SOIL QUALITY OF KIKUYU, RYEGRASS AND CLOVER PASTURE MIXTURES IN THE TSITSIKAMMA

by

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ABSTRACT

South African soils have long been classified as being severely degraded. The state of the soils is even more pronounced in sandy soils that are managed for pasture production in the Tsitsikamma region. This is mainly due to the fact that these soils have poor soil organic matter (SOM) content and poor soil fertility. The result of this is nutrient leaching which leads to contamination of ground water; water loss through deep percolation resulting in wasteful irrigation; poor pasture yields which have a direct influence on farm efficiency and profitability. Such occurrences are more detrimental in the dairy farming industry because the quality of soil and quantity of pasture produced has an overriding influence on the main farm produce, which is milk. A system of continuous supply of nutrients and irrigation is not a sustainable system for dairy farmers as it results in enormous financial pressure. Better strategies that ensure effective use of resources need to be developed and implemented and must compliment sustainable farming. Assessment of soil quality is one of the fundamental methods that have long been identified as tools, which farmers can use in order to improve farm efficiency.

Soil quality as defined by Karlen *et al.* (1996) is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation. Managing and understanding soil quality means evaluating and managing soil so that it functions optimally now, and in the future. Land managers should be monitoring changes in soil quality on a regular basis, and using this to adopt sustainable practices, which aims to improve the productivity of soil (Doran, 2000). Soil quality can only be measured by assessment of its indicators which vary according to cropping systems. The general consensus amongst researchers is ensuring that indicators of soil quality should reflect the soils' chemical, physical and biological status. In this study selected indicators of soil chemistry (extractable P, exchangeable Ca, K, Mg and Na, pH (KCl)); soil physics (bulk density (BD)) and soil biology (total carbon (C), active C, total nitrogen (N), C/N ratio, PMN rate and inorganic N) were measured. The selection thereof was based on their ease and reliability of measurement, the sensitivity of the measurement to changes in soil management as well as

the skills essential for interpreting the results. The study was carried out in the Tsitsikamma region of the Eastern Cape where farms distributed in the upper and lower Tsitsikamma region were selected as study sites. The farms were selected based on the criteria that they were all irrigated farms with kikuyu, ryegrass and clover pasture mixtures, they had adopted minimum tillage or no tillage practices, had pastures established for at least 6 years, and lastly had accurate records of management practices that had been implemented, especially those relating to fertiliser application. An average of 5675 soil samples were analysed across the farms. These samples were taken at increments of 0-15, 15-30, 30-45 and 45-60 cm, respectively. The samples were analysed using the Veris spectrophotometer probe otherwise known as the Veris P4000. Calibration soil samples were also taken and analysed by a commercial laboratory (BemLab, De Beers RD, Somerset West, South Africa) in order to standardize the soil samples analysed with the Veris P4000.

Based on the selected indicators, the objectives of the study were structured to answer 3 principal research questions, namely: Firstly, do the farms in the Tsitsikamma differ significantly within soil depth? The soil depth comparison was done at increments of 0-15, 15-30, 30-45 and 45-60 cm respectively, while farm comparisons were done at a 0-30 cm increment; Secondly, are management practices responsible for variations observed in the Tsitsikamma region?; And lastly, which soil quality indicators play the most significant role in the variations observed?

Data used for this study was presented in concentration (% or mg/kg) and in stock (kg/ha) values. The analysis of variance was measured at 99% confidence level. Values that had significant differences had p values < 0.001, whereas those that showed no significant difference had p values > 0.001. Correlations between soil quality indicators were analysed using two-tailed Pearson correlation tests at 1% and 5% level. Principal component analysis (PCA) was computed using SPSS statistical program.

The findings showed that both the upper and lower Tsitsikamma followed the same trend in terms of nutrient movement through soil depth. It was observed that the most significant differences occurred within the 0-30 cm depth for all indicators except for pH (KCl) and C/N ratio. The two former indicators showed statistical significances in all depth layers with a very gradual decline with depth in both regions of the Tsitsikamma.

The results further showed that farms differed significantly within this region and that management practices had a significant influence in the differences observed. This was clearly illustrated in the PCA conducted, which grouped the farms according to similar management practices with those farms that had a more biological approach falling in the same category. Incidentally, the farms that had been more chemical dependent fell into their own category. Furthermore, farms that exhibited better SOM indicators generally held more nutrients, even though no heavy applications of those nutrients were done in the sampling year. Farms that were observed to also have more concentration of nutrients in the soil, even with poor SOM content, had applied those nutrients in chemical fertilisers during the sampling year. This therefore justified as to why those farms also had more nutrients in the soil.

The PCA conducted also showed that 54% of the variations observed in the Tsitsikamma region could be explained in the following order by these indicators: total N, pH, exchangeable Ca, exchangeable Mg, total C, active C, exchangeable K and BD. These findings emphasised the need for farmers to not only focus on replenishing or managing N in the soil, but also to pay careful attention to pH, exchangeable Ca, exchangeable Mg, total C, exchangeable K, and BD in order to improve soil quality. The findings also highlighted the urgent need for farmers to change their line of thinking and abandon soil management practices that enhance soil degradation, a problem that is very common in South Africa. Proper management of soil quality is vital in ensuring sustainable soil management and food security; therefore researchers along with governments need to build a better transfer of knowledge to farmers in order to ensure the former.

Keywords: soil quality, soil organic matter, soil fertility, mixed pasture management

CHAPTER 1

INTRODUCTION

1.1 Motivation

South African soils have long been classified as being severely degraded by the international soil reference and information center (UNEP-ISRIC, 1997). Soil degradation is defined by Johns (2015) as the "decline in soil quality caused by its improper use, usually for agricultural, pastural, industrial or urban purposes". This development which was first published in 1997 in the World Atlas Desertification forces South African land owners to abandon their indigenous soil management methods, as new and innovative systems are required.

This state of the soils is even more pronounced in sandy soils that are managed for pasture production in the Tsitsikamma region of the Eastern Cape. This is mainly due to the fact that these soils have low soil organic matter (SOM) content and are therefore prone to nutrient leaching, erosion and water loss through runoff and deep percolation. These soil characteristics are unfavorable because they put the farmer in a position of constantly having to maintain soil nutrients and water irrigated, in order to drive production. This practice is untenable and has shown to not be cost effective as more farmers get into debt due to poor cash flow resulting from mostly fertiliser and feed costs. It is because of this that better soil quality measures need to be introduced to farmers in order to help mitigate the situation.

It is well understood that, soil quality is not a new concept; in fact, in the past 20 years a lot of indicators of soil quality have been established and implemented in different farming systems. However, the indicators measured are not easy to communicate to the farmer and are expensive to analyse. Soil quality has been defined in many scientific studies; a more holistic definition is given by Karlen *et al.* (1997) which states that, "soil quality is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation".

According to Terblanche (P. Terblanche, Trace and Save™, 97 AD Keet Street, Jefferey's Bay, 6301), the idea of soil quality has drawn the attention of many farmers and agricultural consultants because of its equal consideration of soil biological, chemical and physical properties. It is crucial to understand that the principles of soil quality revolve around integrating these properties and taking them into account when soil management decisions are taken.

Managing and understanding soil quality means evaluating and managing soil so that it functions optimally now, and in the future. Land managers should be monitoring changes in soil quality on a regular basis, and using this to adopt sustainable practices which aim to improve the productivity of soil (Doran, 2002).

According to Terblanche P, farmers naturally recognize the importance of good soil management because it produces the cheapest source of feed for their dairy herds (P. Terblanche, Trace and Save™, 97 AD Keet Street, Jefferey's Bay, 6301: Personal communication, 2015). This view is also supported by the dairy farmers in the Tsitsikamma. In the past, dairy farmers relied on the excessive application of nutrients, and physically working the soils as means to get the required yield. These practices have changed in other parts of the world due to evidence (e.g. Swanepoel *et al.,* 2014) arising of declining soil fertility resulting from such practices, as well as changes in the global economy and markets, which had a negative influence on fertiliser prices and feed. The negative impact of soil disturbance and oversupply of nutrients have been extensively researched and reported by Doran (2002); Stafanic and Gheorghita (2006) as well as Swanepoel *et al.* (2014). These practices are relevant because in the study area, they are still seen as norms for improving soil productivity.

Farmers in the Tsitsikamma region recognize that their management practices are what ensure that milk is produced by healthy livestock in a socially responsible, environmentally friendly and profitable manner. Sustainable dairy farming systems therefore need to find a balance between achieving each of these goals. The challenge of finding this balance has proven difficult for some farmers, due to the necessity of changing from traditional farming practices. These combined aims can be accomplished though if the correct management systems are implemented (Doran *et al.,* 1996; Doran, 2002).

Because soil quality relates to the long-term success of the broader agricultural industry, it is important that researchers simplify the methods as much as possible in order to have a meaningful impact to the farmer. It is also important to note that, although each farm is managed in isolation, it still is part of a greater ecosystem; therefore, specific soil quality indicators, and their norms, should be identified specifically for each cropping system. These indicators should communicate relevant information quickly and easily to land managers, who are not necessarily experts in soil science (Jesinghaus, 1999). The correct management practices at farm level can result in these indicators being improved for the benefit of both the farmer and the ecosystem.

1.2 Hypothesis

Soil management practices have a huge influence on soil quality. Soil quality Indicators depend greatly on the soil's inherent and dynamic properties. Good soil management practices heighten the soil's ability to naturally store and provide nutrients as required by the plant. This is feasible with the correct management practices applied, which positively influences the dynamic soil properties which will be measured using soil quality indicators, which are selected based on their relevance to the type of cropping system and practicability to measure.

1.3 Objectives

The main aim of this study is to measure and evaluate soil quality on mixed dairy pastures in the Tsitsikamma region, using specific quality indicators. The objectives are therefore:

a) To assess the status of selected soil quality indicators on farms
b) to assess whether these soil quality indicators differ with soil depth and between farms
c) to evaluate whether pasture management practices have any influence on soil quality and then suggest sound management practices that will improve soil quality
d) to identify which soil quality indicators have an influence on each other and lastly;
e) to identify soil quality indicators that are responsible for the variations in the Tsitsikamma region.

CHAPTER 2

EFFECT OF PASTURE MIXTURES ON SOIL QUALITY

2.1 Introduction

Well managed pastures can have essential benefits for the soil and environment. Pasture mixtures have a positive impact on soil quality because of the diverse benefits each pasture type contributes to the soil ecosystem. In the environment, well managed pasture mixtures have the potential to reduce soil loss through erosion, better water quality due to better soil buffering capacity, improved plant vigour and yield, improved soil microbial processes, better carbon (C) storage as well as enhanced nutrient holding. Good grazing management which encourage SOM build-up is also critical in ensuring efficient pasture utilization and improved soil quality (Botha *et al.,* 2008).

Kikuyu and ryegrass are the most common pasture mixture combinations in the Tsitsikamma region. These pasture combinations each have different roles they play in the soil. Kikuyu is of lesser quality compared to ryegrass; however, kikuyu is very beneficial in building soil C stocks and improving soil structure because of its vigorous root system. Ryegrass on the other hand is of high quality and is more digestible to cows. It has been also recognised for its role in weed suppression and nutrient cycling processes more specifically processes that involve nitrogen (N) recovery in the soil. Pasture production is most limited by N. Adding a pasture type that enhances N storage and availability is recommended in pasture mixtures (Koening *et al.,* 2002).

Farm managers need to select the correct combinations of pasture when making management decisions. Correct combinations should not only consider leaf quality, yield or ease of management, but they must also consider the benefit of soil quality.

2.2 Value of kikuyu and ryegrass association

Irrigated kikuyu with inter-sowed annual ryegrass is the main source of feed in pasture based dairy farms in Southern Africa (Botha *et al.,* 2008). More than 50% of the Tsitsikamma farming region is used for irrigated pasture dairy farming, mainly planted with kikuyu-ryegrass and clover mixtures. In South Africa, the majority of dairy farming is practiced in the high rainfall areas of the KwaZulu-Natal midlands, and winter rainfall areas of the southern Eastern Cape Province. (P. Terblanche, Trace and Save^{TM}, 97 AD Keet Street, Jefferey's Bay, 6301: Personal communication, 2013). Ryegrass is known to have high nutritional qualities and is also very palatable to the cows; it therefore plays a vital role in supplying high quality grazing in the winter season (Vendramini *et al.,* 2006).

Plant breeders have been studying and researching ways of increasing the grazing season of annual ryegrass due to its good nutritional quality. Although this may benefit the farmer, the price of maintaining ryegrass for a longer season would be costly (Holliday, 2007). Unlike ryegrass, kikuyu pasture which has a much lower quality (Fulkerson *et al.,* 2010), is predominantly grown in summer and is the dominant pasture during the dry season in the Tsitsikamma region. South African dairy farmers normally use kikuyu to transition from one ryegrass season to the other (Holliday, 2007). The resilient nature of kikuyu pasture has caused farmers to manage it with lesser caution than ryegrass.

The association of the two pastures gives benefit to the soil life because of the below grown root diversity which plays an important role in soil mineralisation processes. Kikuyu roots can grow up to 1.5 m, a useful characteristic for SOM movement in the soil, especially in sandy soils. Its thick network of rhizomatous roots helps protect the soil against the effect of harsh environmental conditions such as erosion and runoff (Undersander *et al.,* 2002).

Soils that are planted with kikuyu and ryegrass tend to have a positive SOM build-up. This can be attributed to the presence of a diverse network of roots below ground, with most of the SOM build-up being attributed to kikuyu. This positive association becomes more prominent when coupled with good management practices e.g. grazing at the right leaf stage (4.5 leaf for kikuyu and 3-3.5 leaf for ryegrass (P. Terblanche, Trace and Save^{TM}, 97 AD Keet Street, Jefferey's Bay, 6301: Personal communication, 2014)) that promote good soil quality.

2.3 Value of over sowing kikuyu-ryegrass pastures with clover

The declining soil fertility in the sandy soils of the Tsitsikamma region coupled with N fertiliser costs have led to renewed interest in legumes. As a result, the role of legumes as a natural soil N supply in pasture based dairy systems has gained importance (Chapman *et al.,* 1996). Growing legumes as an intercrop improves soil quality through their beneficial effects on soil biological, chemical and physical conditions. When properly managed; i.e. grown with a compatible crop in an intercropping system, either red or white clover will enhance the N supplying power of the soil, increase the reserves of SOM, stimulate soil biological activity, and improve soil water holding capacity and soil structure (Frame and Newbould, 1986).

Clover is an important herbage legume crop in low-input sustainable pastures in temperate regions of the world. It is often grown in association with perennial ryegrass although in recent years, some farmers in the dairy industry have grown white or red clover (*Trifolium repens* and *Trifolium pretense*) in association with ryegrass and kikuyu (Sprent and Mannetje't, 1996). Clover is able to fix atmospheric N which becomes available when the plant roots decay (Ball and Lacefield, 1994; Clark and Harris, 1995). This translates into economic savings for farmers who plant clover to provide the N their pastures need rather than purchasing and applying N-based fertilisers. In thin stands, clover can fix up to 50 kg N/ha per year, however thick stands of clover can fix up to 200 kg N/ha in a year (Jennings, 2009). The former amount of N fixed, roughly translates to R2 174/ha based on the 2015 N/kg cost of R10.87 that could be saved on fertiliser cost. It is however important to note that there are many variables that influence the process of N fixation, it is difficult to quantify accurately how much has been fixed and will be available for the plant to use.

Bates and Beeler (2010) at the University of Tennessee showed that ryegrass over-sown with white clover, or a combination of white clover, red clover and annual ryegrass, will produce more and better quality silage than a pure ryegrass pasture.

Clovers are more digestible and contain more nutrients than grasses. Their presence in a pasture improves the palatability of the forage, which will increase the amount and quality of the forage the animal consumes. The biological N fixation process is the most efficient way to supply the large amounts of N needed by legumes to produce high grass yields with high protein content. The low C/N ratio of stems and leaves causes the crop to decompose much more rapidly and release N to the soil solution. Herbage legumes obtain between 50-80% of their total N requirements through biological fixation. When the legume dry matter decomposes, it adds N to the organic N pool in the soil, which can be readily mineralized over time depending mainly on the soil N levels (Paul and Clark, 1996). Another added benefit of clover is in the fact that the N form stored or fixed, is more stable and less prone to ammonia volatilization, leaching or denitrification, and therefore possesses less environmental pollution potential as opposed to chemical N fertilisers (Russelle, 2004).

2.4 Indicators of soil quality under kikuyu, ryegrass and clover pasture mixtures

Soil quality indicators are defined by Jesinghaus (1999) as, "the representations that communicate correct and relevant information quickly and easily to people who are not necessarily experts in the field". It is imperative that selected soil quality indicators are suitable and relevant to that specific cropping system. It is well understood that various soil quality indicators have been investigated and implemented in different farming systems. However, some of these indicators measured are not easily understood by the farmer, expensive to analyse and in most cases are not relevant to permanent pasture production systems. The soil quality indicators discussed below have been selected as key indicators for this study and are identified as easy to communicate to farmers, relevant and cost effective for the cropping system in which this study took place.

2.4.1 Soil chemical properties

- *Soil pH*

pH is one of the important chemical properties of the soil because its significance is highly linked with nutrient availability and transformation (Wander *et al.,* 1994; Rousk *et al.,* 2009). According to the Natural Resources Conservation Service (NRCS, 1998), a pH range of 5.5-6.5 is usually most preferred for plant growth because most plant nutrients are readily available in that range and this is also the optimum range for high microbial activity in the soil. In acidic soils, where pH levels fall below 5.5, availability of phosphorous (P), calcium (Ca) and magnesium (Mg) becomes limited.

One of the essential processes in the soil that are influenced by soil pH is the mineralisation process. Mineralisation of SOM is a key process regulating the cycling of nutrients in soil. According to Haynes and Swift (1993), decomposition of SOM occurs over the entire pH range but the rate decreases progressively below a pH of about 6.

A study that was conducted in Wisconsin by Dancer *et al.* (1973) showed that mineralisation was not affected by pH in the range 4.7-6.6, though, nitrification decreased 3 to 5 fold as pH decreased. This is collaborated by a study conducted. The investigation revealed a 5-fold decrease in bacterial growth and a 5-fold increase in fungal growth with lower pH. Although soil pH is recognized as an important regulator of microbial activity (Haynes, 1986) and the composition of the microbial population (Paul and Clark, 1996), the agronomic significance of its effect has been difficult to assess.

- *Nutrient concentration*

Plants are only able to uptake nutrients in the soil solution. Plant available nutrients are held or stored in ionic form which could be negative or positive. Soil nutrients that are positively charged e.g. Ca^{2+} are called cations and can be held by the soil's exchange sites; on the other hand, soil nutrients that are negatively charged e.g. $H_2PO_4^-$ are referred to as anions and cannot be held by the soil's exchange sites. The exchange sites are found on the surface of colloids that originate from either the clay or SOM fractions. This means that soils that have a high content of clay and SOM will have a high nutrient holding capacity; therefore any management practice that promote SOM build-up, consequently promotes nutrient build-up as well (Snapp, 2011).

Sandy soils generally have a low nutrient holding capacity due to the absence of negative surface that is found in clay (Kinsey and Walters, 2006). It is important that land owners that farm on sandy soil build SOM as means to minimize nutrient loss and increase their soil's cation exchange capacity. A measurement of these nutrients provides a farmer with a relative idea of his soil's fertility status and it is the basis of these nutrient quantities that direct the farmer on how to plan his fertiliser recommendation (Hodges, 1998; Kinsey and Walters, 2006).

2.4.2 Soil biological properties

- *SOM and active C*

SOM content is most likely the most recognized indicator of soil fertility (Weil *et al.,* 2003). This fraction has no definite chemical composition; however organic carbon (C) is the dominant elemental constituent of organic matter. Thus, soil organic C (SOC) is recognized by its high elemental C content usually found in humic forms. SOM is estimated to contain approximately 58% C of which along with N; are the primary driving nutrients behind soil microbial related process (Reeves, 1997). SOC is divided into passive C pool which is the slowly altered pool and much more resistant to decomposition by soil microorganisms, as well as the active C (labile) pool which refers to the readily available fractions of SOC that fuel the soil food web and therefore, greatly influences nutrient cycling and soil biological activity (Weil *et al.,* 2003). Paustian *et al.* (1997) reported that, the part of SOC that represent the active C pool are microbial biomass C, particulate organic matter and soil carbohydrates, measured as enthrone-reactive C.

Improving soil quality is one of the main goals of sustainable farming practices. This means utilizing the resources on farm as efficiently as possible and minimizing imported nutrients in the farming system. This goal can be achieved if farmers invest in building SOM as means to improve nutrient use efficiency by plants. SOM acts a cementing or binding agent of the soil and its increase essentially increases the soils nutrient and water holding capacity, mineralisation rate and soil resilience, which is beneficial to highly erodible sandy soils (Reeves, 1997; Hodges, 1998). Active C is a good indicator to measure in order to get a relative idea of the mineralisation process and soil microbial balance and diversity.

According to the soil health assessment handbook from Cornell University, when active C levels are low in the soil, i.e. $< 0.05\%$ in sandy soils, the decomposition process is rather slow, than when the active C content is high; i.e. $> 0.08\%$ (Gugino *et al.,* 2009). Most microbial linked processes in the soil are slowed down if there is not a readily available energy source for the microorganisms. The University of Tuscia in Italy found that the C/N ratio in the biologically active pool is significantly smaller in soils under conventional farming methods than those under conservation farming systems (Lagomarsino *et al.,* 2006). This means that the active C pool increases with the increase in organic material in soils. It is therefore imperative that farmers implement on-farm soil management practices that support SOM build-up in order to improve their soil quality.

- *C/N ratio*

Soil microorganisms are the most important role players in nutrient cycling. Soil quality is directly linked to, and defined by the activity of soil microorganisms as a whole. Soil microorganisms have a C/N ratio near 8:1. They must acquire sufficient C and N from the environment in which they live to maintain that ratio of C and N in their bodies. Because soil microorganisms utilise C as a source of energy, not all of the C a soil microorganism consumes remains in its body; a certain amount is lost as carbon dioxide during microbial respiration (USDA-NRCS, 2011).

A C/N ratio of 20 is considered to be the optimum point where either net N mineralisation or net immobilisation will occur. In actual truth both these processes occur concurrently in soil. This therefore makes it difficult for soil scientists to estimate the amount of available soil N from net mineralisation alone. For instance, if the added SOM contains more N in proportion to the C, then N is released into the soil from the decomposing SOM. In contrast, if the SOM has a lower amount of N in relation to the C then the microorganisms will utilise the soil N for further decomposition, resulting in immobilisation of soil N, which will not be available to the plant (Manzoni *et al.,* 2008).

Measuring and understanding C/N ratios of material added to the soil is important to manage soil cover and nutrient cycling. Creating a quality environment for soil microbes should therefore be the goal of producers interested in improving soil quality, because soil is a biological system that functions only as well as the organisms that inhabit it (Aitkenhead and McDowell, 2000).

- *Potentially mineralisable N*

N is regarded as one of the primary essential elements for plant growth. Snapp *et al.* (1998) reported that, more than 98% of N in soils used for irrigated pastures is in the organic form. This form of N is not available to plants as it still needs to undergo the process of mineralisation (Khalil *et al.,* 2005; DeAngelis, 2006). Mineralisation is defined as the microbial process whereby organic N is converted to plant available mineral or inorganic N (Crohn, 2004). The amount of inorganic N produced is influenced chiefly by the SOM content and microbial diversity and population, therefore any factors that influence these will also have an influence on the potentially mineralisable N (PMN) rate (Katterer *et al.,* 1998). Studies have shown that under favourable conditions, i.e. presence of sufficient soil water and SOM as well as optimal temperatures; N turnover from mineralisation processes can produce an estimate of 90-200 kg N/ha/year (Stanford and Smith, 1972; USDA-NRCS, 2014). The supply of N to the plant through mineralisation is a significant element of sustainable farming, as this form of N comes naturally and replenishes itself from the organic N soil reserves (Groffman *et al.,* 1996).

PMN is an important indicator to measure because it gives an indication of the soil's biological activity. This process is not easy to predict without conducting the necessary analysis. However, studies show that knowing the amount of N (Total N) in SOM , as well as the C/N ratio of the soil, can be useful in predicting whether there will be a gradual increase in N availability or a temporal reduction in available N when decomposition occurs (Barker, 2011).

Farmers rely on fertiliser as a source of N for plant growth. This form of N is mostly unstable and easy to loose both by leaching or volatilization and in soils with poor quality, it is not used effectively by plants (Hanely *et al.,* 2015). Land managers need to gain confidence in PMN as potential source of free and more stable N in order to mitigate the cost of fertiliser.

2.4.3 Soil physical properties

- *Bulk density and porosity*

Bulk density is an indicator of soil compaction. It reflects the soil's ability to function for structural support, water and solute movement, and soil aeration. An ideal soil can be described as being 50% solids and 50% pore space, with half the pore space filled with air and half with water. This "ideal" soil would hold sufficient air and water to meet the needs of plants with enough pore space for easy root penetration, while the mineral soil particles would provide physical support and essential plant nutrients (Baggs *et al.,* 2000).

An increase in the soil bulk density reduces the nutrient availability for crops because the root system is restricted, which limits the volume of soil from which nutrients can be extracted. When the soil becomes compacted, it results in a shallow rooting pattern. The crop will become susceptible to water stress which may have a higher impact than the reduced nutrient availability. The effects of soil compaction (soils with a high bulk density) on important microbial driven processes such as mineralisation have been studied to a limited extent (Lee *et al.,* 1996). In heavy textured soils where soil bulk density is most likely to be high, the mineralisation of C and N is depressed from the native organic matter.

2.5 Conclusion

Sustainable soil management should be the goal of every farmer. This means that the soil's physical, biological and chemical properties need to be tested and changes observed over time, in order to make informed sustainable management decisions. Soil quality assessment should be viewed as an important part of sustainable agriculture. Soil quality measurement promotes efficient use of resources and better quality produce. Soil management practices like multispecies cropping and good pasture management are some of the management practices that have been identified to be beneficial to soil quality. It is therefore crucial for farmers to understand the principles of soil quality in order to make sound management decisions that will increase production and overall farm sustainability. Correspondingly, researchers need also to understand that soil quality indicators should be unique, and recommendations thereof cannot necessarily be generalized across all farms or agricultural systems.

CHAPTER 3

MATERIALS AND METHODS

3.1 Study area

The Tsitsikamma region forms a narrow belt west of Humansdorp between the Kareedouw and Tsitsikamma Mountains towards the north and the Indian Ocean towards the south. The area is regarded as the heart of the dairy farming industry in the Eastern Cape. The Tsitsikamma region is named after the San word meaning place of abundant water (SANPARKS, 2004). Owing to a change in rainfall and soil type from east to west, the Tsitsikamma region (Figure 3.1) is divided into the upper Tsitsikamma (UT) and the lower Tsitsikamma regions (LT); as a result, production techniques and adapted enterprises differ in some respects between the two areas.

This research was carried out on 10 pasture based dairy farms in the Tsitsikamma of which an equal number was located in the upper and lower Tsitsikamma regions, respectively. The farms were selected based on the following criteria:

- Pasture mixtures consisting of kikuyu, ryegrass and clover
- Have adopted minimum tillage or no tillage practices
- At least 6 years established pasture mixtures
- Irrigated pasture mixtures
- Availability of accurate fertiliser application rates from the last 6 years

Although the farms have the above in common, they differ in their management practices i.e. they have varying fertiliser application rates, irrigation frequencies as well as grazing tendencies. Table 3.1 and 3.2 provides a summary of the varying management practices on these farms.

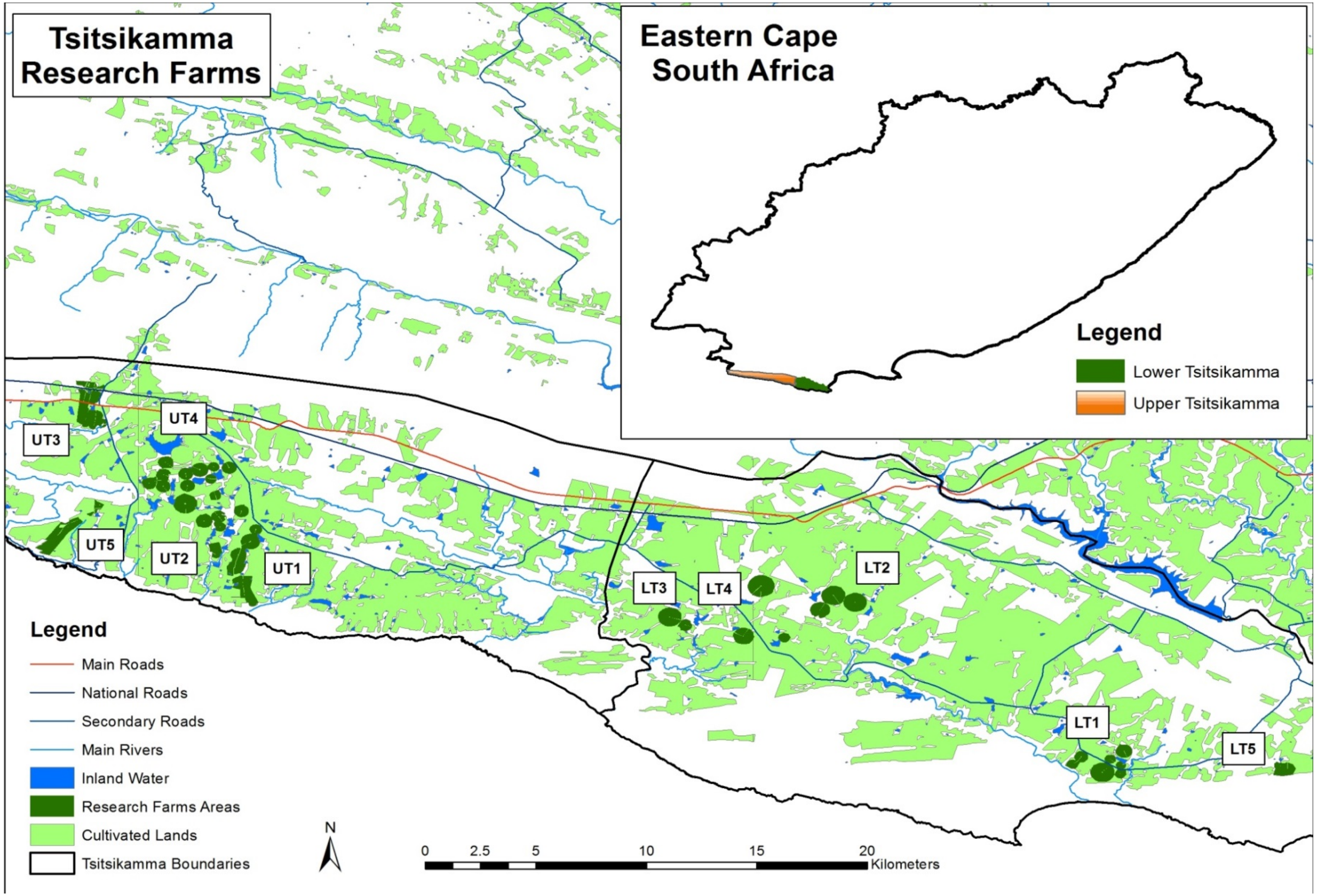


Figure 3.1 Sampling farms in the upper and lower Tsitsikamma (Designed by Jason Deschamps and Craig Galloway, 2015)

Table 3.1 Milking area of study farms in the Tsitsikamma and management practices applied on the farms

Area	Farm number	Milking area (ha)	Applies organic fertiliser or stimulant	Uses chemical herbicide	Planted multiple species	Spreads effluent (liquid or solid)
Upper Tsitsikamma	1	202	No	Yes	Yes	No
	2	137	No	Yes	Yes	No
	3	154	No	Yes	Yes	No
	4	293	Yes	Yes	Yes	No
	5	92	No	Yes	Yes	Yes
Lower Tsitsikamma	1	171	Yes	No	Yes	Yes
	2	166	Yes	Yes	Yes	Yes
	3	82	No	No	Yes	No
	4	143	No	No	Yes	No
	5	42	Yes	No	Yes	Yes

Table 3.2 Fertiliser application during the sampling year on the study farms in the Tsitsikamma region

Area	Farm number	N (kg/ha)	P (kg/ha)	K (kg/ha)	Ca (kg/ha)	Mg (kg/ha)	Na (kg/ha)
Upper Tsitsikamma	1	401	15	81	0	0	0
	2	414	0	269	0	0	0
	3	376	19	270	0	0	0
	4	870	95	284	0	0	0
	5	308	4	70	0	0	0
Lower Tsitsikamma	1	345	11	60	0	0	0
	2	263	14	50	560	0	0
	3	234	0	127	0	0	0
	4	234	0	127	0	0	0
	5	297	43	80	500	0	0

3.2 Topography

The topography of the UT region is flat to rolling and is broken by deep gorges which run from north to south. Major rivers which drain this area are the Bloukrans, Storms and Elands Rivers. The LT region has a rolling topography bisected by gorges which are not as deep as in the UT region. The major rivers which drain this area are the Sand, Klipdrift and Kromme Rivers. Due to the rainfall the majority of rivers in the Tsitsikamma region are perennial. The altitude varies from sea level to approximately 350 m in the north (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

3.3 Geology

The geology of the Tsitsikamma region shows an origin of predominantly Table Mountain sandstone. A narrow strip of Bokkeveld shales exist from Witelsbos, west towards the Bloukrans River. Quaternary dune sand (approximately 2-3 million years), some of which is still in an unstable state covers the eastern coastal belt of the area (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

3.4 Soils

The soils are resulting from Table Mountain sandstone and are generally sandy. These soils naturally have a low pH (3.3-4.5), are leached and thus have a low plant nutrient status. The soils on the level plateau are predominantly hydromorphic (show evidence of intermittent or permanent presence of excess water). The dominant soil series are the Cartref, Kroonstad, Longlands, Katspruit, Constantia and Oakleaf forms. Series of the Clovelly and Avalon forms are less dominant and make up the balance in the better drained areas. Organic matter accumulation is a prominent feature of the soils in the Tsitsikamma region. Subsoil material is often extensively stained by mobile humus material which due to its mobility is responsible for the dark brown colour of stream and river water (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

3.5 Climate

- *Rainfall*

The Tsitsikamma region is generally a high rainfall area. The rainfall varies from approximately 700 mm in the east to 1250 mm in the west and the distribution is relatively even throughout the year. The rainfall does however peak in autumn and spring while December, January and February are relatively dry months. Mean monthly rainfall data from weather stations at Cape St. Francis, Klipdrift and Witelsbos are given in Table 3.3 (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

- *Temperature*

The Tsitsikamma region experiences mild winter and summer temperatures. Snow falls are recorded on nearby mountain peaks; however, frost is a rarity during winter. A five year summary of the mean monthly maximum temperature and mean monthly minimum temperature recorded at Keokama Farm is given in Table 3.4 (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

- *Wind*

In the UT and LT region, prevailing wind is from the south west direction and is often accompanied by cool, moist air. Hot dry berg winds are experienced in the latter part of the winter and in spring; whereas easterly winds are experienced in summer. The wind pattern in the LT region has a much higher wind velocity. These high velocity winds are responsible for wind erosion on unprotected sandy soils and limit cultivation in these areas (F. Weitz, Department of agriculture, Humansdorp, 6300: personal communication, 2013).

Table 3.3 Mean monthly rainfall (mm) recorded from weather stations at Cape St Francis (94 years), Klipdrift (33 years) and Witelsbos (68 years), (ARC-ISCW, 2011)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
94 year analysis												
Mean M	31	31	48	52	73	66	70	72	67	62	50	37
Max D	60	89	149	133	130	67	75	113	156	84	78	85
Max M	109	188	256	1723	251	215	197	185	365	202	188	175
Min M	0	0	0	0	0	0	5	14	4	11	1	0
33 year analysis												
Mean M	57	56	61	73	110	90	87	109	91	88	69	60
Max D	71	83	53	172	163	125	92	93	117	92	104	68
Max M	149	213	146	281	273	319	206	206	23	214	193	144
Min M	6	12	14	14	10	9	18	39	8	16	14	7
68 year analysis												
Mean M	96	82	91	85	98	75	82	104	115	101	100	96
Max D	102	138	100	176	152	186	107	190	136	114	234	197
Max M	253	302	237	219	359	277	199	401	386	220	361	418
Min M	27	12	0	9	0	0	0	12	0	0	23	0

Mean M: Mean monthly rainfall; Max D: The maximum rainfall recorded on any one day; Max M: The maximum rainfall recorded on any one month; Min M: The minimum rainfall recorded on any one month.

Table 3.4 Mean monthly maximum and minimum temperature (^{0}C) recorded at Koekama Farm over 5 years in the Tsitsikamma region

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly maximum temperatures												
AVX	33	35	35	35	31	30	30	31	33	35	31	31
AVEH	24	25	24	23	21	21	20	19	20	22	21	22
Mean monthly minimum temperatures												
AVN	12	12	11	10	7	7	6	5	7	8	9	10
AVEL	16	16	16	15	12	12	11	10	12	13	13	14

AVX : Average of highest monthly maximum temperatures in Tsitsikamma region.

AVEH : Average monthly temperature based on daily maximum temperatures.

AVN : Average of lowest monthly minimum temperatures in Tsitsikamma region.

AVEL : Average monthly minimum temperature based on daily minimum temperatures.

3.6 Soil sampling procedure

Two soil sampling types were used in this study. These are, soil sampling with a probe (referred to as probing) and core sampling. A sample taken with a probe is later referred to as a probe sample whereas one that is taken with a core sample is referred to as a core sample. Probing refers to a systematic soil sampling procedure which does not require the physical taking of a soil sample but rather a direct reading/measurement of various soil quality indicators in the field using a Veris Spectrophotometer probe (Veris P4000), (see Figure 3.2). Core sampling is also a systematic soil sampling procedure which involves taking a physical soil sample with a core sampler (see Figure 3.3), which is analysed in the laboratory for various soil quality indicators.

3.6.1 Soil sampling

Probe and core samples were taken using the Veris P4000, in increments of 0-15, 15-30, 30-45 and 45-60 cm respectively (See Figure 3.2). Core samples are taken in order to calibrate probe samples. The process of probe sample calibration is explained comprehensively in section 3.6.2. The soil quality indicators shown in Table 3.5 were measured with the Veris P4000, except for active C, inorganic N and PMN rate which were measured colorimetrically from core samples in the laboratory. Active C was measured using the permanganate oxidizeable C method adapted from Weil *et al,* (2003), as well as inorganic N and PMN rate using the KCl extraction method (Solorzano, 1969; Cataldo, 1975 and Parfitt *et al.,* 2005).

Table 3.5 Soil quality indicators that were measured for this study

Biological	Chemical	Physical
Total C	Extractable P	Bulk density
Total N	Exchangeable K	
C/N ratio	Exchangeable Ca	
Active C	Exchangeable Mg	
PMN rate	Exchangeable Na	
Inorganic N	pH (KCl)	

3.6.2 Probing and calibration

The Veris P4000 has a UV probe that is attached to it which measures the soil's reflectance (absorbance) at different wavelength. The probe is inserted in the soil up to a desired depth and measures reflectance at wavelength ranges of 350 to 2200 nm. Each wavelength range can record up to 20 spectra per second with each spectra containing up to 380 soil measurements. The soil measurements were then recorded and stored as absorbance values. The absorbance was analysed by the spectrophotometer fixed on the Veris P4000 and the data was simultaneously stored in a laptop attached (Figure 3.2).

Figure 3.2 Veris P4000 (Veris Technologies).

In order to calibrate the data measured by the Veris P4000; 3 calibration core samples (Figure 3.3) were taken at each sampling site. These core samples were taken at the same sampling depth as the probe samples; i.e. 0-15, 15-30, 30-45 and 45-60 cm, respectively. Before a core sample was taken, 4 probe sample readings were taken at 1 m distances from each other around the core sampling point. This was done in order to increase the chances of getting a good calibration (standard). In areas where the slopes differed within one center pivot, extra calibration core samples were taken at varying slopes, so as to factor in the possible influence of different soil types.

Calibration soil samples were analyzed for the soil indicators shown in Table 3.5 by a commercial laboratory (BemLab, De Beers RD, Somerset West, South Africa). Chemical analyses were done according to standard methods (Non-Affiliated Soil Analyses Work Committee, 1990). Analyses that were carried out to determine soil biology are total C and total N (Leco Elemental Combustion Analyzer). Soil chemical indicators analyzed are extractable P Bray 2 (Bray and Kurtz, 1945); pH (2:1 soil 1 M KCl extraction) and exchangeable K, Ca, Mg and Na (1 mol dm^{-3} NH_4 OAc at pH 7). Soil physical indicators were analyzed by both the Veris P4000 and Woodlands Dairy Laboratory. The soil bulk density was determined using the core method, whereas soil water holding capacity was determined by measuring the soil's saturation capacity and field water capacity (method adapted from Viji and Prasanna, 2011).

Figure 3.3 Veris core sampler (Veris Technologies).

3.7 Sampling points and grid design for probing

A sampling point refers to a site in a field where a probe sample was taken. The sampling points for probing on a farm were located using Google Earth maps. A copy of the image of the farm's center pivots was then saved on file and this image of the farm was then imported to the Veris software in order to mark boundaries of the pivots and eliminate pivot tracks. After these parts were discarded, a sample grid was drawn. The sampling grid was generated such that the points for sampling represents 0.3 ha; i.e. 54 X 54 m (Figure 3.4; 3.5 and 3.6). The sampling grid was then converted into a format that is readable by a Global Positioning System (GPS). The sampling points were then transferred to a GPS.

Figure 3.4 Locating a farm using Google earth.

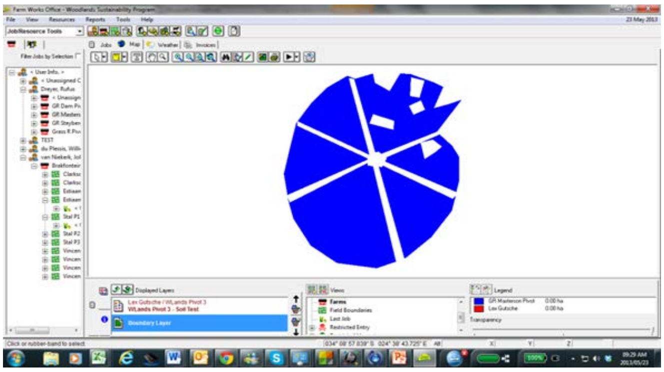


Figure 3.5 Image of the center pivot with stony areas and pivot tracks discarded.

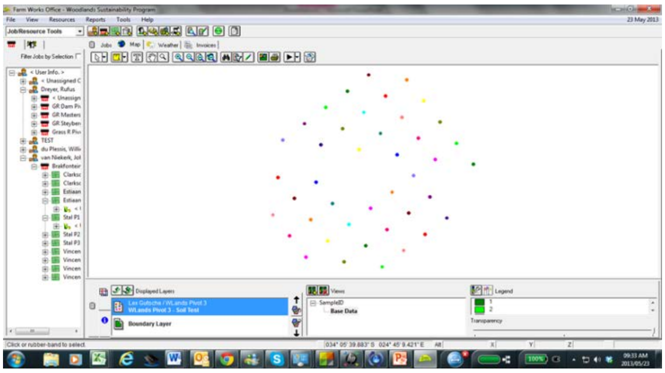


Figure 3.6 Sampling grid image showing sampling points on a center pivot.

3.8 Data Analysis

Data used for this study was presented in concentration (% or mg/kg) and in stock (kg/ha) form. Concentration measurements were obtained from probe and core samples whereas stock measurements were obtained from a conversion of the concentration data to stocks. This conversion was done by taking into account bulk density and sampling depth. Linear mixed model analysis, also known as REML analysis (Payne (Ed.), 2014), was applied to the averages of soil properties over sampling points on center pivots. A nested and weighted analysis was used as the numbers of center pivots (later referred to as pivot) per category (area, farm, and pivot) were very different and therefore only the first 7 pivots were used for analysis. The fixed effects were specified as area, farm, depth and all the interactions between them. The random effect was specified as depth within pivot, pivot within farm and farm within area. Fisher's protected least significant difference test, with the Standardized range (Snedecor and Cochran, 1980), was used to compare means at the 1% level, as the area, farm and pivot variances were not homogeneous (Glass, 1972). Data were analyzed using the statistical program GenStat® (Payne (Ed.), 2014). Correlations between parameters were analyzed using two-tailed Pearson correlation test at 1% and 5% level. Principal component analysis (PCA) was calculated using the SPSS statistical program.

CHAPTER 4

INFLUENCE OF MANAGEMENT PRACTICES ON SOIL ORGANIC MATTER INDICATORS

4.1 Introduction

It is critical to assess, and maintain soil quality in a permanent cropping system (Reeves, 1997). SOM is an important soil quality indicator of fertility status, biological activity and structure (Liu *et al.,* 2006). SOM is “the total complement of organic substances present in the soil, including living organisms of various sizes, organic residues in various stages of decomposition and dark-coloured humus consisting of non-humic and humic substances” (Du Preez *et al.,* 2011).

It is important that land owners maintain SOM in their soil to avoid soil degradation (Cambardella and Elliot 1992; Valarini *et al.,* 2002; Du Preez *et al.,* 2011). Building SOM is beneficial in many ways. It promotes plant growth (through provision of mineral nutrients to plants), improves the soil water retention capacity, enhances soil pore spaces (through networks built by SOM), supports soil life (by providing food for them to continue soil decomposition processes), and provides physical support to plants for optimum growth. Because SOM has a very complex chemical structure, it cannot be measured directly; however methods are available for measuring indicators of SOM (Magdoff and Weil, 2004).

Soil properties like total C, active C and PMN are some of the SOM indicators that have been measured in place of OM in this study. Total C refers to both organic and inorganic C pools in the soil and is used as a measure of food available for microorganisms (Salaville and Barranque, 2011). Active C refers to the easily degradable form of C and is the readily available source of food for the microorganisms. Active C is sometimes referred to as labile C and is composed of particulate OM, microbial biomass C, as well as soil carbohydrates measured as anthrone-reactive C (Weil *et al.,* 2003). PMN is a measure of the active fractions of soil organic N, which is mainly responsible for the release of mineral N through microbial action (Curtin and Campbell, 2006). The main sources of organic N in the soil are microbial biomass along with plant and animal residues (USDA-NRCS, 2009). A combination of these indicators gives a comprehensive idea on the quantity of food available for soil microorganisms as well as the efficiency with which these organisms convert organic nutrients into plant available nutrient forms (Paustian *et al.,* 1997; Weil *et al.,* 2003).

Soil management practices that are detrimental to SOM indicators can alter the soil's potential to supply nutrients, which has a direct impact on yield (Murphy, 2014). These include practices such as soil disturbance, excessive supply of nutrients, over-grazing, over-irrigating and single species cropping. These practices have been cited to have a negative impact on SOM build-up, as well as soil fertility and are discussed comprehensively below.

Effect of soil disturbance

Soil disturbance increases degradation of soil aggregates and microbial activity which are vital in soil water and nutrient storage processes. A noticeable study is by Oorts *et al.* (2006) which was investigating the impact of tillage on SOM stocks and C and N fluxes in grain cropping systems. The study found that soils that have been under no-tillage for 32 years had an increase in C stocks by 5-15% and 3-10% N in stocks when compared to conventional tillage soils for the same number of years. This increase in C stocks under no-tillage can be attributed to improved microbial activity and SOM content; better aggregate stability as well as better soil cover, due to less disturbance from tillage (Liu *et al.,* 2006; Oorts *et al.,* 2006).

Effect of excessive supply of nutrients

Excessive fertiliser application has been found to be harmful to plants (USDA, 2016). This is especially the case in soils where there is not enough water in the soil to effectively dilute the soil solution in order to prevent reverse osmosis in the plant root zone. This process occurs in the soil when the concentration of the nutrient solution is too strong. A strong soil solution can result in negative osmotic pressure on the plant because of the high nutrient content. The amount of dissolved solids outside the plant root cells determines the direction of the water flow in the soil. Soils that are over-fertilised are most likely to suffer from reverse flow of water out of the plant, causing the plant to lose its turgidity resulting in the plant wilting (Weinbaum*,* 1992). A high concentration of nutrients in solution will also have a negative impact on the soil biology, especially fungi and protozoa. Fungi are generally unable to grow under soils that have a high pH and prefer to grow under less concentrated acidic conditions (Ingham, 2010). Protozoa on the other hand would also suffer from reverse osmosis due to high nutrient concentration outside its body. These will have a negative impact on SOM content and accumulation (Martin, 1991; Kinsey and Walters, 2006).

Over fertilisation of soil has also been strongly linked to unavailability of other soil nutrients. Liebig's law of the minimum tells us about the importance of balancing the nutrient contents in the soil, however Wallace (1993) introduced the law of the maximum which states that even with nutrients balanced, if one nutrient is excessively applied, the balance of other nutrients will be null. This can be seen on the Mulder's chart which shows how nutrients in the soil can influence the availability and uptake of each other. For instance, high Ca and Mg content have a negative impact on P availability and uptake in the soil. N has been found to directly affect the availability and uptake of copper (Cu), boron (B), and potassium (K) and these three nutrients play a critical role in plant nutrition (Wallace, 1993; Goldy, 2016).

Effect of overgrazing

Overgrazing has been identified in Africa to account for 49.2% of all soil degradation (Czegledi and Radacsi, 2005). Furthermore, Villamil *et al.* (1997) stated that cow grazing practices that result in overgrazing, affect soil quality by increasing bulk density, mechanical resistance, and water infiltration. Soils that have high bulk density and mechanical resistance are indicative of soil compaction. These soils usually have poor porosity and aggregate stability which are both significant soil parameters that influence soil microbial activity. Proper grazing management can help improve SOM. Grazing pastures at the correct leaf stage allows proper establishment of roots, which play an important role in deep soil exploration for water and nutrients. In the process, SOM is improved and distributed through the soil profile. Well established leaves assist in optimal harvest of energy from the sun through photosynthesis and as a result of that process, SOC stocks are improved (Czegledi and Radacsi, 2005; McCarthy *et al.,* 2014).

Effect of over-irrigation

A study by Evans *et al.* (1996), found that managing irrigation frequency ensures that water is supplied at a rate that is sufficient to the plant and does not suppress the benefits of microbial activity e.g. waterlogging which inhibits the mineralisation processes. This practice is referred to as irrigation scheduling and is important because it ensures water conservation and effective plant water use. Soil water is very important for processes of SOM decomposition, particularly the mineralisation process. Land managers are encouraged to adopt irrigation scheduling practices, because they have a major impact on SOM accumulation and consequently pasture production.

Effect of single species and multispecies cropping

Research has shown multiple species crops are better than single species crops because multispecies help improve soil C, soil biology, and soil structure (Vandermeer, 1989). They also provide improved forage quality for grazing livestock. Multiple species crops can also be used for disease and weed control and a soil C building technique. Research has also shown that by including flowering plants in a pasture mix will increase insect diversity which controls insect attack on crops and attracts birds and other animals. This will increase the ecology of the whole farm ecosystem.

The Tsitsikamma region is known as the heart of the dairy farming industry in South Africa, with farming systems being predominantly pasture based (P. Terblanche, Trace and Save^{TM}, 97 AD Keet Street, Jefferey's Bay, 6301: Personal communication, 2014). These pastures are mostly mixtures of ryegrass, kikuyu and clover. Improving soil quality should be an objective of every land manager in order to maintain adequate pasture growth and meet the farms feed demand. Improving SOM is one of the ways in which farmers can help enhance the soil quality. This is especially important because the Tsitsikamma region has mainly sandy soils which are inherently prone to nutrient leaching, are easily erodible, and have poor nutrient and water holding capacities (Bruand *et al.,* 2005).

The measurements of soil parameters that are indicative of SOM are imperative to this study. It is important to monitor trends in soil indicators over time (e.g. increase or decrease in total C) so that management practices of farmers can be adapted accordingly. The ultimate goal is the improvement of the SOM status.

4.2 Procedure

As was mentioned in Materials and Methods (Chapter 3) the four depth intervals were analysed for organic matter indicators (total C, total N, C/N ratio, active C, PMN rate and inorganic N). Each indicator has been reported in concentration (% or mg/kg) and stock (kg/ha). The stocks were calculated using bulk density. Because the impact of soil density has been taken into account, bulk density will not be discussed comprehensively in this study.

The analysis of variance was calculated at 99% confidence interval. Values that had significant differences had p values of < 0.001, whereas those that showed no significant difference had p values > 0.001. For all parameters with the exception of active C and inorganic N as illustrated by Table 4.1, there were significant differences when comparing the upper and lower Tsitsikamma regions. There were also significant differences for all parameters between all measured soil layers. Therefore, all data presented will look at each region separately. The first set of results will display differences in the two regions for all four measured soil layers i.e. 0-15, 15-30, 30-45 and 45-60cm, respectively. The second set of results presented will show the differences within farms in the two regions at only 0-30 cm soil layer. This is because it was observed that the most significant differences occurred to approximately 30 cm depth. Therefore based on the above logical reasoning results will be discussed extensively up to 30 cm depth.

Table 4.1 Summary of analysis of variance indicating the significant effects of management practices on SOM indicators

Soil parameter	**Area**	**Farm**	**Depth**	**Area x Farm**	**Area x Depth**	**Farm x Depth**	**Area x Farm x Depth**
Total C concentration	✓	✓	✓	✓	✓	✓	✓
Total C stock	✓	✓	✓	✓	✓	✓	✓
Total N concentration	✓	✓	✓	×	✓	✓	✓
Total N stock	✓	✓	✓	×	✓	✓	✓
CN ratio	✓	✓	✓	✓	✓	✓	✓
Active C concentration	×	✓	✓	✓	×	✓	×
Active C stock	×	✓	✓	×	×	×	×
PMN concentration	✓	×	✓	×	×	×	×
PMN stock	✓	×	✓	×	×	×	×
Inorganic N concentration	×	✓	✓	×	×	×	✓
Inorganic N stock	×	×	✓	×	×	×	✓

Significant ✓; Not significant × alpha (α) = 0.01

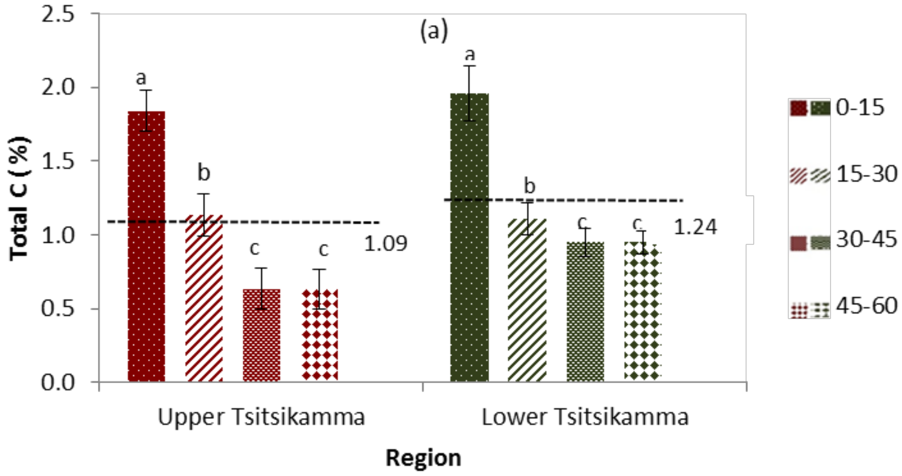
4.3 Results

4.3.1 Total C

Average total C within soil layers

As illustrated by the summary of analysis of variance (Table 4.1), both total C concentration ($F_{1,208}$ = 52.0) and stock ($F_{1,208}$ = 17.3) differed significantly between the upper and lower Tsitsikamma region. Soil layers also showed significant differences for both regions for concentrations ($F_{3,208}$ = 1362) and stocks ($F_{3,208}$ = 910.9). All interactions were significant in the measured concentration and calculated stock (Table 4.1).

Figure 4.1 showed that the LT region had a higher total C build-up through depth compared to the UT region. The mean total C concentration and stock for the UT region was found to be 1.09% and 2324 kg/ha, whereas a higher mean for the LT region was measured at 1.24% and 2452 kg/ha, respectively. In both regions a depletion of total C took place with depth, however this decline was slightly more evident in the UT region. As could be expected, the highest total C values were found in the 0-15 cm soil layer.



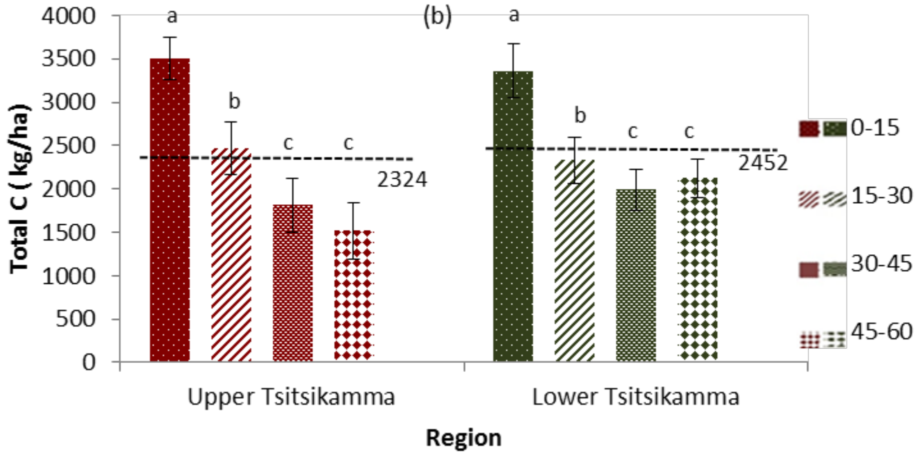
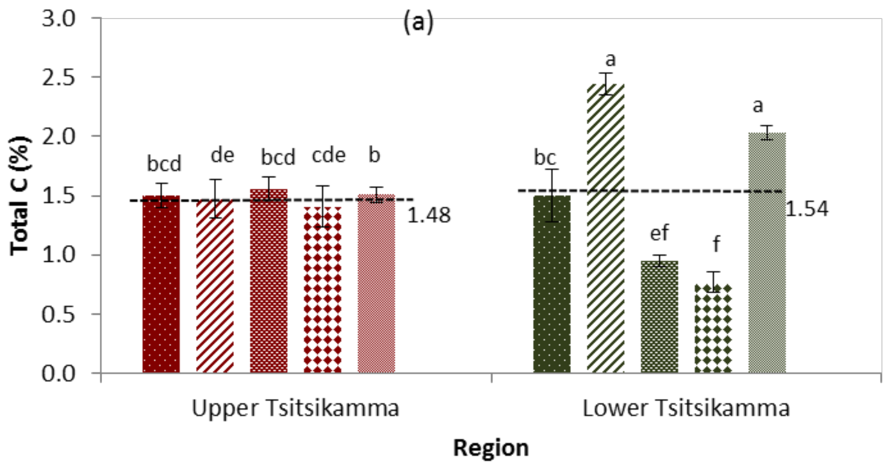


Figure 4.1 The effect of management practices on total C within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average total C concentration, and (b) is the average total C stock.

Average total C within farms

The two Tsitsikamma regions were also found to be significantly different from one another when either total C concentration ($F_{1,52} = 60.5$) or total C stock ($F_{1,52} = 15.4$) were compared. The farms were evidently influenced by management practices based on the significant differences that were observed between farms in measured concentration ($F_{4,52} = 65.9$) and calculated stock ($F_{4,52} = 74.3$). There were also significant interactions for both concentration and stock when regions were combined with farms. As could be seen, the total C concentration (Figure 4.2a) measured indicated that the LT region had a slightly higher average (1.54%) than the UT region (1.48%). The opposite was true for the total C stock calculated in the two regions as demonstrated by Figure 4.2b. Interestingly to note was the uniformity of total C expressed in both concentration and stock on farms in the UT region, while the LT region showed a higher variation between farms.



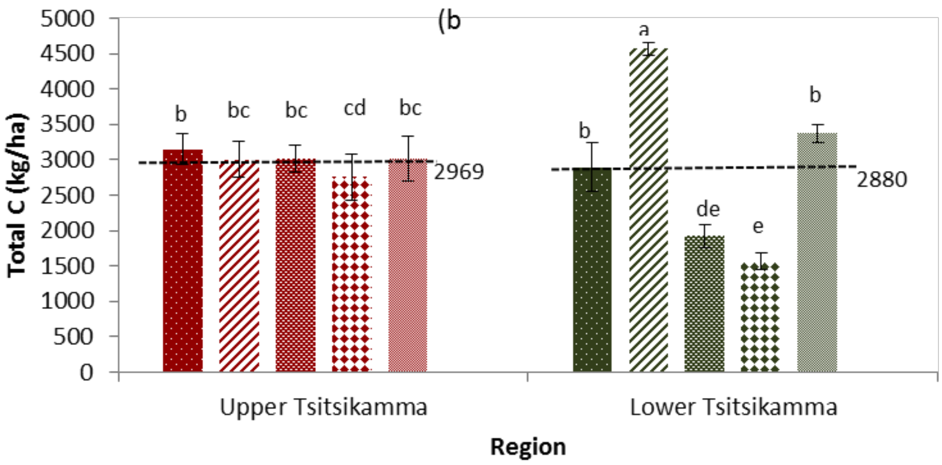


Figure 4.2 The effect of management practices on total C to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average total C concentration, and (b) is the average total C stock.

4.3.2 Total N

Average total N within soil layers

Table 4.1 illustrated that the two regions (LT and UT) varied significantly in terms of concentration ($F_{1,52}$ = 18.7) and stock ($F_{1,52}$ = 40.1) of total N. This significant difference was also seen in the soil layers using concentration measurements ($F_{3, 207}$ = 297) and stock calculations ($F_{3, 207}$ = 345). All interactions except for the combination of regions with farms were found to be significant. Figure 4.3 further showed that the UT region had a higher total

N accumulation through the profile compared to the LT region. This trend was similar to what was found with total C. The mean total N concentration and stock for the UT region was found to be 0.15% and 311 kg/ha, while lower means for the LT region were observed, namely 0.11% and 220 kg/ha, respectively. In both regions a decrease of total N took place with depth. Interesting to note is the significant decline of total N concentration in the LT region below 15 cm whereas the UT region had an expected trend of a gradual decline through depth. As with the total C, the highest total N values were found in the top soil layer.

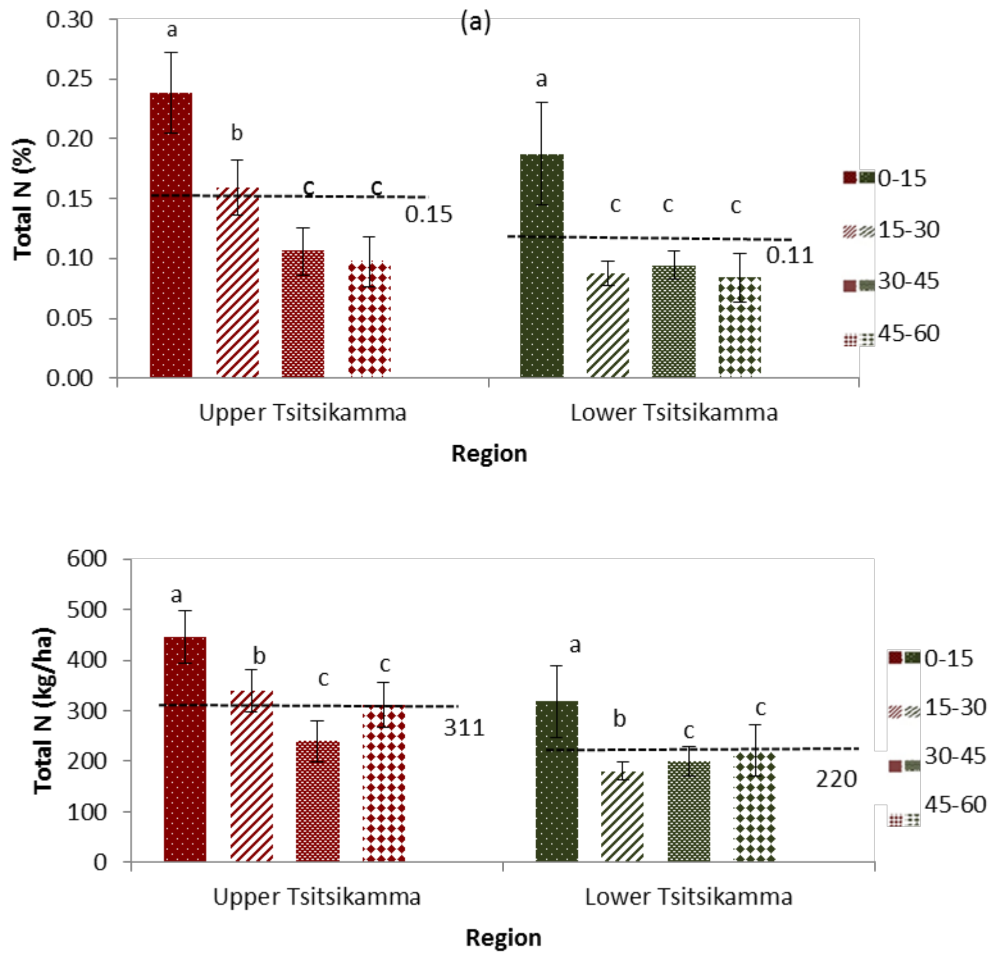


Figure 4.3 The effect of management practices on total N within soil layers comparing the upper and lower Tsitsikamma regions, where (a) is the average total N concentration, and (b) is the average total N stock.

Average total N within farms

The two Tsitsikamma regions (LT and UT) were found to be significantly different in concentration ($F_{1,207}$ = 59.8) and stock ($F_{1,207}$ = 135) values, respectively. The farms also showed significant differences in both regions when concentration was measured ($F_{4, 207}$ = 16.3) and hence stock ($F_{4, 207}$ = 15.8) calculated. The interaction of regions and farms showed no significance on concentration measurements, whilst the opposite was true for the stocks calculated (Table 4.1).

When comparing the farms in both regions, the total N concentration (Figure 4.4a) measured showed that the UT region had a higher average (0.201%) than the LT region (0.144%). The total N stock calculated in the two regions as demonstrated by Figure 4.4b also showed a higher average of 391 kg/ha in the UT region and a lower average of 255 kg/ha in the LT region.

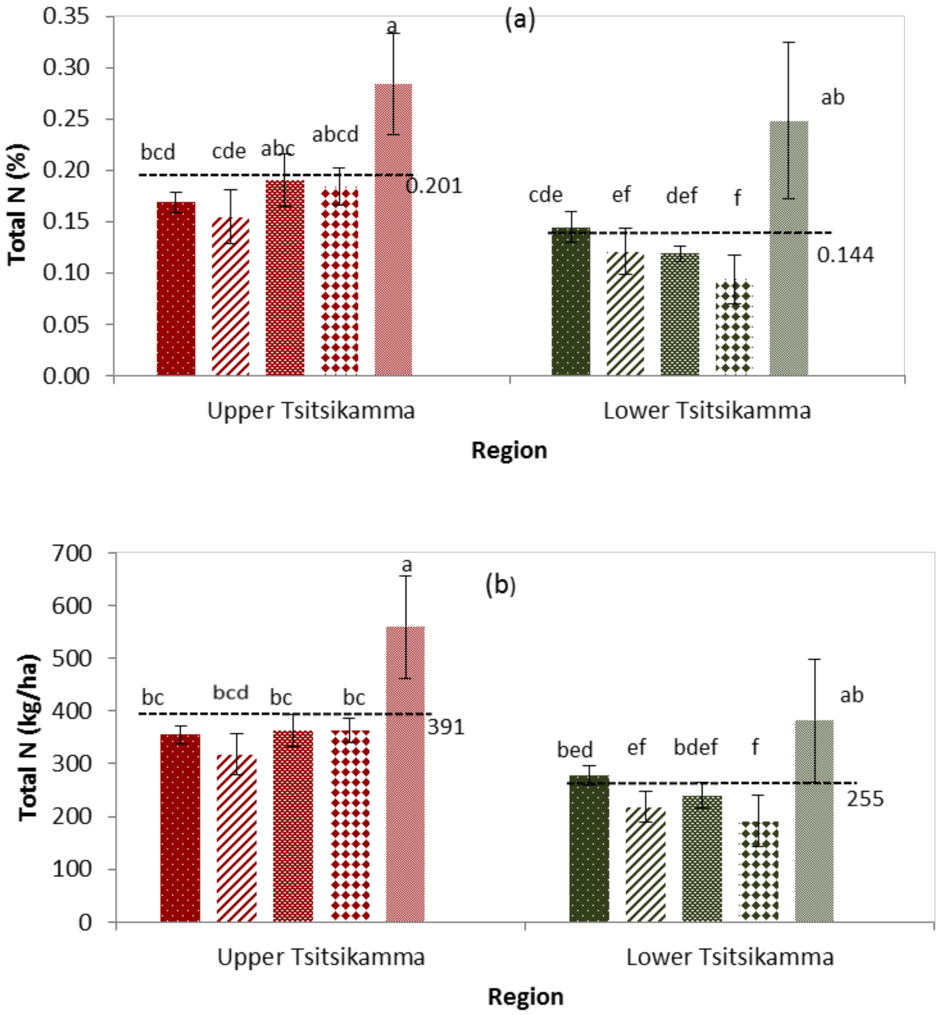


Figure 4.4 The effect of management practices on total N to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average total N concentration, and (b) is the average total N stock .

4.3.3 C/N ratio

Average C/N ratio within soil layers

It was illustrated in Table 4.1 that, the C/N ratios differed significantly in the upper and lower Tsitsikamma regions with an F value of $F_{1,206} = 142$. In both regions the C/N ratio of the soils also differed significantly between soil layers, where $F_{3,206} = 11.8$. The LT region had a higher C/N ratio through depth compared to the UT region as illustrated by Figure 4.5. Significant interactions were also observed for all treatment combinations. The mean C/N ratio for the LT region was 12.3, whereas a mean C/N ratio of 8.27 for the UT region was measured. Both regions illustrated a relatively uniform C/N ratio over depth and this was especially more prominent in the UT region (Figure 4.5).

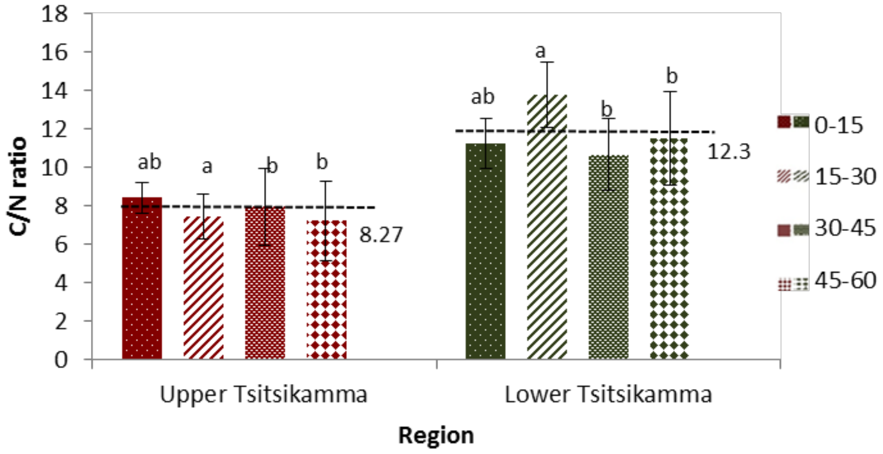


Figure 4.5 The effect of management practices on C/N ratio within soil layers comparing the upper and lower Tsitsikamma regions.

Average C/N ratio within farms

The two Tsitsikamma regions displayed significant differences in C/N ratio to 30 cm depth with $F_{1,206} = 142$. Ratios of C/N between farms differed significantly also; ($F_{4,206} = 117$). Significant differences were also found between the regions and farms combinations. The average C/N ratio was higher in the LT region (11.3) than in the UT region (8.42). In both regions the C/N ratio differed significantly between farms with farm two having the highest ratio (Figure 4.6).

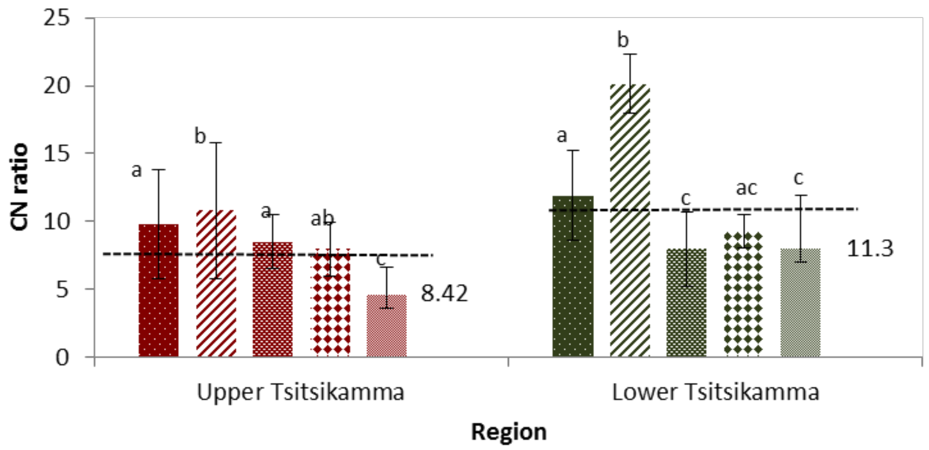


Figure 4.6 The effect of management practices on C/N ratios to 30 cm depth between the upper and lower Tsitsikamma regions.

4.3.4 Active C

Average active C within soil layers

Active C levels showed no significant differences between the upper and lower Tsitsikamma regions for both concentration ($F_{1,206}$ = 0.29) and stock ($F_{1,206}$ = 0.60), respectively. Significant differences were however found between soil layers for both regions regarding concentrations ($F_{3,206}$ = 267.40 and stocks ($F_{3,206}$ = 172.95). No significant interactions were found except for active C concentration in the combinations of regions and farms, as well as farms and soil layers.

The regions followed a similar trend of active C build-up through depth in that the top 15 cm had a higher active C concentration and stock which declined substantially below 30 cm. Although there were no significant differences in active C concentration and stock between the two regions, it is still worth mentioning the higher averages of 281 mg/kg and 583 kg/ha in the UT region compared to averages of 243 mg/kg and 467 kg/ha in the LT region, respectively.

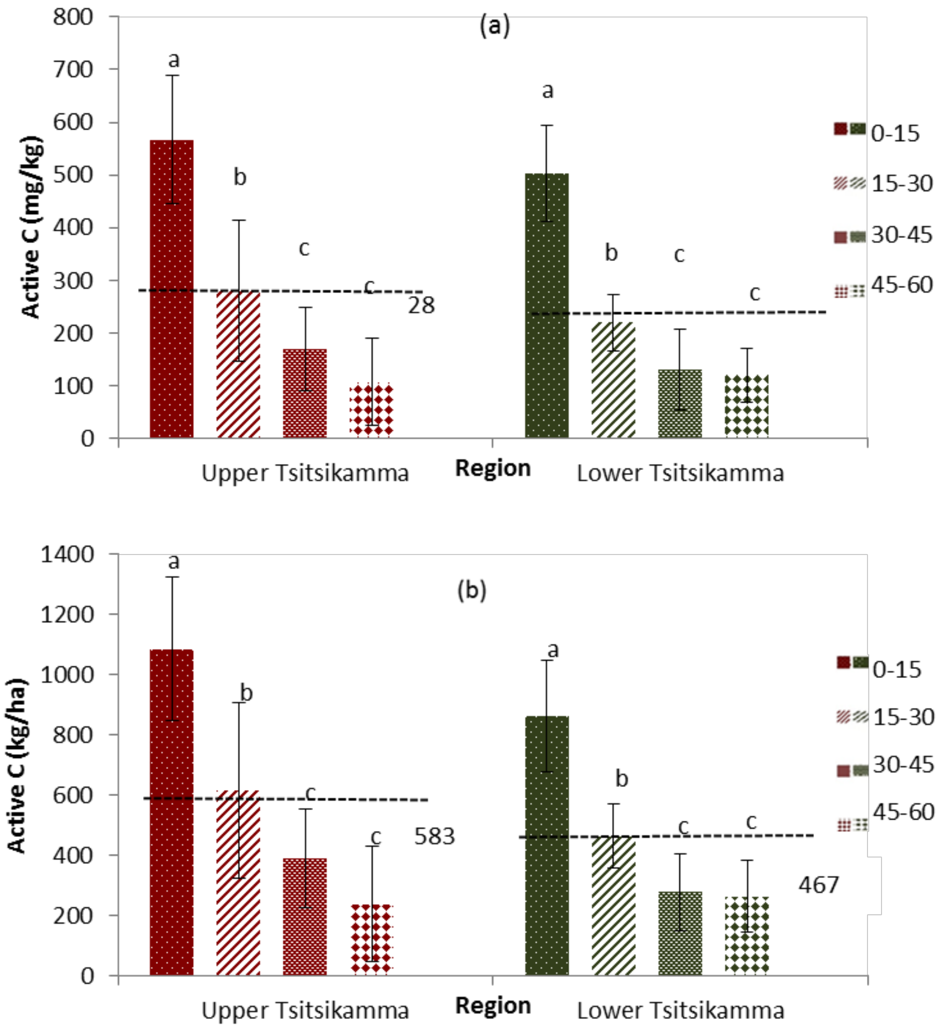


Figure 4.7 The effect of management practices on active C within soil layers comparing the upper and lower Tsitsikamma region, where (a) is the average active C concentration, and (b) is the average active C stock.

Average active C within farms

The analysis of variance showed no significant differences in active C between the two regions for either concentration ($F_{1,52} = 0.038$) or stock ($F_{1,52} = 2.10$). Significant differences were however observed between farms for concentration ($F_{4,52} = 6.52$) and stock ($F_{4,52} = 5.06$), respectively. The interaction of regions and farms only showed significant differences in the concentration measurements and not the stock of active C. The average active C concentration and stock for the UT region were 448 mg/kg and 886 kg/ha and for the LT region 405 mg/kg and 731 kg/ha, respectively. Figure 4.8 showed an interesting trend in active C between farms in the two regions.

The farms in the UT region exhibited higher consistency than the farms in the LT region, which showed a higher variation between farms.

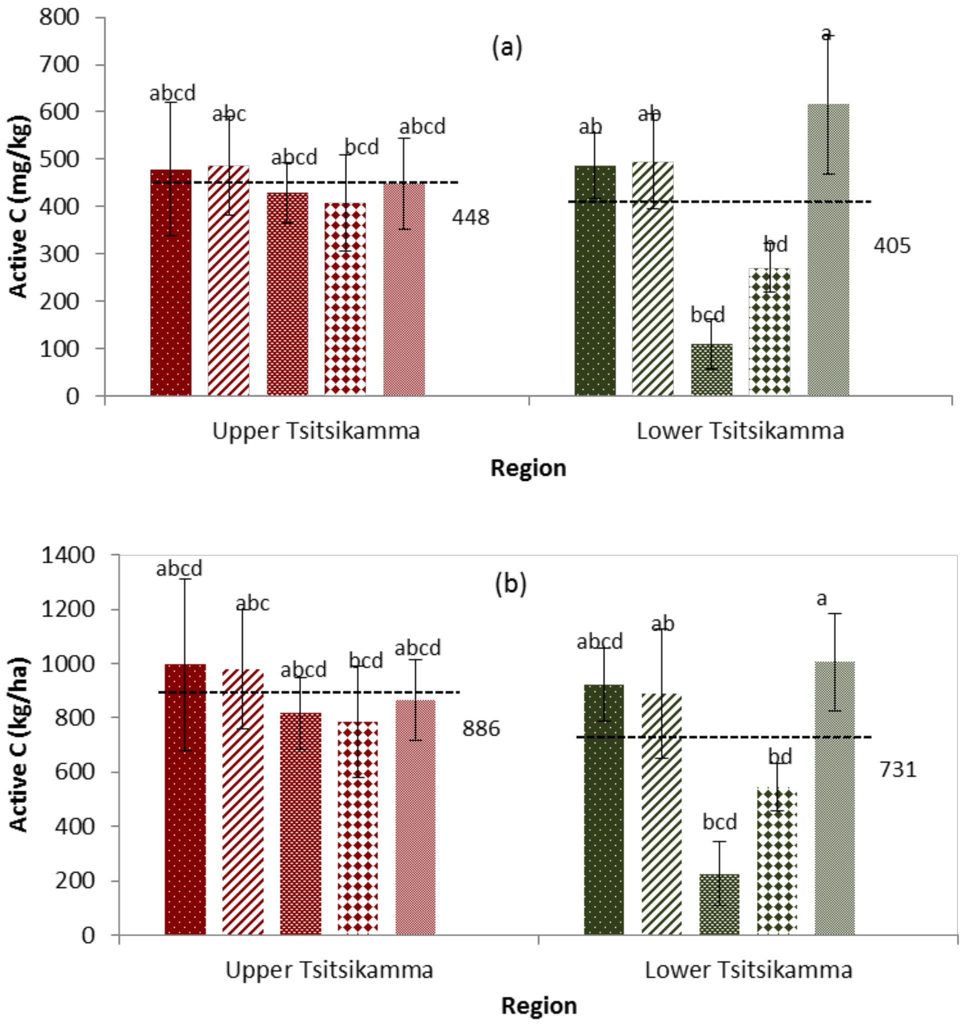


Figure 4.8 The effect of management practices on active C to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average active C concentration, and (b) is the average active C stock.

4.3.5 PMN rate

Average PMN rate within soil layer

Significant differences were found for PMN rates between the upper and the lower Tsitsikamma regions for both concentration ($F_{1,206}$ = 21.8) and stock ($F_{1,206}$ = 15.8). There were also significant differences between soil layers for concentration ($F_{3,206}$ = 21.9) and stock ($F_{3,206}$ = 14.1). No significant differences were found between interactions of any of the combinations. Figure 4.9 showed that in terms of concentration and stock, the UT region had lower PMN rates than the LT region, namely 0.452 mg/kg/week vs 0.882 mg/kg/week and 0.928 kg/ha/week vs 1.82 kg/ha/week. The LT region also exhibited higher PMN rates through soil depth than the UT region, with the highest values evident in the top 15 cm soil layer.

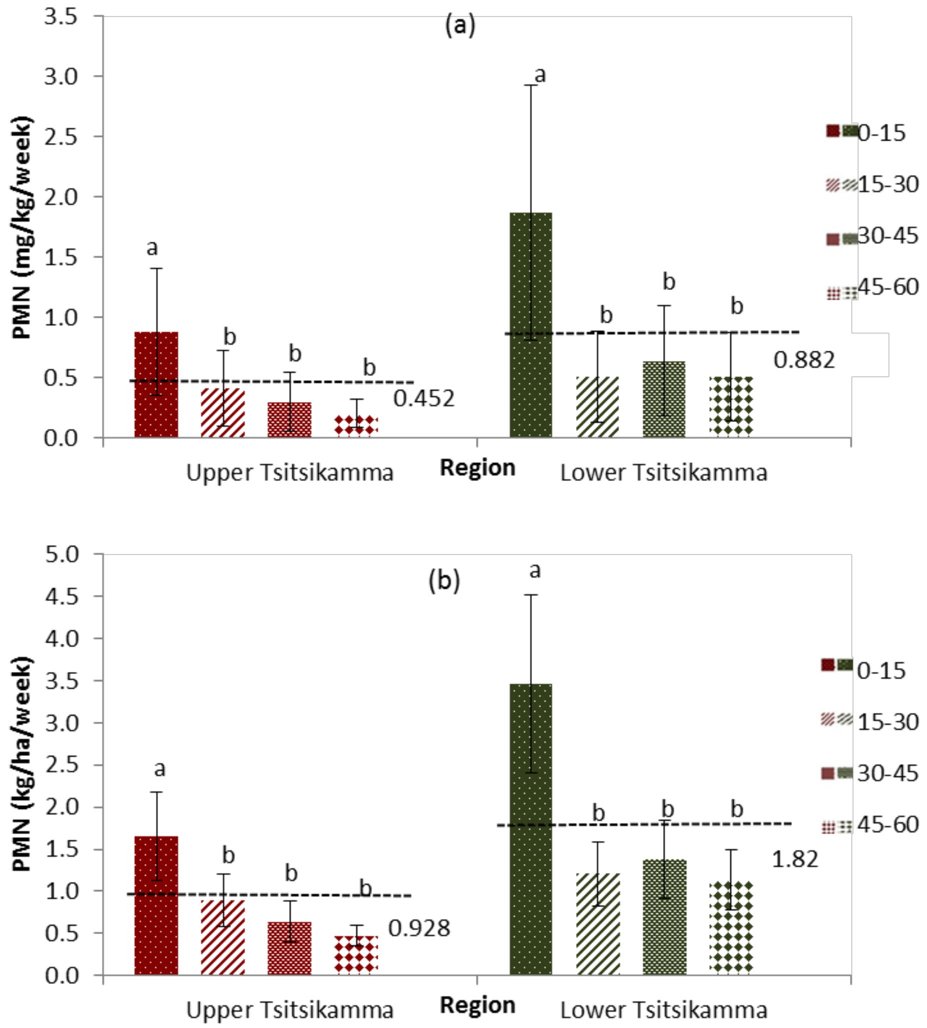


Figure 4.9 The effect of management practices on N mineralisation within soil layers comparing the upper and lower Tsitsikamma region, where (a) is the average PMN concentration rate, and (b) is the average PMN stock rate.

Average PMN rate within farms

The PMN rates in terms of concentration ($F_{1,52} = 4.73$) and stock ($F_{1,52} = 3.07$) did not differ significantly when comparing the upper and lower Tsitsikamma regions. There were also no significant differences observed in PMN rates between farms for either concentration ($F_{4,52} = 0.578$), or stock ($F_{4,52} = 0.476$). The interaction between regions and farms also showed no significant differences in PMN rates. The LT region had a two-fold higher PMN rate (1.46 mg/kg/week and 2.72 kg/ha/week) than the UT region (0.731 mg/kg/week and 1.54 kg/ha/week) as displayed in Figure 4.10.

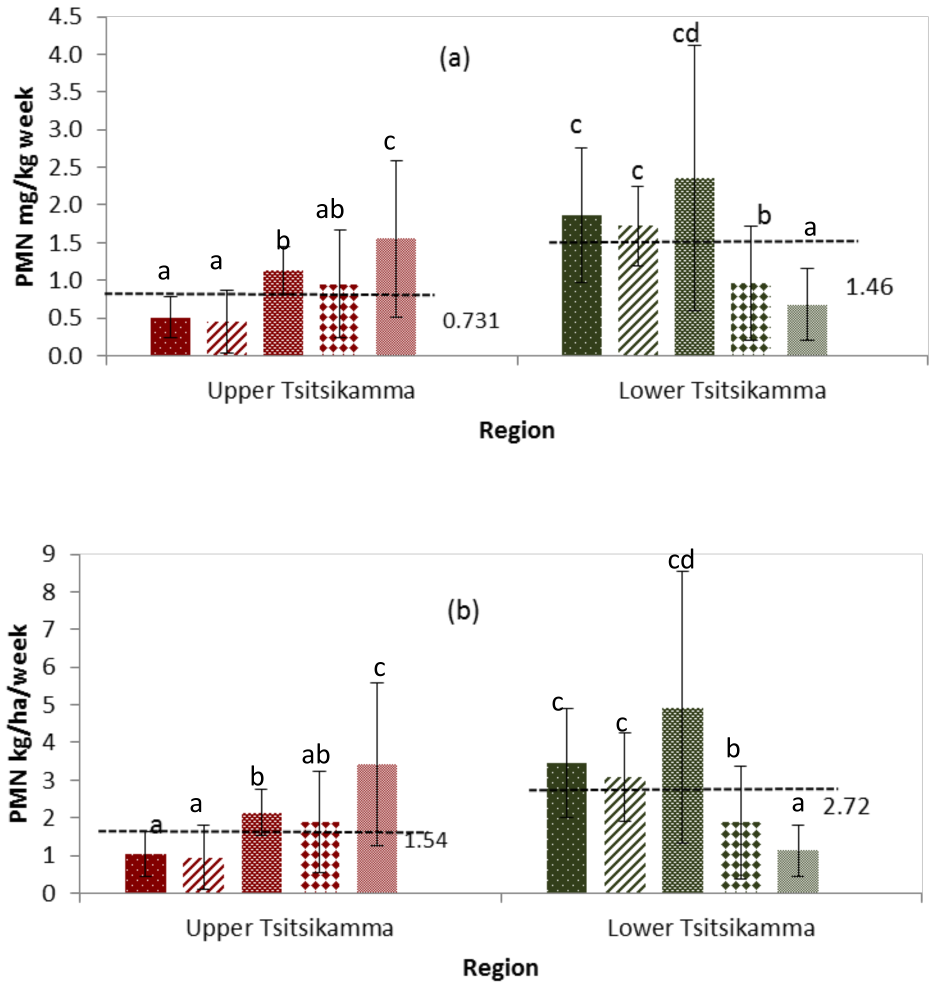


Figure 4.10 The effect of management practices on N mineralisation to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average PMN concentration rate, and (b) is the average PMN stock rate.

4.4.6 Inorganic N

Average inorganic N within soil layers

For inorganic N, concentration ($F_{1,207} = 5.20$) and stock ($F_{1,207} = 4.36$) differences were insignificant between the upper and lower Tsitsikamma regions. Significant differences were conversely found between soil layers for concentration ($F_{3,207} = 36.9$) and stock ($F_{3,207} = 15.7$). Within interactions, significant differences were only observed between the regions and depth combinations as well as the regions, farms and depth combinations for concentration measurements. As demonstrated by Figure 4.11, the top 15 cm soil in both regions had the highest inorganic N and below 15 cm the inorganic N declined slightly. An interesting trend was observed in the UT region where the 45-60 cm soil layer showed higher inorganic N levels than the 15-30 and 30-45 cm soil layers. The average inorganic N concentration and stock in the UT region were 7.03 mg/kg and 15.1 kg/ha, respectively. A lower average of 5.41 mg/kg and 11.0 kg/ha for both concentration and stock was observed in the LT region.

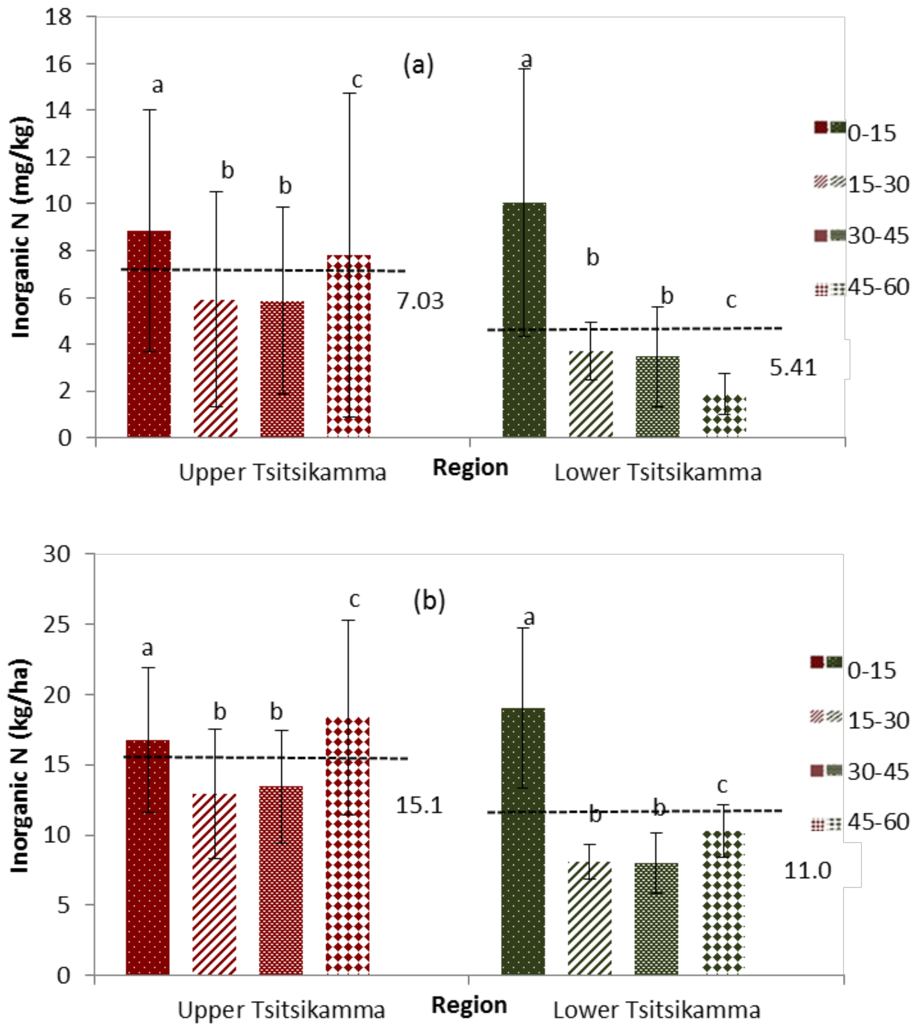


Figure 4.11 The effect of management practices on inorganic N within soil layers comparing the upper and lower Tsitsikamma region, where (a) is the average inorganic N concentration, and (b) is the average inorganic N stock.

Average inorganic N within farms

The analysis of variance showed no significant differences between the upper and lower Tsitsikamma regions in either inorganic N concentration ($F_{1, 52}$ = 0.274) or stock ($F_{1, 52}$ = 0.431). Significant differences were found between farms only for concentration ($F_{4, 52}$ = 6.54) and not for stock ($F_{4,52}$ = 3.92). The combination of regions and farms also showed no significant difference in organic N. Figure 4.12 indicated that the LT region had slightly higher concentration and stock averages (13.4 mg/kg and 25.3 kg/ha) than the UT region (12.9 mg/kg and 23.4 kg/ha).

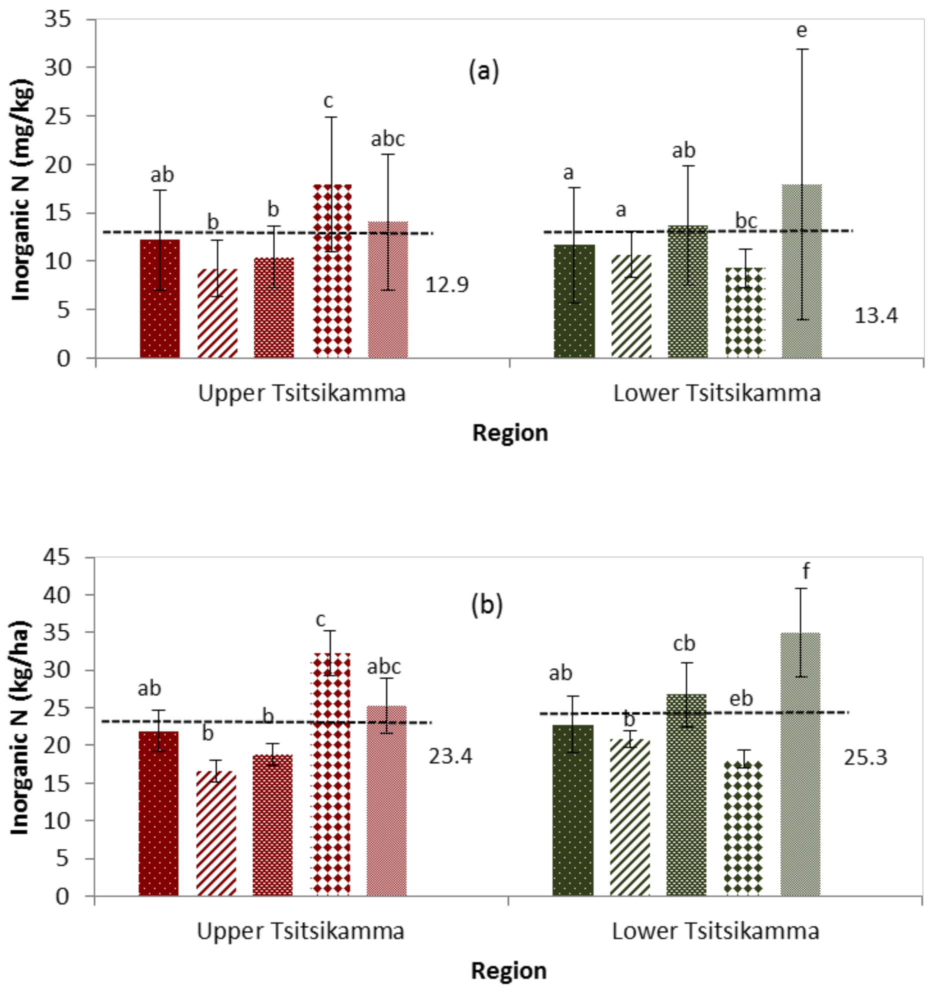


Figure 4.12 The effect of management practices on inorganic N levels to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average inorganic N concentration, and (b) is the average inorganic N stock.

4.4 Discussion and conclusion

The Tsitsikamma region generally had a poor soil quality due to the low OM status of the soils. There was however an exception on some of the farms in the LT region. This exception was observed on 1, 2 and 5 farms of the LT region. These 3 farms had a better SOM status probably because they were 3 of the 4 farms that used compost, chicken litter and spreaded manure effluent onto the pastures. Applying these practices on farms helped stimulate microbial activity, and increased soil nutrient status through slow release organic sources i.e. chicken litter and manure. Applied manure significantly impacts the soil's chemical, physical and biological properties because of increased OM levels attributed to manure application (Follett, 2001).

A study conducted by Roy and Kashem (2014) on the effect of organic manures in changes of some soil properties, established that chicken manure treated soils had a higher organic C content at 15 days of incubation compared to other organic C sources. The application of these organic sources of fertiliser have had a positive impact on the soil C build-up in the LT region, as indicated by high C concentration in the area, a management practice that has not been fully adopted in the UT region. Although the two regions may share similar active C concentrations, the LT region had a higher C/N ratio, PMN rate as well as inorganic N content. The LT region also had a lower total N concentration and also had applied less N in the form of fertiliser.

In contrast, the farms in the UT region had applied more N and as a consequence, more N was measured in the soil system. High N fertilisation has been reported to reduce microbial biomass and functional diversity compared to low N fertilisation systems (He *et al.,* 2012). The mineralisation of N is governed by micro-organisms; therefore any factor that influences the functioning of micro-organisms will essentially have an influence on the mineralisation rate as well. High N input systems coupled with continuous use of herbicides, a common practice in the UT region (see Table 3.2) have a negative impact on soil micro-organisms (Johnson and Colmer, 1954; Magee and Colmer, 1955; Wilkinson and Lucas, 1969; He *et al.,* 2012). Farms that used herbicides and high N fertilisation, showed poor SOM accumulation. This observation gives opportunity to advocate to the farmers the importance of minimising fertiliser N applications as well as herbicide use, as these have been found in the study to negatively impact SOM indicators.

The C/N ratio also plays a vital role in mineralisation processes of both C and N, in fact a C/N ratio above 30 has been reported to encourage net immobilisation, whereas a ratio below 20 would most likely ensure net mineralisation (Davidson *et al.,* 1991). Both of these ratios are not ideal in the soil because net mineralisation encourages rapid OM decomposition, which would result in OM depletion, and higher C/N ratios deplete plant available N. A ratio of 24 in the soil has been reported as the most ideal for optimum and balanced microbial functioning (USDA-NRCS, 2011; Dahmer, 2014).

The average total C stock in the UT region was observed to be slightly higher than that of the LT region, because the soils in the UT region had a much higher bulk density which played a critical role in stock calculations. Baldwin (2003) found that soil density had a huge influence on the C stocks on soils that were planted with maize in a no-tillage system. Multi-species cropping has been reported to improve soil quality due to diverse plants that encourage below-ground microbial diversity (Jones and Miller, 2015). It has also been reported that permanent pasture soils are good in building up SOM, because permanent soil cover helps to regulate and improve soil biological, chemical and physical properties (Fanadzo *et al.,* 2009). The improvement of these properties is essential for soil microbial activity because they are vital for C and N mineralisation processes (Bot and Benites, 2005).

Another important factor to consider is that the majority of the farms in the LT region implemented multi-species cropping systems far earlier than the farms in the UT region. Therefore it is important to acknowledge that multi-species cropping combined with permanent pasture setup had also played a significant role in building C stocks in the Tsitsikamma region.

Jones and Miller (2015) have also reported that good grazing management strategies under irrigated pastures increased soil C stocks. Management strategies like rotational grazing or strip grazing (prioritizing leaf stage), as opposed to continuous or unplanned grazing under permanent pasture systems have been proven to be beneficial for soil biology (Arnall *et al.,* 2006). Rotational grazing is defined by the United States Department of Agriculture (USDA) and NRCS (2009) as a practice whereby livestock are strategically moved to fresh paddocks, or partitioned pasture areas, to allow vegetation in previously grazed pastures to regenerate.

The majority of irrigation farms in the Tsitsikamma region had adopted rotational grazing strategies; however they differed in their allocation systems. Although continuous grazing has been reported to require minimal capital investment and movement of animals, it is not sustainable because it prohibits the pasture from recuperating and the quality of pasture usually deteriorates (Morgan, 2016).

A study by Pavlu *et al*. (2003 and 2006) on the effect of rotational and continuous grazing on vegetation, pointed out that rotational grazing, contrary to continuous grazing can increase pasture productivity by allowing vegetation to recover after short intense grazing periods. It also helps to minimise soil compaction, because animals do not walk longer distances on the same path; the opposite would result in hoof compaction which minimises soil fertility and water infiltration and movement (Andrae, 2003; Morgan, 2016).

It is evident that soil management that encourages SOM build-up is a prerequisite for sustainable and improved soil quality. The burden falls on land managers to try and better understand the principles behind soil quality and continuously implement strategies that build SOM. This can be achieved if strong relationships are formed between researchers and farmers; because both are vital in understanding soil degradation. It is however important that researchers realise that, fixed on-farm constraints need to be considered and that soil management strategies are not necessarily uniform within the industry. Each farmer has a unique story and overall reason behind his or her choice of management system. It is also important to note that the dairy industry is a high input, time consuming, labour intensive and unpredictable business, therefore strategies must be amendable, cost effective, viable and applicable.

CHAPTER 5

INFLUENCE OF MANAGEMENT PRACTICES ON SOIL CHEMICAL INDICATORS

5.1 Introduction

Soil fertility influences potential pasture yield, pasture growth rates, ability for pastures to regrow as well as forage quality (Griffiths and Burns, 2004). The FAO (2005) defines soil fertility as the ability of the soil to supply essential plant nutrients and soil water in adequate amounts and proportions for plant growth and reproduction in the absence of toxic substances, which may inhibit plant growth. Soil fertility is generally recognised as an important aspect of soil management which is easily understood by a majority of farmers. Soil management systems in agriculture should implement practices that are in harmony with the soil and organisms that inhabit it, as these will help to enhance pasture production.

Soil has the potential to be very productive if the complex interaction between the soil's biological, chemical and physical properties is better understood (Johnston, 2011). Subsequently, soil management practices should focus on managing various parameters that consider all three of these aspects, in order to enhance production. Although the focus of this chapter is on soil fertility, it is still important to reiterate the significance of soil biology and soil structure because of the overall impact on nutrient availability and uptake by plants.

Dairy pasture systems remove a significant amount of nutrients from the soil due to grazing and in some cases mechanical removal of grass to make silage bails. Griffiths and Burns (2004) reported that kikuyu pasture yielding 4 t/ha, removed up to 96 kg N/ha, 12 kg P/ha and 100 kg K/ha. Farmers often make silage bails from pastures when growth is in surplus to the feed demand, therefore in order to avoid loss of quality and wastage of food, farmers usually cut the grass and then bail it. In some cases farmers will grow pasture in specific camps just for the purpose of making silage out of the grass. It would be beneficial for soil quality if farmers could let the grass grow longer even when feed demand has been met, as this has a long term benefit to soil fertility. Allowing grass to grow for longer periods helps improve above and below ground biomass. This happens through elongated roots below ground which add to OM reserves, as a result raising microbial population. Above ground biomass is increased through the decaying of older grass leaves and thus also contributing to SOM reserves (Chen *et al.,* 2015). The removal or loss of nutrients in soil causes soils to be depleted in essential nutrients, which are expensive to return and maintain in the soil system. This evidence reiterates the importance of replacing nutrients removed, if long term production is to be sustained.

Nutrient losses become more pronounced in sandy soils because of their susceptibility to nutrient losses due to leaching (Lamb *et al.,* 2015). Good soil quality can be achieved with frequent soil analysis. The determination of the required amounts of nutrients in the soil and the subsequent application thereof, helps in improving soil fertility, productivity and quality especially if nutrients are applied according to the measured requirement (Kassam *et al.,* 2012). Nutrients like P, K and Mg are essential for plant growth and need to be maintained at optimal levels for efficient production.

Soil management practices such as excessive application of fertiliser and irrigation coupled with poor grazing management practice (e.g. over-grazing and poor pasture allocation systems) have been reported to have severe effects on soil fertility and degradation. Well established leaves assists in optimal harvest of energy from the sun through photosynthesis, which is converted to C that is stored in the soil. A shorter grazing cycle will result in poor harvest of this energy from the sun and therefore the build-up of soil C will be much slower (Donaghy, 1998; Chapman, 2011). Johnston (2013) explained that pastures that are grazed at the correct leaf stages (i.e. 2.5-3 leaf stage for rye-grass and 3.5-4 leaf stage for kikuyu) tend to accumulate more SOM, which is key in nutrient and water storage in the soil. Soils that have been over irrigated and also have poor soil C levels are likely to suffer from nutrient leaching, especially unstable nutrients like K and nitrates (NO_3^-) (Johnston, 2013).

Management practices that encourage the loss of nutrients can result in significant losses of soil stability as well as possible profit in the Tsitsikamma region. Before the 1990s, conventional tillage methods were very popular in this region and as a result, soil fertility was very poor (Swanepoel *et al.,* 2015). Farmers relied on excessive fertiliser application in order to get what was then regarded as good growth. Today, with the adoption of no-tillage practices and reduction of fertiliser application by over 75%, in some farms, the same growth has been maintained while in others, more tonnage of pasture have been produced with minimum fertiliser application. The soils have since accumulated OM and improved soil structure, which then consequently improved soil fertility in the area.

Soil nutrient assessment has widely been used for many years as a guide to estimate soil fertility. The interpretation and representation of results for management is however what differs. In this study, extractable P, exchangeable cations (Ca, K, Mg, and Na) and pH (KCl) have been measured as suitable soil fertility indicators. The importance of cations in plant nutrition has been fully established in literature. This study will therefore not focus on these nutrients for the purpose of plant nutrition, but rather on the composition of each nutrient and possible management practices that might have influenced its retention or loss in the soil.

5.2 Procedure

In Chapter 3 (Materials and Methods) it was mentioned that four soil layers were analysed for chemical indicators (extractable P, exchangeable K, Ca, Mg, Na as well as pH (KCl)). All indicators except for pH (KCl) have been reported in concentration (mg/kg) and stock (kg/ha). The stocks were calculated using soil bulk density. Analysis of variance showed clear significant differences at a 99% confidence interval ($p < 0.001$) on the above mentioned parameters between the upper and lower Tsitsikamma regions (Table 5.1). Furthermore, significant differences were found between all the soil layers and both regions showed a similar trend concerning the accumulation of nutrients with depth. This trend will first be discussed within the two regions for all 4 measured soil layers (0-15, 15-30, 30-45 and 45-60 cm), respectively. The second results presented will show the differences within farms in the two regions at only 0-30 cm soil layer. This is because the 0-15 and 15-30 cm soil layers showed significant differences, whereas the lower 30-45 and 45-60 cm showed no significant differences. Hence, a comprehensive discussion is only focusing on the 0-30 cm layers.

Table 5.1 Summary of analysis of variance indicating the significant effect of management practices on soil chemical indicators

Soil parameter	**Area**	**Farm**	**Depth**	**Area x Farm**	**Area x Depth**	**Farm x Depth**	**Area x Farm x Depth**
Extractable P concentration	✓	×	✓	✓	✓	✓	✓
Extractable P stock	✓	×	✓	✓	×	✓	✓
Exchangeable K concentration	✓	×	✓	✓	×	✓	✓
Exchangeable K stock	✓	×	✓	✓	×	✓	✓
Exchangeable Ca concentration	✓	✓	✓	✓	✓	✓	✓
Exchangeable Ca stock	✓	✓	✓	×	×	✓	✓
Exchangeable Mg concentration	×	✓	✓	✓	✓	✓	✓
Exchangeable Mg stock	✓	✓	✓	✓	✓	✓	✓
Exchangeable Na concentration	✓	×	✓	✓	✓	✓	✓
Exchangeable Na stock	×	×	✓	×	✓	✓	×
pH (KCl)	✓	×	✓	✓	✓	✓	✓

✓ Significant; × Not significant alpha (α) = 0.01

5.3 Results

5.3.1 Extractable P

Average extractable P within soil layers

The analysis of variance in Table 5.1 showed significant differences for extractable P in terms of concentration ($F_{1,208}$ = 65.5) and stock ($F_{1,208}$ = 50.1) when the upper and lower Tsitsikamma were compared. Significant differences for this indicator were also found within soil layers concerning either concentration ($F_{3, 208}$ = 390) or stock ($F_{3,208}$ = 175). All interactions showed significant differences, with the only exception being the region and depth for extractable P stocks combinations. Figure 5.1 showed that the LT region had a higher P concentration within the soil layers compared to the UT region.

The mean P concentration and stock values for the UT region were 18.6 mg/kg and 37.9 kg/ha, and those for the LT region were 28.3 mg/kg and 55.5 kg/ha, respectively. In both regions a decrease of extractable P occurred with depth. It is interesting to note the high contents of extractable P in the top 15 cm soil for both Tsitsikamma regions.

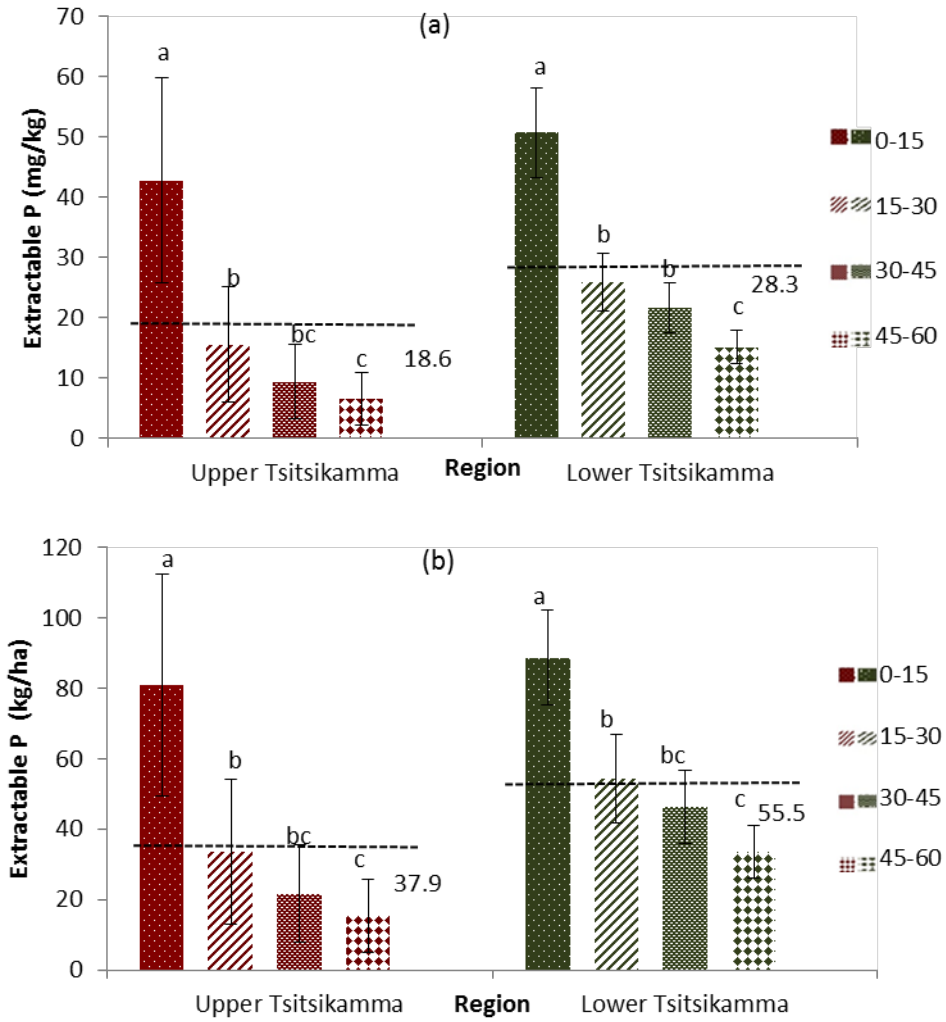
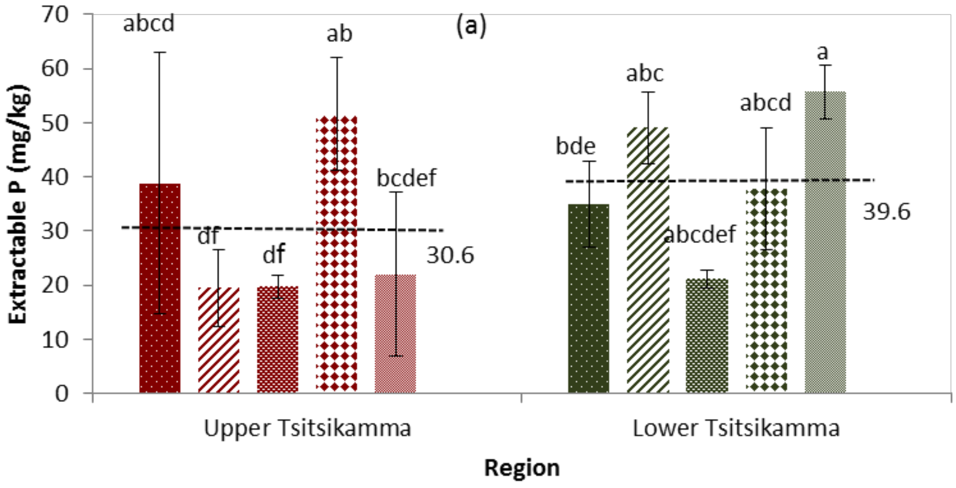


Figure 5.1 The effect of management practices on extractable P within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average extractable P concentration, and (b) is the average extractable P stock.

Average extractable P within farms

There were significant differences in extractable P to 30 cm soil depth between the UT and LT regions. This applied for both concentration ($F_{1,52} = 188$) and stock ($F_{1,52} = 143$) values. Significant differences were found between farms concerning concentrations ($F_{4,52} = 11.3$), but not stocks ($F_{4,52} = 5.28$) of extractable P. The regions and farms combinations however showed significant differences for both concentration and stock values. Figure 5.2 showed that with respect to extractable P concentrations and stocks, the LT region had higher averages (39.6 mg/kg and 74.3 kg/ha) than the UT region (30.6 mg/kg and 60.2 kg/ha).



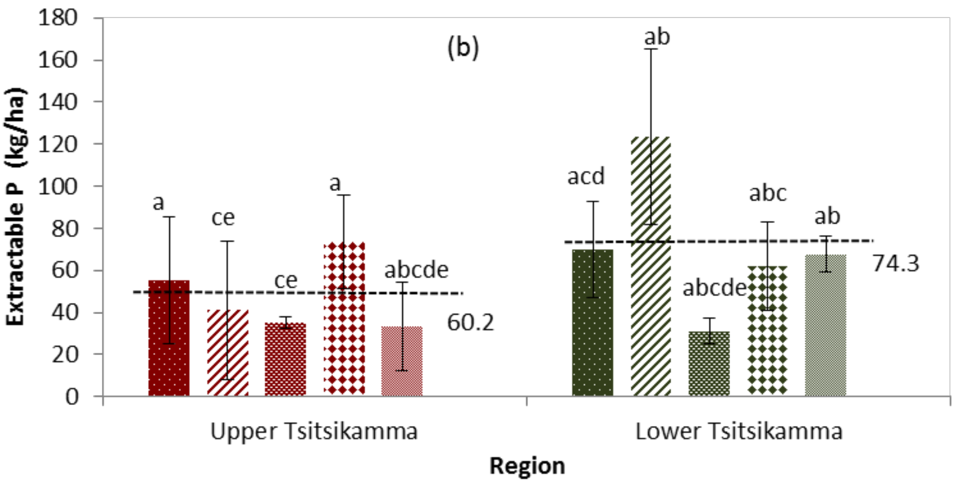


Figure 5.2 The effect of management practices on extractable P to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average extractable P concentration, and (b) is the average extractable P stock.

5.3.2 Exchangeable K

Average exchangeable K within soil layers

In the case of exchangeable K, the UT and the LT regions differed significantly from one another with respect to this nutrient's concentration ($F_{1,208}$ = 25.4) and stock ($F_{1,208}$ = 23.6). Soil layers showed also significant differences in the concentration ($F_{3,208}$ = 320) and stock of exchangeable K ($F_{3,208}$ = 158). All interactions except those between regions and soil layers were significant. Furthermore, Figure 5.3 illustrated that the UT region had higher exchangeable K concentrations and stocks through depth than the LT region. The average concentration and stock of exchangeable K to 60 cm depth were 90.4 mg/kg and 189 kg/ha in the UT region, and 69.7 mg/kg and 140 kg/ha in the LT region, respectively. However, the 0-15 cm soil layer had the highest values in both regions.

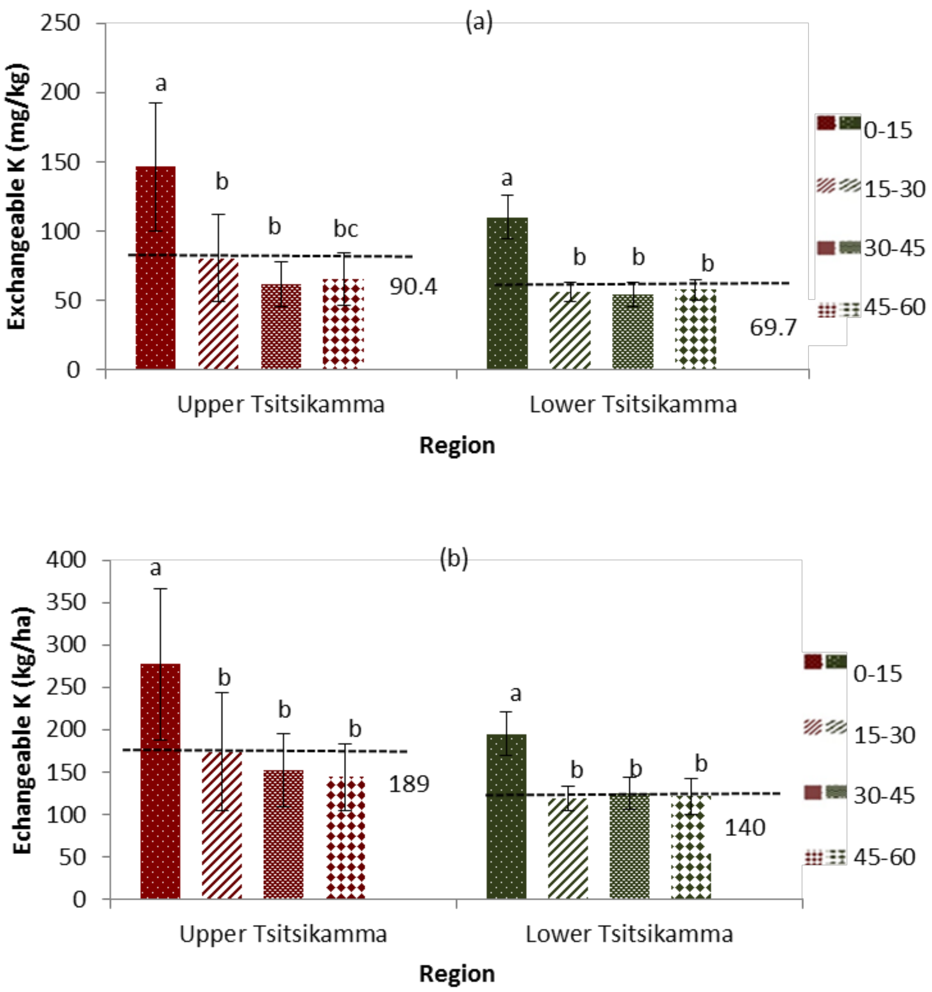


Figure 5.3 The effect of management practices on exchangeable K within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average exchangeable K concentration, and (b) is the average exchangeable K stock.

Average exchangeable K within farms

The farms in the UT and LT regions differed significantly with regard to either exchangeable K concentration ($F_{1,52}$ = 68.0) or stock ($F_{1,52}$ = 62.4). There were also significant differences between farms in these two regions for exchangeable K concentration ($F_{4,52}$ = 7.16) and stock ($F_{4,52}$ = 6.05) in the same soil layers. The only significant interaction was observed between regions and farms with exchangeable K concentration. As shown by Figure 5.4, the LT region had lower average concentrations (83.6 mg/kg vs 121 mg/kg) and stocks (158 kg/ha vs 239 kg/ha) than the UT region. The trend between farms in the UT region was slightly more uniform than in the LT region.

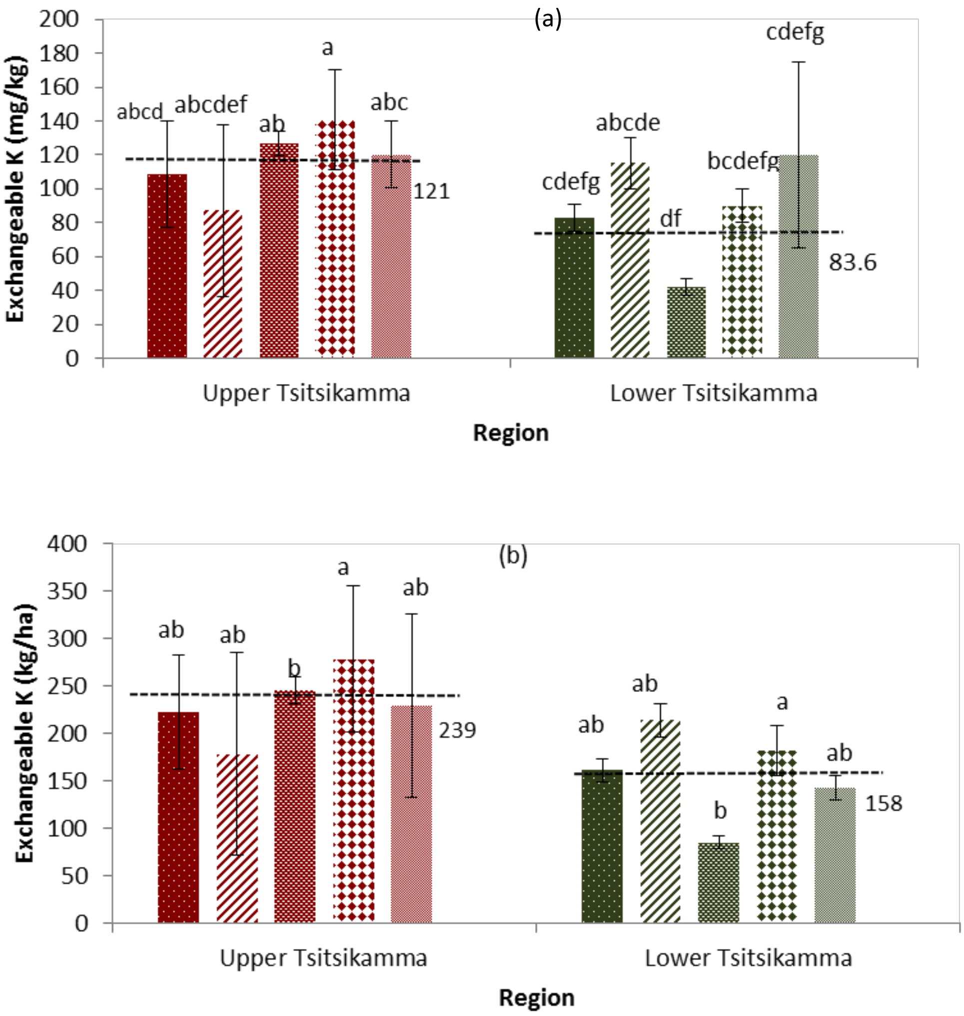
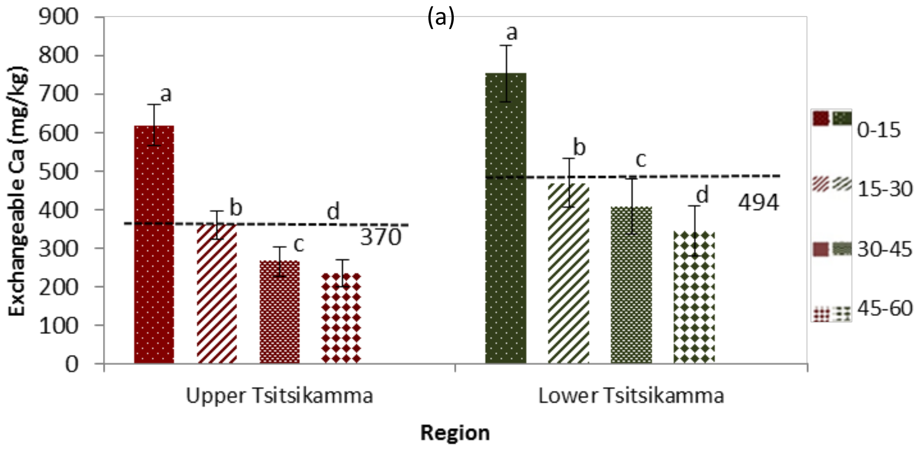


Figure 5.4 The effect of management practices on exchangeable K to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average exchangeable K concentration, and (b) is the average exchangeable K stock.

5.3.3 Exchangeable Ca

Average exchangeable Ca within soil layers

Exchangeable Ca showed significant differences between the two regions of the Tsitsikamma. This observation applied for the concentration ($F_{1,207} = 81.7$) and stock ($F_{1,207} = 57.5$) values. Significant differences were also found within soil layers concerning the concentration ($F_{3,207} = 2120$) and stock ($F_{3,207} = 848$) of exchangeable Ca. Significant interactions only existed between farms and soil layers, as well as between regions, farms and soil layers when exchangeable Ca stocks were calculated. However, for exchangeable Ca concentrations all interactions were significant. As illustrated by Figure 5.5, the LT region had slightly higher concentrations and stocks of exchangeable Ca within soil layers compared to the UT region. The average exchangeable Ca concentrations (494 mg/kg vs 370 mg/kg) and stocks (988 kg/ha vs 779 kg/ha) were higher in the LT region than in the UT region. As could be expected, the trend of exchangeable Ca was similar to that of extractable P, where the highest accumulation of Ca was in the top 15 cm soil.



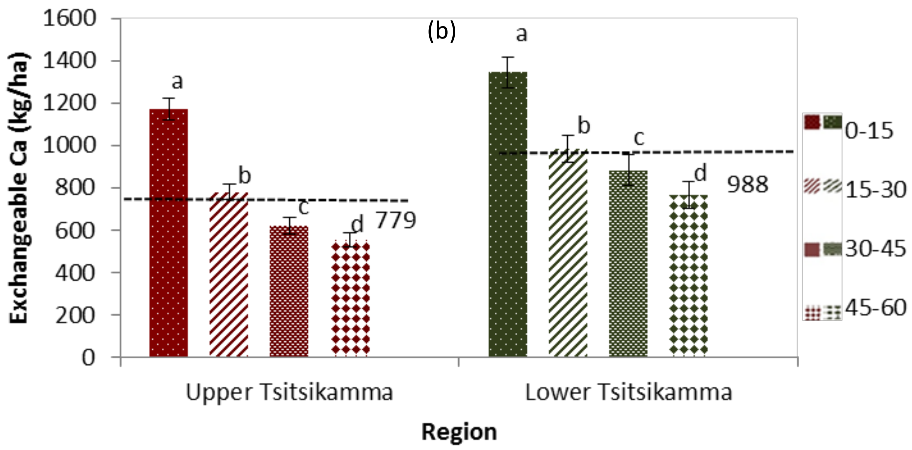
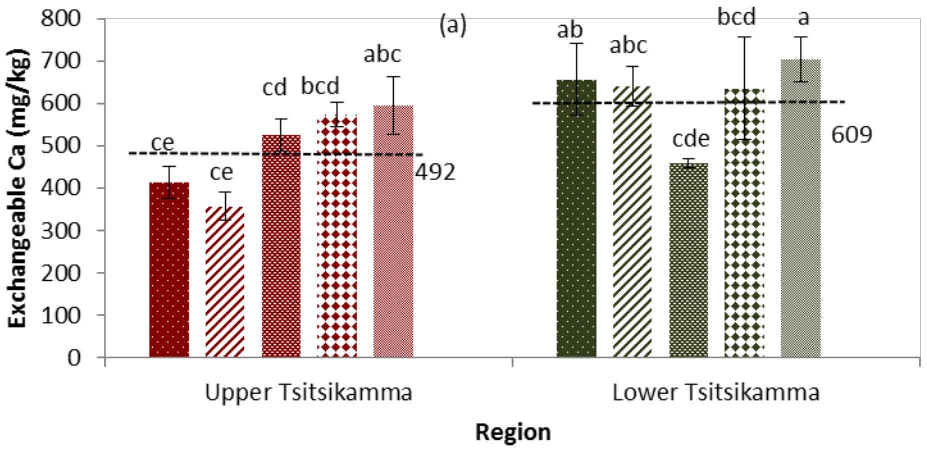


Figure 5.5 The effect of management practices on exchangeable Ca within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average exchangeable Ca concentration, and (b) is the average exchangeable Ca stock.

Average exchangeable Ca within farms

The two regions differed significantly from one another in terms of exchangeable Ca concentration ($F_{1,52}$ = 174) and stock ($F_{1,52}$ = 121) to 30 cm depth. When farms were compared, significant differences were also found in the concentration ($F_{4,52}$ = 13.83) and stock ($F_{4,52}$ = 10.71) values of exchangeable Ca. Significant interactions between farms and soil layers were also noted for exchangeable Ca both concentrations and stocks. The average exchangeable Ca concentration and stock for the LT region were 609 mg/kg and 1157 kg/ha, and for the UT region 492 mg/kg and 973 kg/ha, respectively (Figure 5.6).



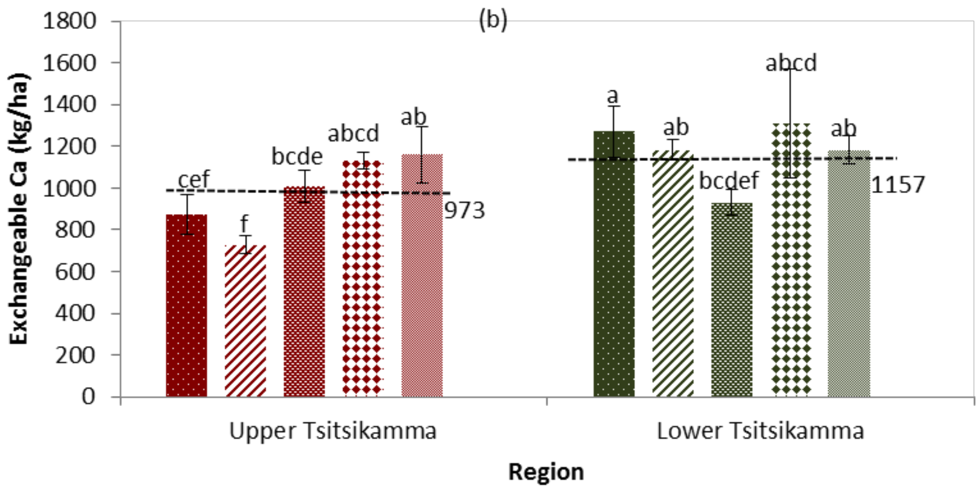


Figure 5.6 The effect of management practices on exchangeable Ca to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average exchangeable Ca concentration, and (b) is the average exchangeable Ca stock.

5.3.4 Exchangeable Mg

Average exchangeable Mg within soil layers

For exchangeable Mg concentration ($F_{1,207}$ = 8.96) and stock ($F_{1,207}$ =18.16), significant differences were found between the UT and LT regions. Similarly with soil layers, significant differences were also found in the concentrations ($F_{3,207}$ = 1009) and stocks ($F_{3,207}$ = 322) of exchangeable Mg. All interactions were significant, irrespective whether exchangeable Mg was expressed in concentration or stock measurements. Figure 5.7 showed that the UT region had higher concentrations and stocks of exchangeable Mg through depth compared to the LT region. The average concentration and stock of exchangeable Mg were 115 mg/kg and 318 kg/ha for the UT region, and 99 mg/kg and 267 kg/ha for the LT region, respectively. Similar to exchangeable Ca, the exchangeable Mg in the top 15 cm soil layer was higher than in the soil layers below.

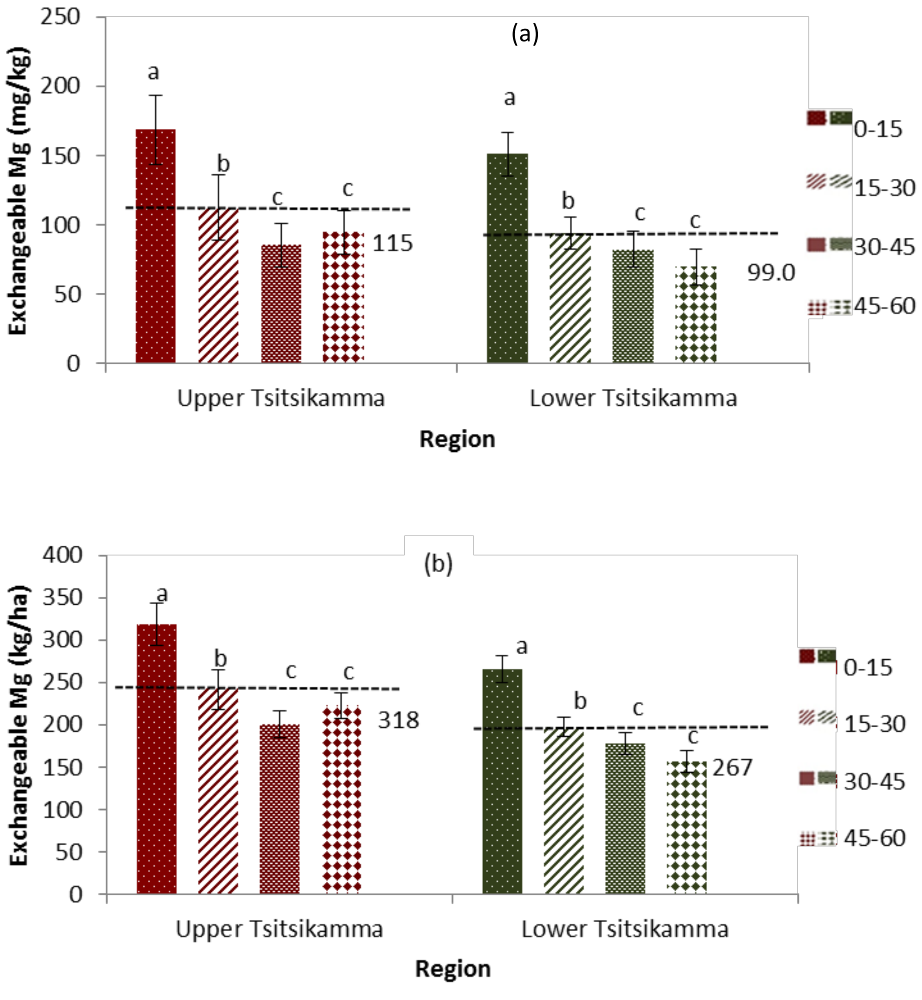


Figure 5.7 The effect of management practices on exchangeable Mg within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average exchangeable Mg concentration, and (b) is the average exchangeable Mg stock.

Average exchangeable Mg within farms

Exchangeable Mg showed no significant difference between the two regions of the Tsitsikamma with respect to either concentration ($F_{1, 52}$ = 0.801) or stock ($F_{1,52}$ = 3.65). However, significant differences were found between farms in concentration ($F_{4,52}$ = 17.02) and stock ($F_{4, 52}$ = 7.38) of exchangeable Mg. The interaction between regions and farms was also significant for exchangeable Mg concentration and stock. The averages for the UT region were 142 mg/kg and 283 kg/ha, and for the LT region 122 mg/kg and 229 kg/ha (Figure 5.8).

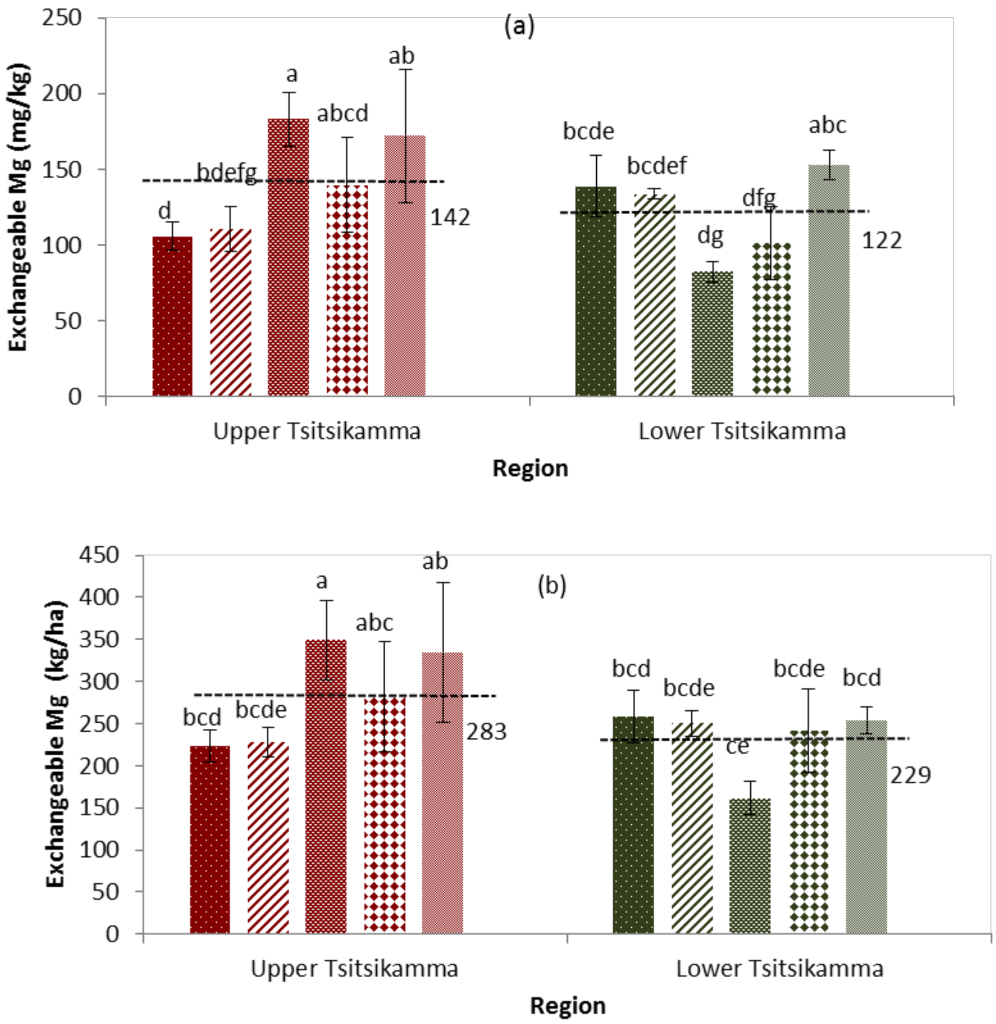


Figure 5.8 The effect of management practices on exchangeable Mg to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average exchangeable Mg concentration, and (b) is the average exchangeable Mg stock.

5.3.5 Exchangeable Na

Average exchangeable Na within soil layers

Significant differences were found between the UT and LT regions concerning exchangeable Na concentration ($F_{1,207}$ = 12.79) but not stock ($F_{1,207}$ = 3.62). However there were significant differences between soil layers for exchangeable Na concentration ($F_{3,207}$ = 282) and stock ($F_{3,207}$ = 18.82). All interactions were significant, except for exchangeable Na stocks in either the regions and farms combinations or the regions, farms and soil layers combinations.

As illustrated by Figure 5.9, the LT region had higher concentrations and stocks of exchangeable Na through depth compared to the UT region. The LT region had averages of 73.0 mg/kg and 112 kg/ha, whereas the UT region had averages of 59.3 mg/kg and 103 kg/ha, respectively. Interestingly, the 30-60 cm soil layers appeared to be uniform in both regions, with the highest exchangeable Na values again in the top soil layer.

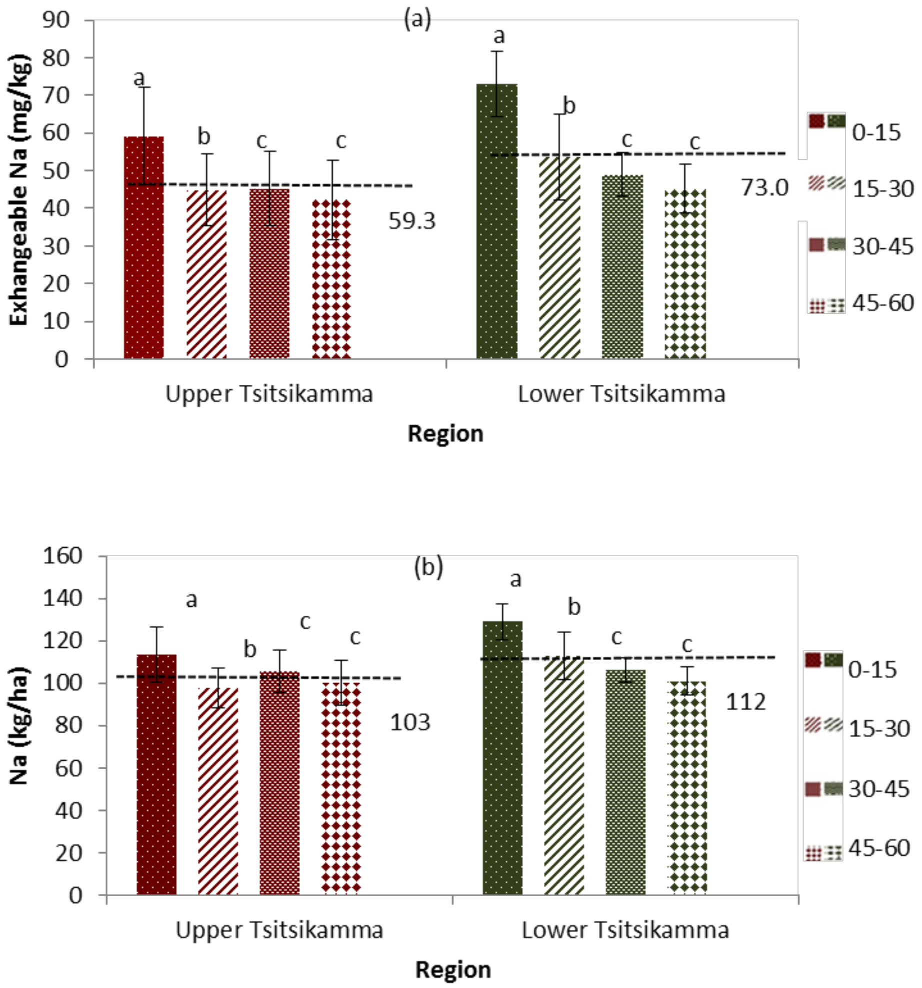


Figure 5.9 The effect of management practices on exchangeable Na within soil layers comparing the upper and lower Tsitsikamma regions within farms, where (a) is the average exchangeable Na concentration, and (b) is the average exchangeable Na stock.

Average exchangeable Na within farms

Significant differences were found for exchangeable Na between the UT and LT regions for both concentration ($F_{1,52}$ = 47.73) and stock ($F_{1,52}$ = 23.5) values. The farms in each region differed significantly with regards to concentration ($F_{4, 52}$ = 27.9) and stock ($F_{4, 52}$ = 8.34) of exchangeable Na. No significant interactions were found for either exchangeable Na concentration or stock. The average concentration and stock of exchangeable Na was respectively 52.1 mg/kg and 105 kg/ha in the UT region, and 64.0 mg/kg and 121 kg/ha in the LT region (Figure 5.10).

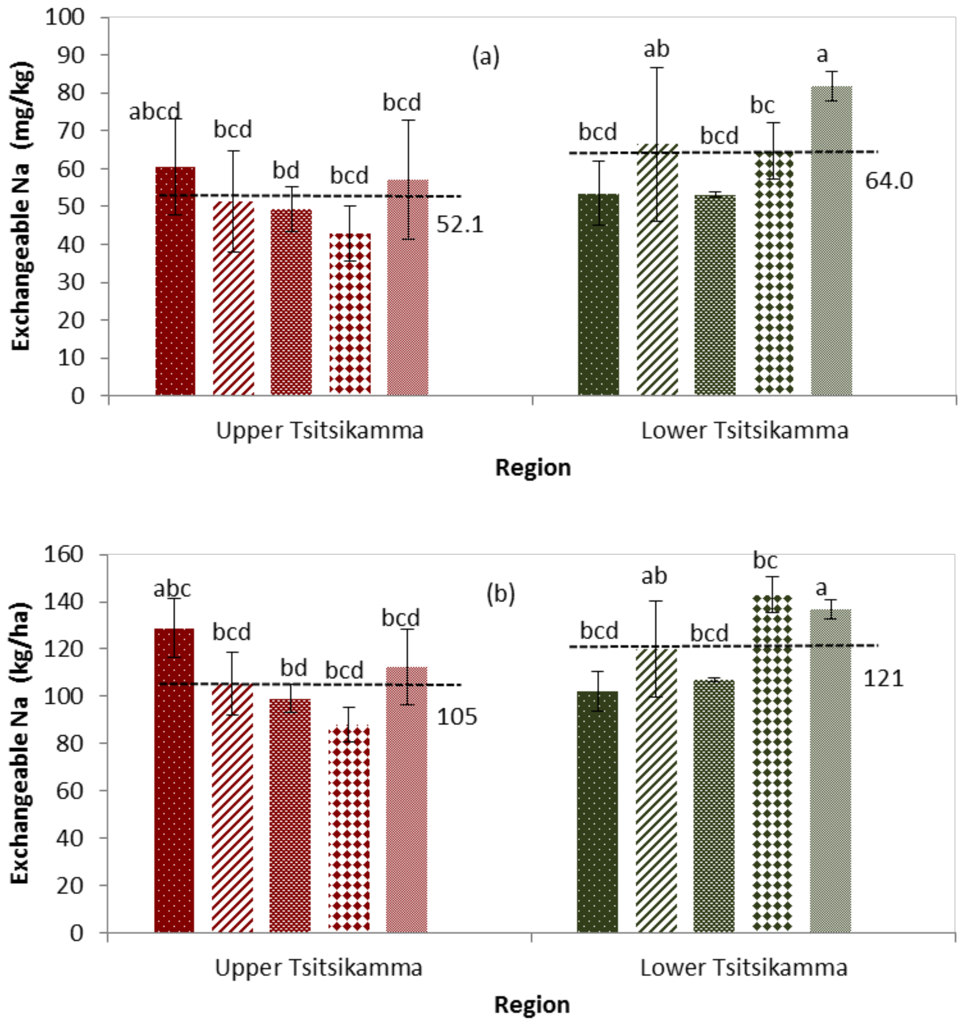


Figure 5.10 The effect of management practices on exchangeable Na to 30 cm depth between the upper and lower Tsitsikamma regions, where (a) is the average exchangeable Na concentration, and (b) is the average exchangeable Na stock.

5.3.6 Soil pH (KCl)

Average soil pH (KCl) within soil layers

The soil pH (KCl) differed significantly between the UT and LT regions ($F_{1,207}$ = 76.23), and also between soil layers ($F_{3,207}$ = 13.78). The different interactions were also significant. As illustrated by Figure 5.11, the LT region had slightly higher soil pH (KCl) values (5.24 vs 4.80) compared to the UT region, with the 0-15 cm soil layer having the highest pH values which gradually declined with depth.

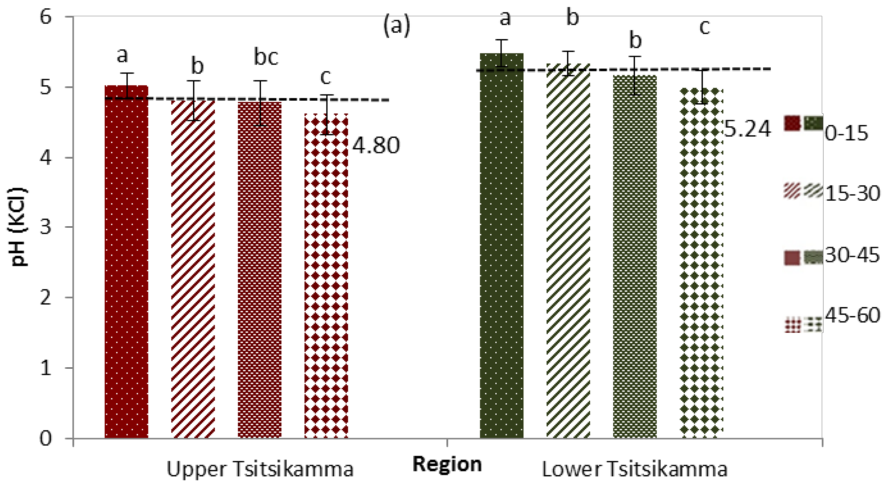


Figure 5.11 The effect of management practices on soil pH (KCl) within soil layers comparing the upper and lower Tsitsikamma regions within farms.

Average soil pH (KCl) within farms

When the pH (KCl) values of the 0-30 cm soil depth were compared in the UT and LT regions, significant differences were found ($F_{1,52}$ = 39.1). There were also significant differences in pH (KCl) observed between farms ($F_{4,52}$ = 11.1). Thus as could be expected, the interaction between regions and farms was significant. The average pH (KCl) value for the LT region was 5.42 and in the UT region it was 4.93 (Figure 5.12).

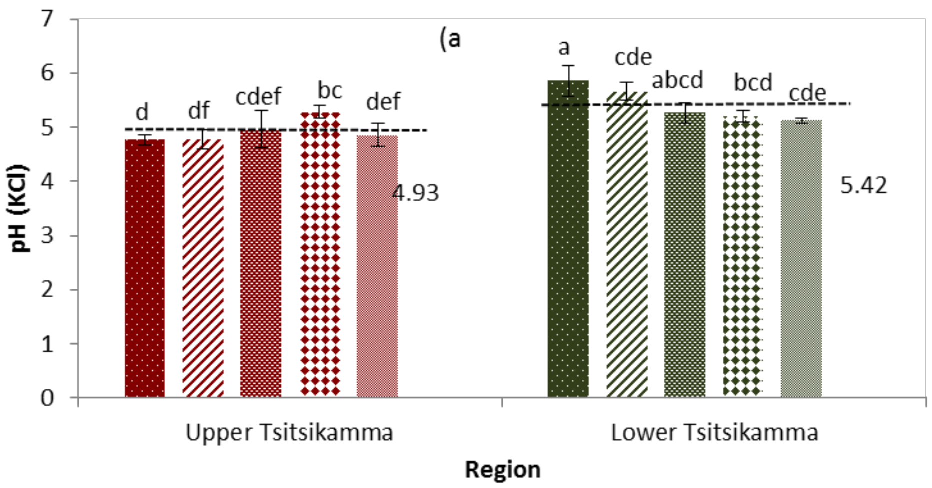


Figure 5.12 The effect of management practices on soil pH (KCl) to 30 cm depth between the upper and lower Tsitsikamma regions.

5.4 Discussion and conclusion

The farms in the Tsitsikamma region had a low soil fertility status because of the poor SOM content in the majority of the farms investigated. This, in association with the sandy nature of these soils aggravates the situation. Sandy soils generally have poor nutrient and water holding capacity (Bruand *et al.,* 2005). The UT region farms had lower extractable P as compared to LT region farms except for farm 4 in the UT region. This is because the farm applied chicken litter and furthermore, it had applied more inorganic P fertiliser than other farms in this region. The majority of the farms in the LT region (Farms 1, 2 and 5) used chicken litter, and thus were more comparable to farm 4 in the UT region. Although farms 1, 2 and 5 in the LT region still applied chemical fertiliser forms of P, their application rates were much lower on average than for the farms in the UT region.

In a study conducted by Chen (2006) it was established that soils that had been pre-treated with compost and organic fertiliser had more extractable P retained in the soil (131 mg/kg), compared to chemical fertiliser treated soils which only retained 34 mg/kg P in soil. It was also found that a combination of compost plus urea retained a similar P amount (40 mg/kg) as chemical fertiliser treated soils.

Additional research has suggested that chicken litter has a more stable form of P and K (Espinoza *et al.,* 2007) and is therefore more effectively used by the plant. Since the forms of nutrients in chicken litter are organic, they are not susceptible to losses through the soil profile as opposed to inorganic fertilisers (Tzen and Chen, 2004). Interesting to note is that, the farms in the LT region applied less P (40 kg/ha) on average in the form of organic and chemical fertiliser P, with one farm even applying as little as 13 kg/ha, than the farms in the UT region (67 kg/ha), which applied only chemical fertiliser P. This evidence clearly shows that organic sources combined with minimal inorganic fertiliser application were a more viable choice than excessive amounts of inorganic fertiliser alone to ultimately contribute in building the soil P reserves.

The LT region also had a higher average SOM content (see Chapter 4) which is composed of organic P found in microbial tissues and plant residues (Dahal, 1977). Residual P is released into available forms in the soil through phosphatase activity, and the process is accelerated when there are high amounts of OM in the soil (Oehl *et al.,* 2002; Nannipieri *et al.,* 2011;

Luo *et al.,* 2014). Therefore high OM contents coupled with the use of compost, which improves soil microbial activity and diversity (Farrell *el at.,* 2014; Luo *et al.,* 2014) may have had an impact on the accumulation of P in LT region soils.

In terms of exchangeable K, the UT region had more K in the upper 30 cm soil layers than the LT region. This variation can be attributed to the fact that more K was imported in the UT region, averaging to 178 kg/ha in contrast to 85 kg/ha that was applied in the LT region during the sampling year. It is however to be noted that farms 1, 2 and 5 in the LT region have a similar K content to the farms in the UT region, with farms 3 and 4 contributing significantly to the lower average of K measured in the area. This is because the farms had a poor SOM content and therefore had poor K retention. They were also the only two farms that did not apply organic fertiliser sources and cattle manure effluent into the pastures, as opposed to farms 1, 2 and 5 in the LT region. It is also to be noted that the majority of K applied on farms 1, 2 and 5 in the LT region is from manure effluent and chicken litter, of which both organic sources have been found to have an impact on macronutrient levels in soils (Culley *et al.,* 1981; Chang *et al.,* 1991; Matsi *et al.,* 2003; Lithourgidis *et al.,* 2007). Qian *et al.* (2005) reported that after 5-7 years of repeated applications of cattle manure into soils planted with cereal crops, extractable K levels were significantly increased. It has been cited in various studies that K is a very mobile cation in soil i.e. can be easily leached, and therefore it is important that land managers improve their SOM content in order to improve K retention (Cooperband, 2002; Bot and Benites, 2005).

Measurements of exchangeable Ca in the Tsitsikamma region were generally low due to low soil pH in association with the sandy nature of the soils in the region. Even so, with the build-up of SOM, Ca retention in the soil can be improved (Anderson *et al.,* 2013). The LT region was observed to have higher Ca levels that the UT region. The LT region also had a higher pH than the UT region, a soil property that is greatly influenced by Ca levels in the soil (Whiting *et al.,* 2015). Both regions had applied very little amounts of lime in the year prior and during the sampling year. The average of imported Ca in the UT region was only 93 kg/ha, whereas a slightly higher import was recorded in the LT region (313 kg/ha). These applications would have very minimal impact in improving soil pH and Ca levels. The most effective way of improving these Ca levels and pH would be through SOM build-up and liming (Ristow *et al.,* 2010). In most reviews, an amount of 2 tons/ha of lime has been found to be more effective in improving soil Ca levels and consequently pH (Ristow *et al.,* 2010; Anderson *et al.,* 2013).

The LT region had lower exchangeable Mg levels as compared to the UT region, however similar to Ca there were very little imports of Mg in both regions during the sampling year. It is rarely the case that farmers in the Tsitsikamma region apply Mg fertilisers, usually the nutrient is returned to the soil through cow manure and urine as well as through feed fed in the pasture paddocks. Most farmers in the region neglect to apply this nutrient, due to its impact on soil compaction which greatly influences soil fertility and water movement in the soil (Astera 2014).

Levels of exchangeable Na in the soil were found to be higher in the LT region farms than in the UT region farms. Since Na has not been reported to be an essential element for plant growth, there were no additions through fertiliser of this nutrient on the farms. It can be assumed that most of the Na found in the soil was from feed fed to the cattle as well as cow manure and urine. It has also been hypothesised that agricultural lands that are near coastal areas are prone to salt deposition through aeolian influx. The salt, sodium chloride (NaCl) is transported by wind from the sea to the land through the spray of the wave foam that results from the wave uprush on the beach (Metternicht and Zinck, 2008). All of the farms investigated in this study were situated near the coast and could have been affected by aeolian influx of salt.

From this investigation it is clear that soil fertility can be maintained and improved if the correct soil management practices are put into place. These management practices must encourage build-up of SOM and improve soil microbial composition, which helps in releasing essential nutrients to the soil. It is also important to have soil analyses done more frequently in order to avoid over or under application of soil nutrients, as required by the plants. An excessive application of nutrients does not necessarily guarantee that the nutrients will be stored in the soils, especially in sandy soils that are low in SOM. Instead, land managers need to rely on the soil to be able to naturally supply nutrients and use external sources of fertiliser, only to supplement what the soil could not provide.

CHAPTER 6

IMPORTANT SOIL QUALITY INDICATORS IN MIXED PASTURES OF THE TSITSIKAMMA REGION

6.1 Introduction

Soil quality is the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al.,* 1997). Soil quality cannot be measured directly however; soil quality indicators can be measured that are characteristics of the soil's biological, chemical and physical properties. The types of indicators that are the most useful depend on the function of soil for which soil quality is being evaluated. In recent years, SOM indicators have been found to serve as good soil quality indicators (Wander *et al.,* 1994).

This is due to the association of SOM with improved infiltration rates, nutrient and water holding capacity, soil aggregation as well as nutrient cycling (Woomer and Swift, 1994).

Although it is unanimous that soil quality indicators must integrate soil chemical, physical and biological properties; there are varying findings and views as to which indicators are of importance. For instance, Swanepoel *et al.* (2014) found that extractable P, gravel content, water holding capacity, exchangeable acidity, SOM, penetration resistance and exchangeable Mn were the most sensitive indicators in ryegrass-kikuyu pastures. Gugino *et al.* (2009), reported that important indicators include soil texture, available water capacity, surface and subsurface hardiness, wet aggregate stability, SOM, soil protein index, soil respiration, active C and standard nutrient analysis. In this study, the following soil quality indicators were measured: total C, active C, C/N ratio, PMN rate, inorganic N, extractable P, exchangeable cations (K, Ca, Mg, and Na), pH (KCl) and bulk density (BD). These indicators were selected because of the ease and reliability of measurement, the sensitivity of the measurement to changes in soil management as well as the skills essential for interpreting of the result.

Managing and understanding soil quality means evaluating and managing soil so that it functions optimally now, and in the future. Land managers should be monitoring changes in soil quality on a regular basis, and using this to adopt sustainable practices, which aim to improve the productivity of soil (Doran and Zeiss, 2000). Soil management practices such as tillage, irrigation, fertilisation and pesticide application all play a significant role in altering the soil's quality. For instance, tillage operations like ripping and ploughing can cause direct damage to the soil organisms. Soil structure and biology is the most affected by these practices and the effect on them has many more knock-on effects on other soil properties. On the other hand, controlled irrigation practices can have a positive impact on soil quality, due to better efficient regulation of water entering the soil. Effective irrigation alleviates the soil water regime and reduces the disturbance effect of soil drying and thus increases the length of time during which microorganisms are active in the soil.

The dairy farmers in the Tsitsikamma region naturally recognize the importance of good soil management because it produces for them the cheapest source of feed for their dairy herds. In the past, dairy farmers relied on the excessive application of nutrients, and physically working the soils as means to get the required yield. These practices have changed in other parts of the world due to evidence (e.g. Doran and Zeiss, 2000; Swanepoel *et al.,* 2014) arising of declining soil fertility resulting from such practices, as well as changes in the global economy and markets which had a negative influence on fertilizer prices and hence feed. The negative impact of soil disturbance and oversupply of nutrients have been extensively researched and reported by Doran and Parkin (1994); Stafanic and Gheorghita (2006) as well as Swanepoel *et al.* (2014). These practices are relevant because in the study area, they are still seen as norms for improving soil productivity.

Soil quality relates to the long-term success of the broader agricultural industry, thus it is important that researchers simplify the methods as much as possible in order to have a meaningful impact to the farmer. It is also important to note that, although each farm is managed in isolation, it still is part of a greater ecosystem; therefore, specific soil quality indicators, and their norms, should be identified specifically for each cropping system. These indicators should communicate relevant information quickly and easily to land managers who are not necessarily experts in soil science (Jesinghaus, 1999). Farmers also need to understand that, monitoring soil quality relates to the long-term success of the broader agricultural industry (Zimmer, 2004). A piece of land should not be managed in isolation, but rather as part of a greater ecosystem. The correct management practices can result in these indicators being improved for the benefit of both the farmer and the ecosystem.

6.2 Procedure

6.2.1 Rationale of data screening for analysis

The SPSS statistical programme was used to compute a principal component analysis (PCA) test and a two-tailed Pearson correlation between the soil quality indicators. All soil layers were initially analysed for correlations between the soil quality indicators for both regions and the correlation trend was similar in all soil layers and not significantly different ($p > 0.001$). Therefore, the 0-30 cm soil layer was selected as the representative layer to calculate both the PCA and Pearson correlations for the Tsitsikamma region. Averages for each farm were used to compute these analyses (see Table 6.1).

The Pearson correlation test was calculated between the UT and LT regions separately due to significant differences that were observed between farms (see Chapter 4 and 5). The PCA however, was conducted with pooled data of both the upper and lower Tsitsikamma. The reason for this was because the aim of the PCA was to find out which soil quality indicators influenced one another in the greater Tsitsikamma region and which ones could be associated with the differences observed within each region. It is to be noted that only concentration (% or mg/kg) data was used for analysis in this chapter. The stock data was analysed in the same manner but yielded similar results, hence the decision to use concentration measurements only.

Table 6.1 Summary of means and standard deviation used for the principal component analysis (N = 60)

Soil quality indicators	Mean	Std. Deviation
Total C (%)	1.46	0.28
Total N (%)	0.18	0.06
Active C (mg/kg)	423	129
Extractable P (mg/kg)	33.2	17.7
Exchangeable Ca (mg/kg)	431	233
Exchangeable K (mg/kg)	106	36.8
Exchangeable Mg (mg/kg)	140	37
pH (KCl)	5.113	0.382
BD (g/cm^3)	1.341	0.074

6.2.2 Data reduction procedure for Principal Component Analysis

Initially, the factorability of the 13 soil quality indicators was examined. Several well recognised criteria for the factorability of a correlation were used. Out of the 13 soil quality indicators, 4 of them were below the required 0.30 correlation matrix on the diagonals of the anti-image and were subsequently removed from the analysis. These were PMN rate, inorganic N, C/N ratio as well as exchangeable Na. The remaining 9 soil quality indicators were then analysed for factorability. Firstly, 7 of the 9 soil quality indicators correlated at least 0.40, with at least one other variable, suggesting reasonable factorability.

Secondly, the Kaiser-Meyer-Olkin measure of sampling adequacy was 0.618, above the recommended value of 0.6, and Bartlett's test of sphericity was significant (χ^2_{36}= 174, p value < 0.001). The diagonals of the anti-image correlation matrix were all over 0.5, supporting the inclusion of each item in the factor analysis. Finally, the communalities were all above 0.30 (see Table 6.2), further confirming that each variable shared some common variance with other soil quality indicators. Given these overall criteria, factor analysis was conducted with all 9 soil quality indicators.

Table 6.2 Communalities based on a principle components analysis for 9 soil quality indicators (N = 60)

	Communalities	
Soil quality indicators	**Initial**	**Extraction**
Total C	1	0.526
Total N	1	0.687
Active Carbon	1	0.423
Extractable P	1	0.422
Exchangeable Ca	1	0.722
Exchangeable Mg	1	0.554
Exchangeable K	1	0.321
pH (KCl)	1	0.716
BD (g/m^3)	1	0.611

After data reduction, the PCA procedure was used because the primary purpose was to identify and compute soil quality indicators that have an influence on each other and those that significantly influenced soil quality in the Tsitsikamma region. The initial eigen values showed that the first factor explained 32% of the variance, the second factor 22% of the variance, the third factor 13% of the variance, and the fourth factor 12% of the variance. The fifth, sixth, seventh, eighth and ninth factors had a combined eigen value of 33%, each factor explaining 7% on average, where the factor solutions were examined using both varimax and oblimin rotations of the factor loading matrix. The two factor solution, which explained 54% of the variance, was preferred because of the previous theoretical support, the 'leveling off' of eigen values on the scree plot after two factors, and the insufficient number of primary loadings and difficulty of interpreting the third factor and subsequent factors.

6.3 Results

6.3.1 PCA analysis in the Tsitsikamma region

A PCA analysis plotting farms according to their association between each other was drawn (see Figure 6.1). There were 3 rotated factors that clearly showed interaction with each other and these were grouped as low N fertiliser input and high soil C farms (LT1, LT2 and LT5); moderate N fertiliser input and low soil C (UT1, UT2, UT3 and UT5) and high N fertiliser input and low soil C farms (LT3, LT4 and LT 5). It was intriguing to see an association between LT1, LT2 and LT5 as these were the farms that were identified to have good SOM indicators in Chapter 4. It was also interesting to see that farms that had similar soil management practices were associated to each other, meaning that the soils develop in the same manner under similar management practices. According to PCA, it is apparent that the results clearly separate the two regions of the Tsitsikamma.

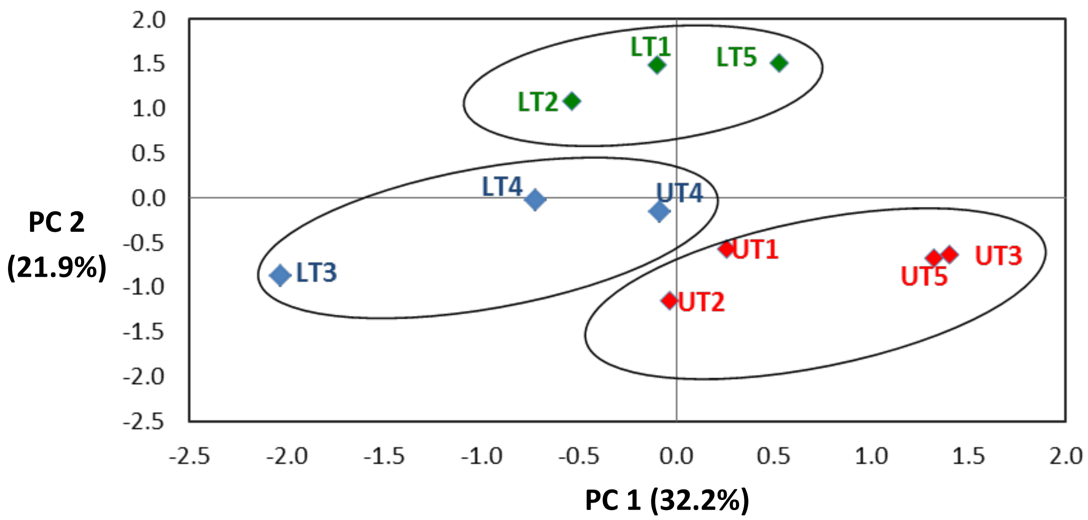


Figure 6.1 PCA factor analysis dividing the Tsitsikamma region farms into three groups. Group one indicated in green are the low N fertiliser input and high C farms, group two indicated in red are moderate N fertiliser input and low C farms and group three indicated in blue are high N fertiliser input and low C farms.

The 9 selected soil quality indicators were also drawn in a PCA analysis as illustrated in Figure 6.2. The PCA revealed 3 rotated factors that can be associated with one another and those that can be associated with the differences observed in the Tsitsikamma region. These were identified as soil chemical indicators (pH, P, Ca), soil health indicators (total C, total N, active C, K, Mg) and soil physical indicators (bulk density). These factors were found to be responsible for

54% of the variances observed in the Tsitsikamma region. It is interesting to see K and Mg being the only soil fertility indicators that could be closely associated with total C, total N and active C. Exchangeable Ca, P and pH (KCl) had a close association as would be expected. Total N and Mg had the highest positive loadings (0.818 and 0.734) on PC 1 whereas PC 2 showed pH and Ca as the indicators with the highest positive loadings (0.806 and 0.759), respectively. The higher the loading, the more important that variable is in explaining variation found within the region.

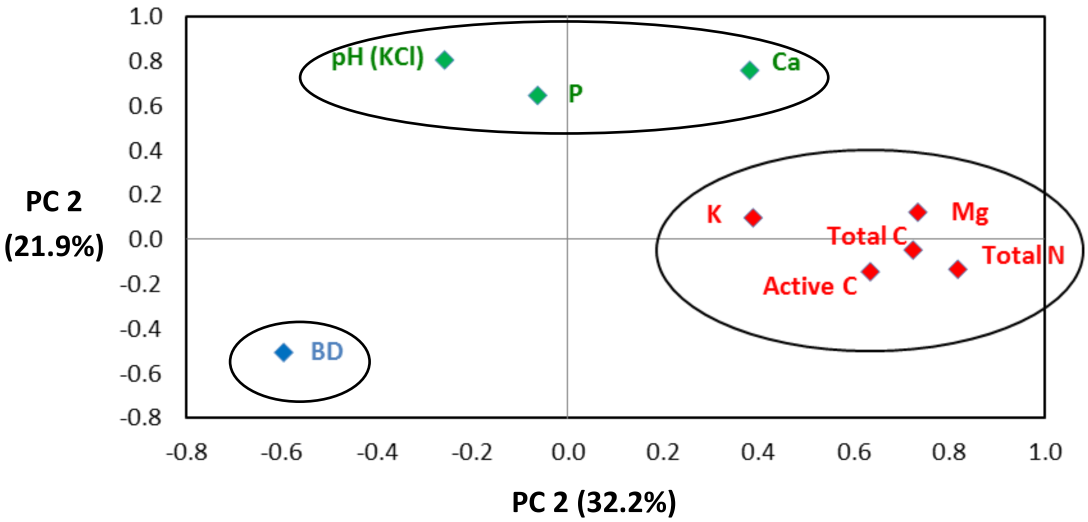


Figure 6.2 PCA factor analysis dividing soil quality indicators into three classes. Class one indicated in green represents soil chemical indicators, class two indicated in red represents soil health indicators, and class three indicated in blue represents soil physical indicators.

6.3.2 Correlations between measured soil quality indicators in the upper Tsitsikamma region

Two-tailed Pearson correlational analysis was used to examine the relationship between soil quality indicators in the UT region. Based on the results of the study reported in Table 6.3, all soil quality indicators correlated to at least one variable, except for PMN rate which did not correlate with any variable at both 1% and 5% significant levels. The measured pH (KCl) and P were both strongly correlated with each other ($r = 0.46$; $p < 0.01$). Na on the other hand had a strong correlation with BD ($r = 0.36$; $p < 0.05$) whereas BD correlated strongly with Mg ($r = 0.52$; $p < 0.01$). K had a strong correlation with P ($r = 0.42$; $p < 0.01$). Interestingly, results indicated an inverse strong correlation between Ca and C/N ($r = -0.70$; $p < 0.01$), on the other hand, C/N also indicated an inverse correlation with total N ($r = -0.87$; $p < 0.01$). Total C correlated strongly with BD ($r = -0.52$; $p < 0.01$) and active C strongly correlated with total C ($r = 0.44$; $p < 0.01$).

Table 6.3 Correlation analysis at 30 cm soil layer between soil quality indicators measured in the UT region. All significant correlations are indicated in bold

Soil quality indicators	pH (KCl)	P	Na	K	Ca	Mg	Total C	Total N	BD	Active C	PMN rate	C/N
pH (KCl)	1	**0.46****	**-0.33***	0.26	**0.40****	0.14	**-0.43****	-0.22	-0.20	**-0.39***	0.11	-0.05
P	**0.46****	1	-0.27	**0.42****	0.16	-0.06	**-0.33***	-0.23	-0.03	-0.11	-0.13	0.02
Na	**-0.33***	-0.27	1	-0.13	-0.13	0.17	0.09	0.08	**0.36***	0.05	-0.09	0.01
K	0.26	**0.42****	-0.13	1	**0.36***	**0.32***	-0.24	0	-0.17	0.09	-0.16	-0.13
Ca	**0.40****	0.16	-0.13	**0.36***	1	**0.54****	0.01	**0.58****	**-0.51****	-0.14	0.21	**-0.70****
Mg	0.14	-0.06	0.17	**0.32***	**0.54****	1	0.17	**0.49****	**0.52****	-0.06	0.02	**-0.48****
Total C	**-0.43****	**-0.33***	0.09	-0.24	0.01	0.17	1	**0.45****	**-0.52****	**0.44****	0.06	-0.01
Total N	-0.22	-0.23	0.08	0	**0.58****	**0.49****	**0.45****	1	**-0.51****	0.07	0.09	**-0.87****
BD	-0.20	-0.03	**0.36***	-0.17	**-0.51****	**0.52****	**-0.52****	**-0.51****	1	0.14	-0.03	**0.52****
Active C	**-0.39***	-0.11	0.05	0.09	-0.14	-0.06	**0.44****	0.07	0.14	1	-0.16	0.20
PMN rate	0.11	-0.13	-0.09	-0.16	0.21	0.02	0.06	0.09	-0.03	-0.16	1	-0.11
C/N	-0.05	0.02	0.01	-0.13	**-0.70****	**-0.48****	-0.01	**-0.87****	**-0.52****	0.20	-0.11	1

** Correlation is significant at the 0.01 level (two-tailed)

* Correlation is significant at the 0.05 level (two-tailed)

6.3.3 Correlations between measured soil quality indicators in the lower Tsitsikamma region

Soil quality indicators were analysed using two-tailed Pearson correlation analysis in the LT region. Similarly to UT region correlations, all indicators correlated to at least one variable, except for PMN rate which did not correlate to any variable. The results of the correlations are shown in Table 6.4. In contrast to the UT region correlations, measured pH (KCl) and Na both strongly correlated to each other ($r = -0.59$; $p < 0.05$). Also pH (KCl) only correlated with Na in the LT region, whereas in the UT region it had correlated with P, total C, Ca, active C as well as Na.

Extractable P which had strongly correlated with pH in the UT region showed a strong correlation with total C in the LT region ($r = 0.53$; $p < 0.05$). Similarly to the UT region, total C correlated inversely strong with BD (r -0.74; $p < 0.01$). Total C also showed a very strong positive correlation with active C ($r = 0.70$; $p < 0.01$).

In the LT region, K correlated more with Mg ($r = 0.65$; $p < 0.01$), as opposed to the high P correlation that was observed in the UT region. Exchangeable Mg and Ca correlated highly with each other ($r = .946$; $p < 0.01$). It is interesting to note that both variables also correlated very highly to active C; $r = 0.81$ and 0.70 for Mg and Ca, respectively with $p < 0.01$ in both cases. Total N correlated highly negative with BD ($r = -0.79$; $p < 0.01$), and also with active C a strong correlation was noted ($r = 0.70$; $p < 0.01$). Active C had its highest correlation with Mg ($r = 0.81$; $p < 0.05$) as well as total C and total N. The C/N ratio only had a correlation with total C ($r = 0.50$; $p < 0.05$).

Table 6.4 Correlation analysis at 30 cm soil layer between soil quality indicators measured in the LT region. All significant correlations are shown in bold

Soil quality indicators	pH (KCl)	P	Na	K	Ca	Mg	Total C	Total N	BD	Active C	PMN rate	C/N
pH (KCl)	1	-0.22	**-0.59***	0.16	0.12	0.13	0.08	0.13	0.18	0.25	0.32	-0.06
P	-0.22	1	**0.48***	**0.53***	0.36	**0.48***	**0.53***	0.34	**-0.51***	**0.47***	-0.42	0.20
Na	**-0.59***	**0.48***	1	0.24	**0.49***	**0.48***	0.15	0.33	-0.45	0.20	-0.42	-0.21
K	0.16	**0.53***	0.24	1	**0.60****	**0.65****	0.44	0.02	-0.23	0.46	-0.24	0.43
Ca	0.12	0.36	**0.49***	**0.60****	1	**0.95****	0.40	**0.52***	**-0.51***	**0.70****	-0.14	-0.19
Mg	0.13	**0.48***	**0.48***	**0.65****	**0.95****	1	**0.64****	**0.57***	**-0.62****	**0.81****	-0.12	0.01
Total C	0.08	**0.53***	0.15	0.44	0.40	**0.64****	1	**0.54***	**-0.74****	**0.70****	-0.06	**0.50***
Total N	0.13	0.34	0.33	0.02	**0.52***	**0.57***	**0.54***	1	**-0.79****	**0.75****	-0.08	-0.42
BD	0.18	**-0.51***	-0.45	-0.23	**-0.51***	**-0.62****	**-0.74****	**-0.79****	1	**-0.69****	0.20	0.02
Active C	0.25	**0.47***	0.20	0.46	**0.70****	**0.81****	**0.70****	**0.75****	**-0.69****	1	0.07	-0.03
PMN rate	0.32	-0.42	-0.42	-0.24	-0.14	-0.12	-0.06	-0.08	0.20	0.07	1	0.01
C/N	-0.06	0.20	-0.21	0.43	-0.19	0.01	**0.50***	-0.42	0.02	-0.03	0.01	1

** Correlation is significant at the 0.01 level (two-tailed)

* Correlation is significant at the 0.05 level (two-tailed)

6.4 Discussion and conclusion

The PCA that was drawn for comparing farms confirmed that the two regions have varying management practices. Farms LT1, LT2 and LT5 were found to have similarities because they were grouped in the same category by the PCA. It was expected that these farms would associate with each other as they had similar approaches of soil management (see Chapter 3, Table 3.1 and 3.2). This evidence corroborates that irrespective of soil type, management practices that encourage SOM increase will yield better soil quality. The remaining farms of the LT region (LT3 and LT4) were grouped amongst farms of the UT region, which were high N input and low soil C farms. These two farms in LT region were managed in a similar manner with some of the farms in the UT region. This means that good quality soil is not necessarily region specific but rather is built through good soil management. In other words, SOM build-up and its advantages will benefit a farm no matter where it is located in the Tsitsikamma. The discussion below elaborates on which indicators were found to be the most responsible for the variation observed in the Tsitsikamma region.

The results of the PCA between soil quality indicators showed that total N, pH, exchangeable Ca and Mg played a very significant role in the variation observed in the Tsitsikamma region. It can for that reason be assumed that any management practice that alters the above mentioned indicators will have a significant impact on soil quality. In Chapter 3 and 4, it was indicated that although the LT region had a lower total N accumulation compared to the UT region, the soils in the LT region generally had build-up more SOM and have more acceptable C/N ratios. This is important to acknowledge because the LT region on average had applied 275 kg N/ha in the sampling year, compared to an average of 474 kg/ha applied in the UT region, with one farm applying as much as 870 kg N/ha per year. Contradictory to the UT region, most of the N that was applied in the LT region was in an organic fertiliser form. The majority of the total N accumulated in the Tsitsikamma region is from cow dung, urine N (returned to soil during grazing) and from fertilisers.

Since lower total N amounts in the soil and low N applications were found to be an advantage for the LT region, it should be noted that excessive N application amounts do not always equal better soil quality. Excessive application of N in the soil can result in ground water and surface water contamination. N is converted into nitrate and ammonium forms in soil by soil organisms and it is the nitrate form of N that possesses possible danger to water sources. Nitrate-N is very unstable in the soil and therefore prone to leaching. High levels of nitrates and P in water promote excessive growth of algae. When algae dies and decomposes, it releases high levels of SOM enhancing the amount of decomposing organisms. The result of that is high demand for oxygen which when depleted results in the death of other aquatic organisms such as fish. This process is referred to as eutrophication.

Both Tsitsikamma regions had not applied any lime during the sampling year, however, the LT region had a better nutrient retention capacity due to more total C that was measured, resulting in much higher exchangeable Ca to be retained in the soil. This would have a direct impact on soil pH since pH has been cited to be largely influenced by cation concentration, more specifically exchangeable Ca (Whittinghill and Hobbie, 2012). Lake (2000), found that soils with more exchangeable Ca in the exchange sites generally had higher pH measurements. The same was found in the Tsitsikamma region (see Chapter 5).

The role of total C in the soil has also been established in numerous publications including Weil *et al.* (2003), who recognised the active C fraction as the fraction that needs to be carefully monitored. This has been supported by Gugino *et al.* (2009) on their publication where they cite active C fraction as the most sensitive SOM indicator to management and easiness to measure. Other soil quality indicators that have been mentioned by Gugino *et al.* (2009), which were measured in this study, are PMN rate and inorganic N concentration, however they did not meet the requirements of the PCA conducted and were subsequently removed from the analysis.

Exchangeable K, another soil quality indicator which had been highlighted by the PCA analysis plays a significant role in pasture production and is one of the nutrients that is severely deficient in soils of the Tsitsikamma region. Imas and John (2013) reported that, a deficiency of exchangeable K may have serious repercussions on yield and quality. When exchangeable K is deficient it causes loss of turgor pressure in the leaves and results in closing of the stomata and a reduction in the rate of transpiration and CO_2 assimilation (Humbert, 1968). The result of this is plant wilting and can lead to serious yield reductions. Based on this, it is evident why exchangeable K had been identified to be one of the important indicators that had an influence on soil quality in the Tsitsikamma region.

Extractable P and BD are other indicators that were found to have an impact on the differences observed in the Tsitsikamma region. Although the LT region had applied less P than the UT region (14 vs 26 kg P/ha on average), the LT region still had higher P measurements than the UT region. The form of P applied in the LT region was mostly from chicken litter, whereas the UT region applied mostly mono ammonium phosphate (MAP) fertiliser which is less stable in the soil compared to P from chicken litter. This evidence again reiterates the benefit of organic fertilisers, which are widely used in the LT region.

These findings confirm that land managers do not only need to focus on replenishing or managing N in the soil, but also need to pay careful attention to total C, pH, extractable P, exchangeable K, Ca, Mg, and BD in order to improve soil quality. This also confirms that the soil is a very complex system of which its functioning cannot be concluded by solely focusing on one soil property. Researchers and advisors have to view soil as a dynamic system and make recommendations based on the integrated depiction of all soil properties.

According to the correlation analysis, the soil quality indicators that were measured were all interconnected to each other; therefore monitoring their trends in the soil is essential to establishing a soil's potential in the Tsitsikamma region. It is clear based on the correlations that the two regions of the Tsitsikamma had very different management practices. This was supported by the fact that the two regions exhibited different outcomes on the correlations between the soil quality indicators. The UT region had fewer significant correlations than the LT region. Soil quality indicators like total C, total N, and active C, C/N ratio, pH, extractable P, exchangeable K, Ca, Mg and BD had significant impacts on other nutrients in the soil. Although some of the indicators that are listed above were not included in the PCA, they still play an important role in nutrient interaction processes.

In the UT region, exchangeable Ca and BD had the highest number of correlations, indicating that these two indicators primarily impacted most soil quality indicators in the region. Exchangeable Ca also showed a high negative correlation with the C/N ratio. No evidence was found in literature as to why this is the case in the UT region. On the other hand, BD correlated inversely in all correlations except for exchangeable Mg and Na, which was also its highest correlation. Clancy (2009) reported that Na causes the soil to lose favourable structural properties, resulting in impaired drainage and increased compaction. Myers *et al.* (1988) also found that soil high in Mg may exhibit tendencies of surface or subsurface compaction, or poor internal drainage. These findings might justify the positive correlation found between BD, exchangeable Mg and Na.

The high inverse correlation between total N and C/N ration again reiterates why excessive application and accumulation of N in the soil can have a negative impact on soil microbial activity. Too low C/N ratios may induce rapid mineralisation rates, which would result in rapid depletion of SOM reserves especially if there is no steady supply of C in the soil. The negative correlation that was found between total C and BD confirmed that farmers need to build soil C in order to minimise the impact of soil compaction. BD is one of the indicators that is usually used to determine soil compaction (Page-Dumroesetotal *et al.,* 1999). The correlations in the LT region were somewhat different to the UT region. In the following order, these indicators had the highest correlations: Exchangeable Mg > total C > active C > exchangeable Ca > BD > total N. Similarly to the UT region, BD and exchangeable Mg showed a positive correlation with each other, while BD and total C as well as active C indicated an inverse strong correlation. The most interesting correlations were between active C, total N, exchangeable Ca and Mg. Active C is the C fraction that is readily available as an energy source for the microorganisms (Weil *et al.,* 2003). It plays a key role in SOM decomposition and build-up, as well as processes related to nutrient cycling in the soil. Increased active C levels therefore indicate rapid C mineralisation which results in the release of plant nutrients. Based on the correlations in the LT region, an increase in active C will increase the quantity of total N, exchangeable Ca and Mg in the soil.

It is interesting that no correlation was found between total N and C/N ration in the LT region, in contrast to the UT region. This means that there was no significant interaction between these indicators in the region. It is also interesting that a positive correlation was found between total C and C/N ration, an observation that was not found in the UT region. Based on the findings from the correlations, it can be assumed that the UT region was more chemical dependent than the LT region according to the correlations that were found. The stronger correlations and more correlations with SOM indicators evident in the LT region supported these findings.

It is evident from correlations studied that the farmers in the Tsitsikamma region need to invest in building SOM as it had an overall impact on soil quality. Managing soil quality is vital for optimum production in dairy pastures. The whole system of dairy farming relies heavily on energy provided by pasture and feed brought on to the farm. The farmer needs to utilise energy in the pastures as efficiently as possible before resorting to supplements to make up for energy shortage. The best way to improve pasture growth is through good management of soil and pasture. Efficient soil management can be achieved if relevant soil quality indicators are measured, monitored and replaced only when necessary in adequate quantities. That system, along with other efficient holistic farm management systems will put the farmer in the right path towards sustainable farming.

CHAPTER 7

SUMMARY, RECOMMENDATIONS AND CONCLUSION

7.1 Summary

The overriding purpose of this study was to determine the quality of the soils in the Tsitsikamma region. The study also sought to assess soil quality variations within the upper and lower Tsitsikamma regions, soil layers as well as within farms. The soil layer comparison was done at increments of 0-15, 15-30, 30-45 and 45-60 cm respectively, while farm comparisons were done at a 0-30 cm increment. The study also explored whether soil management practices had any influence on soil organic matter and chemical indicators. The eventuality was then to recognise which soil quality indicators were responsible for the differences observed in the region and whether similar correlations between indicators would be observed between the two regions. Because of the complexity of soils and their management thereof, in order to accomplish these goals, it became necessary to choose farms that reached some prerequisite standards. These standards were:

- farms must have kikuyu, ryegrass and clover pasture mixtures;
- they must be irrigated;
- adopted minimum or no tillage practices;
- established the pasture mixtures in at least 6 years and lastly;
- have records of accurate fertiliser application rates.

It is well understood that soil quality is not a new concept; in fact, in the past 20 years a lot of indicators of soil quality have been established and implemented in different farming systems. There is however a huge gap between research and industry mostly caused by the fact that farmers struggle to relate to current soil quality indicators because of two main reasons; (1) the indicators are too expensive to analyse and (2) they are also difficult to understand and influence over the short term.

Therefore, soil quality indicators that are less complex, cost effective and have swift response to management are necessary in the field, as these would assist the producer to better understand the principles of soil quality management.

7.2 Empirical findings

The main empirical findings are presented chapter specific and these chapters are:

- Influence of soil organic matter (SOM) indicators on soil quality in the Tsitsikamma;
- Influence of soil chemical indicators on soil quality in the Tsitsikamma; as well as
- Important soil quality indicators in mixed pastures of the Tsitsikamma region.

This section will produce the observed results to answer the study's three main questions which were:

1. *Do the farms in the Tsitsikamma differ significantly within depth?*

The findings regarding nutrient movement showed a significant decline in nutrients through depth, more especially between the 0-15 and 15-30 cm increments. These findings are broadly in line with results observed by Jobbagy *et al.* (2001) where he found that nutrients that most often limit plant growth (e.g. P and K) have shallower distributions through the soil profile. Many studies reveal that the 15-20 cm soil layer is where most significant processes occur and the most effective layer for plant nutrition (Anderson *et al.,* 2010). In this study, it was however observed that the most significant differences occurred in the 0-30 cm layer and below that soil layer, no significant differences were found. These findings closely coincides with the observations of Stewart *et al*. (1990) who identified the 0-35 cm soil layer as the effective root zone for trees in Australia where a profile of 0-150 cm was studied.

2. *Are management practices responsible for variations observed in the Tsitsikamma region?*

In the study I found that soil management practices have a significant impact on overall soil quality indicators. These management practices are however limited to the ones that were considered in this study. The most important practices which have been found to correlate closely to soil quality were fertiliser application rates, type of fertiliser applied i.e. organic vs chemical fertiliser sources, herbicide applications as well as pasture management strategies. The SOM indicators were observed to respond more positively when strategies that enhance SOM build-up were implemented e.g. application of organic fertilisers, proper grazing management that is based on leaf stage, application of effluent manure back into pasture and less or no application of chemical herbicides and or pesticides.

This was more clearly illustrated in the PCA conducted which grouped the farms according to similar management practices and coincidentally, those farms that had a more biological approach fell in the same category. Incidentally, the farms that had been more chemical dependent fell into the same category.

Farmers generally rely more on chemical fertiliser as it is easier for them to directly associate these fertilisers with soil analysis results. Also because soil chemistry is easy to measure, understand and manage. In contrast, it is not easy to comprehend the concept or principles of soil biology as there are still a lot of gaps in this field and the measurements of the biology are not direct and rather give results that deduce the soil's biological activity. This combined with the fact that there is no quick-fix method for soil biology causes the farmer to be more inclined to rather focus on the soil chemistry. An interesting observation seen, showed that soils that had exhibited better SOM indicators, generally held more nutrients even though no heavy applications of those nutrients were done in the sampling year. These findings are consistent with previous research which positively associates increased SOM with improved nutrient holding capacity of soils (Funderburg, 2001; Hoyle, 2016). Farms that were observed to also have more concentration of nutrients in the soil, even with poor SOM indicators had applied those nutrients in chemical fertilisers during the sampling year. This therefore justified as to why those farms also had more nutrients in the soil.

3. *Which soil quality indicators play the most significant role in the variations observed?*

The study found in the following order that 54% of the variations observed in the Tsitsikamma region could be explained by the following indicators: total N, pH, exchangeable Ca, exchangeable Mg, total C, active C, exchangeable K and BD. These indicators play a critical role in pasture productivity and need careful management. Farmers in the Tsitsikamma region generally pay more attention to N application in their soils than any of those indicators identified by the PCA. These findings emphasised the need for farmers to not only focus on replenishing or managing N in the soil but also need to pay careful attention to pH, exchangeable Ca, exchangeable Mg, total C, exchangeable K, and BD in order to improve soil quality. They also confirmed the need to view the soil as a complex system which its functioning cannot be concluded by solely focusing on one soil property. Researchers and advisors have to view soil as a dynamic system and make recommendations based on the integrated depiction of all soil properties. The study also revealed what indicators correlate better with each other under certain management systems. For instance, not the same indicators that correlated highly in the UT region were seen in the LT region. In the UT region, exchangeable Ca and BD had the highest number of correlations indicating that these two indicators primarily impact most soil quality indicators in the region. In the LT region, the following indicators: exchangeable Mg, total C, active C, exchangeable Ca, BD and total N showed the highest correlations with other indicators. An interesting observation was that the LT region farms had more SOM indicators correlating well with other indicators than the UT region farms.

7.3 Recommendation for future research

This research was solely based on monitoring soil response to management by monitoring important aspects of the chemical, physical and biological properties of soil. No measurements were done in order to correlate soil quality with pasture yield. This is an important aspect that needs to be further researched in order to fully claim sustainable management of soil. Theoretically, good soil management practices must not only be visible in the soil, they need to be linked to better pasture yield and quality. Therefore, there is a need for further investigations linking soil quality, pasture yield and pasture quality. These also need to be linked to cow nutrition as well as milk yield and quality.

There also needs to be research directed at clearly giving the predicted timeline which indicates the soil adjustment period before the farmer can see optimum results when implementing management strategies that complement soil quality. Improved soil quality should minimise nutrient leaching, fertiliser application, effective use of water and higher pasture yield. Farmers value a management system that encourages overall farm profitability; therefore further investigations also need to be carried out in order to determine whether improved soil quality can be directly linked to farm economic efficiency.

7.4 Conclusion

The study gives a summary of indicators that farmers need to focus on as well as management practices that improve soil quality. It has also highlighted a huge gap that exists between the farmer and the researcher. Each of these categories has valuable insight that can be used to answer many questions that remain unanswered in the field of soil science. It is therefore imperative that a bridge of knowledge transfer is built so as to be more efficient. Farmers have to understand that managing soil quality is vital for optimum production in dairy pastures. Dairy farming relies heavily on energy provided by pasture and feed brought on to the farm. Farmers therefore need to produce farm food in a sustainable manner of which its foundation begins with soil quality management. Effective growth and utilisation of pasture is the most economically sensible way of satisfying the farms feed demand. Only after pasture has been utilised efficiently can external sources be considered. Sustainable soil management can be achieved if relevant soil quality indicators are measured, monitored and replaced only when necessary in adequate quantities. On the other hand, researchers must recognise that, fixed on-farm constraints need to be considered and that soil management strategies are not necessarily uniform within the industry. Each farmer has a unique story and overall reason behind his choice of management system. It is also important to note that the dairy industry is a high input, time consuming, labour intensive and unpredictable business, therefore strategies must be amendable, cost effective, viable and applicable.

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