobilization or mineralization(Van Cleemput and Boeckx, 2002).

The mechanical treatment had the highest C:N and the lowest amount of available nitrogen with the straw mulch treatment obtaining the lowest C:N ratio and the highest available nitrogen (Figure 33). This corresponds with work done by Harmsen and Van Schreven (1955) who found that a high C:N is often associated with a low N availability as well as inversely low C:N ratios associated with high N availability (Harmsen and Van Schreven, 1955).

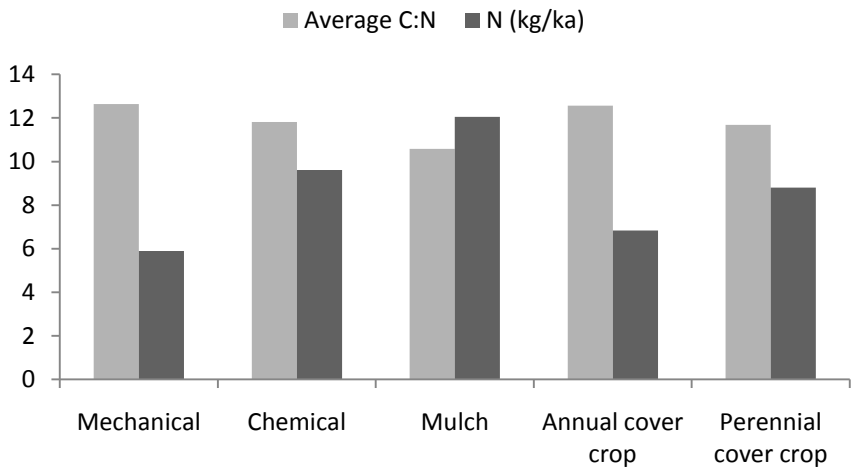


Figure 33. Carbon nitrogen ratio vs. nitrogen availability

Table 24. Total Organic Nitrogen ($kg.ha^{-1}$) and Potential Mineralizable Nitrogen ($kg.ha^{-1}$)

Treatment Name	Organic N ($kg.ha^{-1}$)	PMN * ($kg.ha^{-1}$)
Mechanical	5.90	0.33
Chemical	9.61	0.33
Straw mulch	12.05	0.26
Annual cover crop	6.84	0.26
Perennial cover crop	8.81	0.43

*Data did not differ significantly at the 5% level.

5.2.7 Soil Respiration (SR)

During the soil respiration process, oxygen is consumed by soil microorganisms and carbon dioxide is generated. Since respiration is essential for all life forms in soil, it provides a measure of the soils biological activity (Jacinthe and Lal, 2006). Soil management practices, which favour residue input and decomposition and that minimize respiratory carbon losses, is in due course likely to result in the net increase in soil carbon stocks (Jacinthe and Lal,

2006). The soil carbon stocks for the pedoderm have been calculated for the various soil management treatments (Table 25).

Table 25. Total Soil Organic Carbon (kg.ha^{-1}) of soil pedoderm per soil management treatment

Treatment Name	Soil Organic Carbon (kg C.ha^{-1})
Mechanical	76.96
Chemical	110.88
Straw mulch	133.25
Annual cover crop	80.49
Perennial cover crop	95.26

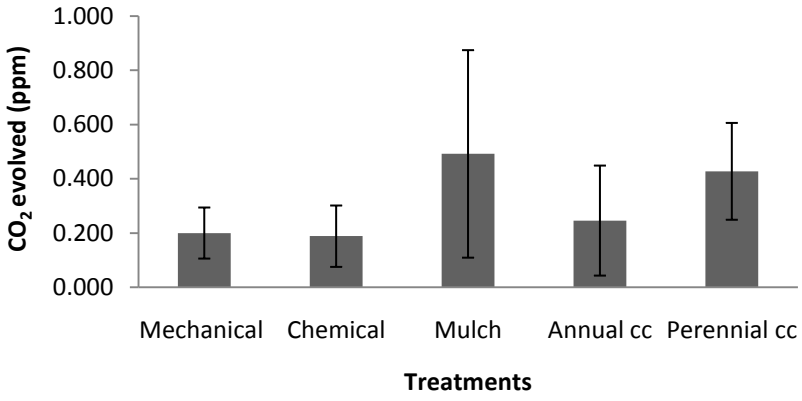


Figure 34. Soil respiration (CO_2 ppm) for soil management treatments

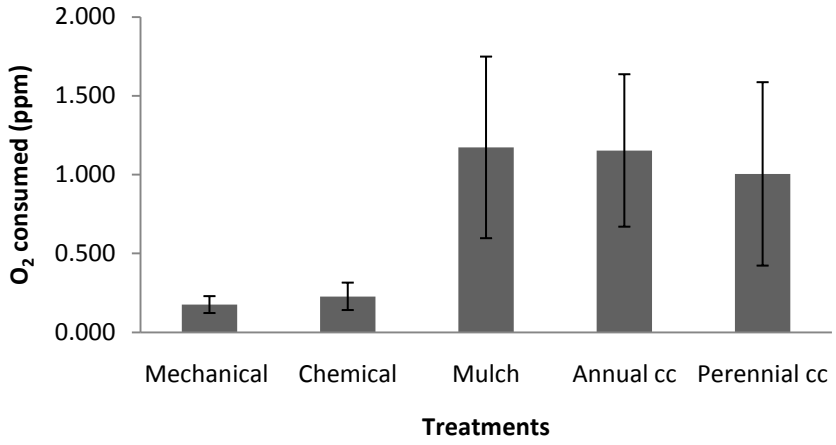


Figure 35. Oxygen consumed during short incubation period for soil management treatments

The incorporation of plant and animal biomass carbon into the soil organic content (SOC) pool relys strongly on the soil microbial processing thereof. Consequently, high levels of microbial activity, which is directly related to soil respiration, suggests an increase in the SOC pool. The straw mulch treatment obtained the highest soil respiration rate which incidently also has the highest organic matter content. The mechanical treatment had the lowest soil respiration rate as well as the lowest organic matter content. Both responses are expected since factors that control respiration includes the supply of organic matter to soil microbes. The above responses concur with the general findings of Jacinthe and Lal (2006) that soil respiration increases nearly proportionally with the amount of residue added to the soil.

The results from the statistical analysis conducted found significantly higher mean values for the chemical and annual cover crop treatments, with the straw mulch and perennial cover crop treatments having significantly lower respiration rates. The determined values below detection limits of the method were removed from the dataset (APPENDIX III) and these results are presented in Figure 34.

5.2.8 Soil fauna

The soil fauna results were obtained from the ARC-Infruitec-Nietvoorbij and reproduced with permission.

The micro-anthropod and earthworm counts reported in this study was conducted by the Agricultural Research Council and is included in order to compare the observed earthworm counts with the soil biological indicators measured in this study.

The micro-anthropod study did not show any significant difference in mite abundance or diversity in any of the treatment plots. The study identified three collembolan and four mite species which still requires classification (Benga, 2009). The total amount of microanthropods was found to be highest (± 350-400 microanthropods.m^{-2}) in the annual cover crop treatment, with the straw mulch treatment exhibiting the lowest number (below 100 microanthropods/m^2) of microanthropods. These counts do not compare with soil microbial biomass results or soil organic carbon content, in which the straw mulch treatment plots yielded the highest values in comparison to the rest of the treatments plots. The reason for this occurence is not clear. The abundance is expected in what are refered to as “hot spots” in the soil. These are zones in the soil located either in the root-rhizosphere, in regions of organic detritus accumulation and also in earthworm-influenced zones (Coleman, 2002). The results as analysed by Benga (2009) is given in APPENDIX III.

The earthworm study concluded that no signficant differences was found between treatments when earthworms were used as a bioindicator for this specific study site. It was however found observed that the straw mulch treatment had higher adult and juvenile earthworm counts than the other treatments. The results as analysed by Maboeta (2009) is listed in APPENDIX III.

5.5. Summary and conclusions

Interpreting the soil biological indicators in this study was done with respect to the indicators effect on overall soil function. The soil microbial biomass is related to the

microbial catalytic potential and repository for C and N function of soil. Thus SMB should be interpretated is affects on this function.

The high SMB found in the straw mulch treatment suggests more active functioning microbes essential catalytic functions in soil. This corresponds with the determined respiration rate. This repsonse provides a factor when assessing biological properties in that respiration rate should be done so in relation to the amount of fuel (organic matter content) for the process of respiration i.e. comparing total soil carbon content with that of the amount of C losses (CO_2) due to respiration.

Soil productivity and N supplying potential is indicated by soil PMN. Generally soils with high levels of nitrogen-rich organic matter have the highest populations of microbes involved in nitrogen mineralization and the highest PMN rates (Gugino et al., 2007). This was not the case in the study with the exact opposite occuring where the treatment which had the highest organic matter content exhibited to lowest PMN rate. Reasons for this occurrence is not clear, but could be related to the method of determination conducted on the extract or the duration of the incubation period.

The soil faunal study, consisting of micro-anthropods and earthworm adundance, was thought to be useful to compare the faunal counts with the various soil biological indicators. Only the earthworm counts followed the same trend as the biological indicators measured during the study. The micro-anthropod study concluded that the annual cover crop treatment yieled the highest number of micro-anthropods, which was not expected given the high soil microbial activity in the straw mulch treatment,which was expected to also have the most abundant microoanthropods.

6. Discussion of soil health and soil quality assessment vs. the public health system

6.1. Introduction

Soil health quality) is defined *as the capacity of soil to function* (Larson and Pierce, 1994). As mentioned in previous chapters, the terms soil health and soil quality are often used synonymously (Larson and Pierce, 1994; Karlen, Andrews and Doran, 2001; Doran, 2002; Scholter, *et al*., 2003) with preference to the term soil quality, by scientists and soil health by producers (Romig, Garlynd, Harris and McSweeney, 1995). This definition and concept defined by Larson and Pierce (1994) has not been accepted by all scientists (Sojka and Upchurch, 1999).

The criticism towards the soil health (quality) concept include, "*premature acceptance of an incomplete formulated and largely untested paradigm*; the *concept has not yet been thoroughly analytically challenged*; *assessments have been drawn from a relatively narrow crop production and ecological perspective to positively or negatively weight soil quality assessment factors"* (Sojka and Upchurch, 1999). For this reason, the concept requires further exploration to address the shortcomings identified by the broader soil science community.

Doran and Parking (1994) emphasizes that any new definition of soil health (quality) must be broad enough to encompass the multifaceted nature of soil. In the past, the evaluation of soil health (quality) has been compared to a medical examination for humans in the sense that certain measurements need to be taken as basic indicators of functioning of the system (Larson and Pierce, 1991).

This chapter takes a look at an alternative approach to understanding soil health (quality) with the focus of defining health and quality separately. For this, definitions and concepts

will be borrowed from the public health system and compared to that of agricultural systems.

6.2. Terms borrowed from public health

In the comparison of the public health system with an agricultural system, human health is the priority of the public health system, and the condition of the agricultural natural resources (*soil, water and plant*), is the priority of the agricultural system. Health may be viewed as the "*human side of the dynamic equilibrium between the organisms and its environment"*, that interface is the place where health is mainly determined (Breslow, 2004). In the comparison of human health with soil health, soil health could then possibly be viewed as the *dynamic equilibrium between the soil organisms and its environment*, that interface is the place where health is mainly determined (adapted from Breslow, 2004). The four broad factors affecting human health are genetics and human biology, personal behaviour, environmental influences and health care (White and Duncan, 2002). In soil health, factors which impact soil and land management practices have been identified as determinants of the health of soil for a specific use (Lal, 1999). Perhaps a more suited comparison is that of human health to plant health, since both pathogenic organisms can be identified for plants and humans. For plants, the organisms potentially harmful to plants include other plants, fungi, bacteria, viruses, insects, mites, nematodes and other organisms in the plants environment (*air, water and soil*) affecting the plant health (Ebbels, 2003). The water, air and soil quality are also of fundamental importance in agricultural systems (Gregorich and Carter, 1997; Ayers,1994; Emberson *et al*., 2003). Soil quality in agricultural systems is comparative to the environment it serves, meaning, the soil needs to fulfil its various functions to ensure optimal crop production (Kibblewhite, Ritz and Swift, 2007). These functions, important for crop growth include supporting plant growth; regulating water; regulating gases; regulating energy and buffering or filtering (Carter *et al*., 1997).

In human health, food and oxygen are of the most critical components of human life (Breslow, 2004). Inadequate food is a major threat to human health. Since oxygen is

abundant, human nutrition is said to constitute a dominant factor in human health. Interestingly, society has evolved largely to supply enough food for people through migration and development of agriculture (Breslow, 2004). An example of this is the increased support from China's government in terms of financing advanced methods of crop production to improve and secure present and future food security (Arkesteijn, 1998).
In the same manner, in crop production, soil fertility and air are critical in plant life and has, in the past, been used to measure soil quality (Donavan and Casey, 1998). In soils suitable for crop production, soil fertility, (*which refers to the ability of a soil to supply plant nutrients*), is a paramount factor in plant growth (Foth and Ellis, 1997). In relation to the evolution of society, as described by Breslow (2004), crop production is initially established on fertile soils. Agricultural systems have hence evolved in order to ensure high soil fertility to provide optimum nutrition for crop production (Hossner and Juo , 1999).

6.3. Comparison of agricultural system to public health system

The agricultural system is multifaceted consisting of national, provincial and local government; agribusinesses or co-operatives; farmers; type of enterprise; and the natural agricultural resources (Figure 36).

In the agricultural system, soil quality may be impacted by any of the components of the agricultural system (Figure 1). For example, laws passed in government regarding use of chemicals on land or laws regarding land use such as the Conservation of Agricultural Resources Act, 1983 (Act No 43 of 1983), may affect soil health (quality). The act makes provision for "*the control over the utilization of the natural agricultural resources of South Africa in order to promote the conservation of the soil, the water sources and the vegetation and the combating of weeds and invader plants; and for matters connected therewith*".

Another example of this is the ratification of the Montreal Protocol in 1990, committing South Africa to the phasing out of ozone depleting substances, which included methyl bromide (DEAT, 1999). Methyl bromide was widely used on soil as a broad spectrum pesticide for insects, nematodes and pathogens (Sharma, 2003). Since soil quality

assessments include the evaluation of biological indicators such as soil microbe diversity (van Bruggen and Semenov, 2000), the use of chemicals such methyl bromide, substantially decrease plant pathogenic microorganisms, and likely, some *non-pathogenic* (UNEP, 2006) will have a direct effect on soil quality since soil microbe diversity has been part of minimum datasets used in soil quality assessments.

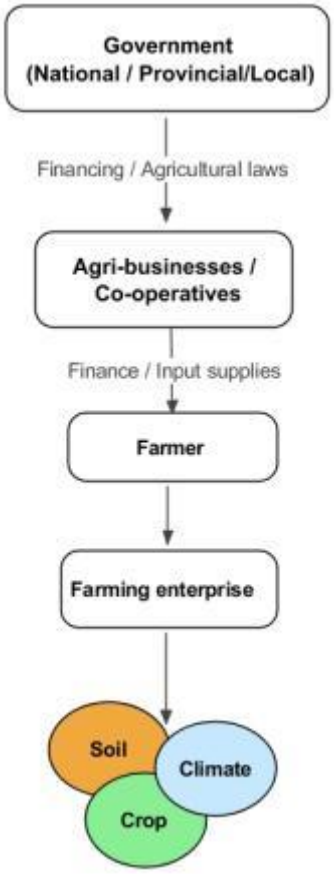


Figure 36. Multilevel agricultural system

6.4. Soil quality, soil health and the public health system

Soil quality provides a measure of soil function, the terms soil health and soil quality have been acceptably used interchangeably (Doran and Parkin, 1994). In public health, the terms

health and quality are not used interchangeably, where health refers to the *dynamic equilibrium between the organisms and its environment* and quality to an *inherent or distinguishing characteristic; a property*.

Public health refers to the health of a whole population (Stephen, 2004). Furthermore, public health measures its progress by the health status of the population it serves. Health as defined by the World Health Organization as "*a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity*".

The broad definition of health, is the dynamic equilibrium the organism and its environment (Breslow, 2004), with the major influences on health status relating to specific "health practices". In the case of human health, practices such as moderate eating, 7-8 hours of sleep per day, moderate alcohol usage, not smoking, eating breakfast, not snacking and moderate physical activity are considered as health practices (Belloc and Breslow, 1972).

The public health system is multifaceted with interrelated subdivisions namely environmental health, occupational health, epidemiology, biostatistics, health services, social and behavioural health (Winslow, 1920). Agriculture is also multifaceted with related subdivisions similar to that of the public health system (Figure 37).

Public health is also the combination of sciences, skills and beliefs that are directed to the maintenance and improvements of health through collective or social actions (Koplan, Bond, Merson, Reddy, Rodriguez, Sewankambo and Wasserheit, 2009). The goals of the public health system is to prevent disease in population; reduce disease and premature death , disability; and reduce discomfort in the population (Breslow, 2004).

The protection, preservation and restoration of good health is made possible by making the environment safe, promoting sensible behaviour, immunizing against infections, maintaining good nutrition, and providing prudent health care, including prenatal care. All these are the tasks of the public health services.

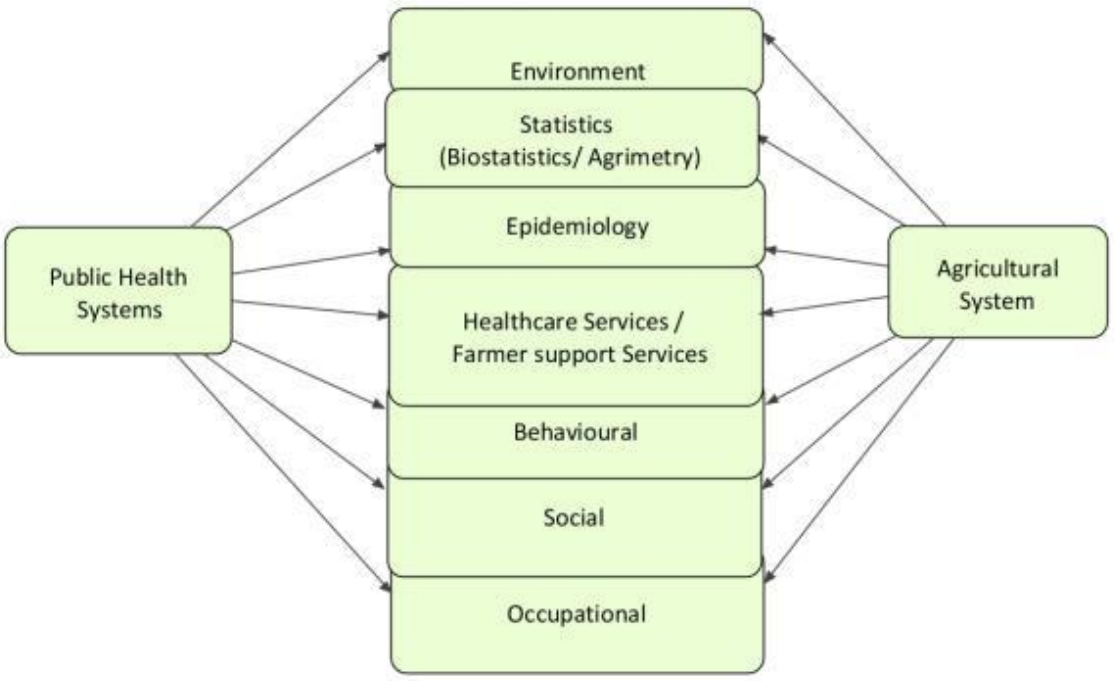


Figure 37. Mutlifacted Public Health System and Agricultural System

The ultimate purpose of the public health system is to improve the human condition. Human health is a function of public environment, which is directly dependent on the public health system. The agricultural system can be compared to the public health system. Just as human health is influenced by the public health system, plant health is influenced by agricultural system.

Another angle taken to understanding public health is by means of the health field concept which consists of four broad elements. These include i) human biology, ii) environment, iii) lifestyle and iv) the healthcare organization. The health field concept in agriculture could potentially consist of four broad elements namely i) plant biology, ii) environment, iii) cropping system and iv) the department of agriculture.

Frameworks used to describe the dimensions of the public health system, do so in terms of capacity (inputs), processes (practices and outputs) and outcomes (Turnock, 2008). Other frameworks make use of determinants, immediate outcomes and health outcomes to

describe the public health system (Breslow, 2004). The health of a crop (cropping system) can also be described in terms of determinants, immediate outcomes and health outcomes. In this case, soil quality, and the components thereof, would be of the determinants in the cropping system (Figure 38.)

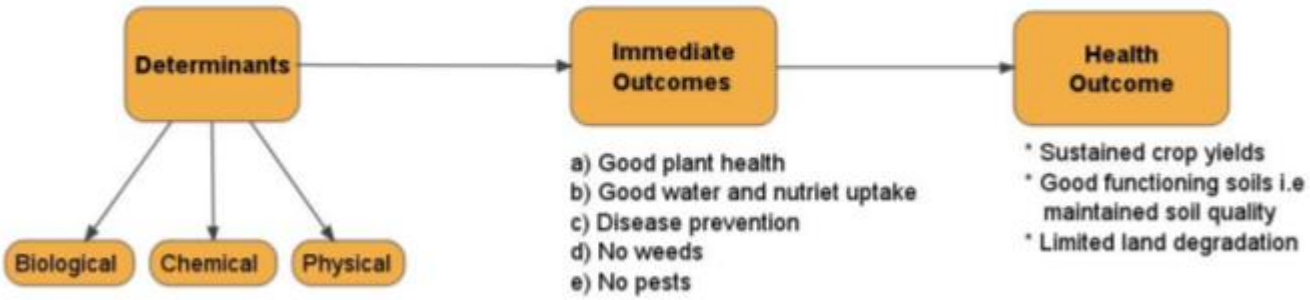


Figure 38. Framework for cropping system health

6.5. Conclusion and summary

In conclusion, the term soil quality should gain preference to the use of the term soil health when referring to the capacity of the soil to function (*supporting plant growth; regulating water; regulating gases; regulating energy and buffering or filtering*). Consequently, the terms soil health and soil quality, are not synonymous. This is contrary to previous definitions which use these terms interchangeably. As stated earlier, in public health, the terms health and quality are not used interchangeably, where health refers to the *dynamic equilibrium between the organisms and its environment* and quality to an *inherent or distinguishing characteristic; a property.*

The term *health*, in agriculture, ought to be restricted to defining the status of living organisms in an environment (*air, water and soil*) and *quality* restricted to defining the *inherent or distinguishing characteristic* of a resource.

7. Conclusions and Recommendations

7.1. Summary of Findings and Conclusions

The purpose of the study was to evaluate the soil conditions under different management practices in vineyards in Robertson, South Africa. The evaluation was based on the current approach of the concept of soil health and soil quality and briefly explores the present reservations concerning the definition of the soil health and soil quality concept.

In this study, the soil quality of the topsoil was characterised by analyzing the selected soil quality indicators and comparing the indicator values with the threshold values for optimum crop (vine) growth. The physical indicators analyzed were soil texture; soil water content; bulk density and aggregate stability. None of the treatments had limiting physical properties in terms of vine growth. In terms of soil quality, none of the physical conditions created by the treatments resulted in unfavourable soil conditions or quality for crop growth.

The chemical indicators analyzed were soil pH, EC, extractable N,P,K and organic matter content. Of these indicators measured, none yielded values below the specific indicator threshold values, thus no management intervention is needed to obtain optimum soil quality conditions, for optimal vine growth.

In terms of the biological indicators, the high soil microbial biomass and soil respiration found in the straw mulch treatment, suggests that there are more active functioning microbes, microbes essential for catalytic functions in soil. Since soils which have high levels of nitrogen-rich organic matter generally have the highest populations of microbes involved in nitrogen mineralization and the highest PMN rate, it was expected that the straw mulch treatment would yield the highest PMN rate. This was not the case in the study with the exact opposite occuring where the treatment, which had the highest organic matter content, presented to lowest PMN rate. Reasons for this occurrence is not clear, but could be related to the method of determination conducted on the extract or the duration of the incubation period.

The study also investigated the possible differences in soil quality which could be caused as a result of agricultural traffic within the treatment plots. For this reason, the *pedoderm* referring to the "*thin layer of soil at the interface with the atmosphere",* was studied to reveal differences in soil management practices. With the regard to soil chemical properties, the chemical indicators, N and OM content was generally higher *In* tracks than *Between* tracks. The exchange cations measured (Ca, Mg, Na and K) all had higher values for *Between* tracks than *In* tracks. This occurrence was found to be more prevalent within the 0-50 mm soil depth, a feature common in conservation type soil management where pedodermal expression is greatest. Overall, the treatment that can be rated most sustainable in terms of the yielding the most desired soil quality, was the straw mulch treatment. The land use sustainability of the other treatments did not yield results below the threshold values.

Regarding the soil fauna of the various soil management treatments, the earthworm counts followed the same trend as the biological indicators measured during the study. The micro-anthropod study concluded that the annual cover crop treatment yielded the highest number of micro-anthropods, which was not expected given the high soil microbial activity in the straw mulch treatment.

The use of the terms health and quality, when referring to the soils' condition, the term soil quality should gain preference to the use of the term soil health when referring to the capacity of the soil to function (*supporting plant growth; regulating water; regulating gases; regulating energy and buffering or filtering*). This implies that the terms soil health and soil quality, are not synonymous which is contrary to previous definitions which use these terms interchangeably. In public health, the terms health and quality are not used interchangeably, and therefore the term *health*, in agriculture, ought to be restricted to defining the status of living organisms in an environment (*air, water and soil*) and *quality* restricted to defining the *inherent or distinguishing characteristic* of a resource.

7.2. Summary of Contributions

The purpose of study was to (i) identify suitable soil quality indicators for vineyards in the Robertson area; (ii) analyze the soil quality indicators for different soil management

treatments; (iii) evaluate the effect of various soil management treatments on the overall soil functionality, by comparing measured indicators to the soil property threshold values, for optimal vine growth; iv) establish a more consistent understanding and use of the terms *health* and *quality,* as understood and used in the general science community, with particular reference to public health.

On the onset of the study, the threshold values for the various indicators used had not been identified for the specific soil-crop-climate scenario. The threshold values were taken from relevant published literature where available. This was initially challenging to obtain since soil quality assessments had not previously been conducted in the study area. The data obtained and threshold values (Table 26) used in this study may serve as possible reference data for future soil quality assessments for viticultural soils in the Robertson area.

Table 26. List of soil quality indicator thresholds identified for optimal vine growth in the Robertson study area.

Soil quality indicator	***Threshold values/range for optimum vine growth***	***Literature reference***
Soil texture	**	n/a
Soil bulk density (sandy clay loam soil)	1.55-1.75 $g.cm^{-3}$	Morris and Lowry, 1988
Gravimetric Water content	**	n/a
Aggregate stability	**	n/a
pH	6-7	FSSA, 2007
EC	400 $mS.m^{-1}$	Richards,1954
Available N	20-40 kg $N.ha^{-1}$	Conradie,1994
Available P	30 $mg.kg^{-1}$	Conradie,1994
Extractable K	120 $mg.kg^{-1}$	Conradie,1994
Soil Organic Matter content	**	n/a
Soil Microbial Biomass	**	n/a
Potential Mineralizable Nitrogen	**	n/a
Soil Respiration	**	n/a
Soil Fauna	**	n/a

** Not found in published literature n/a not applicable

With the terms quality and health not being synonymous, the soil quality concept can, without confusion, be integrated as a component of a health assessment of the health of an agricultural system. Where the health assessment of the agricultural system requires an assessment of all natural resources affecting agricultural health, i.e. water, air and soil quality.

7.3. Suggestions for Further Research

This study was limited to evaluation of the land use sustainability of the soil management practices in terms of the soil quality assessed. In future, other parameters affecting the sustainability should be included when evaluating the sustainability of soil management. The parameters include, economic and social impact assessments, since these parameters are included in the broader definition of sustainability.

The soil quality assessment methods used in this work was done according to methods used in previous work, as well as soil analytical methods as accepted by experienced soil scientist within the study area. The interrogation of the analytical methods used in previous work would be beneficial for future soil quality assessments in the given region.

Soil quality assessments which include the pedological soil forms and families could be useful in predicting soil quality with knowledge on the soil forms of an area. This might also be useful in determining the economic value of certain soil forms as related the soil quality.

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APPENDICES

APPENDIX I Soil physical indicators methods and materials of analysis

The following experimental procedures were used in the analysis of the soil chemical properties.

1. **Texture analysis (pipette method)**

Following the pre-treatment, the soil is dispersed by means of hexametaphoshate and the various size fractions of the suspension extracted at time intervals which are calculated from Stokes' equation for the sedimentation of spherical particles (Gee and Bauder, 1986).

Apparatus

- Glass sedimentation cylinders 1dm3
- 50cm Hand stirrer
- 25cm3 Lowy pipette
- Constant temperature
- Set of 100mm diameter sieves with lid and receiving pan (2; 0.5; 0.25; 0.106; 0.053mm)
- Hot plate, waterbath, thermometer, drying oven, high speed stirrer or reciprocate shaker, crucibles, centrifuge.

Reagents

- Hydrogen peroxide (H_2O_2): 30-35 volume percent
- Sodium acetate (NaOAc), 1mol.dm^{-3} , pH 5: Dissolve 82g NaOAc in 1dm^3 of distilled water. Adjust to pH 5 with acetic acid
- Sodium hydroxide (NaOH), 0. 1mol.dm^{-3} : Dissolve 4g NaOH in 1dm^3 of distilled water
- Hydrochloric acid (HCl), 0.2mol.dm^{-3} :Dilute 18cm3 concentrated HCl to 1dm^3 of distilled water
- Calgon dispersing solution: Dissolve 35.7g sodium hexametaphosphate [$(NaPO_4)_6$] and 7.94g sodium carbonate (Na_2CO_3) in 1dm^3 of distilled water

- Sodium citrate/bicarbonate solution: Dissolve 88.4g sodium citrate ($Na_3C_6H_5O_7.2H_2O$) in 1dm^3 of distilled water and adjust to pH 5. Add 125ml of 1$mol.dm^{-3}$ sodium bicarbonate (84g $NaHCO_3$ dissolved in 1dm^3 distilled water) to each 1dm^3 of citrate solution

Procedure

Coarse fraction (>2mm)

The entire sample is spread on a large sheet and left to air dry. Then determine the mass of the sample after gently crushing the sample in a porcelain mortar and pass sample through 2mm sieve. If fine soil adheres to the larger particles, wash the coarse material with water. Determine the mass of dry, washed >2mm particles and express as a percentage of entire sample.

Fine soil (<2mm)

Determine the mass of the representative <2mm air dried soil sample (10g for clay, 20g for loams, 40g for sandy loams and 80g for sands). Depending on the properties of the sample, cementing agents will need to be removed. These may be organic material, carbonates, siliceous or iron oxide cementing agents. For the preparation of the samples for the study, carbonates; organic matter and iron oxides were removed. The procedure for removal of these recenting agents will be described.

Removals of carbonates

- Carbonate removal is only needed if the soil pH in water is greater than 6.8.
- Place the soil sample into a 250cm^3 centrifuge tube and add approximately 100cm^3 0.2$mol.dm^3$ HCl to soil. When CO_2 bubbles are no longer generated, centrifuge until supernatant is clear. Decant the supernatant. Wash the soil twice by shaking with 50cm^3 de-ionised water, centrifuging and discarding the supernatant when it is clear

Removal of organic matter

- Transfer the sample to a 250ml glass beaker with distilled water

- Add 5cm^3 H_2O_2 to the suspension, stir and cover with a watch glass.
- When frothing ceases, remove cover and heat on water bath. Evaporate the excess water but not to dryness. Continue adding the peroxide until most of the organic material has been destroyed (judging by the bleached colour of the sample). After the final addition of the peroxide, heat the sample for approximately an 1hour to destroy excess peroxide. Wash the sample free of soluble compounds by centrifuging. Dry the sample overnight in an oven at 105^{o}C and determine the mass. The mass of the oven dried peroxide treated sample is the base mass (F) for calculating the percentage of the various size fractions.

Removal of iron oxides

Iron oxide rich soils do not completely disperse with calgon as the dispersing agent.

- 150cm^3 citrate-bicarbonate buffer is added to the peroxide treated sample. The sample is shaken to disperse the sample.
- Add 3g $Na_2S_2O_4$ gradually as the sample may froth. Heat for 30min in a water bath of 80^{o}C. Stir the suspension intermittently. Remove from the water bath and centrifuge. The clear supernatant and subsequent washes for iron determination. If the sample is not completely grey repeat the citrate bicarbonate-dithionite treatment. Wash the sample twice with 50cm^3 distilled water. If the supernatant is not clear, use a high speed centrifuge.
- Dry the sample overnight at 105^{o}C and determine the mass.

Dispersion of sample

Add 10cm^3 calgon dispersing solution to the pretreated oven dried sample. Transfer the suspension quantitatively to a 250cm^3 centrifuge bottle. Make the volume up to approximately 150cm^3 with distilled water, seal with a stopper and shake overnight on a

horizontal reciprocating shaker. Alternately, the suspension can be transferred to a dispersion cup and mixed for 5min with an electric mixer.

Separation of sand fractions

Wash the dispersed sample on a 0.053mm sieve, passing the silt and clay through the sieve via a funnel into a 1000cm3 cylinder. Continue washing until the percolate is clear. Remove the sieve from the cylinder and quantitatively transfer sand to tarred evaporation dish or water. Dry at 105oC to constant mass. Transfer the dried sand to a nest of sieves arranged from top to bottom with decreasing size in the following order : 0,5; 0.25, 0.106; 0.53mm and a pan. Shake the sieves on a save shaker for approximately 10minuntes. Determine the mass of each fraction (A) and the residual silt plus clay (G) that passed through the 0.053mm sieve. A precision of 0.01g is sufficient.

Determination of silt and clay with pipette

Fill the cylinder with the silt and clay suspension to the $1dm^3$ mark. Cover the cylinder with a watch glass. Place the cylinder in a constant temperature room of 20^oC. After equilibrium, stir the suspension thoroughly with a hand stirrer for 30sec in a vertical direction. Note the time when stirring is terminated. After the appropriate time interval for determining the 0.05mm fraction (coarse silt + fine silt + clay), lower the closed Lowy pipette to a depth of 30cm into the suspension.

Withdraw a $25cm^3$ sample with gentle suction (12sec). Discharge the sample into a tarred evaporating dish. Rinse the pipette with distilled water and add to evaporating dish. Evaporate the water and dry at 105^oC to constant mass, cool in desiccators and determine the mass. Repeat this procedure at the specified times to determine the 0.02mm fraction (fine silt + clay) and the 0.002mm fraction (clay).

In these two determinations the sample is withdraw at a depth of 10cm. For the clay fraction, a sampling depth of 7cm can be used to reduce the settling time in order to complete the determination during an 8hr working day.

Table 1. Settling times (calculated for g=981cm.s^{-2}) of fine silt and clay as a function of temperature and a depth of 10cm

Temperature °C	**Fine silt (0.02mm) min:sec**	**Clay (0.002mm) hr:min**
15	05:17	08:48
16	05:09	08:34
17	05:01	08:21
18	04:53	08:09
19	04:46	07:57
20	04:39	07:45
21	04:32	07:34
22	04:26	07:23
23	04:20	07:13
24	04:14	07:03
25	04:08	06:53

Calculations

A = mass (g) of sand fraction

B = mass (g) of pipetted coarse silt plus fine silt plus clay

C = mass (g) of pipetted coarse fine silt plus clay

D = mass (g) of pipetted clay

E = mass correction of dispersing agent (0.01g)

F= mass (g) pretreated oven dry total sample

G = mass (g) of residual silt and clay that passed through the 0.053mm sieve

Silt and clay fractions:

Percent coarse silt = $\frac{(B-C)\times 1000\times 100}{F\times 25}+\frac{G\times 100}{F}$ **.....(eq.8)**

Percent fine silt = $\frac{(C-D)\times 1000\times 100}{F\times 25}$ **…….(eq.9)**

Percent clay = $\frac{(D-E)\times 1000\times 100}{F\times 25}$ **……..(eq.10)**

Determination of textural class by means of textural triangle

If the particle size distribution of a known soil, the textural class may be determined from a diagram defining particle size limits of the various textural classes. The textural triangles used in the Republic of South Arica are shown in figure below and are based on the international classification for soil separates. The method used to determine a textural class must be reported as classes obtained from a textural triangle will not necessarily correspond with those of a finger test.

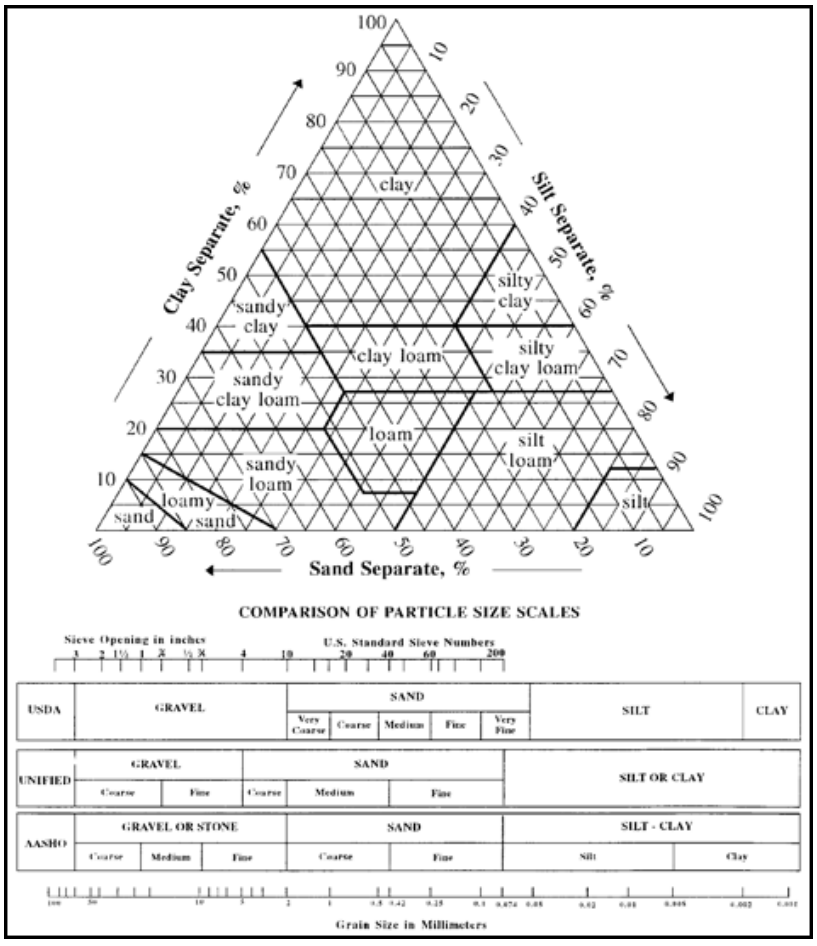


Figure 1. Soil texture triangle (USDA)

Treatment Name	Position	% Gravel >2mm	%Sand 2.0-0.05mm	% Coarse silt 0.05-0.02mm	% Fine silt 0.02-0.002mm	% Clay <0.002mm	Textural class
Mechanical	*Between tracks*	17.43	58.43	14.11	1.33	10	Sandy clay loam
Mechanical	*In tracks*	44.18	58.61	23.93	8.88	17.08	Sandy loam
Chemical	*Between tracks*	28.87	54.75	18.43	9.84	12.47	Sandy loam
Chemical	*In tracks*	39.25	57.6	25.46	2.05	18.44	Sandy clay loam
Straw mulch	*Between tracks*	64.64	53.29	15.76	6.79	12.23	Sandy clay loam
Straw mulch	*In tracks*	47.88	47.86	22.71	0.64	18.69	Loam
Annual cover crop	*Between tracks*	43.52	61.24	15.37	3.31	9.26	Sandy loam
Annual cover crop	*In tracks*	53.02	59.63	12.35	1.33	7.33	Sandy loam
Perennial cover crop	*Between tracks*	62.41	49.39	19.36	6.02	16.04	Sandy clay loam
Perennial cover crop	*In tracks*	57.68	51.31	22.35	2.73	17.08	Sandy clay loam

Table 2. Soil particle determination dataset

2. Gravimetric water content

Method

In order to determine the gravimetric water content of a particular soil sample, the water mass must be determined by drying the soil to constant weight and measuring the soil sample mass after and before drying. The water mass (or weight) is the difference between the weights of the wet and oven dry samples. The criterion for a dry soil sample is the soil sample that has been dried to constant weight in oven at temperature at 105 ^{o}C.

Materials

- Oven at 105^{o}C temperature
- A balance of precision of ±0.001 g.
- Porcelain dish

Procedure

- Weigh the porcelain dish, and record this weight (tare").
- Place a soil sample of about 10 g in the dish and record this weight as (wet soil + tare).
- Place the sample in the oven 105°C, and dry for 24 hours or overnight.
- Weigh the sample, and record this weight as weight of (dry soil + tare).
- Return the sample to the oven and dry for several hours, and determine the weight of (dry

  soil +tare).

Calculations

The moisture content in dry weight basis may be calculated using the following formula:

Θ_g **: Soil water content (g/g)** = $\frac{(\textit{weight if moist soil – weight of oven dried soil})}{\textit{weight of oven dried soil}}$ **...(eq.11)**

Table 3. Gravimetric water content

TREATMENT NAME	REPLICATION	POSITION	Gravimetric water content (g/g)
Mechanical	1	*Between tracks*	4.03
Mechanical	2	*Between tracks*	3.34
Mechanical	3	*Between tracks*	5.42
Mechanical	4	*Between tracks*	2.81
Chemical	1	*Between tracks*	3.06
Chemical	2	*Between tracks*	3.58
Chemical	3	*Between tracks*	3.53
Chemical	4	*Between tracks*	9.62
Straw mulch	1	*Between tracks*	5.81
Straw mulch	2	*Between tracks*	6.56
Straw mulch	3	*Between tracks*	5.40
Straw mulch	4	*Between tracks*	7.58
Annual cc	1	*Between tracks*	3.70
Annual cc	2	*Between tracks*	4.65
Annual cc	3	*Between tracks*	4.71
Annual cc	4	*Between tracks*	3.94
Perennial cc	1	*Between tracks*	4.03
Perennial cc	2	*Between tracks*	2.80
Perennial cc	3	*Between tracks*	4.88
Perennial cc	4	*Between tracks*	3.49
Mechanical	1	*In tracks*	4.03
Mechanical	2	*In tracks*	6.64
Mechanical	3	*In tracks*	3.92
Mechanical	4	*In tracks*	3.06
Chemical	1	*In tracks*	4.11
Chemical	2	*In tracks*	2.52
Chemical	3	*In tracks*	4.17
Chemical	4	*In tracks*	4.95
Straw mulch	1	*In tracks*	5.49
Straw mulch	2	*In tracks*	4.21
Straw mulch	3	*In tracks*	6.62
Straw mulch	4	*In tracks*	8.06
Annual cc	1	*In tracks*	5.38
Annual cc	2	*In tracks*	5.82
Annual cc	3	*In tracks*	4.09
Annual cc	4	*In tracks*	3.90
Perennial cc	1	*In tracks*	7.82
Perennial cc	2	*In tracks*	3.80

Perennial cc	3	*In tracks*	3.97
Perennial cc	4	*In tracks*	4.38

3. Bulk density

In the field, bulk density is be determined by driving a cylinder of known volume ($V_{cylinder}$) into the soil and thereby obtaining a core of natural soil. The soil is then weighed and dried and the amount of water and dry soil (m_{dry}) is determined. By dividing the mass of dry soil by the volume of cylinder, a figure for bulk density (ρ_b) is obtained (Lyon *et al.,* 1955). The standard methods used for determining bulk density are the clod and core method. In the past, work done relating to soil quality, bulk density was determined by means of the core method (Larson and Pierce, 1991; Doran and Parkin, 1994; Sparling, 2006; Gugino, Idowu, Schindelbeck, van Es, Wolfe, Moebius, Thies, and Abawi, 2007). and was also used in this study .

Core method

Bulk density measurement should be performed at the soil surface and/or in a compacted zone. Samples were collected in the track as well as between the track. To get a more representative bulk density measurement of the area, additional samples were taken. The method is adapted from the Guideline for Soil Quality Indicator Assessment compiled by the United States Department of Agriculture (USDA).

Materials

- 4.5cm diameter ring
- hand sledge
- wood block
- garden trowel
- flat-bladed knife
- Brown paper bags and marker pen

- scale (0.1 g precision)
- 1/8 cup (30 mL) measuring scoop
- access to an oven

Procedure

- Using the hand sledge and block of wood, drive the 4.5cm diameter ring, bevelled edge down, to a depth of 7.5cm.
- Dig around the ring and with the trowel underneath it, carefully lift it out to prevent any loss of soil
- Remove excess soil from the sample with a flat bladed knife. The bottom of the sample should be flat and even with the edges of the ring
- Touch the sample as little as possible. Using the flat bladed knife, push out the sample into a plastic sealable bag. Make sure the entire sample is placed in the plastic bag. Seal and label the bag.
- Weigh the soil sample in its bag. [If the sample is too heavy for the scale, transfer about half of the sample to another plastic bag. The weights of the two sample bags will need to be added together.
- Weigh an empty plastic bag to account for the weight of the bag
- Weigh the soil subsample in its brown paper bag.
- Place the brown bag with the subsample in a oven and dry overnight at 105^{o}C. Weigh the dry subsample in its brown paper bag.

Calculations

Soil water content (g/g) = $\frac{\text{(weight of moist soil - weight of oven dry soil)}}{\text{weight of oven dry soil}}$ **.....(eq.12)**

Soil bulk density (g/cm_3) = $\frac{\text{oven dry weight of soil (g)}}{\text{volume of soil } (cm^3)}$ **.....(eq.13)**

Table 4. Bulk density of the 0-50 mm soil depth samples

	BETWEEN TRACK		IN TRACK	
TREATMENT	**M_{DRY}**	**ρ_{bulk}**	**M_{DRY}**	**ρ_{bulk}**
B1H1	62.67	0.79	116.45	1.47
B1H1	92.74	1.17	138.12	1.74
B1H1	80.08	1.01	133.93	1.69
B1H2	.	.	.	.
B1H2	.	.	.	.
B1H2	.	.	.	.
B1H3	74.18	0.93	117.48	1.48
B1H3	91.94	1.16	120.95	1.52
B1H3	101.20	1.27	128.72	1.62
B1H4	117.37	1.48	154.03	1.94
B1H4	120.13	1.51	109.97	1.38
B1H4	111.78	1.41	140.24	1.77
B2H1	122.46	1.54	116.34	1.46
B2H1	103.24	1.30	116.75	1.47
B2H1	89.90	1.13	90.33	1.14
B2H2	133.93	1.69	142.13	1.79
B2H2	105.15	1.32	85.29	1.07
B2H2	128.63	1.62	105.53	1.33
B2H3	132.98	1.67	141.85	1.79
B2H3	95.56	1.20	105.11	1.32
B2H3	89.21	1.12	112.74	1.42
B2H4	101.02	1.27	117.30	1.48

B2H4	108.92	1.37	132.59	1.67
B2H4	110.96	1.40	89.52	1.13
B3H1	130.66	1.64	115.74	1.46
B3H1	137.39	1.73	108.73	1.37
B3H1	101.88	1.28	152.61	1.92
B3H2	132.10	1.66	123.28	1.55
B3H2	140.93	1.77	143.05	1.80
B3H2	134.32	1.69	120.52	1.52
B3H3	.	.	.	.
B3H3	.	.	.	.
B3H3	.	.	.	.
B3H4	123.79	1.56	142.54	1.79
B3H4	152.84	1.92	86.65	1.09
B3H4	133.44	1.68	132.68	1.67
B8H1	112.05	1.41	125.76	1.58
B8H1	122.99	1.55	134.72	1.70
B8H1	117.26	1.48	124.78	1.57
B8H2	108.41	1.36	113.13	1.42
B8H2	91.01	1.15	98.95	1.25
B8H2	117.56	1.48	137.90	1.74
B8H3	109.71	1.38	136.90	1.72
B8H3	86.01	1.08	117.25	1.48
B8H3	118.76	1.49	129.52	1.63
B8H4	117.88	1.48	103.54	1.30
B8H4	129.35	1.63	135.19	1.70
B8H4	95.16	1.20	130.17	1.64
B13H1	103.83	1.31	110.18	1.39
B13H1	96.61	1.22	82.74	1.04
B13H1	120.38	1.52	121.27	1.53

B13H2	97.87	1.23	79.46	1.00
B13H2	92.05	1.16	100.00	1.26
B13H2	96.34	1.21	129.74	1.63
B13H3	99.55	1.25	120.32	1.51
B13H3	112.96	1.42	104.89	1.32
B13H3	85.15	1.07	129.70	1.63
B13H4	103.32	1.30	121.04	1.52
B13H4	140.85	1.77	125.87	1.58
B13H4	108.62	1.37	139.73	1.76

4. Water Aggregate Stability

The method is based on the percent soil remaining on a sieve following wet sieving (Herrick, Whitford, de Soyza, Van Zee, Havstad, Seybold and Walton, 2001).

In total, a set of ten samples were used for this analysis. The same set of samples was used for particle size distribution was used in the water aggregate stability analysis. The wet sieving consisted of rinsing 10g sample of soil with distilled water through a nest of three sieves (> 2mm, 0.25-2,0mm, and 0.106-0.25 mm). The portions remaining in the respective sieves were then quantitatively transferred to porcelain evaporative dishes and dried at 105˚C overnight. This process constitutes one wet-sieving cycle. The process was repeated for a second time on the same sample and the fractions remaining on the respective size sieves were taken to represent the water stable aggregates.

Table 5. Aggregate percentages of water stable aggregates, dry aggregates and texture analysis fractions

Water stable aggregates (WSA)

Treatment Name	0.106 - 0.250 mm	0.25- 2.00mm	>2.00mm
Mechanical	31.74	36.90	29.54
Chemical	23.19	62.39	9.82
Straw mulch	21.23	41.49	34.57
Annual cover crop	28.93	52.42	18.25
Perennial cover crop	36.46	47.64	17.52

Dry aggregates (DA)

Treatment Name	0.106 - .250 mm	0.25- 2.00mm	>2.00mm
Mechanical	8.93	29.36	63.90
Chemical	11.43	37.16	49.20
Straw mulch	0.67	6.27	92.48
Annual cover crop	0.53	5.84	92.76
Perennial cover crop	3.14	32.37	65.23

Texture Analysis Fractions (TAF)

Treatment Name	0.106 - 0.250 mm	0.25- 2.00mm	>2.00mm
Mechanical	72.03	27.97	30.81
Chemical	72.95	27.05	34.06
Straw mulch	70.39	29.61	56.26
Annual cover crop	73.22	26.78	48.27
Perennial cover crop	67.10	32.90	60.05

APPENDIX II Soil chemical indicators datasets

The following experimental procedures were used in the analysis of the soil chemical properties.

Table 1. Soil chemical properties (0-200 mm)

TREATMENT NAME	REPLICATION	pH (H_2O)	EC	Ca	Mg	Na	K	P	N	C	C:N
			(mS/m)	cmol(+)/kg	cmol(+)/kg	cmol(+)/kg	cmol(+)/kg	mg/kg	%	%	
Mechanical	1	8.69	100.9	17.84	2.92	0.28	1.08	29.65	0.09	1.5	16.67
Mechanical	2	8.6	86.6	11.2	2.35	0.26	1.02	90.06	0.08	0.9	11.25
Mechanical	3	8.43	88.1	7.79	2.64	0.27	0.97	43.45	0.07	0.72	10.29
Mechanical	4	8.5	112.1	11.72	2.6	0.27	1	85.31	0.07	0.82	11.71
Chemical	1	7.82	50.6	5.08	2.58	0.26	1.07	59.14	0.07	0.69	9.86
Chemical	2	8.53	92.9	14.03	3.16	0.22	0.95	35.84	0.05	0.84	16.8
Chemical	3	8.44	96.2	8.22	2.28	0.26	1.09	69.13	0.06	0.55	9.17
Chemical	4	8.5	97	11.87	3.34	0.26	1.04	38.53	0.07	0.88	12.57
Mulch	1	8.51	89.8	8.11	3.44	0.26	1.35	67.23	0.07	0.73	10.43
Mulch	2	8.63	90.3	14.07	2.54	0.21	1.26	82.45	0.08	0.8	10
Mulch	3	8.49	95.5	10.83	3.5	0.23	1.38	91.97	0.07	0.67	9.57
Mulch	4	8.46	120.9	8.85	3.04	0.24	1.44	87.21	0.07	0.79	11.29
Annual cc	1	8.35	66.2	9.56	2.82	0.26	1.19	93.55	0.09	0.85	9.44
Annual cc	2	8.3	111.4	8.07	2.81	0.36	1.39	33.93	0.05	0.88	17.6
Annual cc	3	7.98	74.3	5.62	2.94	0.25	0.94	56.13	0.07	0.81	11.57
Annual cc	4	7.64	62	4.42	2.68	0.3	0.81	31.24	0.04	0.56	14
Perennial cc	1	8.33	76.3	7.03	2.84	0.22	1.15	73.26	0.08	0.82	10.25
Perennial cc	2	8.42	115.5	12.75	2.83	0.22	1.18	80.87	0.07	0.82	11.71
Perennial cc	3	8.01	75.3	5.66	2.97	0.25	1.18	90.7	0.06	0.82	13.67
Perennial cc	4	8.26	99.4	9.42	2.71	0.34	1.08	47.57	0.1	0.94	9.4

Table 2. Soil chemical properties (0-50 mm)

TREATMENT NAME	REP	POSITION	pH (H_2O)	EC		Ca	Mg	Na	K	SOM	N	C	C:N
				mS/m		cmol(+)/kg	cmol(+)/kg	cmol(+)/kg	cmol(+)/kg	%	%	%	
Mechanical	1	BETWEEN TRACK	8.12	13.49	134.9	16.37	3.75	0.37	1.37	3.61	0.14	2.1	15
Mechanical	2	BETWEEN TRACK	7.94	12.71	127.1	16.14	4.46	0.38	1.43	1.96	0.1	1.14	11.88
Mechanical	3	BETWEEN TRACK	6.87	7.89	78.9	13.47	4.49	0.43	1.35	2.12	0.11	1.23	11.18
Mechanical	4	BETWEEN TRACK	8.09	12.72	127.2	14.01	3.14	0.42	1.33	1.94	0.1	1.13	11.89
Chemical	1	BETWEEN TRACK	.	.	.	.	.	.	.	4.01	0.2	2.33	11.65
Chemical	2	BETWEEN TRACK	7.82	12.17	121.7	15.87	4.36	0.36	1.14	3.87	0.18	2.25	12.5
Chemical	3	BETWEEN TRACK	6.93	6.95	69.5	10.8	4	0.41	1.48	3.34	0.17	1.94	11.41
Chemical	4	BETWEEN TRACK	7.74	11.98	119.8	15.39	4.05	0.36	1.43	3.65	0.17	2.12	12.47
Mulch	1	BETWEEN TRACK	7.43	11.03	110.3	12.13	5.66	0.44	1.17	3.54	0.19	2.06	10.84
Mulch	2	BETWEEN TRACK	7.93	18.08	180.8	14.21	4.4	0.39	0.99	3.97	0.19	2.31	12.16
Mulch	3	BETWEEN TRACK	7.9	11.89	118.9	13.43	5.33	0.37	1.3	3.44	0.17	2	11.76
Mulch	4	BETWEEN TRACK	7.94	20.5	205	12.45	4.98	0.36	1.79	5.49	0.27	3.19	11.81
Annual cc	1	BETWEEN TRACK	7.48	23	230	12.71	4.02	0.47	1.22	2.65	0.13	1.54	11.85
Annual cc	2	BETWEEN TRACK	6.83	8.13	81.3	9.1	3.97	0.41	1.25	1.98	0.11	1.15	10.45
Annual cc	3	BETWEEN TRACK	6.92	11.78	117.8	11.44	5.16	0.46	0.89	2.27	0.1	1.32	13.33
Annual cc	4	BETWEEN TRACK	6.28	22.6	226	7.95	4.52	0.45	0.92	1.98	0.1	1.15	11.98
Perennial cc	1	BETWEEN TRACK	7.13	9.64	96.4	12.87	5.44	0.59	1.25	3.23	0.15	1.88	12.53
Perennial cc	2	BETWEEN TRACK	7.29	15	150	10.51	5.61	0.37	1.41	6.35	0.3	3.69	12.3
Perennial cc	3	BETWEEN TRACK	6.4	7.78	77.8	5.7	3.29	0.44	1.24	5.47	0.24	3.18	13.25
Perennial cc	4	BETWEEN TRACK	7.63	9.81	98.1	13.81	4.49	0.44	1.26	0.34	2.48	0.2	0.08
Mechanical	1	IN TRACK	8.03	11.1	111	18.43	4.73	0.54	1.19	2.72	0.11	1.58	14.36
Mechanical	2	IN TRACK	7.71	16.16	161.6	17.71	4.98	0.57	1.22	2.17	0.1	1.26	12.6

Mechanical	3	IN TRACK	7.31	12.68	126.8	13.85	4.45	0.47	0.94	2.34	0.11	1.36	12.36
Mechanical	4	IN TRACK	8.01	13.7	137	16.45	4.1	0.41	1.05	1.79	0.08	1.04	13
Chemical	1	IN TRACK	.	.	.	.	.	.	.	3.29	0.18	1.91	10.61
Chemical	2	IN TRACK	7.84	11.75	117.5	14.53	4.4	0.46	1.16	2.79	0.15	1.62	10.8
Chemical	3	IN TRACK	6.78	11.01	110.1	13.09	4.58	0.57	1.41	2.87	0.16	1.67	10.44
Chemical	4	IN TRACK	7.45	12.27	122.7	17.07	4.95	0.52	1.16	3.39	0.16	1.97	12.31
Mulch	1	IN TRACK	7.59	10.97	109.7	11.54	6.02	0.47	1.19	2.1	0.14	1.22	8.71
Mulch	2	IN TRACK	7.62	21.8	218	17	5.65	0.5	1.35	3.06	0.16	1.78	11.13
Mulch	3	IN TRACK	7.28	15.67	156.7	16.11	6.73	0.5	1.26	1.86	0.11	1.08	9.82
Mulch	4	IN TRACK	6.53	17.79	177.9	17.43	7.09	0.57	1.19	2.87	0.16	1.67	10.44
Annual cc	1	IN TRACK	7.86	12.62	126.2	14.52	5.22	0.57	1.43	2.94	0.16	1.71	10.69
Annual cc	2	IN TRACK	6.75	9.54	95.4	10.85	4.87	0.63	1.14	2.96	0.13	1.72	13.23
Annual cc	3	IN TRACK	6.82	12.58	125.8	12.87	5.19	0.58	1.13	1.84	0.09	1.07	12.3
Annual cc	4	IN TRACK	6.7	10.28	102.8	8.5	4.06	0.5	1.07	2.1	0	1.22	.
Perennial cc	1	IN TRACK	7.24	12.78	127.8	14.81	6.45	0.39	2.1	3.04	0.17	1.77	10.41
Perennial cc	2	IN TRACK	7.43	16.62	166.2	12.62	6.11	0.48	1.78	2.49	0.12	1.45	12.08
Perennial cc	3	IN TRACK	6.5	17.94	179.4	13.93	6.12	0.56	1.75	2.2	0.1	1.28	12.8
Perennial cc	4	IN TRACK	7.52	16.28	162.8	8.64	4.99	0.63	1.33	1.81	0.09	1.05	11.29

APPENDIX III Soil biological indicators datasets

The following experimental procedures were used in the analysis of the soil biological properties.

Table 1. Soil Microbial Biomass data

Treatment Name	Initial %C	Control (%C)	SMB (Control %C- Initial %C**)	Average SMB for positive results
Mechanical	1.42	1.64	0.22	
Mechanical	0.99	1.05	0.06	
Mechanical	1.19	1.19	0.01	**0.10**
Mechanical	1.21	1.13	-0.08	
Mechanical	1.79	1.78	-0.01	
Mechanical	1.40	1.14	-0.26	
Mechanical	0.98	0.95	-0.03	
Mechanical	1.29	1.21	-0.08	
Chemical	1.16	0.91	-0.25	
Chemical	1.32	1.28	-0.04	
Chemical	0.88	0.78	-0.10	
Chemical	1.05	1.25	0.20	
Chemical	0.77	0.78	0.02	**0.11**
Chemical	1.17	1.08	-0.09	
Straw mulch	0.85	1.25	0.40	
Straw mulch	1.51	2.57	1.06	
Straw mulch	2.05	2.06	0.02	
Straw mulch	2.80	2.84	0.04	
Straw mulch	1.14	1.16	0.03	
Straw mulch	2.42	2.64	0.23	
Straw mulch	3.19	1.64	-1.55	
Straw mulch	2.87	3.96	1.09	**0.41**
Annual cc	1.09	1.24	0.15	
Annual cc	1.20	1.17	-0.03	
Annual cc	1.10	1.20	0.10	
Annual cc	1.73	1.56	-0.17	
Annual cc	1.36	1.36	0.00	
Annual cc	1.11	1.11	0.01	

Annual cc	1.09	0.90	-0.19	
Annual cc	1.12	1.18	0.07	**0.08**
Perennial cc	2.17	1.50	-0.67	
Perennial cc	2.35	2.64	0.29	
Perennial cc	1.86	1.75	-0.11	
Perennial cc	1.85	1.82	-0.03	
Perennial cc	1.37	1.34	-0.03	
Perennial cc	2.21	1.74	-0.47	
Perennial cc	1.01	2.72	1.72	**1.00**
Perennial cc	2.34	1.05	-1.29	

Table 2. Potential Mineralizable Nitrogen (PMN) data

Treatment Name	**N_7 (NH_4 ppm)**	**N_{inital} (NH_4 ppm)**	**N_7-$N_{initial}$**	**N_o** 1 week incubation at $35^{O}C$ (**N_o= 19.05N_t**)
Mechanical	2.3	0.8	1.5	43.815
Mechanical	1.6	0.1	1.5	30.48
Mechanical	5	0.5	4.5	95.25
Mechanical	1.3	0.8	0.5	24.765
Chemical	1.3	0.2	1.1	24.765
Chemical	2.4	0.7	1.7	45.72
Chemical	4.3	1	3.3	81.915
Chemical	3.3	1	2.3	62.865
Chemical	1.1	1.6	-0.5	20.955
Chemical	4.7	0.2	4.5	89.535
Straw mulch	2.8	0.8	1.8	53.34
Straw mulch	1.5	0.9	1.9	28.575
Straw mulch	3.5	0.8	0.7	66.675
Straw mulch	2.5	0.9	1.6	47.625
Straw mulch	1.2	0.4	0.8	22.86

Annual cc	2.7	0.9	2.4	51.435
Annual cc	2	0.7	2	38.1
Annual cc	2.2	0.6	1.4	41.91
Annual cc	2.5	0.9	1.3	47.625
Annual cc	2.6	1	1.5	49.53
Annual cc	2.5	0.4	2.2	47.625
Annual cc	2	0.9	1.6	38.1
Annual cc	4.7	0.4	1.6	89.535
Perennial cc	4.6	0.1	4.5	87.63
Perennial cc	5	0.7	4.3	95.25
Perennial cc	4.8	0.4	4.4	91.44
Perennial cc	2.1	1.1	1	40.005

Table 3. Soil Respiration (SR) data

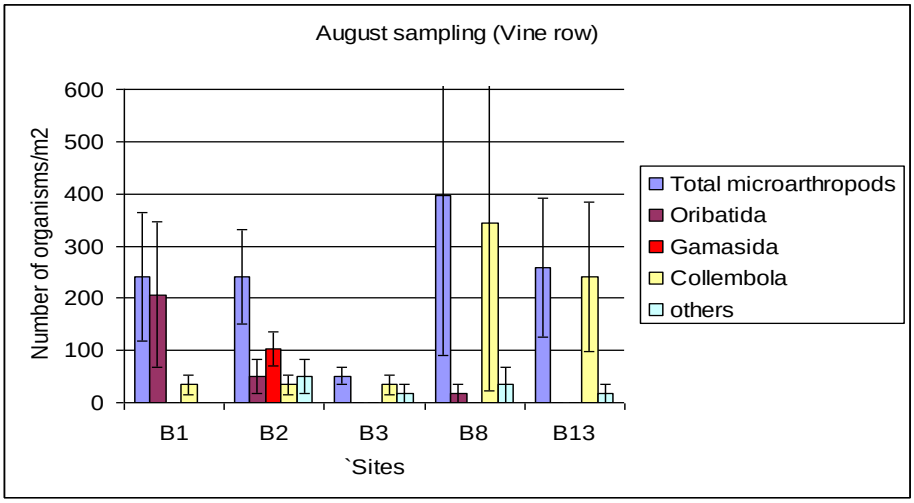
Treatment Name	CO_2 (ppm)	C_2H_4 (ppm)	O_2 (ppm)	CO_2 evolved (CO_2 sample - CO_2 air) sample) ppm	Oxygen consumed (O_2 air - O_2 sample) ppm
Mechanical	0.410	0.000	21.683	0.380	0.261
Mechanical	0.166	0.000	21.820	0.136	0.124
Mechanical	0.300	0.000	21.826	0.270	0.118
Mechanical	0.207	0.000	21.780	0.177	0.164
Mechanical	0.208	0.000	21.711	0.178	0.233
Mechanical	0.179	0.000	21.771	0.149	0.173
Mechanical	0.140	0.000	21.791	0.110	0.153
Chemical	0.363	0.000	21.753	0.333	0.191
Chemical	0.304	0.000	21.630	0.274	0.314
Chemical	0.237	0.000	21.704	0.207	0.240
Chemical	0.234	0.000	21.603	0.204	0.342
Chemical	0.092	0.000	21.801	0.062	0.143
Chemical	0.080	0.000	21.809	0.050	0.135

Straw mulch	0.181	0.000	21.922	0.151	0.022
Straw mulch	0.240	0.000	20.907	0.210	1.037
Straw mulch	0.316	0.000	21.001	0.286	0.943
Straw mulch	0.673	0.000	20.818	0.643	1.126
Straw mulch	1.284	0.000	19.969	1.254	1.975
Straw mulch	0.242	0.000	20.733	0.212	1.211
Straw mulch	0.663	0.000	20.907	0.633	1.037
Straw mulch	0.210	0.000	20.684	0.180	1.260
Straw mulch	0.886	0.000	20.007	0.856	1.937
Annual cc	0.194	0.000	21.232	0.164	0.712
Annual cc	0.094	0.000	20.775	0.064	1.169
Annual cc	0.291	0.000	20.593	0.261	1.351
Annual cc	0.280	0.000	20.596	0.250	1.348
Annual cc	0.067	0.000	20.811	0.037	1.133
Annual cc	0.257	0.000	21.581	0.227	0.363
Annual cc	0.378	0.000	20.664	0.348	1.280
Annual cc	0.173	0.000	21.029	0.143	0.915
Annual cc	0.749	0.000	19.842	0.719	2.102
Perennial cc	0.409	0.000	20.922	0.379	1.022
Perennial cc	0.743	0.000	20.065	0.713	1.879
Perennial cc	0.566	0.000	20.248	0.536	1.696
Perennial cc	0.246	0.000	21.580	0.216	0.364
Perennial cc	0.575	0.000	21.038	0.545	0.906
Perennial cc	0.382	0.000	21.302	0.352	0.642
Perennial cc	0.281	0.000	21.425	0.251	0.519

	CO_2 (ppm)	C_2H_4 (ppm)	O_2 (ppm)
Clean air	**0.030**		
Standard	**8.320**	**20.263**	**11.561**
Laboratory Air	**0.097465**		**21.94403**

Table 4. Results of earthworm study conducted by Maboeta (2009) on study site.

	Mean Biomass	Mean number		
Treatment Name		**Adults**	**Juveniles**	**Cocoons**
Mechanical	3.81 ± 2.31	21.33 ± 19.96	26.67 ± 21.99	0.00 ± 0.00
Chemical	5.85 ± 4.38	53.33 ± 66.40	72.00 ± 45.02	18.67 ± 26.8
Mulch	6.51 ± 4.20	74.67 ± 43.98	77.33 ± 71.80	13.33 ± 21.27
Annual cover crop	6.33 ± 4.70	13.33 ± 19.41	34.67 ± 25.16	2.67 ± 5.96
Perennial cover crop	6.92 ± 3.90	66.67 ± 60.16	40.00 ± 27.3	3 5.33 ± 13.06



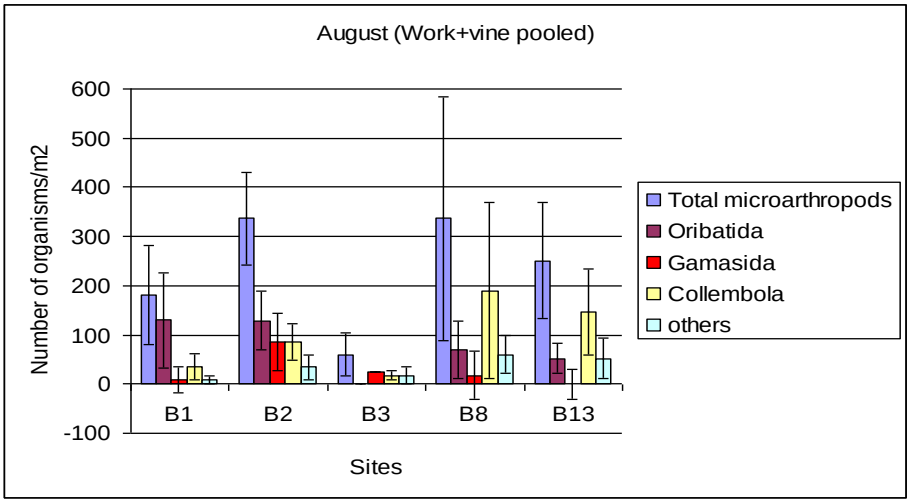


Fig ure 1. The mean (±SE) number per m^2 of Oribatida, Ganasida, Collembola and other micro-arthropods collected in plots for the soil management treatments

APPENDIX IV Statistical data

1. Statistical analysis of soil properties for the 0-50 mm soil depth

ANOVA for treatment Gravimetric Water Content

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	2.70	0.90	0.34	0.79
Treatment	4	22.19	5.55	2.12	0.14
Block(Treatment)	12	31.37	2.61	1.07	
Pos	1	0.40	0.40	0.16	0.69
TreatxPos	4	5.73	1.43	0.58	0.68
Error	15	36.75	2.45		
Corrected Total	39	99.13			

t Tests (LSD) for treatment Gravimetric Water Content

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	2.614307
Critical Value of t	2.17881
Least Significant Difference	1.7614

t Grouping	Mean	N	Treatment
A	6.22	8	Mulch
B A	4.52	8	Annual cc
B	4.44	8	Chemical
B	4.40	8	Perennial cc
B	4.16	8	Mechanical

t Tests (LSD) for Gravimetric Water Content for position

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	2.44995
Critical Value of t	2.13145
Least Significant Difference	1.055

t Grouping	Mean	N	Pos
A	4.85	20	I
A	4.65	20	B

t Tests (LSD) for Gravimetric Water Content tmt x pos

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	2.44995
Critical Value of t	2.13145
Least Significant Difference	2.3591

t Grouping		Mean	N	Pos
	B	3.90	4	MexB
B	A	4.41	4	MexI
B	A	4.95	4	CxB
	B	3.94	4	CxI
	A	6.34	4	MuxB
B	A	6.10	4	MuxI
B	A	4.25	4	AnxB
B	A	4.80	4	AnxI
	B	3.80	4	PexB
B	A	4.99	4	PexI

ANOVA for treatment Bulk density

Source	DF	Sun of Squares	Mean Square	F Value	Pr > F
Model	22	0.55	0.03	4.59	0.00
Error	13	0.07	0.01		
Corrected Total	35	0.62			

R-Square	Coeff Var	Root MSE	Bulk density Mean
0.89	6.37	0.07	1.16

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.06	0.02	3.50	0.05
Treatment	4	0.15	0.04	6.70	0.00
Block(Treatment)	10	0.11	0.01	1.99	0.12
Pos	1	0.09	0.09	17.25	0.00
TreatxPos	4	0.14	0.04	6.63	0.00

t- Tests (LSD) for Bulk density of treatment x position

Alpha	0.05
Error Degrees of Freedom	13
Error Mean Square	0.005453
Critical Value of t	2.16037
Least Significant Difference	0.1201
Harmonic Mean of Cell Sizes	3.529412

Means with the same letter are not significantly different.

t Grouping	Mean	N	Pos
D	0.95	3	MexB
A	1.30	3	MexI
C	1.11	4	CxB
B C	1.14	4	CxI
A	1.33	3	MuxB
B A	1.26	3	MuxI
C	1.11	4	AnxB
B A	1.25	4	AnxI
D C	1.06	4	PexB
B C	1.15	4	PexI

t Tests (LSD) for treatment Bulk Density

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	0.010831
Critical Value of t	2.22814
Least Significant Difference	0.1234
Harmonic Mean of Cell Sizes	7.058824

Means with the same letter are not significantly different.

t Grouping	Mean	N	Treatment
A	1.30	6	Mulch
B A	1.18	8	Annual cc
B	1.13	6	Mechanical
B	1.13	8	Chemical
B	1.10	8	Perennial cc

ANOVA for treatment for soil pH

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	2.26	0.75	2.60	0.11
Treatment	4	3.33	0.83	2.86	0.08
Block(Treatment)	11	3.20	0.29	4.29	
Pos	1	0.08	0.08	1.12	0.31
TreatxPos	4	0.60	0.15	2.23	0.12
Error	14	0.95	0.07		
Corrected Total	37	10.41			

t Tests (LSD) for pH

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.290687
Critical Value of t	2.20099
Least Significant Difference	0.6128
Harmonic Mean of Cell Sizes	7.5

t Grouping			Mean	N	Treatment
		A	7.76	8	Mechanical
	B	A	7.43	6	Chemical
	B	A	7.53	8	Mulch
		B	6.96	8	Annual cc
		B	7.14	8	Perennial cc

t Tests (LSD) for pH

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.067693
Critical Value of t	2.14479
Least Significant Difference	0.181

t Grouping	Mean	N	Pos
A	7.40	19	B
A	7.31	19	I

t Tests (LSD) for pH

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.067693
Critical Value of t	2.14479
Least Significant Difference	0.4075

t Grouping			Mean	N	Pos
	B	A	7.76	4.00	MexB
		A	7.77	4.00	MexI
B	A	C	7.50	3.00	CxB
B	D	C	7.36	3.00	CxI
		A	7.80	4.00	MuxB
E	D	C	7.26	4.00	MuxI
		E	6.88	4.00	AnxB
	E	D	7.03	4.00	AnxI
E	D	C	7.11	4.00	PexB
E	D	C	7.17	4.00	PexI

Dependent Variable: EC

R-Square	Coeff	Var	Root	MSE	EC	Mean
0.78	23.10	7955	3.11	5149	13.	43921.00

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	58.30	19.43	1.07	0.40
Treatment	4	99.62	24.91	1.37	0.31
Block(Treatment)	11	200.00	18.18	1.87	
Pos	1	7.07	7.07	0.73	0.41
TreatxPos	4	113.80	28.45	2.93	0.06
Error	14	135.86	9.70		
Corrected Total	37	614.65			

t Tests (LSD) for EC

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	18.18147
Critical Value of t	2.20099
Least Significant Difference	4.8464
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
B A	12.56	8	Mechanical
B	11.02	6	Chemical
A	15.97	8	Mulch
B A	13.82	8	Annual cc
B A	13.23	8	Perennial cc

t-Test for Between Tracks vs In tracks

t Tests (LSD) for EC

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	9.704154
Critical Value of t	2.14479
Least Significant Difference	2.1677

t Grouping	Mean	N	Pos
A	13.87	19	I
A	13.01	19	B

t Tests (LSD) for EC

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	9.704154
Critical Value of t	2.14479
Least Significant Difference	4.8794

t Grouping	Mean	N	Pos
E B D A C	13.41	4.00	MexI
B D A C	15.38	4.00	MuxB
E	10.37	3.00	CxB
E B D C	11.68	3.00	CxI
E B D A C	11.70	4.00	MexB
A	16.56	4.00	MuxI
B A	16.38	4.00	AnxB
E D C	11.26	4.00	AnxI
E D	10.56	4.00	PexB
B A C	15.91	4.00	PexI

Dependent Variable: Ca

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	264.68	11.51	2.76	0.03

R-Square	Coeff Var	Root MSE	Ca	Mean
0.82	15.20	2.04	13.	37658.00

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	16.01	5.34	0.69	0.57
Treatment	4	135.41	33.85	4.40	0.02
Block(Treatment)	11	84.60	7.69	1.84	
Pos	1	26.26	26.26	6.29	0.03
TreatxPos	4	2.40	0.60	0.14	0.96
Error	14	58.41	4.17		
Corrected Total	37	323.09			

t- Tests (LSD) for Ca

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	7.690462
Critical Value of t	2.20099
Least Significant Difference	3.1519
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
A	15.80	8	Mechanical
B A	14.46	6	Chemical
B A	14.29	8	Mulch
C	10.99	8	Annual cc
B C	11.61	8	Perennial cc

t Tests (LSD) for Ca

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	4.172322
Critical Value of t	2.14479
Least Significant Difference	1.4214

t Grouping	Mean	N	Pos
A	14.21	19	I
B	12.55	19	B

t Tests (LSD) for Ca

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	4.172322
Critical Value of t	2.14479
Least Significant Difference	3.1994

t Grouping	Mean	N	Pos
A	16.61	4	MexI
B A	15.52	4	MuxI
B A	15.00	4	MexB
B A	14.90	3	CxI

B	A	C	14.02	3	CxB
B	D	C	13.06	4	MuxB
B	D	C	12.50	4	PexI
	D	C	11.69	4	AnxI
		D	10.72	4	PexB
		D	10.30	4	AnxB

Dependent Variable: Mg

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	26.45057654	1.15002507	4	0.0049

R-Square	Coeff Var	Root MSE	Mg Mean
0.867838	10.9	0.53	4.8
	6988	6398	89737

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	1.25	0.42	0.81	0.51
Treatment	4	11.90	2.98	5.82	0.01
Block(Treatment)	11	5.63	0.51	1.78	
Pos	1	6.38	6.38	22.17	0.00
TreatxPos	4	1.29	0.32	1.12	0.39
Error	14	4.03	0.29		
Corrected Total	37	30.48			

t Tests (LSD) for Mg

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.511608
Critical Value of t	2.20099
Least Significant Difference	0.813
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
A	5.73	8	Mulch
B A	5.31	8	Perennial cc
B C	4.63	8	Annual cc
C	4.39	6	Chemical
C	4.26	8	Mechanical

t Tests (LSD) for Mg

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.287723
Critical Value of t	2.14479
Least Significant Difference	0.3733

t Grouping	Mean	N	Pos
A	5.30	19	I
B	4.48	19	B

t Tests (LSD) for Mg

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.287723
Critical Value of t	2.14479
Least Significant Difference	0.8402

t Grouping			Mean	N	Pos
		A	6.37	4	MuxI
	B	A	5.92	4	PexI
	B	C	5.09	4	MuxB
	D	C	4.84	4	AnxI
D	C	E	4.71	4	PexB
D	C	E	4.64	3	CxI
D	C	E	4.57	4	MexI
D	C	E	4.42	4	AnxB
D		E	4.14	3	CxB
		E	3.96	4	MexB

Dependent Variable: Na

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	23	0.16	0.01	1.31	0.31

R-Square	Coeff Var	Root MSE	Na Mean
0.682567	15.7 5832	0.07 3981	0.4 69474

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.00	0.00	0.62	0.62
Treatment	4	0.02	0.01	2.77	0.08
Block(Treatment)	11	0.02	0.00	0.39	
Pos	1	0.11	0.11	19.23	0.00
TreatxPos	4	0.01	0.00	0.37	0.83
Error	14	0.08	0.01		
Corrected Total	37	0.24			

t Tests (LSD) for Na

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.00215
Critical Value of t	2.20099
Least Significant Difference	0.0527
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
A	0.51	8	Annual cc
B A	0.49	8	Perennial cc
B	0.45	8	Mulch
B	0.45	8	Mechanical
B	0.45	6	Chemical

t Tests (LSD) for Na

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.005473
Critical Value of t	2.14479
Least Significant Difference	0.0515

t Grouping	Mean	N	Pos
A	0.52	19	I
B	0.42	19	B

t Tests (LSD) for Na

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.005473

Critical Value of t	2.14479
Least Significant Difference	0.1159

t Grouping	Mean	N	Pos
A	0.57	4	AnxI
B A	0.52	3	CxI
B A C	0.52	4	PexI
B A C	0.51	4	MuxI
B D A C	0.50	4	MexI
E B D A			
C	0.46	4	PexB
E B D C	0.45	4	AnxB
E D C	0.40	4	MexB
E D	0.39	4	MuxB
E	0.38	3	CxB

Dependent Variable: K

R-Square	Coeff	Var	Root	MSE	K	Mean
0.79366	14.1	9537	0.18	3307	1.2	91316

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.06	0.02	0.44	0.73
Treatment	4	0.64	0.16	3.46	0.05
Block(Treatment)	11	0.51	0.05	1.37	
Pos	1	0.01	0.01	0.31	0.59
TreatxPos	4	0.60	0.15	4.43	0.02
Error	14	0.47	0.03		
Corrected Total	37	2.28			

t Tests (LSD) for K

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.045984
Critical Value of t	2.20099
Least Significant Difference	0.2437
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
B	1.24	8	Mechanical
B A	1.30	6	Chemical
B A	1.28	8	Mulch
B	1.13	8	Annual cc
A	1.52	8	Perennial cc

t Tests (LSD) for K

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.033601
Critical Value of t	2.14479
Least Significant Difference	0.1276

t Grouping	Mean	N	Pos
A	1.31	19	I
A	1.27	19	B

t Tests (LSD) for K

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.033601
Critical Value of t	2.14479
Least Significant Difference	0.2871

t Grouping	Mean	N	Pos
A	1.74	4	PexI
B	1.37	4	MexB
C B	1.35	3	CxB
C B	1.31	4	MuxB
C B	1.29	4	PexB
C B	1.25	4	MuxI
C B	1.24	3	CxI
C B	1.19	4	AnxI
C B	1.10	4	MexI
C	1.07	4	AnxB

Dependent Variable: N

R-Square	Coeff Var	Root MSE	N Mean
0.63	**180.10**	**0.36**	**0.20**

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.34	0.11	0.90	0.47
Treatment	4	0.68	0.17	1.36	0.31
Block(Treatment)	12	1.51	0.13	0.95	
Pos	1	0.24	0.24	1.84	0.20
TreatxPos	4	0.67	0.17	1.27	0.33
Error	15	1.99	0.13		
Corrected Total	39	5.43			

t Tests (LSD) for N

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.126053
Critical Value of t	2.17881
Least Significant Difference	0.3868

t Grouping	Mean	N	Treatment
A	0.46	8	Perennial cc
A	0.17	8	Mulch
A	0.17	8	Chemical
A	0.11	8	Mechanical
A	0.10	8	Annual cc

t Tests (LSD) for N

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.132347
Critical Value of t	2.13145
Least Significant Difference	0.2452

tGrouping	Mean	N	Pos
A	0.28	20	B
A	0.12	20	I

t Tests (LSD) for N

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.132347
Critical Value of t	2.13145
Least Significant Difference	0.5483

t Grouping	Mean	N	Pos
A	0.79	4	PexB
B	0.21	4	MuxB
B	0.18	4	CxB
B	0.16	4	CxI
B	0.14	4	MuxI
B	0.12	4	PexI
B	0.11	4	MexB
B	0.11	4	AnxB
B	0.10	4	MexI
B	0.10	4	AnxI

Dependent Variable: C

R-Square	Coeff Var	Root MSE	C Mean
0.77	**30.16**	**0.51**	**1.68**

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.88	0.29	0.65	0.60
Treatment	4	2.94	0.74	1.61	0.23
Block(Treatment)	12	5.48	0.46	1.77	0.15
Pos	1	1.80	1.80	6.97	0.02
TreatxPos	4	1.79	0.45	1.73	0.20
Error	15	3.87	0.26		
Corrected Total	39	16.76			

t Tests (LSD) for C

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.456756
Critical Value of t	2.17881
Least Significant Difference	0.7363

t Grouping	Mean	N	Treatment
A	1.98	8	Chemical
A	1.91	8	Mulch
A	1.81	8	Perennial cc
A	1.36	8	Annual cc
A	1.36	8	Mechanical

t Tests (LSD) for C

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.257838
Critical Value of t	2.13145
Least Significant Difference	0.3423

t Grouping	Mean	N	Pos
A	1.90	20	B
B	1.47	20	I

t Tests (LSD) for C

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.257838
Critical Value of t	2.13145
Least Significant Difference	0.7653

t Grouping			Mean	N	Pos
		A	2.39	4	MuxB
		A	2.24	4	PexB
	B	A	2.16	4	CxB
B	A	C	1.79	4	CxI
B		C	1.44	4	MuxI
B		C	1.43	4	AnxI
B		C	1.40	4	MexB
		C	1.39	4	PexI
		C	1.31	4	MexI
		C	1.29	4	AnxB

Dependent Variable: SOM

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	38.14	1.59	2.08	0.07

R-Square	Coeff Var	Root MSE	SOM Mean
0.77	**30.22**	**0.88**	**2.90**

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	2.61	0.87	0.64	0.60
Treatment	4	8.70	2.18	1.61	0.24
Block(Treatment)	12	16.22	1.35	1.77	
Pos	1	5.31	5.31	6.94	0.02
TreatxPos	4	5.29	1.32	1.73	0.20
Error	15	11.49	0.77		
Corrected Total	39	49.62			

t Tests (LSD) for SOM

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	1.351524
Critical Value of t	2.17881
Least Significant Difference	1.2665

t Grouping	Mean	N	Treatment
A	3.40	8	Chemical
A	3.29	8	Mulch
A	3.12	8	Perennial cc

A	2.34	8	Annual cc
A	2.33	8	Mechanical

t Tests (LSD) for SOM

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.76571
Critical Value of t	2.13145
Least Significant Difference	0.5898

t Grouping	Mean	N	Pos
A	3.26	20	B
B	2.53	20	I

t Tests (LSD) for SOM

Alpha	0.05
Error Degrees of Freedom	15
Error Mean Square	0.76571
Critical Value of t	2.13145
Least Significant Difference	1.3188

t Grouping	Mean	N	Pos
A	4.11	4	MuxB
A	3.85	4	PexB
B A	3.72	4	CxB
B A C	3.09	4	CxI
B C	2.47	4	MuxI
B C	2.46	4	AnxI
B C	2.41	4	MexB
C	2.39	4	PexI
C	2.26	4	MexI
C	2.22	4	AnxB

Dependent Variable: C_N

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	24	127.05	5.29	1.17	0.39
Error	14	63.41	4.53		
Corrected Total	38	190.46			

R-Square	Coeff Var	Root MSE	C_N Mean
0.67	**18.46**	**2.13**	**11.53**

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	10.80	3.60	0.79	0.52
Treatment	4	24.16	6.04	1.33	0.31
Block(Treatment)	12	75.36	6.28	1.39	0.28
Pos	1	0.03	0.03	0.01	0.94
TreatxPos	4	16.70	4.17	0.92	0.48

t Tests (LSD) for C_N

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	6.279848
Critical Value of t	2.17881
Least Significant Difference	2.7687
Harmonic Mean of Cell Sizes	7.777778

t Grouping	Mean	N	Treatment
A	12.78	8	Mechanical
A	11.98	7	Annual cc
A	11.52	8	Chemical
A	10.83	8	Mulch
A	10.59	8	Perennial cc

t Tests (LSD) for C_N

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	4.529264
Critical Value of t	2.14479
Least Significant Difference	1.4623
Harmonic Mean of Cell Sizes	19.48718

t Grouping	Mean	N	Pos
A	11.55	19	I
A	11.52	20	B

t Tests (LSD) for C_N

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	4.529264
Critical Value of t	2.14479
Least Significant Difference	3.281
Harmonic Mean of Cell Sizes	3.870968

t Grouping		Mean	N	Pos
	A	13.08	4	MexI
B	A	12.49	4	MexB
B	A	12.07	3	AnxI
B	A	12.01	4	CxB
B	A	11.90	4	AnxB
B	A	11.65	4	PexI
B	A	11.64	4	MuxB
B	A	11.04	4	CxI
B	A	10.03	4	MuxI
	B	9.54	4	PexB

Dependent Variable: SMB

R-Square	Coeff	Var	Root	MSE	SMB	Mean
0.37252	1142	8.42	0.69	1720	0.0	6053

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.33	0.11	1.15	0.37
Treatment	4	0.25	0.06	0.65	0.64
Block(Treatment)	11	1.07	0.10	0.20	
Pos	1	0.04	0.04	0.09	0.77
TreatxPos	4	2.28	0.57	1.19	0.36
Error	14	6.70	0.48		
Corrected Total	37	10.68			

t Tests (LSD) for SMB

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.096964
Critical Value of t	2.20099
Least Significant Difference	0.3539
Harmonic Mean of Cell Sizes	7.5

t Grouping	Mean	N	Treatment
A	0.16	8	Mulch
A	-0.01	8	Annual cc
A	-0.02	8	Mechanical
A	-0.04	6	Chemical
A	-0.07	8	Perennial cc

t Tests (LSD) for SMB

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.478476
Critical Value of t	2.14479
Least Significant Difference	0.4813

t Grouping	Mean	N	Pos
A	0.04	19	I
A	-0.03	19	B

t Tests (LSD) for SMB

Alpha	0.05
Error Degrees of Freedom	14
Error Mean Square	0.478476
Critical Value of t	2.14479
Least Significant Difference	1.0835

t Grouping	Mean	N	Pos
A	0.61	4	MuxI
A	0.23	4	PexB
A	0.02	3	CxI
A	0.01	4	MexB
A	-0.01	4	AnxI
A	-0.01	4	AnxB
A	-0.05	4	MexI
A	-0.11	3	CxB
A	-0.28	4	MuxB
A	-0.38	4	PexI

Dependent Variable: PMN

R-Square	Coeff Var	Root MSE	PMN Mean
0.51	**-2670.00**	**11.33**	**-0.42**

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	197.12	65.71	0.60	0.63
Treatment	4	15.21	3.80	0.03	1.00
Block(Treatment)	11	1208.53	109.87	0.86	0.60
Pos	1	17.82	17.82	0.14	0.72
TreatxPos	4	305.89	76.47	0.60	0.67
Error	13	1668.64	128.36		
Corrected Total	36	3413.20			

t Tests (LSD) for PMN

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	109.8661
Critical Value of t	2.20099
Least Significant Difference	12.072
Harmonic Mean of Cell Sizes	7.304348

t Grouping	Mean	N	Treatment
A	0.60	7	Mulch
A	-0.14	8	Annual cc
A	-0.38	8	Mechanical
A	-0.79	6	Chemical
A	-1.37	8	Perennial cc

t Tests (LSD) for PMN

Alpha	0.05
Error Degrees of Freedom	13
Error Mean Square	128.3567
Critical Value of t	2.16037
Least Significant Difference	8.0505
Harmonic Mean of Cell Sizes	18.48649

t Grouping	Mean	N	Pos
A	-0.32	18	I
A	-0.52	19	B

t Tests (LSD) for PMN

Alpha	0.05
Error Degrees of Freedom	13
Error Mean Square	128.3567
Critical Value of t	2.16037
Least Significant Difference	18.152
Harmonic Mean of Cell Sizes	3.636364

t Grouping	Mean	N	Pos
A	8.41	3	MuxI
A	4.38	4	PexB
A	0.48	3	CxI
A	0.14	4	MexB
A	-0.09	4	AnxI
A	-0.19	4	AnxB
A	-0.91	4	MexI
A	-2.06	3	CxB
A	-5.26	4	MuxB
A	-7.12	4	PexI

2. Statistical analysis of soil properties for the 0-200 mm soil depth

Ho: μ1=μ2=μ3=μ4=μ5
(no differences between treatments)
P<0.05 indicates differences. We are taking a 5% change to reject Ho.

Dependent Variable: pH

This analysis is not reliable, because of the outliers look further down for (ii) anova analysis: marked outliers removed

R-Square	Coeff Var	Root MSE	pH Mean
0.56	2.78	0.23	8.34

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.17	0.06	1.05	0.41
Treatment	4	0.64	0.16	3.00	0.06
Error	12	0.64	0.05		
Corrected Total	19	1.46			

t Tests (LSD) for pH

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.053727
Critical Value of t	2.17881
Least Significant Difference	0.3571

t Grouping	Mean	N	Treatment
A	8.56	4	Mechanical
A	8.52	4	Mulch
B A	8.32	4	Chemical
B A	8.26	4	Perennial cc
B	8.07	4	Annual cc

Dependent Variable: pH (outliers removed from dataset)

R-Square	Coeff Var	Root MSE	pH Mean
0.89	0.97	0.08	8.41

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.1508	0.0503	7.5700	0.0062
Treatment	4	0.3859	0.0965	14.5200	0.0004
Error	10	0.0664	0.0066		
Corrected Total	17	0.6032			

t Tests (LSD) for pH

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	0.006644
Critical Value of t	2.22814
Least Significant Difference	0.1367
Harmonic Mean of Cell Sizes	3.529412

t Grouping	Mean	N	Treatment
A	8.56	4	Mechanical
B	8.21	3	Annual cc
A	8.52	4	Mulch
A	8.49	3	Chemical
B	8.26	4	Perennial cc

Dependent Variable: EC

R-Square	Coeff Var	Root MSE	EC Mean
0.46	18.99	1.71	9.01

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	17.40	5.80	1.98	0.17
Treatment	4	12.02	3.01	1.03	0.43
Error	12	35.10	2.93		
Corrected Total	19	64.52986			

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	2.925293
Critical Value of t	2.17881
Least Significant Difference	2.6351

t Grouping	Mean	N	Treatment
A	9.91	4	Mulch

A	9.69	4	Mechanical
A	9.16	4	Perennial cc
A	8.42	4	Chemical
A	7.85	4	Annual cc

Dependent Variable: Ca

R-Square	Coeff Var	Root MSE	Ca Mean
0.49	32.41	3.11	9.61

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	49.52	16.51	1.70	0.22
Treatment	4	60.82	15.21	1.57	0.25
Error	12	116.37	9.70		
Corrected Total	19	226.7148			

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	9.697484
Critical Value of t	2.17881
Least Significant Difference	4.7977

t Grouping	Mean	N	Treatment
A	12.14	4	Mechanical
B A	10.47	4	Mulch
B A	9.80	4	Chemical
B A	8.72	4	Perennial cc
B	6.92	4	Annual cc

Dependent Variable: Mg

R-Square	Coeff Var	Root MSE	Mg Mean
0.29	12.25	0.35	2.85

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.09	0.03	0.25	0.86
Treatment	4	0.52	0.13	1.06	0.42
Error	12	1.46	0.12		
Corrected Total	19	2.072295			

t Tests (LSD) for Mg

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.121887
Critical Value of t	2.17881
Least Significant Difference	0.5379

t Grouping	Mean	N	Treatment
A	3.13	4	Mulch
A	2.84	4	Chemical
A	2.84	4	Perennial cc
A	2.81	4	Annual cc
A	2.63	4	Mechanical

Dependent Variable: Na

R-Square	Coeff Var	Root MSE	Na Mean
0.38	14.37	0.04	0.26

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.00	0.00	0.71	0.57
Treatment	4	0.01	0.00	1.34	0.31
Error	12	0.02	0.00		
Corrected Total	19	0.02738			

t Tests (LSD) for Na

Please look at the second analysis where the outlier is removed

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.001406
Critical Value of t	2.17881
Least Significant Difference	0.0578

t Grouping	Mean	N	Treatment
A	0.29	4	Annual cc
A	0.27	4	Mechanical
A	0.26	4	Perennial cc
A	0.25	4	Chemical
A	0.24	4	Mulch

Dependent Variable: Na (outliers removed)

R-Square	Coeff Var	Root MSE	Na Mean
0.74	6.28	0.02	0.25

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.0034	0.0011	4.5900	0.0287
Treatment	4	0.0037	0.0009	3.6800	0.0432
Error	10	0.0025	0.0002		
Corrected Total	17	0.0096			

t Tests (LSD) for Na

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	0.000249
Critical Value of t	2.22814
Least Significant Difference	0.0265
Harmonic Mean of Cell Sizes	3.529412

t Grouping	Mean	N	Treatment
A	0.27	4	Mechanical
B A	0.25	4	Chemical
B	0.24	4	Mulch
A	0.27	3	Annual cc
B	0.23	3	Perennial cc

Dependent Variable: K

This analysis is not reliable, because of the outliers look further down for (ii) anova analysis: marked outliers removed

R-Square	Coeff Var	Root MSE	K Mean
0.61	11.81	0.13	1.13

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.03	0.01	0.54	0.66
Treatment	4	0.30	0.08	4.25	0.02
Error	12	0.21	0.02		
Corrected Total	19	0.544255			

t Tests (LSD) for K

Please look at the second analysis where the outlier is removed

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.017767
Critical Value of t	2.17881
Least Significant Difference	0.2054

t Grouping	Mean	N	Treatment
A	1.36	4	Mulch
B	1.15	4	Perennial cc
B	1.08	4	Annual cc
B	1.04	4	Chemical
B	1.02	4	Mechanical

Dependent Variable: K

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.386	0.055	7.030	0.002

R-Square	Coeff Var	Root MSE	K Mean
0.82	7.94	0.09	1.11

Source	DF	SS	Mean Square	F Value	Pr > F
Block	3	0.0231	0.0077	0.9800	0.4361
Treatment	4	0.3629	0.0907	11.5700	0.0006
Error	11	0.0862	0.0078		
Corrected Total	18	0.4723			

Significant differences between treatments.Reject Ho. Look at t test

t Tests (LSD) for K

Alpha	0.05
Error Degrees of Freedom	11
Error Mean Square	0.00784
Critical Value of t	2.20099
Least Significant Difference	0.1423
Harmonic Mean of Cell Sizes	3.75

t Grouping	Mean	N	Treatment
C B	1.02	4	Mechanical
C B	1.04	4	Chemical
A	1.36	4	Mulch
C	0.98	3	Annual cc
B	1.15	4	Perennial cc

Dependent Variable: P

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	3184.71	454.96	0.78	0.61

R-Square	Coeff Var	Root MSE	P Mean
0.31	37.47	24.11	64.36

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	379.60	126.53	0.22	0.88
Treatment	4	2805.11	701.28	1.21	0.36
Error	12	6977.39	581.45		
Corrected Total	19	10162.1			

t Tests (LSD) for P

This is a confirmation of the anova results

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	581.4493
Critical Value of t	2.17881
Least Significant Difference	37.15

t Grouping	Mean	N	Treatment
A	82.22	4	Mulch
A	73.10	4	Perennial cc
A	62.12	4	Mechanical
A	53.71	4	Annual cc
A	50.66	4	Chemical

Dependent Variable: N

R-Square	Coeff Var	Root MSE	N Mean
0.40	19.72	0.01	0.07

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.00	0.00	1.13	0.38
Treatment	4	0.00	0.00	1.19	0.36
Error	12	0.00	0.00		

Corrected Total	19	0.003895

t Tests (LSD) for N

This is a confirmation of the anova results

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.000193
Critical Value of t	2.17881
Least Significant Difference	0.0214

t Grouping	Mean	N	Treatment
A	0.08	4	Perennial cc
A	0.08	4	Mechanical
A	0.07	4	Mulch
A	0.06	4	Chemical
A	0.06	4	Annual cc

Dependent Variable: C

This analysis is not reliable, because of the outliers look further down for (ii) anova analysis: marked outliers removed

R-Square	Coeff Var	Root MSE	C Mean
0.40	22.65	0.19	0.82

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.11	0.04	1.07	0.40
Treatment	4	0.17	0.04	1.21	0.36
Error	12	0.41	0.03		
Corrected Total	19	0.691095			

No significant treatment differences (p=0.3553>0.05). Do not reject Ho

t Tests (LSD) for C
Please look at second (ii) analysis

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.034445
Critical Value of t	2.17881
Least Significant Difference	0.2859

t Grouping	Mean	N	Treatment
A	0.99	4	Mechanical
A	0.85	4	Perennial cc
A	0.78	4	Annual cc
A	0.75	4	Mulch
A	0.74	4	Chemical

Dependent Variable: C

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	0.11	0.02	4.42	0.02

R-Square	Coeff Var	Root MSE	C Mean
0.76	7.62	0.06	0.80

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	0.0645	0.0215	5.8400	0.0143
Treatment	4	0.0495	0.0124	3.3600	0.0545
Error	10	0.0368	0.0037		
Corrected Total	17	0.1508			

t Tests (LSD) for C

Alpha	0.05
Error Degrees of Freedom	10
Error Mean Square	0.003681
Critical Value of t	2.22814

Least Significant Difference	0.1018
Harmonic Mean of Cell Sizes	3.529412

t Grouping	Mean	N	Treatment
A	0.85	4	Perennial cc
B A	0.85	3	Annual cc
B A C	0.81	3	Mechanical
B C	0.75	4	Mulch
C	0.74	4	Chemical

Dependent Variable: C_N

R-Square	Coeff Var	Root MSE	C_N Mean
0.30	23.06	2.74	11.86

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Block	3	19.48	6.49	0.87	0.48
Treatment	4	19.36	4.84	0.65	0.64
Error	12	89.79	7.48		
Corrected Total	19	128.6228			

No significant treatment differences (p=0.6397>0.05). Do not reject Ho

t Tests (LSD) for C_N

This is a confirmation of the anova results

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	7.482164
Critical Value of t	2.17881
Least Significant Difference	4.2142

t Grouping	Mean	N	Treatment
A	13.15	4	Annual cc

A	12.48	4	Mechanical
A	12.10	4	Chemical
A	11.26	4	Perennial cc
A	10.32	4	Mulch

APPENDIX V Pedological description of study area

1. SOIL PROFILE B1H4

NATIONAL SOIL PROFILE NO : 45

Map/photo : 3319DD Robertson
Latitude + Longitude:33° 49' 19.7'' / 19° 52' 36.4''
Land Type No :
Climate Zone :
Altitude :
Terrain Unit: Lower Footslope
Slope:
Slope Shape : Straight
Aspect :
Microrelief : None
Parent Material Solum : Origin unknown, local colluvium, local colluvium
Weathering of underlying material: Unknown
Underlying Material : Limestone
Alteration of underlying material : Normal weathering

Soil form and family: Augrabies shilowa
Surface rockiness : None
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Vineyards
Water table : None
Described by : I. Mathys
Date Described : 28 June 2010

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-200	dry colour: dark reddish brown 5YR3/4; texture: loamy sand; structure: weak fine granular; consistence: loose, loose, non-sticky; few angular gravel 2-6mm; few roots; gradual smooth transition.	Orthic
B1	200-800	moist colour: dark reddish brown 5YR3/4; texture: sandy clay loam; structure: weak fine granular; consistence: soft, friable, slightly sticky; non-hardened free lime, slight effervescence; common angular coarse gravel 6-25mm; colluvial ; common roots; gradual smooth transition.	Neocarbonate

B2	800-1200	dry colour: strong brown 7.5YR4/6; moist colour: yellowish red 5YR4/6; texture: sandy clay; structure: weak fine granular; consistence: soft, friable, non-sticky; non-hardened free lime, moderate effervescence; common angular coarse gravel 6-25mm; colluvial ; common roots; gradual	Neocarbonate

2. SOIL PROFILE B2H3

NATIONAL SOIL PROFILE NO : 48
Map/photo : 3319DD Robertson
Latitude + Longitude:33° 49' 18.7'' / 19° 52' 34''
Land Type No :
Climate Zone :
Altitude :
Terrain Unit: Lower Footslope
Slope:
Slope Shape : Straight
Aspect :
Microrelief : None
Parent Material Solum : Origin unknown, local colluvium, local colluvium
Weathering of underlying material: Unknown
Underlying Material : Limestone
Alteration of underlying material : Normal weathering

Soil form and family: Trawal katmakoep
Surface rockiness : None
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Vineyards
Water table : None
Described by : I. Mathys
Date Described : 28 June 2010

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-200	dry colour: strong brown 7.5YR4/6; texture: loamy sand; consistence: hard, firm, sticky, plastic; few coarse gravel 6-25mm.	Orthic
B1	200-400	dry colour: dark reddish brown 5YR3/4; moist colour: dark reddish brown 5YR3/4; texture: silty clay loam; consistence: slightly hard, slightly firm, slightly sticky, slightly plastic; common coarse gravel 6-25mm; few roots.	Neocarbonate

B2	400-600	dry colour: strong brown 7.5YR4/6; moist colour: reddish brown 5YR4/4; texture: sandy clay loam; consistence: hard, slightly firm, slightly sticky, slightly plastic; common coarse gravel 6-25mm; thin iron and/or manganese pan ; few roots.	Dorbank

3. SOIL PROFILE B2H4

NATIONAL SOIL PROFILE NO : 47
Map/photo : 3319DD Robertson
Latitude + Longitude:33° 49' 20.4'' / 19° 52' 31.9''
Land Type No :
Climate Zone :
Altitude :
Terrain Unit: Lower Footslope
Slope:
Slope Shape : Straight
Aspect :
Microrelief : None
Parent Material Solum : Origin unknown, local colluvium, local colluvium
Weathering of underlying material: Unknown
Underlying Material : Limestone
Alteration of underlying material : Normal weathering

Soil form and family: Oudtshoorn baroe
Surface rockiness : None
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Vineyards
Water table : None
Described by : I. Mathys
Date Described : 28 June 2010

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-300	dry colour: brown to dark brown 7.5YR4/4; texture: clay loam; structure: moderate medium single grain; consistence: soft, friable, sticky, plastic; very few coarse gravel 6-25mm; few roots.	Orthic
B1	300-500	dry colour: yellowish red 5YR5/6; moist colour: dark reddish brown 5YR3/4; texture: sandy loam; structure: weak medium subangular blocky; consistence: soft, loose, non-sticky, non-plastic; common coarse gravel 6-	Neocuntanic

		25mm; common roots.	
B2	500-650	dry colour: reddish yellow 5YR6/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; structure: weak medium subangular blocky; consistence: soft, loose, non-sticky, non-plastic; many coarse gravel 6-25mm; common roots.	Dorbank

4. SOIL PROFILE B3H3

NATIONAL SOIL PROFILE NO : 46
Map/photo : 3319DD Robertson
Latitude + Longitude:33° 49' 20.2'' / 19° 52' 33.5''
Land Type No :
Climate Zone :
Altitude :
Terrain Unit: Lower Footslope
Slope:
Slope Shape : Straight
Aspect :
Microrelief :
Parent Material Solum : Origin unknown, local colluvium, local colluvium
Underlying Material : Limestone
Geological Group / Formation : Mainly shale and shist with sandstone, conglomerate, grit and limestone of the Malmesbury Group as well as talus and gravel

Soil form and family: Augrabies shilowa
Surface rockiness : None
Surface stoniness : None
Occurence of flooding : None
Wind erosion : None
Water Erosion : None
Vegetation / Land use : Vineyards
Water table : None
Described by : I Mathys
Date Described : 28 June 2010
Weathering of underlying material: Unknown
Alteration of underlying material : Normal weathering

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-200	dry colour: dark brown 7.5YR3/4; moist colour: very dark brown 10YR2.5/2; many slickensides; common	Orthic

		organic cutans; few roots; clear transition.	
B1	200-350	dry colour: red 7.5R4/6; moist colour: dark reddish brown 2.5YR3/4; many slickensides; common clay cutans; colluvial ; common roots; gradual transition.	Neocarbonate
B2	350-550	dry colour: reddish brown 5YR4/4; moist colour: dark yellowish brown 10YR3/6; common roots; gradual transition.Neocarbonate	Neocarbonate

5. SOIL PROFILE B13H1

NATIONAL SOIL PROFILE NO : 44

Map/photo : 3319DD Robertson

Latitude + Longitude:33° 49' 20.8'' / 19° 52' 34.2''

Land Type No :

Climate Zone :

Altitude :

Terrain Unit: Lower Footslope

Slope:

Slope Shape : Straight

Aspect :

Microrelief : None

Parent Material Solum : Origin unknown, local colluvium, local colluvium

Weathering of underlying material: Unknown

Underlying Material : Sedimentary rocks (unspecified)

Alteration of underlying material : Normal weathering

Soil form and family: Augrabies shilowa

Surface rockiness : None

Surface stoniness : None

Occurence of flooding : None

Wind erosion : None

Water Erosion : None

Vegetation / Land use : Vineyards

Water table : None

Described by : I. Mathys

Date Described : 28 June 2010

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0-150	Dry state; dry colour: yellowish red 5YR4/6; texture: sandy clay loam; structure: weak medium crumb; consistence: hard, slightly firm, slightly sticky, slightly plastic; common clay cutans; few ; clear smooth transition.	Orthic
B1	150-500	Dry state; dry colour: yellowish red 5YR5/8; moist colour: dark reddish brown 2.5YR3/4; texture: fine sandy clay loam; structure: moderate medium crumb; consistence: hard, slightly firm, slightly sticky, slightly plastic; discontinuous slight nodular pan cementation of iron and manganese oxides; common clay cutans; few ; few roots; clear smooth transition.	Pedocutanic
B2	500-750	Dry state; dry colour: reddish yellow 5YR6/6; moist colour: dark reddish brown 2.5YR3/4; texture: sandy loam; structure: moderate medium crumb; consistence: slightly hard, friable, sticky, plastic; discontinuous slight nodular pan cementation of iron and manganese oxides; non-hardened free lime, slight effervescence; common clay cutans; common ; thin iron and/or manganese pan single occurrence, lower part of horizon; common roots; gradual tonguing transition.	Pedocutanic
C	750-1100	Dry state; moist colour: yellowish red 5YR4/6; texture: clay; structure: weak medium crumb; consistence: slightly hard, friable, sticky, plastic; non-hardened free lime, moderate effervescence; common carbonate cutans; common angular ; thin iron and/or manganese pan multiple occurrence, throughout horizon; common roots; gradual tonguing transition.	Soft carbonate