ORGANIC AND MINERAL FERTILIZER FIELD TRIAL ON ROOIBOS TEA UNDER NORTHERN CAPE CLIMATIC CONDITIONS

by

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DECLARATION

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ABSTRACT

Prior to this study there was little or no information regarding fertilizer recommendations for cultivated rooibos tea under Northern Cape growing conditions. The first aim of the study was to examine the effect of application rate of various commercial brands of compound NPK organic and mineral fertilizers on one-year old rooibos plants under Nieuwoudtville field conditions in the Northern Cape. The second aim was to study the availability of NPK in the soil during the winter months, when rooibos plants usually accumulate nutrients for the dry summer growth period. The third aim was to examine the effect of vermicompost tea (VCT) solutions and water on rooibos nutrient uptake and tea yields and rhizosphere microbial diversity. The final aim was to assess the economic feasibility of organic and mineral fertilizer application on the farms used in the field trials.

Field trials were established, during a prolonged drought, at Rogland and Blomfontein Farms in the Nieuwoudtville region in June 2017. One-year old rooibos plants were fertilised as a completely randomised design at three different NPK ratios (2:3:2; 3:1:5; 3:2:4) and application rates based on a phosphorus (P) application of 3.3, 10, 30 and 60 mg P/kg, as rooibos is known to be sensitive to P toxicity. The fertilizers and application rates were selected based on previous rooibos greenhouse and field trials. A field trial was conducted at Rogland to determine the effect of the application of VCT solutions and water on one-year old rooibos plant growth and rhizosphere microbial diversity. Parameters measured include climate, soil water content and temperature, soil pH, electrical conductivity (EC), exchangeable cations, Bray II P, micronutrients, total carbon and nitrogen, foliar macro and micronutrient concentrations, plant survival and tea yields. Economic costs relating to rooibos production, such as labour; pesticides, fertilizers, transport and harvesting were used to determine the gross margin and economic feasibility of fertilizer application on rooibos production.

In the wet winter months mineral fertilizers were more effective for plant nutrient uptake as organic fertilizers appeared not to mineralise effectively. The lower N and K fertilizer application rates proved to be most plant efficient, as higher applications were likely lost through leaching or weed interception, while P fertilizer application had a low efficiency level. Foliar NPK concentrations peaked in July and decreased in August due to plant growth stimulated by warm and dry drought conditions. The application rate of 60 mg P/kg and above 87 (N) and 110 (K) mg/kg of organic and mineral fertilizers significantly affected soil fertility by significantly increasing soil pH, ECEC and K, while the chicken-manure based fertilizer enhanced soil and plant uptake of micronutrients. The application of P at a rate of 3.3 – 10 mg/kg stimulated above-ground plant growth in the organic and mineral fertilizer treatments with higher P applications having a negative effect on rooibos production. No significant interactive effect of N and K on biomass production was found. The application of P increased soil Bray II P, however failed to reach the intended target levels likely due to P fixation occurring in the acid soils. The increase in soil Bray II P failed to significantly increase foliar P likely due to drought conditions and weed competition, which could have led to lower availability for rooibos plant uptake.

The application rate of 3.3 and 30 mg P/kg in the organic and 30 and 60 mg P/kg in the mineral fertilizers significantly increased plant survival indicating that one-year old rooibos plants are more resistant to P fertilization than shown in previous field studies on rooibos seedlings. The application of 30 N; 10 P; and 50 K mg/kg in the 3:1:5 mineral fertilizer produced the highest survival-adjusted yield by increasing yield by 64.5 % compared to the control treatment. However, the highest gross margin was achieved in the first and second treatment level of the mineral 3:2:4 and organic 2:3:2 fertilizers which increased the gross margin by 40.2 and 20.8 %, respectively.

The application of VCT solutions had no significant effect on rooibos survival or tea yields compared to the same volume of tap water. Thus it was shown that the application of tap water resulted in significant increases in plant survival (23 – 31 % higher), resulting in lower tea yields due to higher plant density (38 – 66 % lower) compared to the control. The application of water and VCT solutions increased soil pH, which appeared to negatively affect Mn foliar levels. The application of VCT solutions significantly enhanced foliar P and reduced foliar Al, likely due to organic acids it contained. Bacterial species richness and diversity was significantly enhanced by the application of VCT in the winter months, whereas fungal communities were unaffected.

The study suggest that under drought conditions the application of mineral fertilizers of up to 30 N and 50 K mg/kg be applied with 10 mg P/kg to one-year old rooibos plants to increase tea yields and gross margin. This information can be applied to improve management of soil fertility in rooibos tea production and to increase the production yield in an economically sustainable manner without compromising soil quality and the surrounding environment.

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1 GENERAL INTRODUCTION AND RESEARCH AIMS

Rooibos tea (*Aspalathus linearis*) is indigenous to South Africa and believed to be first utilized by the Khoi people to produce a herbal tea (Joubert & Schulz, 2006). The natural distribution of the rooibos tea plant is limited to the winter rainfall region of the western interior of the country (Louw, 2006), and occurs in acidic, nutrient-poor sandstone soils (Dahlgren, 1968; van Heerden, *et al*., 2003). Production areas occur in the Cederberg and Sandveld areas of the Western Cape and the Bokkeveld area of the Northern Cape (O'Donoghue & Fox, 2009). The cultivation of rooibos has increased over the years and has become one the most commercialized fynbos species to be cultivated from the wild (Stassen, 1987; van Heerden, *et al*., 2003).

The domestic and international demand for rooibos tea has increased over the years with demand increasing drastically between 1990 and 2004 (Le Clercq, *et al*., 2009). The processed rooibos plant is sold as herbal a tea or as extracts for the food and cosmetic industry (Joubert & Schulz, 2006). Production increased from 524 tonnes in 1955 to over 15 000 tonnes in 2015 (SARC, 2016), with international markets increasing from 750 tonnes (1993) to over 7 000 tonnes (2015) and the domestic market increasing from 2 600 tonnes (1984) to 8 000 tonnes (2015) (Joubert & de Beer, 2011; SARC, 2016). This increase is largely due to the high international demand for health promoting products (Tregurtha & Vink, 2002). In the domestic market alone the retail value of the cultivated produce is estimated at R429 million (Joubert & de Beer, 2011).

The increasing demand, especially in the international market, has resulted in cultivated production areas increasing from 14 000 ha (1991) to 36 000 ha (2007) (Pretorius, 2007), with approximately 95 000 ha being used presently for the continuous production of rooibos (Smith, 2014). However, due to the loss of approximately 90% of natural renosterveld and fynbos vegetation (Kemper, et al., 1999), production area expansion is limited. This limits the expansion of rooibos cultivation and the removal of natural fynbos and succulent karoo vegetation. To meet the domestic and international demand for rooibos, producers need to increase their yield without increasing the area of cultivated land or over-harvesting from wild rooibos populations. One way to approach this problem is by incorporating the use of organic or mineral fertilizers in the production of rooibos. Plants that grow in nutrient-poor soils, such as *A. linearis*, naturally produce small amounts of litter and a vast majority of the nutrients are removed from the soil by harvesting the rooibos. By incorporating the use of fertilizers into the production system one can improve rooibos tea yields and prevent the exhaustion of soil nutrients.

Most scientific research on *A. linearis* has been focused on the health benefits of the plant and optimising the tea quality. Little research has been done on optimal field soil conditions and the use of organic and mineral fertilizers for enhancing production of rooibos over the long-term. Recent studies have been conducted under field conditions and the effect of nutrient application (Smith, 2014; Nieuwoudt, 2017; Lourenco, 2018). Nieuwoudt (2017) studied the effect of plant litter and mono-ammonium phosphate (MAP) fertilizer enriched litter on rooibos production, whereas Lourenco (2018) studied the effect of mineral fertilizer on rooibos seedlings under Clanwilliam climatic conditions. However, organic and mineral fertilizer trials are yet to be conducted under Northern Cape conditions in the Nieuwoudtville area.

Therefore, the main aim of the study was to investigate the effect of organic and mineral fertilizers on rooibos biomass production. The study was conducted in the Bokkeveld rooibos producing area around Nieuwoudtville in the Northern Cape, South Africa. The first objective was to determine mineralisation of the applied nutrients and plant nutrient accumulation throughout the winter season **(Chapter 3)**. The nutrient uptake by the plant was monitored and used to identify trends related to nutrient availability and temperature and moisture in the soil. The second research objective **(Chapter 4)** was to investigate the effect of organic and mineral fertilizers, with varying NPK ratios, on soil fertility and rooibos tea yields. Three commercial organic and mineral fertilizers were selected and applied at increasing phosphorus (P) rates that was kept constant across all treatments. The effect of the treatments on soil fertility and rooibos growth was determined 8 months after fertilizer application. The following soil parameters were determined: bulk density, texture, pH (H_2O and KCl), EC, total C and N, exchangeable basic cations and acidity and plant-available P. Plant macro- and micro-nutrients and tea yields were determined.

The third objective **(Chapter 5)** was to investigate effect of vermicompost tea application on plant growth and rhizosphere microbial diversity within the soil. The relationship between microorganisms within the soil and tea yields was also investigated. Determining the effect of fertilizer application on rooibos plant growth can be used to optimally grow rooibos to meet customer demand, however, economic feasibility **(Chapter 6)** of the soil amendments needs to be considered to ensure that the results obtained can be beneficial to farmers.

2 LITERATURE STUDY: INTRODUCTION TO SOIL FERTILITY AND ROOIBOS CULTIVATION

2.1 Soil Fertility

van Bruggen & Semenov (2000) defined a healthy soil as a stable system with resilience to stress, high biological activity and high levels of internal nutrient cycling. The fertility and stability of a soil is dependent on two factors: i) the inherent characteristics of the soil obtained during soil formation; and ii) the present condition of the soil, affected by natural processes or human-mediated management practices (Karlen, *et al*., 1997). Soil fertility can be measured in terms of plant growth (Karlen, *et al*., 1997), but produce quality is also important when it comes to the production of rooibos. Plant nutrients uptake is dependent on the nutrient supply and water content within the soil as plants are unable to obtain nutrients from the dry zone (Tisdale & Nelson, 1975). Therefore, the chemical and physical characteristics of the soil are important in determining the nutrient availability for plant growth.

Several physical and chemical soil properties are measured to determine quality of the soil and its potential to support crop growth. Physical properties include soil texture and bulk density; and chemical properties include soil organic matter content; pH, electrical conductivity (EC), total carbon (C) and nitrogen (N), exchangeable basic cations (K, Mg, Na, Ca) and acidity, plant-available P and trace elements. Soil pH and cation exchange capacity (CEC) affect nutrient availability and the capacity of the soil to support plant growth. Electrical conductivity and soil organic matter play a role in soil structure, water availability and nutrient cycling within the soil (Karlen, *et al*., 1997).

Plants that occur in nutrient-poor soils, such as the fynbos sandstone, produce small amounts of litter and conserve nutrients in their tissues (Hobbie, 1992). The removal of plant nutrients from the soil through harvesting, leaching and erosion and the lack of nutrient input back into the soil can lead to soil fertility decline (Drechsel, *et al*., 2001).

2.1.1 Fertilizers

Conventional Organic Fertilizers

The addition of organic fertilizers to soils provides numerous advantages for plant growth by enhancing the biological activity of the soil; increasing the total organic matter content; and providing a nutrient supply that is balanced (Chen, 2006). The slow nitrification of N and the higher CEC of organic fertilizers benefits soils by increasing its buffering capacity and slowly releasing nutrients for plant uptake (Stamatiadis, *et al.,* 1999). The slower mineralization rates from converting organic N to mobile nitrate in organic soil amendments also decreases the leaching potential of mineral N (Evanylo, *et al*., 2008). The use of organic fertilizers is associated with desired soil properties that include higher pH; total C and N; CEC; water-holding capacity; soil organic matter (Reganold, 1988; Bulluck III, *et al*., 2002; Evanylo, *et al*., 2008); and lower bulk density (Drinkwater, *et al*., 1995). However, it has a high cost to obtain; the nutrient release is slow; and the nutrient content is lower compared to that of mineral fertilizers (Chen, 2006). The slow release of nutrients makes it difficult to supply sufficient amounts of nutrients in a balanced ratio (Kirchmann, *et al*., 2002), which often leads to the slower initial growth of plants compared to plants fertilized by mineral nutrients (Heeb, *et al*., 2006).

Compost Teas

Another organic fertilizer option is the use of vermicompost (VC), which is the end-product that is produced by the decomposition of organic matter with the use of earthworms (Atiyeh, *et al*., 2000; Pienaar & du Plessis, 2007). The organic matter used in producing VC ranges from animal manure; plant residues; food and paper waste; sewage sludge; and industrial waste (Atiyeh, *et al*., 2002; Arancon, *et al*., 2003; Arancon, *et al*., 2004; Garg, *et al*., 2006; Padmavathiamma, *et al*., 2008). The adverse effects associated with agrochemical application in crop production has created a greater interest in the use of organic VC (Arancon, *et al*., 2004).

Benefits of VC includes a nutrient-rich compost; environmentally friendly; additional of beneficial microorganisms; improved soil structure and fertility; improved disease resistance of plants; addition of phytohormones; improved seed germination; enhanced seedling development and root elongation (Atiyeh, *et al*., 2000; Atiyeh, *et al*., 2002; Arancon, *et al*., 2006; Garg, *et al*., 2006; Pienaar & du Plessis, 2007; Padmavathiamma, *et al.,* 2008; Pant, *et al*., 2011; Srivastava, *et al*., 2011). Vermicompost has been found to be beneficial when it only makes up a small proportion of the growth medium (10 - 20 %), whereas high proportions did not increase plant growth (Subler, *et al*., 1998; Arancon, *et al*., 2003).

The use of VC as a fertilizer has been found to be beneficial to the growth of various crops and ornamental plants including: cow-pea, banana and cassava; marigolds, peppers, strawberries and tomatoes; Pak Choi (Chinese cabbage); and petunias (Atiyeh, *et al*., 2000; Atiyeh, *et al*., 2002; Arancon, *et al*., 2003; Arancon, *et al*., 2004; Arancon, *et al*., 2008; Padmavathiamma, *et al*., 2008; Tejada, *et al*., 2008; Singh, *et al*., 2010; Pant, *et al*., 2011). In South Africa the use of VC is limited in agricultural production but it has been used on potatoes, sultana grapes (Kriel, 2008), macadamia nuts, litchis (Joubert, 2012) and the cut flower industry (Newborn, 2017) with beneficial growth results. However, a majority of studies have been conducted under greenhouse conditions and there is limited research on the effect of vermicompost tea on crop production under field soil and climatic conditions and no research on its effect on rooibos tea plants.

Mineral Fertilizers

Mineral fertilizers supply nutrients to the soil that are soluble and in a form that is immediately available for plant uptake; and comparatively it has a lower cost and the nutrient content is higher which enables a lower amount to be applied for each application (Chen, 2006). Mineral fertilizers increase crop yields by increasing above-ground and root biomass due to the supply of plant nutrients that are immediately available and in sufficient quantities (Lopez-Perez, *et al*., 1990).

However, mineral fertilizers have the potential to have a greater negative effect on the soil than organic fertilizers. The nutrients are easily soluble and therefore easily lost through leaching; no additional organic matter is applied to the soil, which leads to the decomposition of available organic matter and results in soil structure degradation.

In sandy soils, such as those found in the Bokkeveld, greater soluble movement can be expected after considerable amounts of rain as it will move downward deeper into the soil (Tisdale & Nelson, 1975). The results obtained by Lourenco (2018) contradict this as the movement of applied N, P and K to deeper horizons was insignificant. Over-application of chemicals can also have negative effects on soil microorganisms and possibly lead to acidification or alkalisation of the soil (Stamatiadis, *et al*., 1999; Chen, 2006; Saha, *et al*., 2008). The long-term use of mineral fertilizers reduces nutrient availability as a result of a decrease soil organic carbon and lowered the pH of the soil (Ge, *et al*., 2010).

2.1.2 Importance of nutrients for plant growth

Nitrogen

Nitrogen (N) is the second most important element required by plants, after carbon, with an optimal growth of 2 – 5 % of total dry weight (Marschner, 1995; Hawkesford, *et al*., 2012). It is available for plant uptake in its inorganic forms of nitrate (NO_3^-) and ammonium (NH_4^+) and forms an integral part of nucleic acid and protein synthesis (Hawkesford, *et al*., 2012). Low N supply and uptake will negatively affect plant productivity and stunt plant growth, with deficiency symptoms first being noticed by chlorosis in older leaves (Hawkesford, *et al*., 2012). Sufficient N supply promotes shoot growth and initiates lateral growth of roots resulting in an increased shoot: root ratio (Hawkesford, *et al*., 2012). The availability of N in soil is influenced by several factors including soil texture, pH, moisture and microbial activity (Robinson, 1994).

Phosphorus

Phosphorus (P) is important for the synthesis of nucleic acids and ATP, which is the energy-rich phosphate required for starch synthesis (Marschner, 1995; Hawkesford, *et al*., 2012). Optimal plant growth occurs at 0.3 - 0.5 % of dry weight, with P toxicity starting to occur at > 1 % of dry weight (Hawkesford, *et al*., 2012). P deficiency results in reduction in leaf size and number, with root growth being less inhibited than shoot growth with increased partitioning of carbohydrates towards roots (Lynch, *et al*., 1991; Hawkesford, *et al*., 2012). In weathered acidic soils the availability of P is low as it is adsorbed onto sesquioxides and precipitates out with Fe and Al. P toxicity starts to occur when the stem tissue and root storage capacity has been reached, resulting in P being stored in the leaves leading to inhibited growth, leaf senescence and micronutrient deficiencies (Leake, 1993).

Potassium

Potassium (K) plays an important role in plant water relations, enzyme activation, protein synthesis and photosynthesis (Hawkesford, *et al*., 2012). Optimal plant growth occurs at 2 – 5 % of dry weight with K deficiency resulting in restricted growth, wilting under drought conditions and chlorosis of plant parts under severe deficiency (Marschner & Cakmak, 1989; Hawkesford, *et al*., 2012). Increased uptake of K under high supply can interfere with the uptake of Magnesium (Mg) and Calcium (Ca) (Hawkesford, *et al*., 2012).

Magnesium

Magnesium (Mg) plays a role in determining the structure of proteins, but most importantly it is the central atom of the chlorophyll molecule (Hawkesford, *et al*., 2012). Optimal plant growth occurs at 0.15 – 0.35 % of dry weight with deficiency resulting in a decrease in photosynthesis and root growth, reducing drought resistance (Hawkesford, *et al*., 2012).

Calcium

Calcium (Ca) plays a role mainly as a structural component in cell walls and linkages of phospholipids (Hawkesford, *et al*., 2012). Optimal plant growth occurs at 0.1 – 5 % of dry weight, but can be up to 10 % without having detrimental effects on plant growth (Hawkesford, *et al*., 2012). At a low soil pH, higher Ca concentration is required to facilitate efficient root growth, whereas deficiency is more detrimental in fruit production due to fungal diseases (Hawkesford, *et al*., 2012).

Iron

Iron (Fe) is the second most abundant metal in the earth’s crust, however its solubility is low (Broadley, *et al*., 2012). Fe is required for protein synthesis, chloroplast development, and photosynthesis and enzyme activity. Fe deficiency inhibits chloroplast development, root elongation and the development of proteoid roots. Critical deficiency concentration in leaves range between 50 – 150 mg Fe/kg dry weight, whereas toxicity appears at concentrations above 500 mg Fe/kg dry weight (Broadley, *et al*., 2012).

Manganese

Manganese (Mn) plays a role in enzymes activation, photosynthesis, protein synthesis, and cell division and extension (Broadley, *et al*., 2012). Mn critical deficiency, 10 – 20 mg Mn/kg dry weight, rapidly declines dry matter production, photosynthesis and chlorophyll content (Shenker, *et al*., 2004). Mn toxicity levels vary greatly among plant species, but can be identified by interveinal chlorosis and induced deficiencies of Ca, Mg, Fe and Zn (Broadley, *et al*., 2012).

Copper

Copper (Cu) plays roles in photosynthesis, respiration, C and N metabolism and catalysing redox reactions (Broadley, *et al*., 2012). Critical deficiency occurs at 1 – 5 mg Cu/kg dry weight, resulting in stunted growth and bleaching of young leaves (Broadley, *et al*., 2012). Toxicity starts to occur at 20 – 30 mg Cu/kg dry weight, inhibiting root growth before shoot growth is affected (Lexmond & van der Vorm, 1981; Broadley, *et al*., 2012).

Zinc

Zinc (Zn) plays a role in enzyme activation, protein synthesis, carbohydrate metabolism and membrane maintenance (Broadley, *et al*., 2012). Zn deficiency occurs in highly weathered acid and calcareous soils, with the critical deficiency level occurring at 15 – 20 mg Zn/kg dry weight (Broadley, *et al*., 2012). The most noticeable deficiency symptoms are stunted growth due to shortened internodes and decrease in leaf size (Broadley, *et al*., 2012). Zn toxicity is rarely found in natural soils, however can be found in soils contaminated by mining activities and sewage sludge (Broadley, *et al*., 2007). Critical toxicity starts to occur at 100 – 300 mg Zn/kg dry weight and causes chlorosis in young leaves and inhibits photosynthesis (Broadley, *et al*., 2012).

Boron

Boron (B) plays a role in cell wall structure, metabolism, membrane function and reproductive growth and development (Broadley, *et al*., 2012). B is easily leached under high rainfall conditions and plant availability decreases with an increase in pH (Broadley, *et al*., 2012). B deficiency ranges from 20 – 70 mg B/kg dry weight causing shortened internodes and interveinal chlorosis on older leaves. B toxicity starts to occur above 400 mg B/kg dry weight causing marginal or tip chlorosis on older leaves (Broadley, *et al*., 2012).

2.1.3 Chemical soil parameters

Soil pH

Soil pH is the measurement of the hydrogen ion activity, which is used to determine whether the soil is acidic or alkaline. The pH affects soil mineral solubility, nutrient availability for plant uptake and the activity of bacteria and fungi in the fynbos soil environment (Smith, 2014). Acidic conditions (pH < 7) are common in higher rainfall areas as basic cations are leached from the soil, while an alkaline (pH > 7) soil is associated with a low rainfall region (Arias, *et al*., 2005).

Soil Electrical Conductivity (EC)

Electrical conductivity (EC) is used to quantify soil salinity and is the measurement of the total concentration of soluble salts in the soil solution (Corwin, 2002). EC is influenced by soil salinity, soil water content, bulk density, clay content and organic matter (Corwin & Lesch, 2005). General EC values for crop growth range between 0 – 0.8 $dS.m^{-1}$ with excess salts having a negative effect on plant growth and the soil – water balance (Arias, *et al*., 2005).

Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) refers to the supply of macronutrients (Ca, Mg, K, and Na) that are available in the soil for plant uptake. CEC is related to the organic matter and clay content of the soil and is influenced by the soil pH and salt content (Arias, *et al*., 2005).

2.1.4 Physical soil parameters

Texture

Soil texture is quantified in terms of the content of sand, silt and clay. Different textures result in different soil pore sizes, which have an effect on the chemical and biological characteristics of the soil. Soil texture has a major effect on the mechanical resistance of soil, thereby influencing the growth of roots (Daddow & Warrington, 1983).

Bulk density

Bulk density is the ratio of the weight of oven-dried soil to its volume, with bulk densities ranging from < 1.0 to 1.7 $g.cm^{-3}$ (Arias, *et al*., 2005; Lynch, *et al*., 2012). Increasing bulk density increases root – soil contact but it limits root elongation as soil resistance increases and air and water movement decreases (Tisdale & Nelson, 1975; Arias, *et al*., 2005).

2.1.5 Soil microbial diversity

The soil environment is thought to contain majority of the undiscovered biodiversity with only approximately 3 % of bacterial and fungal species having been described (Slabbert, 2008). The microbial communities that occur in the soil are affected by the heterogeneity of the soil environment and variations in soil physical and chemical properties and habitat structure above the soil (Slabbert, 2008). Factors that influence a microbial environment include soil organic compounds, texture, aeration, water content, pH, temperature and above-ground plant diversity (Slabbert, 2008). A sandy soil favours the occurrence of aerobic microorganisms due to better aeration (McGechan, *et al*., 2005), however higher water content serves for a medium in which soil microbes live and move (Slabbert, 2008). A soil temperature of 20 – 40 °C is optimal for microbial activity (Roper, 1985) with seasonal variation in temperature affecting the species richness and occurrence. Warmer temperatures favour bacteria with cooler temperatures favouring fungal activity (Wang, *et al*., 2003).

The idea of a diverse ecosystem being more resilient to change was first proposed by MacArthur (1955), with an increased diversity leading to an increased ecosystem stability (Griffiths, *et al*., 1997; Nannipieri, *et al*., 2003). Ways to measure the diversity and differences between microbial communities include the measurement of the alpha and beta diversity. Alpha diversity is defined as the diversity of a specific group of organisms within a specific area and is determined by measuring species richness (Slabbert, 2008). Alpha diversity is measured using two indices: the Simpson Index (Simpson, 1949) and Shannon-Weaver Index (Shannon, 1948). The Simpson Index is a measure of dominance and the Shannon-Weaver Index a measure of entropy, with both expressing the level of diversity in a particular habitat. Beta diversity is the variation of the species composition between different communities (Anderson, *et al*., 2006).

Rooibos tea is associated with *Mesorhizobium* rhizobia species (Elliot, *et al*., 2007) that form nodules on the roots and can withstand pH of 3 – 4 (Muofhe & Dakora, 2000). The rhizobia has a positive effect on plant growth through nitrogen fixation and by producing plant growth promoting compounds

(Brink, *et al*., 2017). Agricultural activity usually results in the decline of soil microbial activity (Griffiths, *et al*., 2001), however bacterial diversity and species richness in the rhizosphere of commercial and wild honeybush have been found to be alike (Brink, *et al*., 2017), with similar results being found in rooibos plants.

2.2 Rooibos production

2.2.1 History

Rooibos, *A. linearis*, is endemic to South Africa and was first used by the indigenous Khoisan people as a herbal tea. Rooibos is one of 218 species of the *Aspalathus* genus with narrow leaves which limits moisture loss during the warm dry summers (SARC, 2016). In 1904 Benjamin Ginsberg saw the economic value of cultivating rooibos tea (Joubert & de Beer, 2011) and the first cultivation experiments were conducted by Dr P. le Fras Nortier by collecting seeds in the Cederberg mountains in the 1930's (Weiss, 1961). The method of seed collection and seedling germination does not undergo selective breeding, therefore resulting in a high genetic diversity within cultivated rooibos tea. Molecular data has shown a high level of genetic diversity leading to significant morphological and haplotypic variation in wild rooibos (Malgas, *et al*., 2010) with the genetic structure of a plant limited to the extent which the plant is able to develop and grow (Tisdale & Nelson, 1975).

In 1954 the Rooibos Tea Control Board was established to control tea quality, expand the market and to stabilize the industry (Gerz & Bienabe, 2006; Joubert & de Beer, 2011). The board was disbanded in 1993 and in 2005 the South African Rooibos Council (SARC) was established to coordinate marketing, research and development (Joubert & de Beer, 2011). The rooibos production industry plays an integral part of the livelihoods of people as it provides employment to more than 8000 farm workers (Rhoades, 1996). The Government Gazzette Notice 911 of 2013 which prevents the misuse of the rooibos brand, was introduced so that new products that use the word "Rooibos" must be 100 %, or the main ingredient must be rooibos (SARC, 2016). In 2014, the Rooibos trademark was placed under Geographical Indicators (GI) which protects the naming rights of rooibos grown in a specific area in South Africa (DAFF, 2016; SARC, 2016). It promotes local economic growth and allows the rural communities to compete in the market and South Africa is the only exporter of rooibos (DAFF, 2016). The rooibos tea sector is governed and supported by various institutions including the Western and Northern Cape departments of agriculture; national department of trade and industry; and local municipalities (Gerz & Bienabe, 2006).

Production was only 524 tonnes in 1955 and increased to 4000 tonnes by 1993 (Joubert & de Beer, 2011). The production of rooibos increased by 1.3 % per annum between 2001 and 2006 with a total of 9000 tonnes of rooibos produced in 2006 (DAFF, 2006). During this same time period the total gross value of rooibos production increased by 4.2 % per annum (DAFF, 2006). The production of rooibos peaked in 2008/09 with 18 000 tonnes produced, however it has steadily declined to approximately 10 500 tonnes in 2015 (DAFF, 2016). The gross value of production peaked in 2007 at R155 million and decreased to R60 million in 2010, this decline was attributed to the steady decline in producer prices (DAFF, 2016). The producer price declined from R12.50/kg in 2006 to R4.50/kg in 2010 and then increased again to R29/kg in 2015 and was R30/kg in 2018. The large increase to R29/kg is largely due to the increase in production and exports (DAFF, 2016). Presently, the domestic market consumes between 4500 – 5000 tonnes, while the rest is exported to international markets (DAFF, 2016). Rooibos tea currently only makes up 0.3% and 10% of the global tea and herbal tea market, respectively (DAFF, 2016).

The global consumption in 2015 was 15 000 tonnes with a large export market where Germany (30.5 %), Netherlands (15.7 %), Japan (15.3 %) and the United Kingdom (11.9 %) are the major importers of the produce (SARC, 2016). Since 1993, the export of rooibos has increased by over 700 %, with a further predicted increase (Pretorius, *et al*., 2011). However, 90 % of the exported rooibos is exported as bulk to external traders and processors, which limits profitability. This reliance on international manufacturers and distributors limits the economic growth of the industry (DAFF, 2015).

2.2.2 Adaptation to nutrient poor environments

Rooibos tea plants occur in nutrient poor sandy acidic soils and have adapted to acquire nutrients from the soil. Due to the inherent low P levels in the soil, plants have adapted by producing cluster roots, that are efficient in P uptake (Hawkins, *et al*., 2008), increased exudation of carboxylates (Shane, *et al*., 2003) and form symbiotic relationship with arbuscular mycorrhizae and rhizobial symbiosis with the N-fixing *Bradyrhizobium* bacteria (Marschner, 1995; Reddell, *et al*., 1997; Hawkins, *et al*., 2011). Cluster roots describe bunches of hairy rootlets that increases the surface area of the root system and largely occur in the shallow soil horizons (Lamont, 1982; Lynch & Brown, 2001). This increase in the root surface area is correlated with an increased acquisition of nutrients, especially phosphorus (Itoh & Barber, 1983; Keerthisinghe, *et al*., 1998; Lambers, *et al*., 2006). Mycorrhizal fungi located on the cluster roots are further able to acquire nutrients that are in small soil pores and out of reach of the plant roots (Smith & Read, 2008). Unique strains of root-nodule N-fixing bacteria isolated from rooibos tea grow in a very acidic environment at a pH of 3 or 4 (Muofhe & Dakora, 1998). Legumes require additional mechanisms to overcome acidic conditions to enhance symbiotic relationships with microbes and nutrient acquisition (Raven, *et al*., 1990). Plant roots release HCO_3^- and OH^- organic acids (Dakora & Phillips, 2002) that modifies the rhizosphere environment and facilitates microbial establishment (Muofhe & Dakora, 2000). The release of carboxylates through root exudation plays an important role in the mobilisation and uptake of nutrients from inorganic sources in the soil (Gardner, *et al*., 1983). Rhizosphere soil pH of rooibos tea plants have been found to be significantly increased due to the decarboxylation of organic acids exudated by the roots (Muofhe & Dakora, 2000).

Rooibos plants have also been known to have tap roots that can extend to more than two metres (Morton, 1983). Under dryland conditions the presence of a tap root is important for the plants survival and production during the summer drought where water-stress conditions cause a significant decline in biomass production (Lotter, *et al*., 2014a). The plant has adapted to the dry summer conditions by taking up and storing nutrients. Nutrients are taken up from the soil and stored during the wet winter months, and then in the dry summer conditions, September to May, plant growth is stimulated and nutrient concentrations diluted (Mooney & Rundel, 1979; Jeschke & Pate, 1995).

2.2.3 Phosphorus toxicity in Fynbos plants

Majority of the research conducted on low soil P environments has been done in Australia, but soils and many plants are similar to that found in the Fynbos region. Fynbos soils, and that of south-western Australia, have low nutrient levels, especially N and P, with many of the plants in the region (Proteaceae and Fabaceae) adapted to the low soil P concentrations that range from 0.8 to 8 mg P/kg soil (Hawkins, *et al*., 2008), but can withstand up to 70 mg P/kg (Witkowski & Mitchell, 1987). Proteaceae grow well at a foliar P concentration of 0.03 % with P toxicity experienced at 1 – 4 % (Shane, *et al*., 2004a). Vascular plants that occur in nutrient poor soils have adapted to acquiring P from low soil levels, but many are sensitive to P and display P-toxicity symptoms easily.

P uptake and shoot growth in fynbos plants are separated by several months, therefore P taken up during the winter must be stored and then mobilized during summer for shoot growth (Shane, *et al*., 2004a). The capacity of the stem tissues to store P is limited and once exceeded P-toxicity symptoms develop in the leaves (Parks, *et al*., 2000). Toxicity symptoms include growth inhibition, early leaf senescence and necrotic colouring on leaves (Shane, *et al*., 2004a). Research has shown that plants, that are adapted for soils with low P levels, have a low capacity to regulate P-uptake when additional P is supplied, even at low levels (Parks, *et al*., 2000; Shane, *et al*., 2003; Hawkins, *et al*., 2008; Lourenco, 2018). These plants have failed to develop a feedback system that controls P uptake, which increases the chance of P toxicity when P fertilizer are applied (Bowen, 1981). It has also been suggested that plants that occur in low P soils have P-transport systems that are always up-regulated, therefore continuous uptake of P occurs (Shane, *et al*., 2004b).

A small increase in the natural P concentration of soil can negatively affect plant growth and survival (Lambers, *et al*., 2013) of Proteaceae when the same P concentrations are harmless to other plants (Shane, *et al*., 2004b). An increase in P uptake has also shown to have a negative influence on cluster root formation in Mediterranean plants (Shane, *et al*., 2004a). A slight increase in P addition stimulates cluster root formation but at higher P application rates cluster roots are significantly negatively affected (Shane, *et al*., 2004b). These studies indicate that rooibos tea, a Fynbos plant, is also susceptible to P toxicity when exposed to unnaturally high soil P levels, however at the same time the natural low soil P levels is also thought to be the growth limiting factor (Maistry, *et al*., 2013). Therefore establishing the optimal soil P level for optimum growth of rooibos tea is important to optimize yield production.

2.2.4 Production area and cultivation

Production only occurs in the Cederberg and Sandveld areas of the Western Cape, and the Bokkeveld area in the Northern Cape (Fig. 2.1) (O'Donoghue & Fox, 2009). The environment receives winter rainfall (200 – 450 mm/year), has deep coarse acidic sandy soils and temperatures vary between 0 – 45 °C (SARC, 2016). It is a dryland crop and production varies according to the amount of rainfall (SARC, 2016).To develop new fields authorisation is required from the National Department of Agriculture (DAFF) and Provincial Environmental Authorities to develop virgin land or old fields that has remained uncultivated for more than 10 years (Pretorius, *et al.,* 2011). If a producer wants to clear more than 300 m^2 of indigenous vegetation in an endangered ecosystem; more than one hectare in critically biodiversity areas; or more than five hectares in any area, a basic assessment is required to be conducted (Pretorius, *et al*., 2011). A full scoping and environmental impact report is required if more than 100 ha of virgin soil is to be altered (Pretorius, *et al*., 2011).

In terms of the cultivation process, seeds are collected from the field and germinated in nurseries and seedlings are transplanted to the field after the first winter rain in May/June (Cheney & Scholtz, 1963). The method of seed collection and seedling germination leads to large genetic and phenological variation in cultivated rooibos plants (Joubert, *et al*., 2008). After a year of growth the top part of the plant is cut ('topped') to stimulate branching, the plant is then harvested yearly in the late summer or early autumn for five to six years (Cheney & Scholtz, 1963). The name "rooibos" refers to the traditional fermentation process of cutting, bruising and wetting of the leaves; the leaves undergo enzymatic oxidation which turns the green leaves into a red colour and enhances the tea flavour (Gerz & Bienabe, 2006; SARC, 2016). During processing of the leaves two thirds of mass is lost during fermentation and drying (DAFF, 2015). After five years of rooibos production, live plants are completely removed from the plantations and dead plants are ploughed into the field.

2.2.5 Effect of nutrient application on rooibos plants

There have been greenhouse trials done by Joubert, *et al*., (1987) investigating the effect of macronutrients (N, P, Ca, Mg, and K) on rooibos seedlings over a 3-month period. High P levels and the addition of Mg inhibited plant growth and the seedlings responded positively to the addition of low additions of N and lime. The concentration of 10 – 15 mg N/kg; 15 – 20 mg/kg Bray II P; and 60 mg/kg Bray II K showed to be optimum for rooibos seedling growth (Joubert, *et al*., 1987).

Stassen (1987) investigated the monthly nutrient uptake trends for rooibos plants over a 2-year period and estimated soil nutrient losses due to harvesting of tea. Most nutrient uptake occurred during the winter months and that an estimated 27.6 kg N, 1.8 kg P and 6.9 kg K should be applied per hectare to make up for the nutrient lost by harvesting 1500 kg/ha tea.

Muofhe & Dakora (1999) conducted a pot-trial study and found that biomass production and N-fixation in rooibos grown in acidic soil, collected from the Clanwilliam area, was significantly improved by the addition of N (ammonium nitrate) and P (potassium phosphate) which was fed continuously to the plants as a hydroponic solution. Maistry, *et al*. (2015) conducted a short-term hydroponic greenhouse trial on rooibos seedlings and found that the addition of N to the plants stimulated P uptake and the formation of cluster roots. Seedling above-ground biomass increased when N and P was added simultaneously and concluded that both N and P are the limiting nutrients in fynbos soils (Maistry, *et al*., 2015).

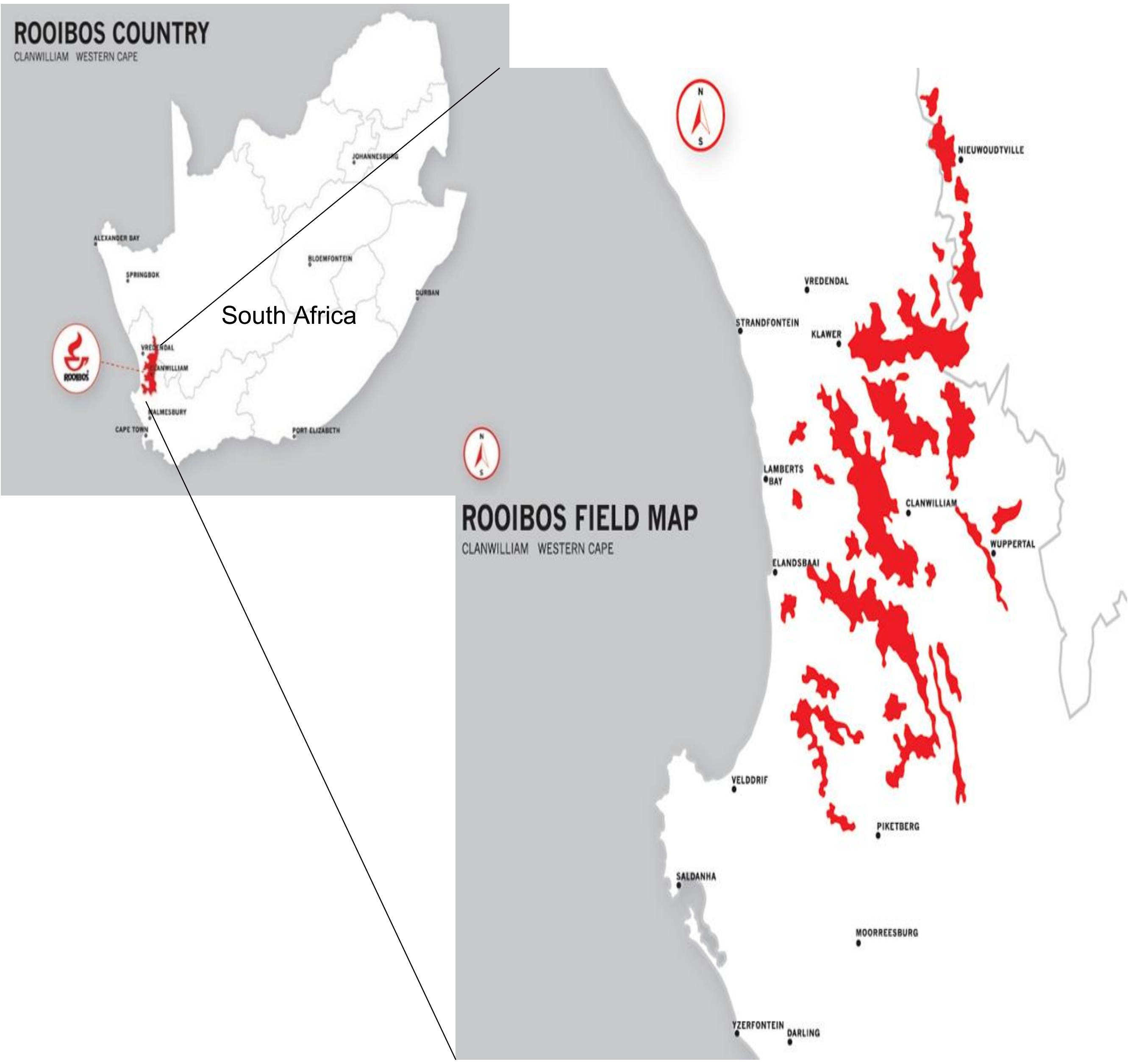

Figure 2.1: Map of the Rooibos Tea production areas within the Western and Northern Cape, South Africa (Rooibos Ltd, n.d.)

Chimphango, *et al*., (2015) studied the effect of organic cultivation of rooibos on the soil nutrient status in the Nieuwoudtville area by monitoring soil organic matter and plant nutrients from 2005 to 2009. There was a positive correlation ($p < 0.001$) between soil C and K^+, Ca^{2+}, Mg^{2+} and Na^+ (Chimphango, *et al*., 2015); indicating that organic matter within the soil is important for the availability of plant nutrients.

A fertilizer field trial on rooibos seedlings grown until 1 year of age in the Clanwilliam region by Lourenco (2018), found the application of 15 – 30 mg P/kg stimulated biomass production during the first four winter/spring months after planting, which supported the results found by Joubert, *et al.,* (1987). However, after the wetter months during the hot dry summer the application of P significantly suppressed plant growth and survival (Lourenco, 2018). This indicated a negative effect of P application on rooibos seedlings under field conditions. An earlier field trial in the same region found supportive results with a negative correlation between soil Bray II P and above-ground biomass production of 2-year old plants (Smith, *et al*., 2018). Foliar P was also negatively correlated with above-ground biomass yields, possibly due to P toxicity (Smith, 2014). Both Smith (2014) and Lourenco (2018) concluded that the application of composts or fertilizers are beneficial to rooibos plant growth, as long as soil P is not elevated to significantly higher levels. The split application of 20 – 40 mg K/kg increased biomass yields by almost 50 %, with the application accompanied by 20 mg N/kg recommended for rooibos seedlings at planting (Lourenco, 2018).

Nutrient availability in soils is important however; in crop production, the yield produced is more dependent on the water supply than on any other environmental factor (Kramer & Boyer, 1995). This is supported by a study by Lotter, *et al*. (2014a), which found that rooibos plants grown under drought conditions in a greenhouse trial were found to invest more in root growth, limiting the production of above-ground biomass. Mycorrhizal fungi are known to increase the plant's drought resistance, however high soil P levels have a strong negative influence on mycorrhizal colonization of rooibos plants (Smith, *et al*., 2018).

Therefore determining the effect of fertilizer application on more established rooibos plants under different climatic conditions will be beneficial for optimal production under Northern Cape field conditions.

2.3 Study area

2.3.1 Introduction

The research was conducted in the Northern Cape rooibos district on the Bokkeveld Plateau, within the farming district of Nieuwoudtville, which is situated approximately 350 km north of Cape Town. The area is well known for its vegetation diversity and is rich in bulb species. International and local tourists visit the area in early spring, August to September, to witness the wild flower display of the natural veld. The primary agricultural activities in the area includes wheat, sheep and rooibos farming (O'Farrell, *et al*., 2007).

The Nieuwoudtville rooibos production area falls within the Greater Cederberg Biodiversity Corridor (GCBC), thereby restricting the expansion of rooibos agricultural activities as the natural sandveld fynbos and succulent karoo vegetation is a threatened natural habitat that is under formal protection. The GCBC extends from the northern West Cost (west) to the Tanqua Karoo (east) and from Baviaanberg (south) to Nieuwoudtville (north) and covers an area of approximately 1.2 million hectares (Low, *et al*., 2004). Three vegetation types occur within the Bokkeveld-Nieuwoudtville subregion; these include Bokkeveld Sandstone Fynbos; Nieuwoudtville Shale Renosterveld; and Nieuwoudtville-Roggeveld Dolerite Renosterveld. The different vegetation types give rise to the high species diversity of wild flowers and bulbous species. However, large areas of the natural vegetation have been transformed by agriculture and few areas are under formal protection, such as the Oorlogskloof Nature Reserve.

2.3.2 Experimental Location

The experimental sites were situated in the Nieuwoudtville district, within one of six main rooibos production areas. The fields used were situated on the farms Rogland and Blomfontein in the Nieuwoudtville district (Fig. 2.2). Rogland is situated 22 km north of Nieuwoudtville in the North-Bokkeveld region and Blomfontein is 43.2 km south of Nieuwoudtville in the South-Bokkeveld region. These sites were chosen as they contained fields with unfertilized one-year old rooibos plants and have contrasting rainfalls. Rogland is known to receive 450 – 550 mm rainfall per annum while Blomfontein only receives approximately 350 – 450 mm rainfall per annum.

Both sites have a relatively flat topography and no fertilizer has been applied to the soil at the sites within the last 15 years. Weeds within the plantations are controlled mechanically with a disc-harrowing implement and when necessary pesticides are sprayed to control crop-damaging insects. At both sites the rooibos seedlings were planted in July 2016.

Figure 2.2: Google Earth map indicating the location of the proposed study sites Rogland, situated in the North-Bokkeveld, and Blomfontein, in the South-Bokkeveld, in the Northern Cape, South Africa

2.3.3 Climate

The Bokkeveld Plateau falls within the winter-rainfall region with most of the rain falling from May to August. There are occasional thunderstorms that occur during spring and summer but the area is dependent on the more constant and predictable winter rainfall. The highest annual rainfall occurs on the edge of the escarpment, varying between 500 and 650 mm, and then it declines to 350 mm as one heads more east and inland towards Nieuwoudtville (Manning & Goldblatt, 1997). At Nieuwoudtville the average temperature is highest during February and lowest in July. The average rainfall and temperature data for Nieuwoudtville from 1990 – 2012 can be seen in Figure 2.3 and Figure 2.4.

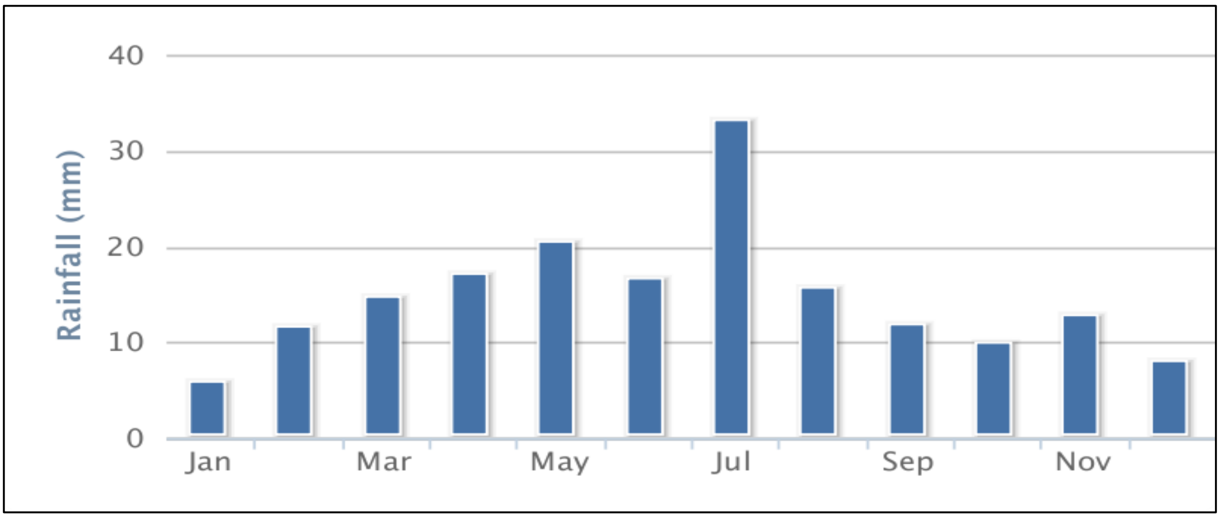

Figure 2.3: Summary of rainfall in the Nieuwoudtville area between 1990 and 2012. (The World Bank Group, 2016)

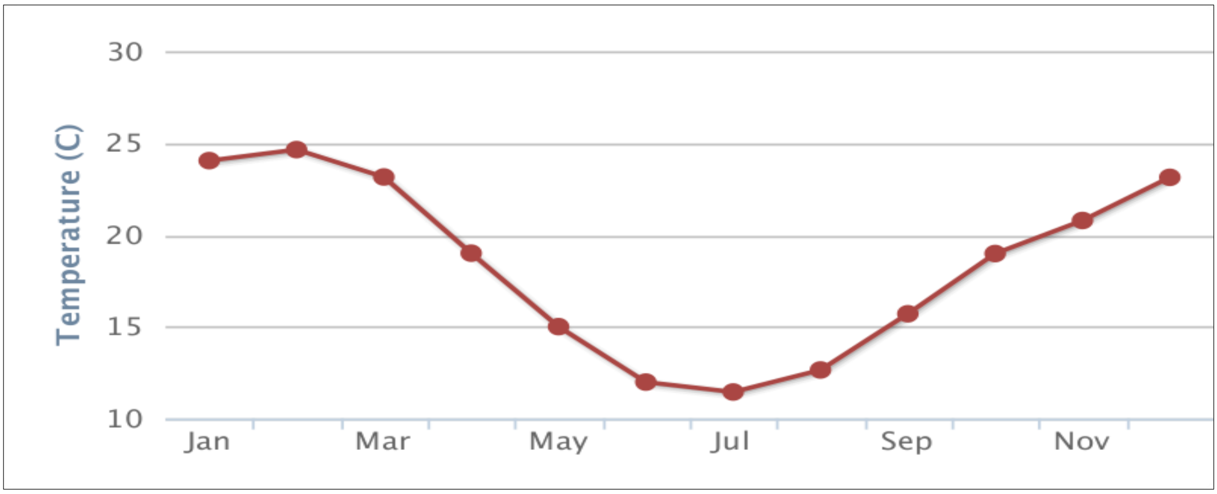

Figure 2.4: Summary of the average temperature in the Nieuwoudtville area between 1990 and 2012 (The World Bank Group, 2016).

2.3.4 Geology

The northern Sandveld is dominated by unconsolidated tertiary and quaternary deposits consisting of calcareous sands and calcretes, and neutral to acid sands (Low, *et al*., 2004). The Table Mountain Group (TMG) also makes up the majority of the Bokkeveld and Cederberg mountain ranges with isolated "koppies" (inselbergs) scattered across the landscape (Low, *et al*., 2004).

2.4 Conclusions

There is a demand for research to focus on nutrient application on rooibos plants under field growing conditions to better understand rooibos cultivation and to provide producers with information that they can implement in their agricultural practices. Fertilizer field trials will contribute to the development and implementation of a fertilizer application schedule that can lead to the increased production of rooibos. A better understanding of the preferred NPK ratio of rooibos will contribute to increasing the efficiency and effectiveness of fertilizer use in the rooibos production system. The option to use either organic or inorganic fertilizers also needs to be investigated as both have their separate advantages. Organic fertilizers slowly release nutrients, therefore not rapidly elevating soil nutrient levels, which is beneficial for rooibos plants as it is adapted to nutrient poor soils. However, with inorganic fertilizers it is easier to control the amount and types of nutrients that are applied, and the applied nutrients are immediately available for plant uptake. This further highlights the need to investigate the effect of the application of organic and inorganic fertilizers on rooibos plant survival and growth. Scientifically it will add to understanding how plants react to nutrient addition under field conditions throughout different seasons. The results will provide farmers scientific evidence on how the rooibos plants react to different treatments and provide them with information to make informed decisions to further improve their production and financial gains.

No field trials have been done to date on the effect of organic and mineral fertilizers on rooibos plant growth under Northern Cape climatic conditions. Previous studies were either conducted under greenhouse or other climatic conditions or failed to incorporate organic and mineral fertilizers. It is important to examine the effect of fertilizer application on soil fertility and plant growth to identify relationships between soil properties and increased yield production. The effect of vermicompost tea on soil microbial activity and rooibos plant growth needs to be investigated as it can provide farmers with an alternative fertilizer to improve production.

3 RESEARCH UNIT 1: NUTRIENT RELEASE AND UPTAKE OF ORGANIC AND MINERAL FERTILIZERS BY ROOIBOS TEA DURING WINTER RAINFALL MONTHS

3.1 Introduction

Limited research has been done on mineralisation of fertilizers, soil nutrient availability and nutrient uptake by rooibos tea plants in winter months under field conditions. Rooibos is an evergreen leguminous shrub growing in a climate with dry summers and winter rainfall period (Lotter, *et al*., 2014a). The plant is known for accumulating and storing nutrients from the soil during the wet winter months, and then in the dry summer conditions, September to May, plant growth is stimulated and nutrient concentrations diluted (Mooney & Rundel, 1979; Jeschke & Pate, 1995). Nutrient availability varies from organic sources as it is dependent on the source material and microbial activity to promote mineralisation. Microbial activity is further influenced by soil temperature and moisture, with low temperatures reducing mineralisation rates (MacLean & McRae, 1987; Griffin & Honeycutt, 2000; Agehara & Warncke, 2006). Understanding the nutrient availability and uptake from a known applied amount ensures more efficient management and sufficient provision of nutrients for optimal production (Agehara & Warncke, 2006).

Stassen (1987), investigated foliar nutrient levels in the Citrusdal area on two-year old plants and found that majority of nutrients obtained by the plant were taken up during the winter rainfall months with foliar nutrient levels peaking in September and October. Lotter, *et al*. (2014b) also found that rooibos foliar N concentrations were highest at the end of winter. Nieuwoudt (2017) looked at the effect of plant residue treatments on plant nutrient uptake and dry matter yield production. NPK nutrient uptake was highest from July to September, with a fertilizer (mono-ammonium phosphate) enriched treatment having the highest NPK values, indicating a higher uptake during the winter rainfall months. Lourenco (2018) studied the effect of mineral NPK application on rooibos seedlings under Clanwilliam climatic conditions, and found that 15 and 30 mg P/kg stimulated biomass production, whereas higher applications inhibited growth. However, the study was performed under different climatic conditions and only incorporated mineral fertilizers.

The study was therefore implemented to assess mineralisation of fertilizers and how the changes in the soil NPK nutrient status affected the plant NPK uptake under winter rainfall field conditions in the Nieuwoudtville region. This information can be applied to better manage soil nutrient levels and improve efficiency of applied fertilizers.

3.2 Objectives

1. To examine the soil NPK availability of organic and mineral fertilizers during the winter rainfall months under Northern Cape growing conditions

2. To determine the NPK uptake of one-year old rooibos plants of organic and mineral fertilizes during the winter rainfall months

3.3 Methods and materials

3.3.1 Location and description

On the farm Rogland, the plantation that was identified to be suitable for the field trial experiments was situated at 31°13'37'' S; 19°01'08'' E, and at an elevation of 825 m above sea level. On the farm Blomfontein, the plantation that was identified to be suitable for the field trail experiments was situated at 31°42'26" S; 19°07'14" E, and at an elevation of 804 m above sea level. At Rogland, the in-row plant spacing was 300 mm and the between row spacing 750 mm, whereas, at Blomfontein, the in-row plant spacing was 400 mm and the between row spacing 750 mm.

Soil classification

The following soil forms were found at the Rogland and Blomfontein experimental sites: Cartref and Glenrosa (Soil Classification Working Group, 1991).

Cartref (2100) (Fig. 3.1A)

Orthic A horizon: 0 – 200 mm, Dry colour 2.5Y 5/4

E Horizon: 200 – 500 mm, Dry colour 10YR 8/4

Lithocutanic B horizon: > 500 mm, Dry colour 2.5Y 6/6, Rock colour 5YR 6/8, Relic plinthic rock

Profile depth: 650 mm; restriction due to relic plinthic

Glenrosa (1111) (Fig. 3.1B)

Orthic A horizon: 0 – 280 mm, Dry colour 2.5Y 5/2

Lithocutanic B horizon: > 280 mm, Dry colour 10 YR 5/6, Rock colour 5 YR 5/8, Relic plinthic rock

Profile depth: 600 mm, restriction due to relic plinthic

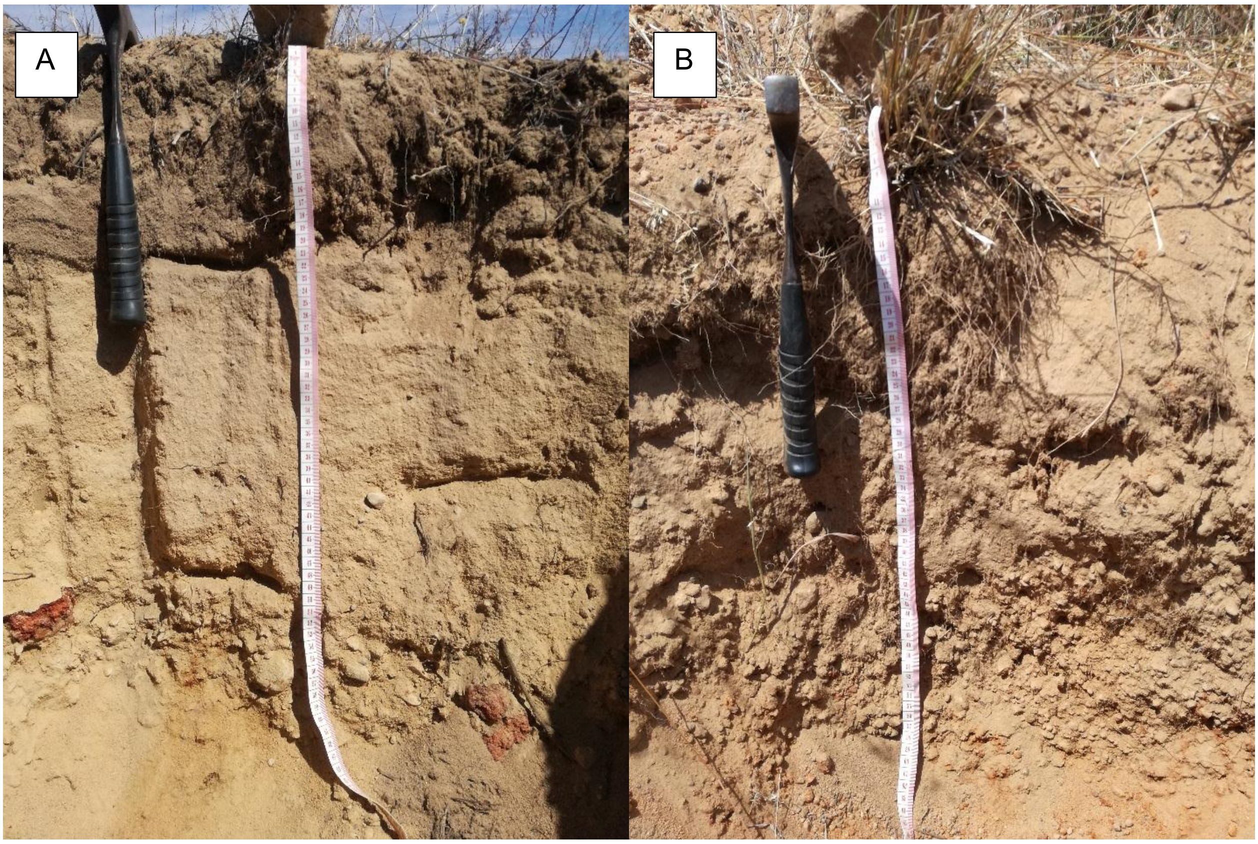

Figure 3.1: A) Cartref (2100) soil form on the Rogland experimental site; B) Glenrosa (1111) soil form on the Blomfontein experimental site

3.3.2 Experimental design

The winter mineralisation trial only occurred on the farm Rogland in the north Bokkeveld region. The trial had seven treatments and consisted of three commercial organic (O232, O324 and O315) and three mineral (M232, M324 and M315) fertilizer treatments, and a control which received no fertilizer. The organic nutrient NPK ratio application treatments were 2:3:2; 3:2:4 and 3:1:5. Both the O232 and O315 treatments were derived from bone meal and animal blood, whereas O324 was chicken-manure based. The mineral fertilizer treatments were blended using urea (46 % N), double superphosphate (20 % P) and KCl (50 % K) to match the NPK ratios of the organic fertilizer treatments. A single P application rate of 10 mg/kg was selected for each organic and mineral fertilizer treatment with N and K application rates varying from 6.7 to 30 and 6.7 to 50 mg/kg, respectively (Table 3.1). The application of 10 mg P/kg was based on previous research and ongoing field trials of optimal P application on rooibos plants. Each treatment was replicated four times in a completely randomized block design.

Treatment plots consisted of 10 rows with each row having five to six one-year old plants covering an area of 27 m^2**.** Fertilizer was band placed, by top-dressing by hand, along the planting rows at a width of 0.6 m therefore the fertilized area was 21.6 m^2, and then worked into the soil to a depth of approximately 15 cm using a spade. This was done to enhance the fertilizer efficiency by applying it close to the roots of the plants. The amount of fertilizer applied was calculated based on the volume of soil to be enriched by the applied fertilizer and the determined dry soil bulk density of 1612 kg/m^3, which is typical for very sandy soils. The fertilizer was applied on 1 June 2017.

A weather station was installed to measure ambient temperature and precipitation and a soil echo logger was installed to monitor soil water content and temperature at five soil depths (5, 15, 25, 40 and 60 cm) in real-time. This information was used to understand the mineralisation rates of the organic fertilizers and nutrient uptake by plants.

Table 3.1: Summary of the amount of NPK (mg/kg) applied in the Winter Mineralisation study on Rogland.

Treatment	Code	NPK applied mg/kg		
		N	P	K
Control	C	0	0	0
Organic / Mineral 2:3:2	O232 M232	6.7	10	6.7
Organic / Mineral 3:2:4	O324 M324	14.5	10	18.3
Organic / Mineral 3:1:5	O315 M315	30	10	50

3.3.3 Soil sampling

Soil samples were collected at the end of the month for three months starting at the end of June and then again in July and August. Four samples were collected within each treatment plot and bulked in the field, therefore four composite soil samples were collected for each treatment. Soil was sampled to a depth of 15 cm using a soil auger. Soil samples were kept cool and mineral N extraction was conducted immediately before extracted solutions were frozen until being tested for mineral N content. Soil was then air-dried and sieved through a 2 mm sieve prior to further analysis.

3.3.4 Plant sampling

Plant samples were collected on a monthly basis in June, July and August 2017. Within each treatment plot two plants were sampled at each sampling event. Samples were collected by destructively harvesting the whole plant and then cut at the soil level to divide the plant into the below – and above-ground biomass. The above-ground biomass was weighed before leaves were separated from the shoots; rinsed with distilled water and then oven-dried before being analysed for mineral nutrient content.

Fertilizer efficiency was calculated using the total plant nutrient uptake, based on foliar concentrations, and the nutrients that were applied by the fertilizers using equations used by (Coblentz, et al., 2016). Nutrient uptake (kg/ha) was calculated by multiplying dry matter mass of the above-ground biomass (kg/ha) with the nutrient concentration (N_{conc}) of the foliar samples (g/kg) using Equation 3.1. Dry matter mass (kg/ha) was calculated by the dry mass of the harvested plant and multiplied by the number of plants expected to occur per hectare. Nutrient recovery was then calculated by dividing the nutrient uptake by the applied nutrients and presented as a percentage using Equation 3.2.

$$Nutrient\ Uptake\ (kg.ha^{-1}) = \frac{Yield\ (kg.ha^{-1}) \text{x}\ N_{conc}}{1000} \qquad \text{(Eq. 3.1)}$$

$$Nutrient\ Recovery\ (\%) = \frac{Nutrient\ Uptake\ (kg.ha^{-1})}{Nutrient\ Applied\ (kg.ha^{-1})} \text{ x } 100 \qquad \text{(Eq. 3.2)}$$

3.3.5 Soil analysis

Mineral N

Mineral N was extracted with 2 M KCl and ammonium and nitrate content was determined colourmetrically using Merck Test kits and a spectrophotometer at 525 nm (nitrate) and 690 nm (ammonium).

Plant-available phosphorus

Plant-available P was determined using the Bray 2 extraction method (Kuo, 1996).

Ammonium acetate extractable potassium

Exchangeable potassium content of the soil was determined using the 1 M NH_4OAc (ammonium acetate) (pH 7.0) method (Sumner & Miller, 1996).

3.3.6 Plant analysis

Foliar plant samples were cut into smaller pieces and oven-dried before being analysed for mineral content. Total macro- and micro-nutrient content of the dried samples were determined using the Kjeldahl method (N), and acid digestion and ICP-MS (P and K) by Elsenburg Plant Laboratory.

3.3.7 Statistical Analysis

Statistical analyses performed using Statistica™ Software (Version 13.3, 2018, Dell Software, Tulsa). The data was tested for significant differences between treatments at a 95 % confidence level.

3.4 Results and discussion

3.4.1 Soil Temperature and Water Content

The monthly average ambient temperatures varied between 9.9 and 11.2 °C with a range between - 3.5 and 29.1 °C. Soil temperature at 15 cm depth varied between a monthly average of 11.3 and 12.4 °C and a range between 4.4 and 20.5 °C. Soil temperature was slightly buffered against very low and high ambient temperatures (Fig. 3.2). The area has a normal annual rainfall of 450 mm, however, in the winter of 2017 the farm only received 87.9 mm, which is 19.3 % of its average annual rainfall. Rainfall decreased throughout the winter months from 41.7 mm in June; 20.7 mm in July and 18 mm in August. Soil water content, at 10 – 20 cm, increased with rainfall from 2.5 to 8 mm in June and maintained relatively stable with rainfall events with a monthly average of 6.9 mm in July. However as rainfall continued to decrease in August so did the soil water content as it decreased to a monthly average of 5.8 mm (Fig. 3.3). This significantly lower rainfall represents the prevailing drought conditions that occurred throughout the duration of the field trial.

Soil temperature and water content had varying effects on soil and plant NPK levels. Foliar nutrient concentrations showed a negative trend with an increase in soil temperature at 15 cm soil depth, whereas a significant positive trend was found with foliar NPK and soil water content. The higher soil water content in July (Fig. 3.4) shows a positive trend with the increase in foliar NPK. During the same time period the relatively lower soil temperature shows a trend with a decrease in soil NPK.

Foliar K showed a negative and soil Bray II P a positive trend with soil temperature at 15 cm. This relation was inversed with soil Bray II P and foliar K having negative and positive trends, respectively, with soil water content at 15 cm.

In the organic treatments mineral N and Bray II P increased and showed a positive trend with soil temperature. Foliar N and K showed a negative trend with soil temperature. Soil water content had the inverse effect with mineral N and Bray II P showing negative trends and foliar N and K showing positive trends with soil water content. In the mineral treatments foliar P and K showed a negative trend with soil temperature, and a positive trend with soil water content.

The positive trend between soil temperature and soil nutrients can be due to various factors. In the organic treatments microbial activity is promoted by an increase in temperature (Agehara & Warncke, 2006) resulting in mineralisation of N and P into plant available forms. The increase in soil temperature is also accompanied by a decrease in soil water content meaning less nutrients are taken up by the plants and soil nutrient reserves are able to accumulate. The negative trend between soil temperature and foliar nutrient concentrations is due to the decreased uptake or the dilution factor caused by increased plant growth that is stimulated by warmer temperatures.

The negative effect of soil water content on soil nutrients is due to increased leaching and plant uptake. The decrease in soil nutrients in the organic treatments is due to the lower soil temperatures that occurs with an increase in soil water content. The lower soil temperatures inhibit microbial activity and therefore inhibits mineralisation of nutrients into plant available forms. The significant trends between soil water content and foliar nutrient concentrations indicate that under higher rainfall plant accumulation of nutrients can be increased. This highlights the negative effect of the drought conditions where only 19.3 % of the annual winter rainfall fell.

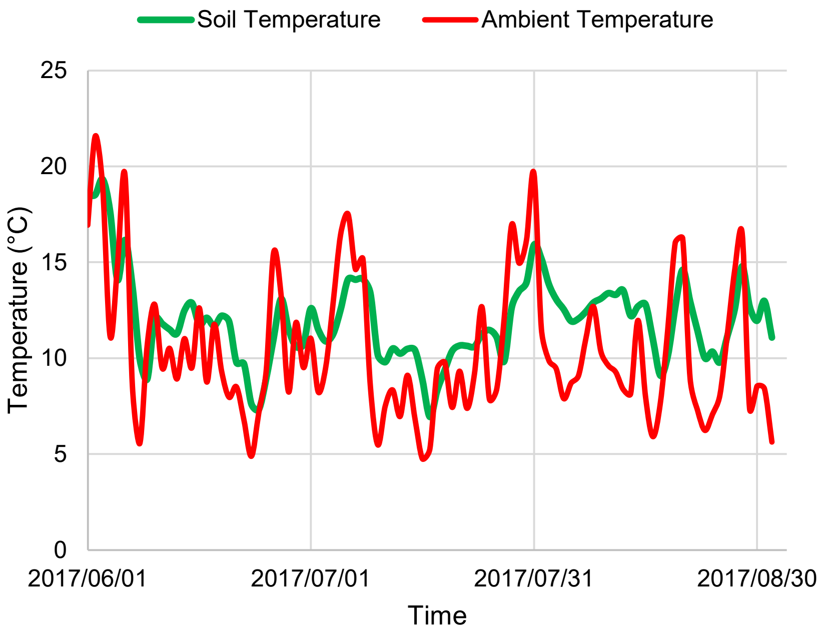

Figure 3.2: Summary of the daily ambient and soil temperatures (˚C) at 10 - 20 cm soil depth during the winter rainfall months (June – August 2017) at the farm Rogland.

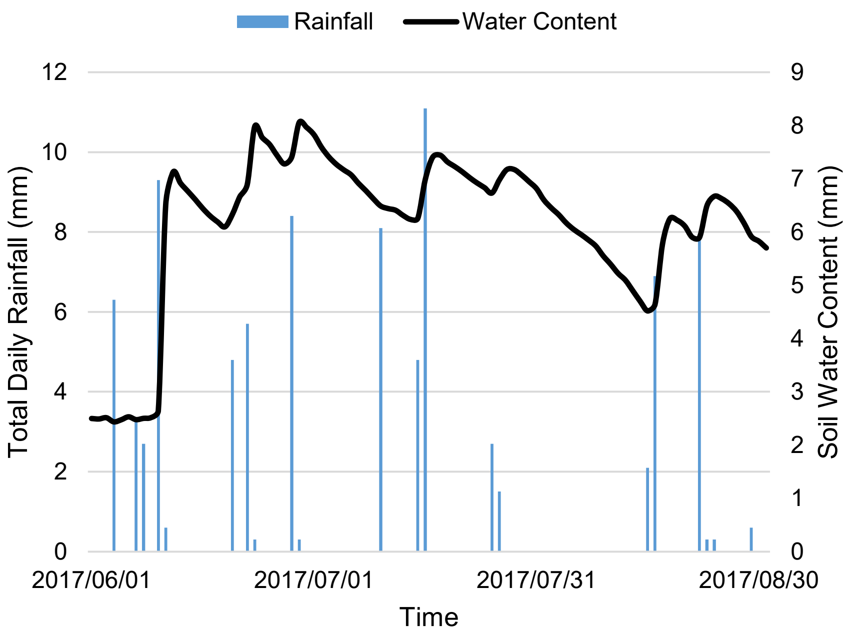

Figure 3.3: Summary of the daily rainfall (mm) and soil water content (mm) at 10 - 20 cm soil depth during the winter rainfall months (June – August 2017) at the farm Rogland.

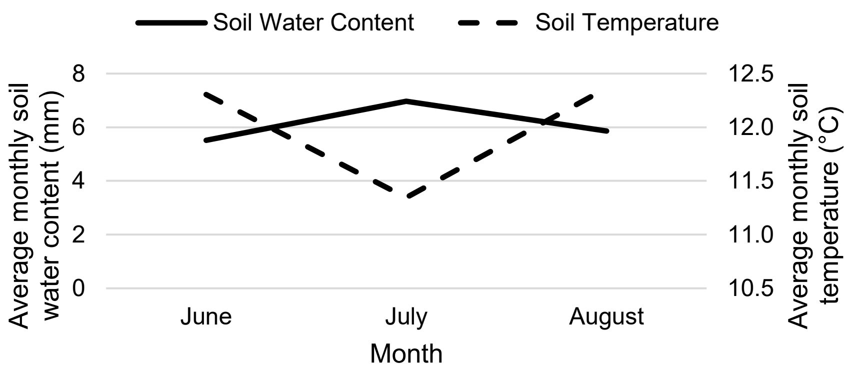

Figure 3.4: Monthly average soil water content (mm/mm) and soil temperature (˚C) at 15 cm soil depth during the winter months

3.4.2 Nitrogen

Soil mineral N was initially higher in the mineral treatments in June, with M315 being significantly higher than the control and organic treatments (Fig. 3.5). This was expected as 30 mg N/kg was applied and is immediately in its inorganic plant available form. All, except M315, declined in July, possibly due to increased plant uptake and/or leaching. In August there was an increase in the control and organic treatments, indicating mineralisation occurring, however the increase was insignificant. Mineral N in the organic treatments showed a positive and negative trend with soil temperature and soil water content at 15 cm depth, respectively. However, organic treatments were never significantly higher than the control, indicating ineffective mineralisation of the applied organic N. The ineffective mineralisation could be due to the low soil temperatures that occurred during the winter months. There was no significant difference in mineral N at the end of the winter months in August. Values within the control and organic treatments are supported by values found by Smith (2014) in the month of June.

Foliar N content varied across all treatments with no clear trend found between applied and soil mineral N and foliar N content (Fig. 3.6). Foliar N showed positive and negative trends with soil water content and soil temperature at 15 cm, respectively. Foliar N levels were comparable to the 1 – 1.9 % found by other field studies (Stassen, 1987; Lotter, *et al*., 2014b; Smith, 2014; Nieuwoudt, 2017); however, it was lower than the 2.3 % found by Lourenco (2018). All, except M315, showed a decline in foliar N in August, possibly due to increase plant growth and dilution of foliar nutrients. The increase in foliar N in M315 in August can be linked to a higher soil mineral N content in July.

Fertilizer efficiency for applied N was significantly higher at the lower application rate, with an efficiency of 56 – 58 % at 24.2 kg N/ha applied (Fig. 3.7). The lower efficiency levels of higher application rates indicate loss of applied N through leaching, however, it is difficult to accurately quantify N uptake from fertilizer as rooibos is associated with biological N-fixing bacteria (Brink, et al., 2017).

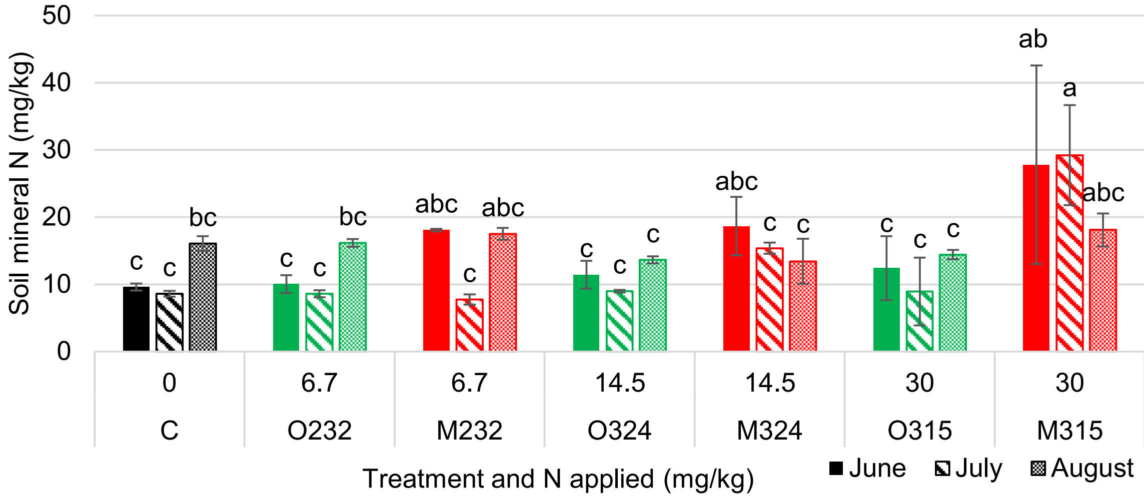

Figure 3.5: Soil mineral N (mean ± SE) of control and fertilizer treatments in the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: C: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

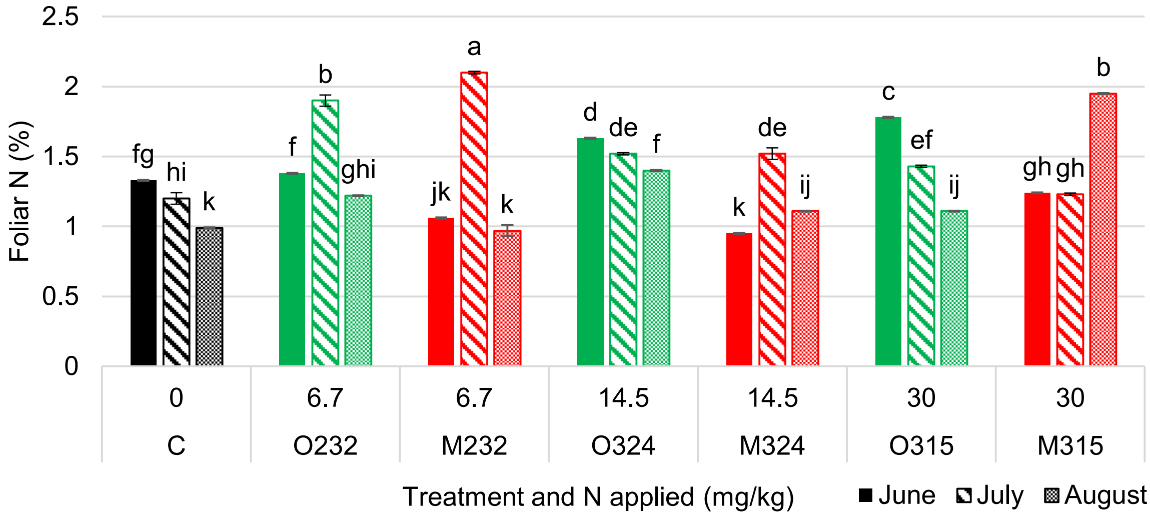

Figure 3.6: Foliar N content (mean ± SE) during the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: C: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

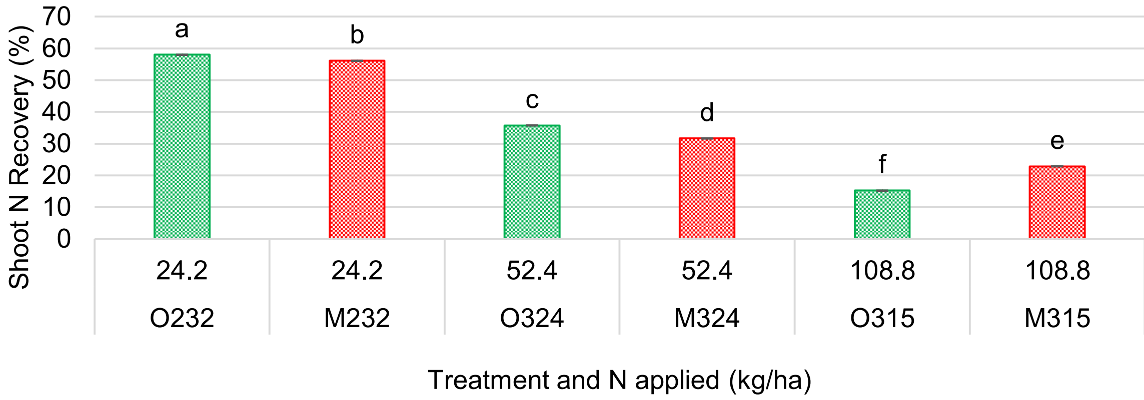

Figure 3.7: Fertilizer efficiency in terms of foliar N content (mean ± SE) three months after fertilizer application. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

3.4.3 Phosphorus

The initial soil Bray II P content of the mineral treatments was higher comparatively to the control and organic treatments. A significant statistical difference was found between the control and M324 and M315 in June (Fig. 3.8). The higher soil Bray II P in the mineral treatments is due to the applied P being plant-available immediately, whereas the organic treatments first have to undergo mineralisation to make the P available for plant uptake. There was a decrease across all fertilizer treatments from June to July. At the end of the winter months there was no statistically significant difference between treatments indicated by a general decrease in the mineral and an increase in the control and organic treatments. Bray II P showed a positive and negative trend with soil temperature and soil water content at 15 cm soil depth, respectively. Organic treatments failed to be significantly higher than the control indicating P mineralisation was insufficient due to low soil temperatures.

The foliar P content varied among all treatments with only O232 being significantly higher than the control in June (Fig. 3.9). The decrease in Bray II P in July is accompanied by an increase in foliar P with a significant increase in the control, M324 and O315. M324 foliar P (0.15 %) was above the 0.1 % toxicity threshold value for fynbos plants (Hawkins, *et al*., 2008), which can have negative effect on plant growth. All other treatments fall within the optimal growth range of 0.3 – 0.5 % P (Marschner, 1995) and are supported by the value of 0.07 % found in the 15 mg P/kg application field study by Lourenco (2018). The decrease in foliar P in August to between 0.05 – 0.09 % is possibly due dilution as plant growth increases, and is comparable to 0.09 % found by Stassen (1987) in the same month. Foliar P in the mineral treatments showed a positive trend with soil water content at 15 cm soil depth.

All treatments had a very low fertilizer efficiency for P (2 – 3.2 %), with the mineral 3:1:5 treatment having a significantly higher efficiency (Fig. 3.10). These low values indicate that translocation of P from roots to shoots is a slow process in rooibos and that P application should not be done on a regular basis.

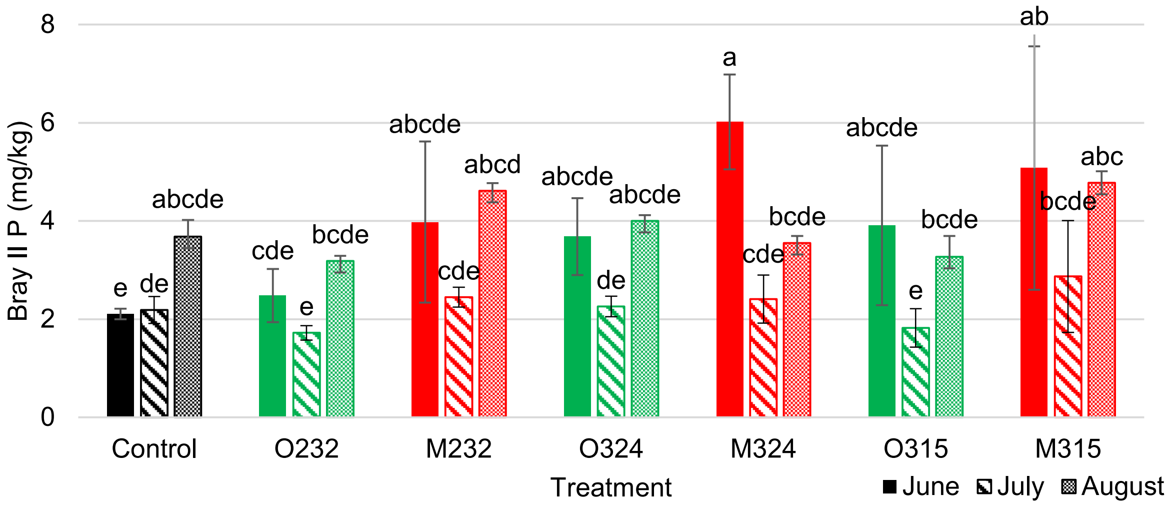

Figure 3.8: Plant available soil P (mean ± SE) in the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

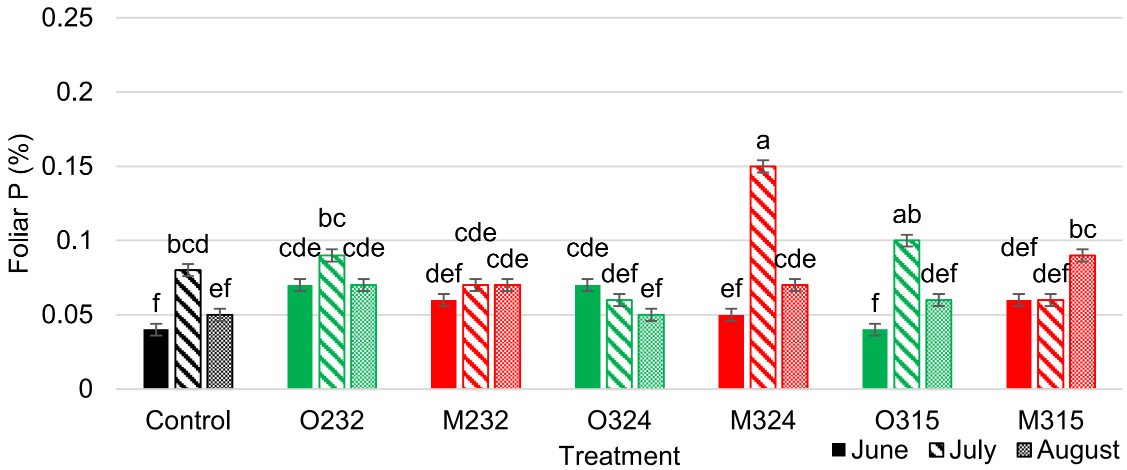

Figure 3.9: Foliar P content (mean ± SE) during the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: C: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

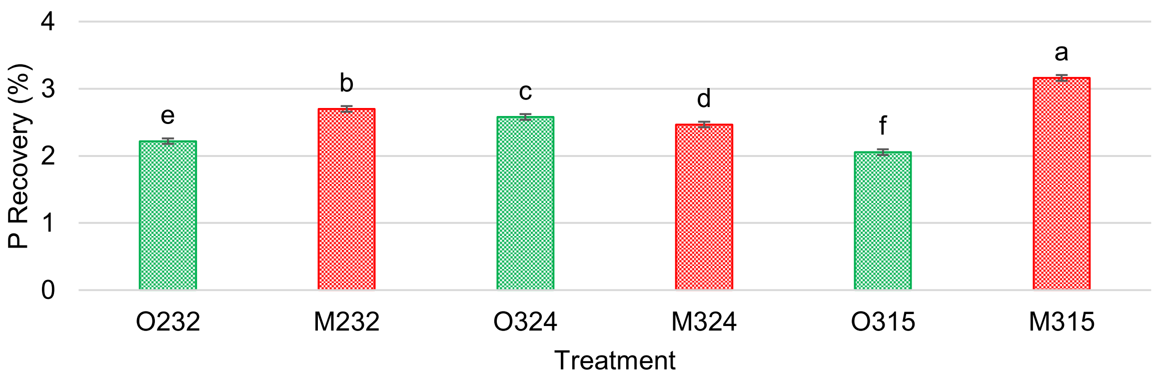

Figure 3.10: Fertilizer efficiency in terms of foliar P content (mean ± SE) three months after fertilizer application. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

3.4.4 Potassium

One month after application the exchangeable K contents in the higher applied K treatment was significantly higher than the control (Fig. 3.11). In June, in the organic treatments exchangeable K showed a positive trend with applied K, however for mineral treatments there was no trend. Exchangeable K decreased in all treatments over time with no significant differences occurring across all treatments in July and August. This decrease is possibly due to plant uptake or leaching during the higher soil water content in July.

Foliar K varied across all treatments with organic treatments initially showing a positive correlation of increased foliar K with applied K (R^2 = 0.9366). The increase in foliar K in July across all treatments (Fig. 3.12) can be linked to the decrease in soil K during the same period. In August foliar K concentrations decrease in all treatments, except M315, possibly due to dilution caused by plant growth. Foliar K showed a negative and positive correlation with soil temperature and soil water content at 15 cm soil depth. At the end of the winter months there was no trend regarding applied or exchangeable soil K and foliar K. Foliar K contents across all treatments and months are low (0.3 - 0.55 %) as it falls below the optimal growth threshold for plants of 2 – 5 % (Marschner, 1995), but are similar to values found in other studies (Stassen, 1987; Smith, 2014, Nieuwoudt, 2017; Lourenco, 2018), indicating norms for rooibos plants.

Fertilizer efficiency for applied K was significantly higher in mineral treatments when compared to organic treatments at the same application rate (Fig. 3.13). The lower application rate (24.2 kg/ha) was significantly higher at 16 – 21 % compared to 12 % (66.5 kg/ha) and 4 % (181.3 kg/ha), however, it is still a low value.

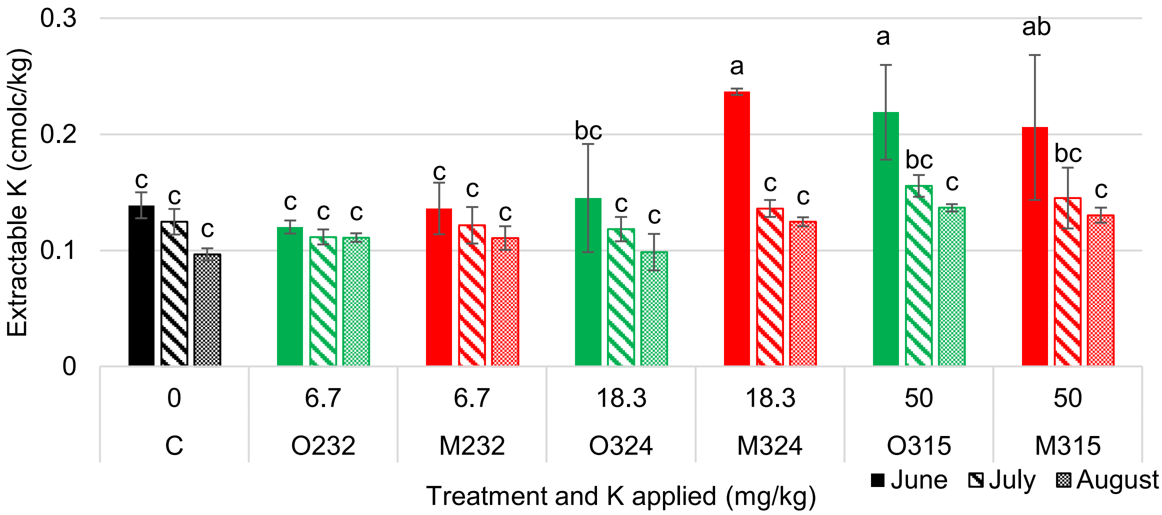

Figure 3.11: Exchangeable K (mean ± SE) of control and fertilizer treatments in the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: C: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

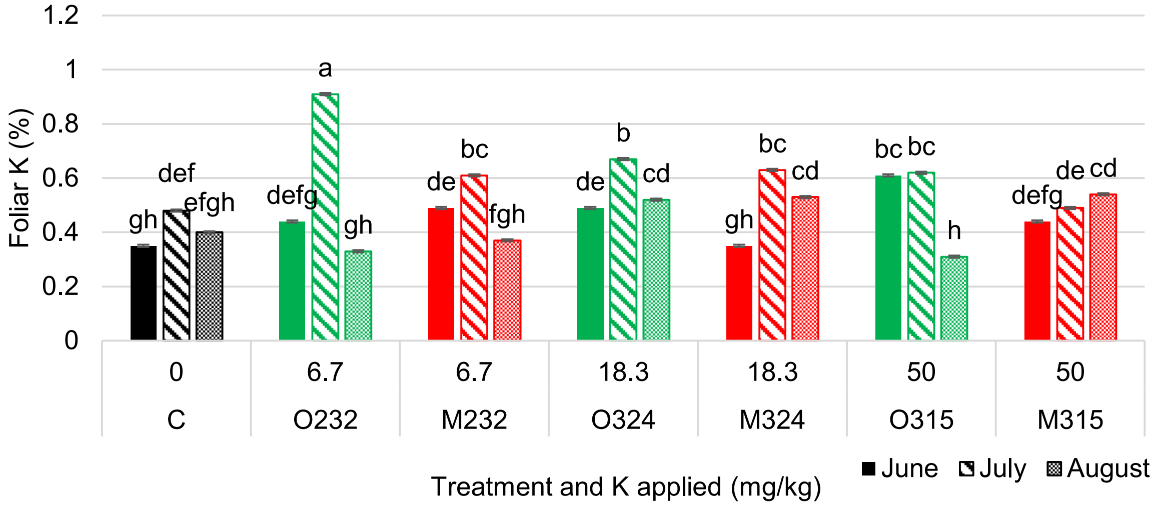

Figure 3.12: Foliar K content (mean ± SE) during the winter rainfall months. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: C: Control; O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

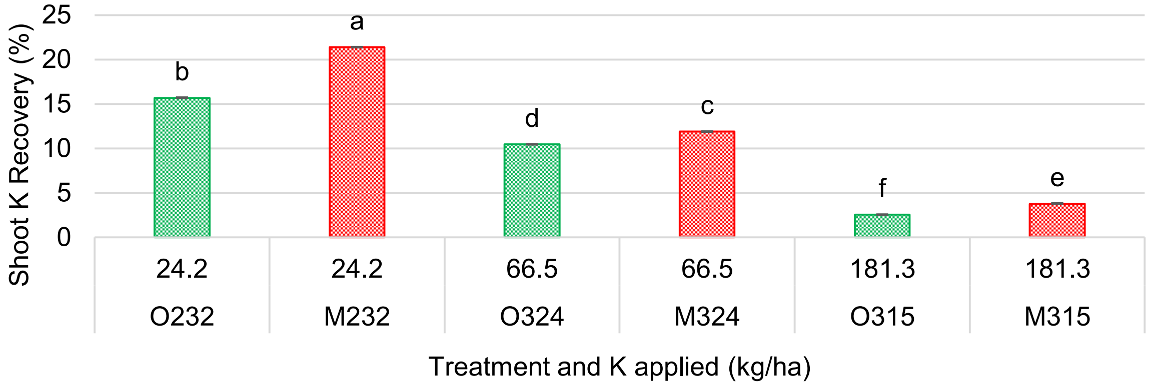

Figure 3.13: Fertilizer efficiency in terms of foliar K content (mean ± SE) three months after fertilizer application. Bars with different lower case letters indicate a significant difference at a 95 % confidence interval. (Treatments: O: Organic fertilizer - indicated by green; M: Mineral fertilizer – indicated by red)

3.5 Conclusions

The mineral fertilizer initially provides a higher source of plant-available nutrients, however, there was an indication the nutrient levels decline over time. This decline is either linked to plant uptake and/or leaching, in the case of N and K, or fixation as for P. Organic fertilizer ineffectively mineralised during the winter months indicating that warmer summer temperatures are required for effective mineralisation to occur. Foliar concentration corresponded to other studies indicating typical foliar nutrient concentrations of rooibos. The earlier peak in foliar nutrient concentrations is linked to the higher soil water content in July and warmer drought conditions in August stimulating earlier plant growth that led to the dilution and decrease in foliar nutrient concentrations. However, the earlier growth can have a negative impact on biomass production as less nutrients are accumulated by the plant. The prevailing drought conditions reduced the time for nutrient accumulation and stimulated earlier plant growth which can limit the biomass production of rooibos tea.

A higher N and P application in the mineral form resulted in a continuous uptake. This does not necessarily mean that there was no plant growth occurring, however, it could indicate that if sufficient nutrients are available that nutrient accumulation will still occur while the plant is growing in warmer conditions. This continued uptake can lead to an increased biomass yield.

Fertilizer efficiency was found to be highest at the lowest application rates of N and K. A higher application rates of N and K are at a loss as the nutrients are possibly lost through leaching. The efficiency of the applied N can even be lower than assumed as is was not quantified how much N was taken up due to N-fixing bacteria associated with the rooibos plant. The low P efficiency indicates that low application rates of P fertilizer should be efficient to sustain plant growth.

The mineral treatment M232 (6.7 mg N, 10 mg P and 6.7 mg K/kg) was the most efficient for NPK uptake across all treatments. The results lead to the conclusion that mineralisation of organic fertilizers is ineffective during the low temperature winter months, therefore the addition of mineral fertilizers will be more effective, in the short-term, as it provides plant-available nutrients during the nutrient uptake season of rooibos plants. The addition of mineral fertilizers under drought conditions also ensures that nutrients are available for plant uptake as soon as the soil water content increases.

4 RESEARCH UNIT 2: EFFECT OF ORGANIC AND MINERAL FERTILIZERS ON SOIL FERTILITY AND ROOIBOS TEA PRODUCTION

4.1 Introduction

Soils in the Cape Floristic Kingdom (CFK) naturally have low amounts of inorganic N and P nutrients, therefore fynbos plant species have adapted to the nutrient-poor soils by forming cluster roots, which are efficient in P uptake (Hawkins, *et al*., 2008). Low available P can greatly inhibit plant root growth which affects the uptake of essential nutrients and inhibits plant growth (Meng, *et al*., 2005). Phosphorus in soil is the most inaccessible of all plant nutrient elements (Holford, 1997). Phosphorus limitation is driven by several factors, including: loss of inorganic and dissolved organic P through leaching; slow release of P from mineral sources; low inputs of P; and the high supply of other mineral resources, such as N, which can cause P limitation (Vitousek, *et al*., 2010). Increasing the P content of the soil can promote plant growth and nutrient uptake, however, by applying unusually high P content to the soil can lead to P toxicity and inhibit plant growth. During the winter months, P is taken up by the rooibos plant and stored in the roots until summer when shoot growth occurs (Jeschke & Pate, 1995; Smith, 2014). Therefore determining the optimum P level, and the associated N and K within the soil, will be advantageous for fertilizer recommendations for rooibos tea production.

Rooibos also forms symbiotic relationships with N-fixing bacteria in N-nodules and Vesicular-arbuscular (VA) mycorrhizae that interact with the plant. Rooibos plants are able to raise its rhizosphere pH, which facilitates nodulation, which is most effective at a pH between 4 and 6.8 (Muofhe & Dakora, 2000). VA mycorrhizae are able to stimulate P nutrition in legumes and in turn promote nodulation and N_2-fixation. Mycorrhizal colonization of roots can also improve root resistance to pathogens (Zeng, 2006) and improve plant resistance to drought (Lehto, 1992).

Both Meng, *et al*. (2005) and Liu, *et al*. (2010) concluded that the integrated use of organic manure or compost and chemical fertilizers enhanced soil organic carbon and crop yields. Therefore, to improve soil fertility, organic fertilizers alone or with chemical fertilizers can be used. However, due to the slow releasing mechanism of organic fertilizers, the increase in plant growth and crop yield can take up to 3 – 5 years before the increase becomes significant (Parr, *et al*., 1992). Rooibos plants are adapted to low nutrient soils, therefore the slow release of nutrients in organic fertilizers might be more advantageous that concentrated mineral fertilizers.

In this chapter the effect of organic and mineral fertilizer application, of varying NPK ratios, on soil fertility and rooibos production was investigated. The soil was analysed for chemical changes in pH, EC, exchangeable acidity and basic cations, plant available P, total C and N, and trace elements. Plant foliar nutrient composition and yield was investigated and correlated with soil properties to determine the effect on plant growth.

4.2 Objectives

1. To investigate the effect of organic and mineral fertilizers on soil fertility.
2. To examine the effect of the application of organic and mineral fertilizers, with three varying NPK ratios, on 1-year rooibos plant properties (plant nutrients and tea yields) under two different rainfall regimes in the Nieuwoudtville region.
3. To determine fertilizer efficiency based on plant nutrient uptake.

4.3 Methods and materials

4.3.1 Site description

The fertilizer field trials were conducted on two farms, Rogland and Blomfontein, with varying climatic and environmental conditions. Rogland was situated in the Northern Bokkeveld region and Blomfontein was situated in the Southern Bokkeveld region. Rooisbos plants were planted in June 2016 and was one year old when the experimental trials commenced.

The soil type and depth at the sites differed with a Cartref (650 mm) and Glenrosa (450 mm) (as described in Chapter 3) occurring at Rogland and Blomfontein, respectively. Both had a coarse sand texture with relic plinthic rock restricting the depth of the soil profile. The sites showed differences in above-ground vegetative growth with the plant density and growth between rooibos plant rows being considerably higher at the Blomfontein site (Fig. 4.1). Both sites had succulent plant growth which was mechanically removed by labourers, however Blomfontein had a higher occurrence of grass growth that was not removed. The presence of the grasses increased competition for applied nutrients for the rooibos plants.

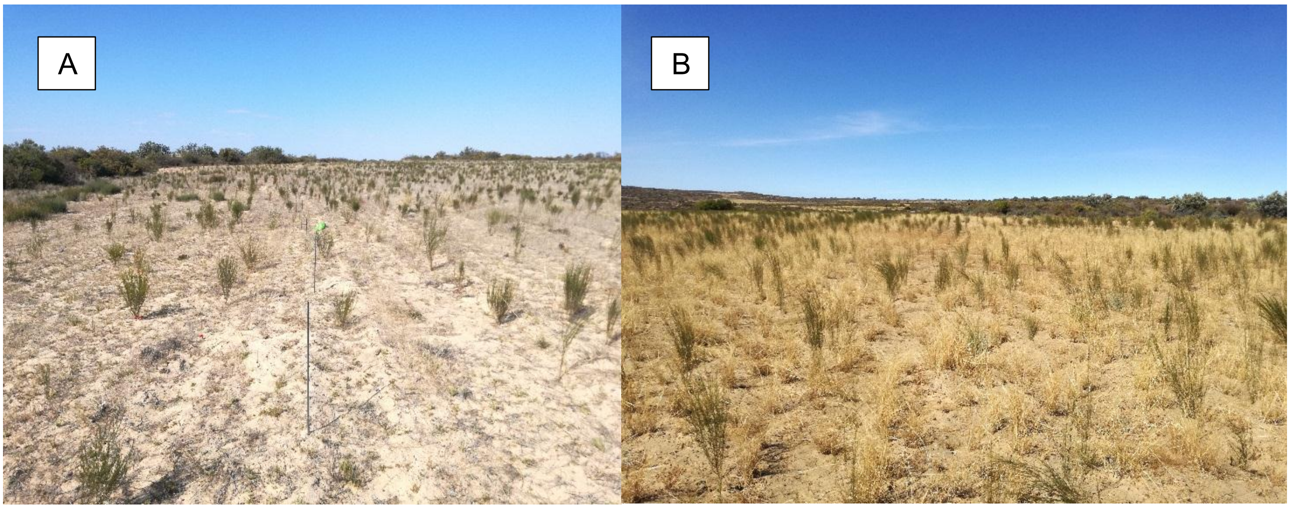

Figure 4.1: Pictures indicating the differences in above-ground vegetative growth occurring between the rooibos plant rows at A) Rogland and B) Blomfontein.

4.3.2 Experimental design

The field trial consisted of three commercial organic (O232, O315 and O324) and three commercial mineral (M232, M315 and M324) fertilizer treatments, with three different NPK ratios, applied at four treatment levels (Table 4.1). The organic nutrient NPK ratio application treatments were 2:3:2; 3:1:5

and 3:2:4. Both the O232 and O315 fertilizers were derived from bone meal and animal blood, whereas the O324 fertilizer was chicken-manure based. The mineral fertilizer treatments were blended using urea ($CO(NH_2)_2$: 46 % N), double superphosphate ($Ca(H_2PO_4)_2$: 20 % P) and potassium chloride (KCl: 50 % K) to match the NPK ratios and nutrient application of the organic fertilizer treatments.. The four treatment levels for each organic and mineral nutrient ratio treatment were based on the P application rate (3.3, 10, 30 and 60 mg P/kg soil) as rooibos is a fynbos species and is known to be sensitive to P. The P application rates were described as low, medium1, medium2 and high. The P application rates were based on previous studies by (Joubert, *et al*., 1987) and on-going field trial research of Mr JFN Smith. Each treatment was replicated four times in a completely randomized block design. The fertilizer was applied on 1 June 2017.

At Rogland (Table 4.1), the replicated plots consisted of 10 rows with each row having five or six plants (Total: 50 - 60 plants), covering an area of 22.5 m^2. Band application of 0.6 m was used therefore only 18 m^2 was fertilized per plot. At Blomfontein, only the lower NP blend, organic 2:3:2 and 3:2:4 and mineral fertilizer equivalents, were evaluated due to financial constraints. Due to the difference in planting density between sites, the Blomfontein plots consisted of 10 rows with each row having 10 plants (Total: 100 plants), covering an area of 48 m^2. Band application of 0.6 m was used therefore only 24 m^2 was fertilized per plot. Plants were topped in August 2017, according to typical rooibos cultivation practices, to promote lateral growth of the bushes.

The fertilizers were band placed by hand along the planting rows of the rooibos plants, and then worked into the soil to a depth of approximately 15 cm using a spade. This was done to enhance the fertilizer efficiency by applying it close to the roots of the plants. The amount of fertilizer applied was calculated based on the volume of soil to be enriched by the applied fertilizer and the determined dry soil bulk density of 1612 kg/m^3.

At each site a logging weather station was installed to measure temperature and precipitation and to calculate potential evaporation at each site. A soil echo logger was installed at each site (in a control block) to monitor soil water and temperature at five soil depths (5, 15, 25, 40 and 60 cm) in real-time. This information was used to understand the mineralisation rates of the organic fertilizers, nutrient uptake and climatic difference between the two sites.

Table 4.1: Organic and mineral NPK treatment applied on Rogland and the amount (kg) applied per hectare. Plot size 22.5 m^2 with a banded application area of 12 m^2

Treatment	Code	NPK applied mg/kg			kg/ha
		N	P	K	
Control	C	0	0	0	0
Organic 2:3:2	O232 (low)	2.2	3.3	2.2	175.1
	O232 (med1)	6.7	10	6.7	525.5
	O232 (med2)	20	30	20	1577
	O232 (high)	40	60	40	3154
Organic 3:1:5	O315 (low)	10	3.3	17	605
	O315 (med1)	30	10	50	1813
	O315 (med2)	90	30	150	5440
	O315 (high)	180	60	300	10880.4
Organic 3:2:4	O324 (low)	4.8	3.3	6.1	671
	O324 (med1)	14.5	10	18.3	2015
	O324 (med2)	43.3	30	55	6045
	O324 (high)	86.7	60	110	12090
Mineral 2:3:2	M232 (low)	2.2	3.3	2.2	82.35
	M232 (med1)	6.7	10	6.7	248.7
	M232 (med2)	20	30	20	746.15
	M232 (high)	40	60	40	1492.25
Mineral 3:1:5	M315 (low)	10	3	17	329.5
	M315 (med1)	30	10	50	988.15
	M315 (med2)	90	30	150	2964.95
	M315 (high)	180	60	300	5930
Mineral 3:2:4	M324 (low)	4.8	3.3	6.1	158.3
	M324 (med1)	14.5	10	18.3	475.15
	M324 (med2)	43.3	30	55	1425.3
	M324 (high)	86.7	60	110	2850.65

4.3.3 Soil sampling

At each experimental site the soil was classified and described according to the South African Soil Classification system (Soil Classification Working Group, 1991) and is described in Chapter 2.

Soil samples were sampled with a soil auger at 0 – 15 cm depth at tea harvest in February 2018 for chemical analysis. Four samples were taken in each treatment replicate and bulked in the field to provide four composite soil samples for each treatment. This was necessary to know the topsoil nutrient levels in each treatment at the start of the trial and end of the trial. All soil samples were air-dried and sieved through a 2 mm sieve prior to analysis.

4.3.4 Chemical analysis

The pH of the soil was determined in both water and 1 M KCl using a 1:2.5 suspension ratio on a mass basis (Thomas, 1996). Soil electrical conductivity (EC) was determined using the saturated paste method in 1:2.5 soil to water ratio on a mass basis (Rhoades, 1996). A soil sample of 5-10 g was ball-milled to a fine powder prior to the determination of total C and N. The total C and N content of the soil will be determined using the Eurovector Elemental Analyzer (dry combustion method). Plant-available P was determined using the Bray 2 extraction method (Kuo, 1996). Exchangeable basic cation content of the soils was determined using the 1 M NH_4OAc (ammonium acetate) (pH 7.0) method (Sumner & Miller, 1996). Exchangeable acidity of the soils was determined using the 1 M KCl extraction method (Thomas, 1996). Plant-available micronutrients (Fe, Cu, Mn, Zn) were determined using the DPTA-extraction method (Westerman & Mickelson, 1990).

4.3.5 Physical Analysis

Texture (five fractions) was analysed by Elsenburg Laboratory to determine the clay, silt and sand content of the soil. Soil bulk density was determined at five soil depths (5, 15, 25, 40 and 60 cm) at each study site using the undisturbed core method (Blake & Hartge, 1986). The bulk density samples were taken in the same hole that was dug to classify the soil form. The mass of the soil core was determined in the laboratory and the total soil volume was determined by taking the measurements of the ring that was used during sampling.

4.3.6 Plant sampling

Plant survival

The number of living plants were counted in each treatment replicate at fertilizer application (June 2017) and again at harvest (February 2018). Plant survival was expressed as the percentage of plants that survived of the original number of plants.

Tea yield

The rooibos plants were harvested in February 2018 and the total biomass yield was determined for each replicate. The number of plants within the replicate was used to determine the average yield per plant (kg/plant). The average number of plants per replicate in June 2017 was used to determine the expected number of plants per hectare. This was then used to calculate the expected yield per hectare per treatment replicate (kg/ha). Survival-adjusted yield was calculated by multiplying the yield per hectare with the plant survival rate.

4.3.7 Plant analyses

Foliar sampling was performed in February 2018 at tea harvest to assess nutrient content. The plant samples were rinsed with distilled water, cut into smaller pieces and oven-dried before dry mass was determined. Total N content of the dried samples was determined using the Kjeldahl method (N), and other essential elements (P, Ca, Mg, K, Na, Fe, B, Zn, Mn, Cu and Al) using acid digestion and ICP-MS by Elsenburg Plant Laboratory. Fertilizer efficiency was calculated as described in Chapter 3.

4.3.8 Statistical Analysis

Statistical analyses performed using Statistica™ Software (Version 13.3, 2018, Dell Software, Tulsa). The data was tested for significant differences between treatments at a 95 % confidence level between the different fertilizer treatments.

4.4 Results and discussion

4.4.1 Preliminary Analysis

The average soil pH values (H_2O) at both field sites were acid which is typical for rooibos cultivation areas within the fynbos vegetation regions (SARC, 2016) (Table 4.2). Total C and N was very low ranging from 0.32 – 0.53 % C and 0.02 – 0.04 % N. Bray II P varied between the two sites, however, both were still relatively low (< 8 mg/kg). Soil ECEC was higher than field conditions in Clanwilliam (Lourenco, 2018), but still low which is expected in coarse sandy soils.

Table 4.2: Average preliminary soil chemical and texture properties (0 – 15 cm) at the field trial sites (R: Rogland; B: Blomfontein) prior to the application of fertilizers.

Study Site	pH (H_2O)	pH (KCl)	EC (µS/cm)	% C	% N	Bray II P (mg/kg)	Ca (cmolc/kg)	Mg (cmolc/kg)	Na (cmolc/kg)	K (cmolc/kg)	Exch. Acidity (cmolc/kg)	ECEC (cmolc/kg)	Cu (mg/kg)	Zn (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Texture
R	5.82	4.91	64.6	0.32	0.02	3.73	0.87	0.32	0.10	0.15	0.09	1.53	0.10	0.22	2.78	15.71	Coarse sand
B	5.37	4.26	110.5	0.53	0.04	7.57	1.02	0.45	0.11	0.13	0.22	1.93	0.08	0.28	6.33	44.15	

4.4.2 Climatic data

The prevailing drought conditions that occurred throughout the study period was evident when one looks at the rainfall received by both farms. Rogland, which has an annual expected rainfall of 450 – 550 mm, only received a total of 161.6 mm and Blomfontein, expected rainfall of 350 – 450 mm, a total rainfall of 208.8 mm. Both farms received rainfall during the winter and summer months however it was the very low winter rainfall that emphasises the drought conditions as both farms are in a winter rainfall region (Fig. 4.2). Rogland received 87.9 mm and Blomfontein 123.6 mm during the winter months, which only makes up 19.5 and 35.3 % of the average annual rainfall, respectively. The differences in soil profile depth of 600 mm at Rogland and 450 mm at Blomfontein has an influence on the water content within the soil. The lower soil depth and higher rainfall at Blomfontein resulted in a higher level of soil water content throughout the experimental trial (Fig. 4.2).

The low rainfall during the hot dry summer resulted in the soil water content (SWC) only increasing at the shallow depths (Fig. 4.3). During the wet months increased rainfall increased the SWC at a depth of 5, 15, 25 and 60 cm, however little or no increase was observed at 40 cm. This can be linked to the low rainfall not reaching deeper depths or low root biomass resulting in water leaching easily to deeper a depth or subsurface flow. The increase in SWC at 60 cm depth is due to the water accumulating on the bedrock at the bottom of the soil profile. The water movement through the profile was slow with it taking up to 18 days between the rainfall event and an increase in SWC at 60 cm. A general decrease occurred in SWC at all depths from September 2017 until a large event in January 2018.

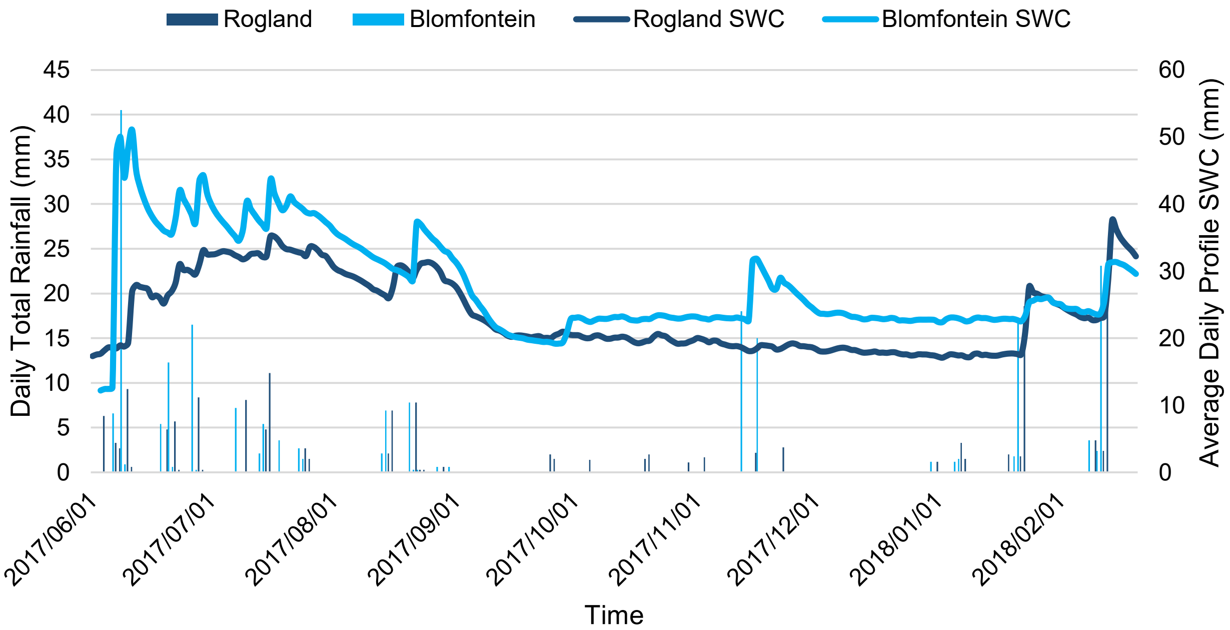

Figure 4.2: Rainfall (mm) and total profile soil water content (mm) of Rogland and Blomfontein during the time period of the experimental trial.

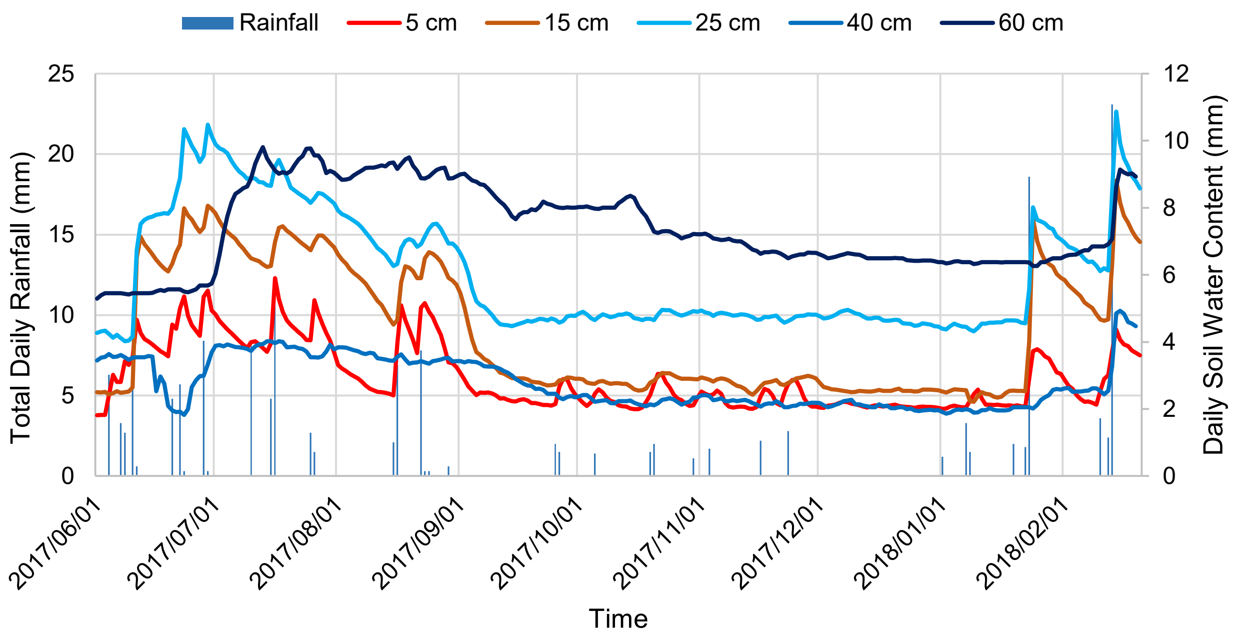

Figure 4.3: Rainfall (mm) and soil water content (mm) at increasing depths at Rogland during the period of the experimental trial.

Ambient temperature (°C) was similar at both sites with a minimum and maximum temperature ranging relatively between the same values (Fig4.4). Rogland had a minimum and maximum temperature of -3.5 and 40.8 °C occurring in July and December 2017, respectively. Blomfontein had a minimum and maximum temperature of -1 and 39.4 °C occurring in August and December 2017, respectively. Monthly average ambient temperatures showed a slight decrease from June to August during the winter months, then increased to peak in January (Rogland) and February (Blomfontein).

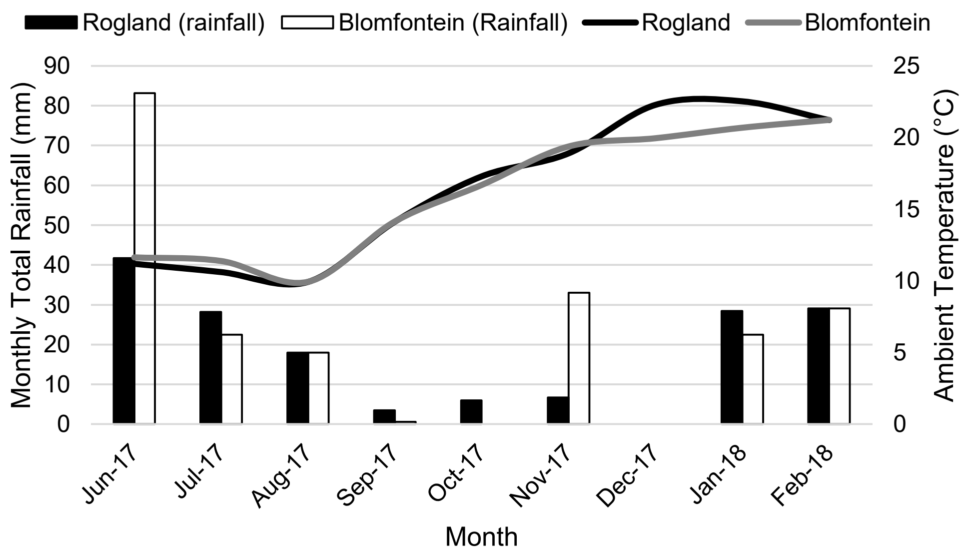

Figure 4.4: Monthly total rainfall (mm) and average ambient temperature (°C) for the study sites Rogland and Blomfontein throughout the study period from June 2017 to February 2018.

4.4.3 Plant Survival and Growth

Plant survival

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on plant survival at both farms. Treatment type had no significant effect on plant survival at Blomfontein (Fig. 4.6), however at Rogland a significant effect was found (Fig. 4.5). P applied at 3.3 and 30 mg P/kg in the organic and 30 and 60 mg P/kg in the mineral fertilizers showed a significant increase in plant survival at Rogland (Fig. 4.7A). No significant changes were found at Blomfontein (Fig. 4.7B), however a negative trend was observed with increased P application in the mineral fertilizer. At Rogland, positive trends were found between plant survival and soil P in the mineral fertilizers.

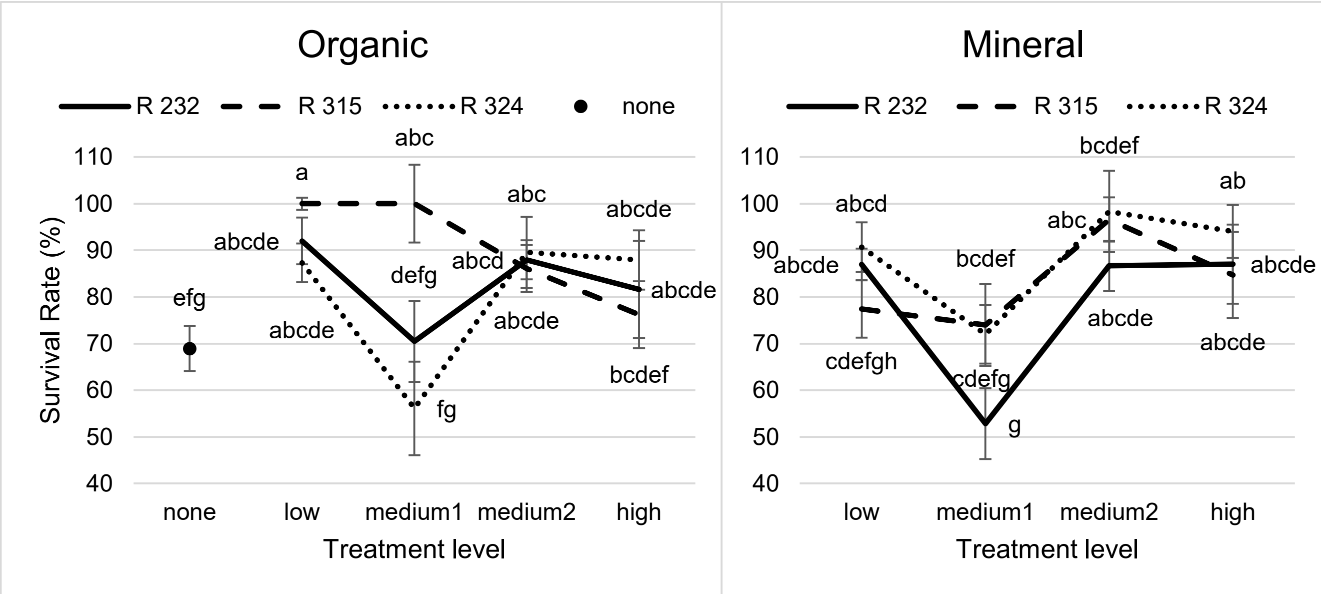

Figure 4.5: Effect of fertilizer type, NPK ratio and treatment application level on plant survival at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

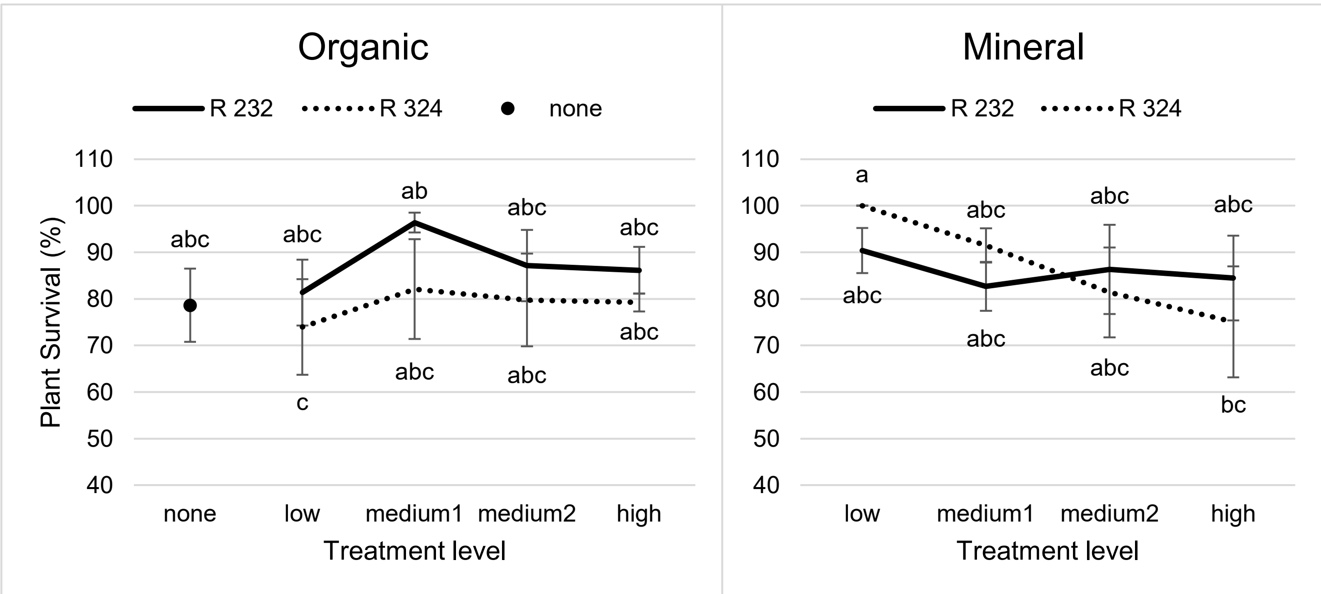

Figure 4.6: Effect of fertilizer type, NPK ratio and treatment application level on plant survival at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

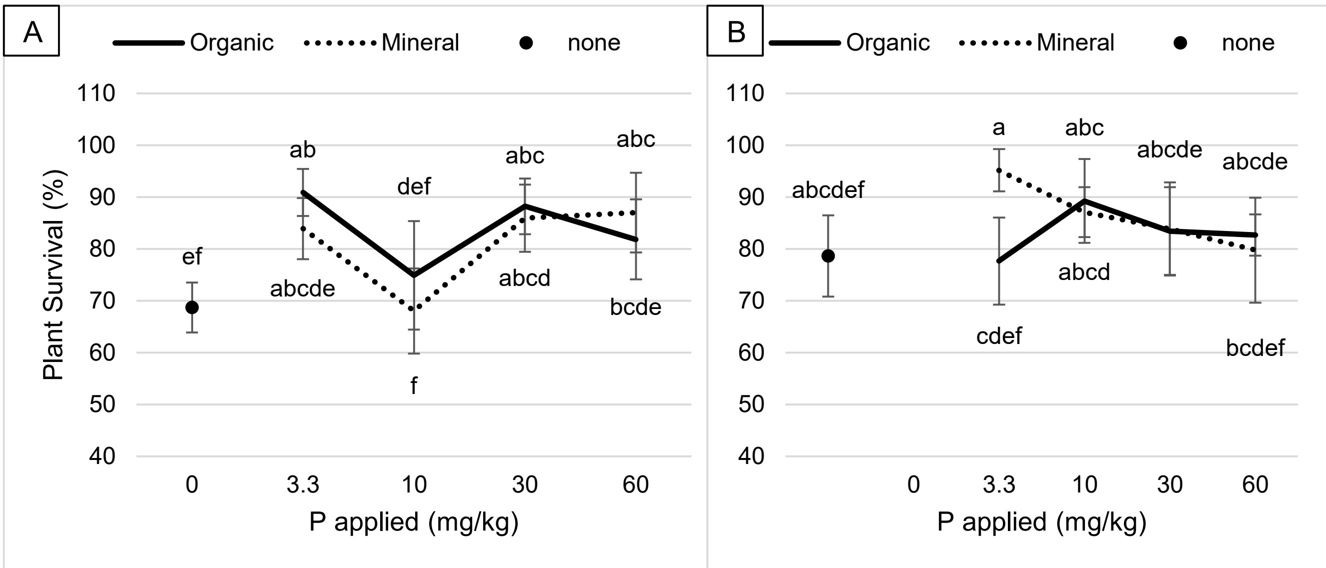

Figure 4.7: Effect of P application on plant survival in the organic (solid line) and mineral (dotted line) fertilizers in February at Rogland (A) and Blomfontein (B). Lowercase letters indicate a significant difference at a 95 % confidence interval.

Tea yield per plant

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on tea yield at both farms. However, treatment level had a significant effect at Rogland (Fig. 4.8) and Blomfontein (Fig. 4.9). Average tea yields per plant were generally higher at Rogland with a yield of 0.2 ± 0.05 kg/plant in the control compared to 0.15 ± 0.07 kg/plant at Blomfontein, however the number of plants harvested was higher at Blomfontein. The higher density of other plants (grasses and succulents) occurring at Blomfontein increased competition for nutrients, potentially inhibiting growth of the rooibos plants. Therefore the lower plant density and competition for nutrients resulted in increased tea yields per plant at Rogland.

Higher tea yields were obtained at Rogland with the highest average tea yield per plant obtained in the organic 3:2:4 fertilizer (0.32 ± 0.2 kg/plant) at the second treatment level (14.5 N; 10 P; 18.3 K mg/kg) and in the mineral 3:1:5 fertilizer (0.3 ± 0.07 kg/plant) at the second treatment level (30 N; 10 P; 50 K mg/kg). At Blomfontein the highest yield was obtained in the organic 2:3:2 fertilizer (0.18 ± 0.1 kg/plant) at the second treatment level (6.7 N; 10 P; 6.7 K mg/kg). At Rogland plant survival was negatively affected at this treatment level, although not significant, therefore less competition resulted in individual plants producing a larger yield.

There was a general decrease in yield per plant with an increase in nutrient application at both farms. At Rogland the application of 10 mg/kg P in the organic and mineral fertilizers had a significantly higher tea yield per plant than other applied treatments, but was not significantly higher than the control (Fig. 4.10A). At Blomfontein tea yield increased at 10 mg P/kg organic fertilizers, however this increase was insignificant (Fig. 4.10B). At Rogland, plant survival was negatively affected at the

10 mg/kg P treatment resulting in less competition for nutrients, therefore plants that survived were larger and produce a higher tea yield.

At Rogland, positive trends were found between tea yield and foliar Mn in the organic and mineral fertilizers and with foliar P in the organic fertilizer. The organic fertilizers also showed a positive trend with foliar P at Blomfontein. A negative trend was found with soil Mg in the organic fertilizers across both farms and with foliar Mg in the mineral fertilizers at Rogland. However these harvest yield values don't consider the effect of the nutrient applications on plant survival.

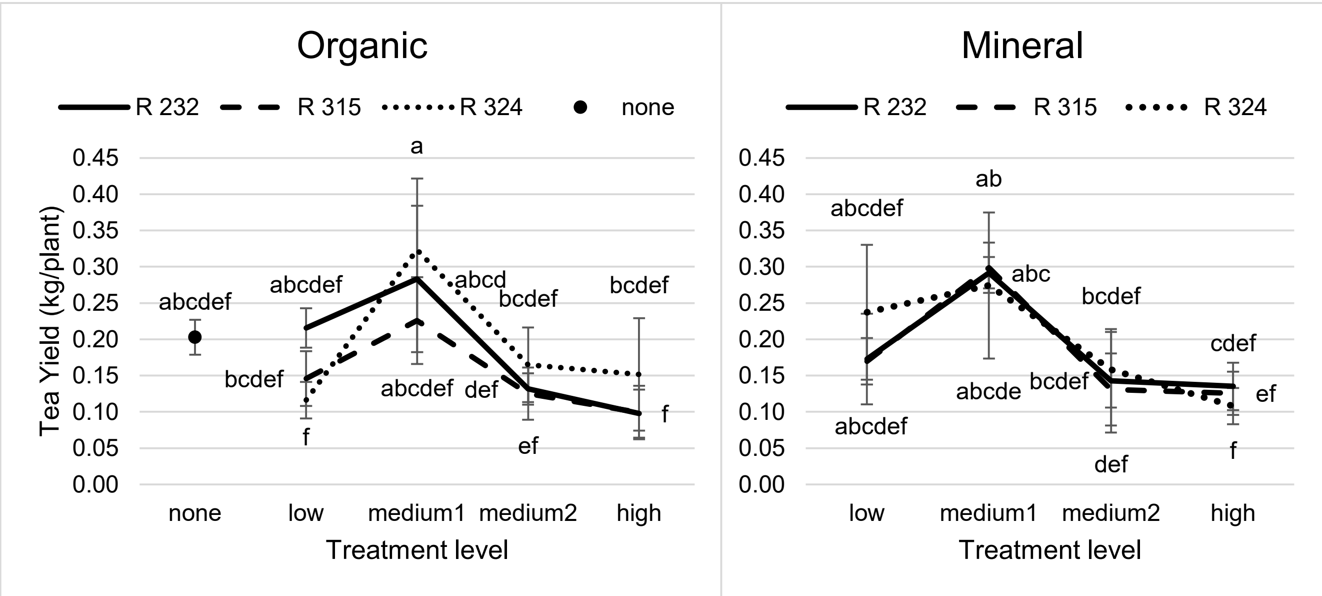

Figure 4.8: Effect of fertilizer type, NPK ratio and treatment application level on average tea yield per plant at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

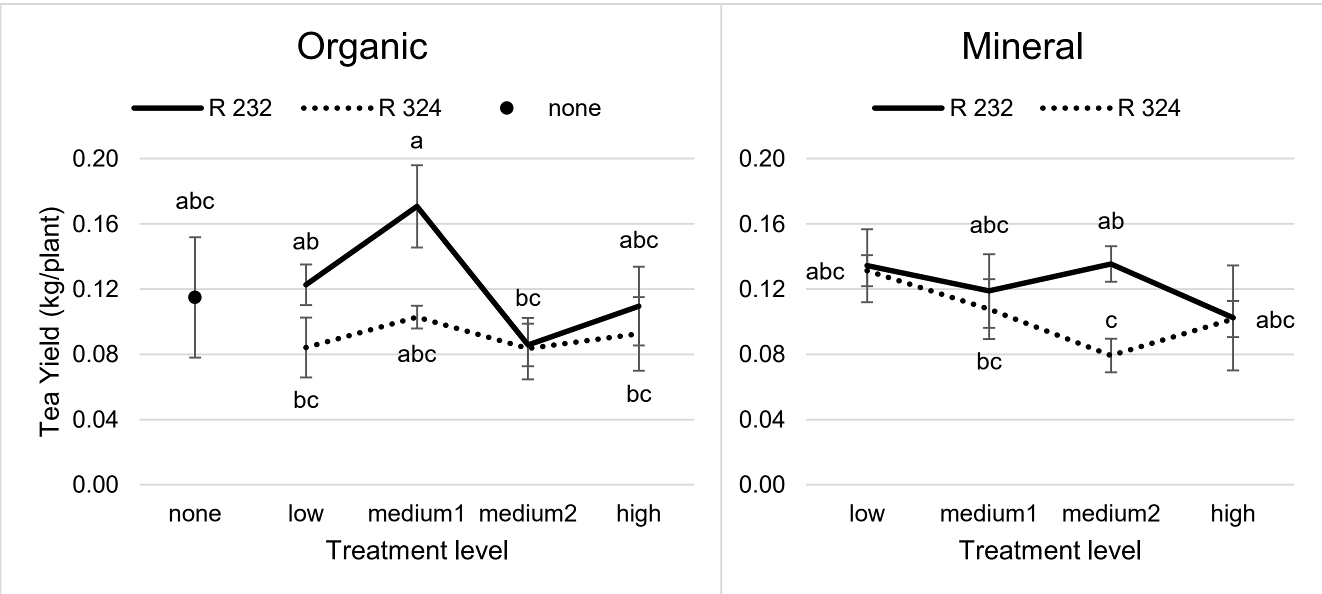

Figure 4.9: Effect of fertilizer type, NPK ratio and treatment application level on average tea yield per plant at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

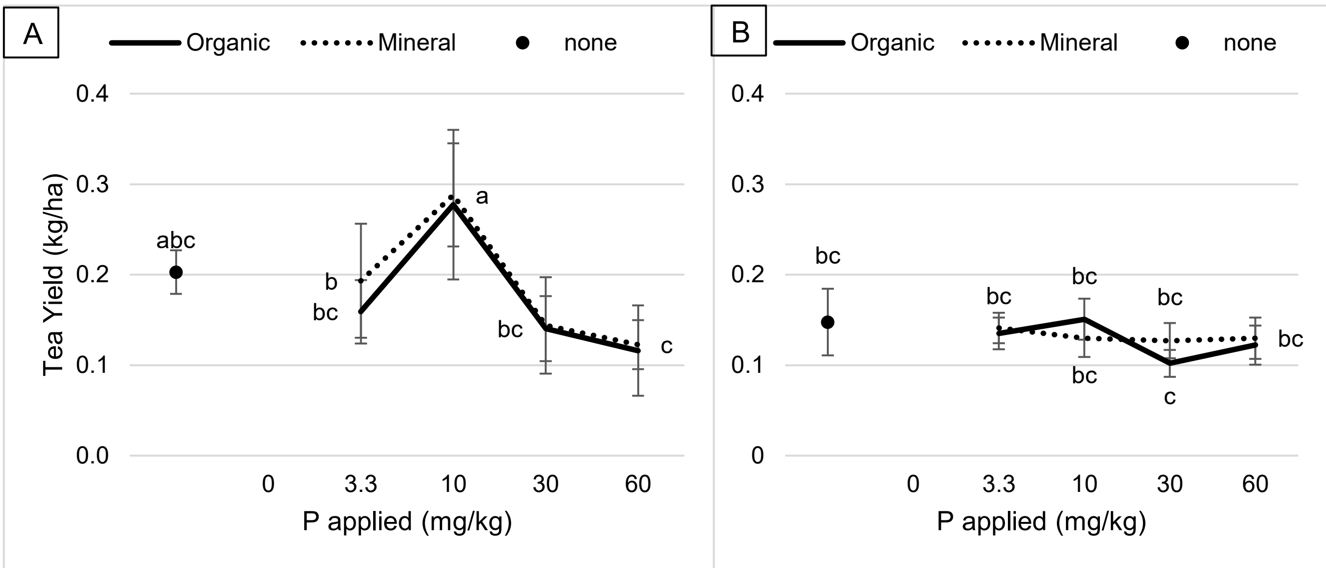

Figure 4.10: Effect of P application on tea yield per plant in the organic (solid line) and mineral (dotted line) fertilizers in February at Rogland (A) and Blomfontein (B). Lowercase letters indicate a significant difference at a 95 % confidence interval.

Survival-adjusted yield per hectare

The effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on survival-adjusted tea yield at both farms. At Rogland, the application of P had a statistically significant effect with the yield decreasing at an application rate above 10 mg/kg P in the organic and mineral fertilizers (Fig. 4.11). The organic (1292 ± 788 kg/ha) and mineral 3:1:5 (1420.3 ± 475 kg/ha) fertilizer at the second treatment level (30 N; 10 P; 50 K mg/kg) produced the highest survival-adjusted yield, with the highest occurring in the latter. At Blomfontein a significant increase was observed in organic 2:3:2 fertilizer (1244 ± 301 kg/ha) at the second treatment level (6.7 N; 10 P; 6.7 K mg/kg), with increased nutrient application significantly decreasing the survival-adjusted tea yields (Fig. 4.12). In the mineral fertilizers the highest survival-adjusted tea yield occurred in the third treatment level of the 2:3:2 fertilizer, however it was not significantly higher than the control.

At both farms in the organic fertilizers the application of 10 mg/kg P (39.3 kg/ha P), although not significantly higher than the control, generally resulted in the highest survival-adjusted yields indicating a preference of rooibos plants, with higher P applications negatively affecting yield (Fig 4.13). In the mineral fertilizers the application of 3.3 and 10 mg/kg P showed to have increased survival-adjusted yields, with higher application having a negative effect. Even with lower rainfall throughout the experimental period the survival-adjusted yields were generally higher at Rogland. The lower survival-adjusted yields at lower nutrient application rates at Blomfontein can be attributed to the higher plant density and increased competition for nutrient uptake by other plant species, including grasses and succulents.

In the organic fertilizers, positive trends were found with foliar P at both farms. Foliar Mn showed positive trends with survival-adjusted yields in the organic and mineral fertilizers at Rogland. This indicates that rooibos plants are not negatively affected by increased Mn uptake, however further research is required to determine to what extent. Foliar Al showed a negative trend with survival-adjusted yield in the mineral fertilizers indicating the negative effect of Al toxicity on rooibos plant growth. The effect of a lower plant survival resulted in yield not being significantly higher at Rogland.

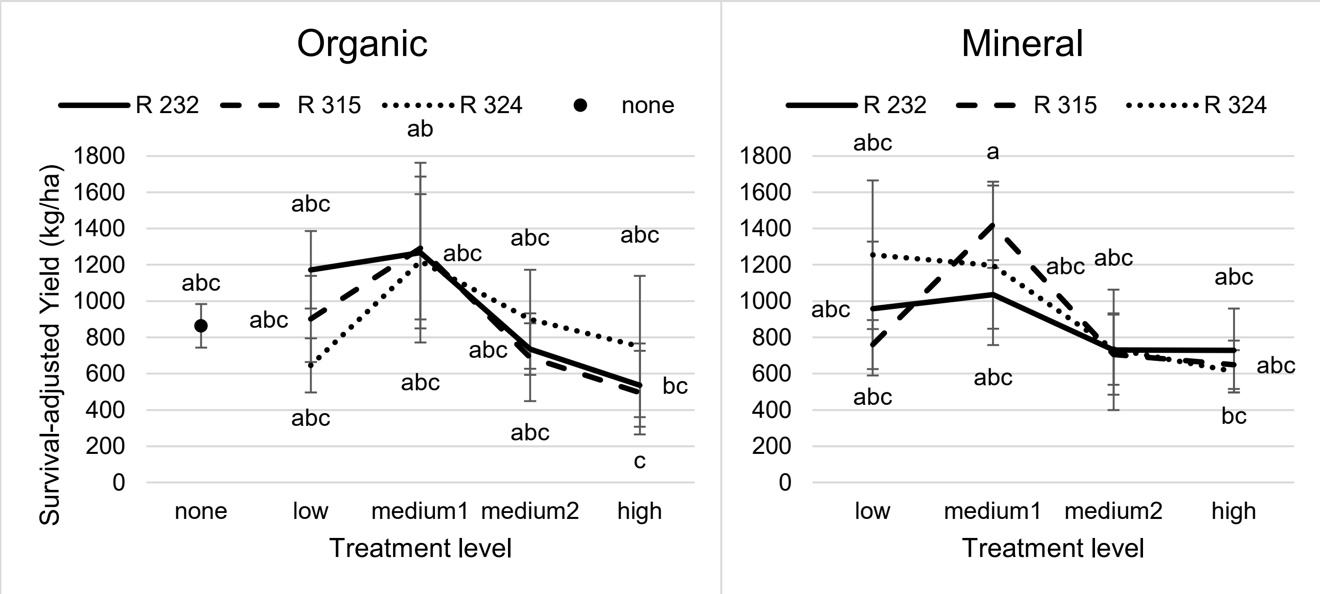

Figure 4.12: Effect of fertilizer type, NPK ratio and treatment application level on survival-adjusted yield at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

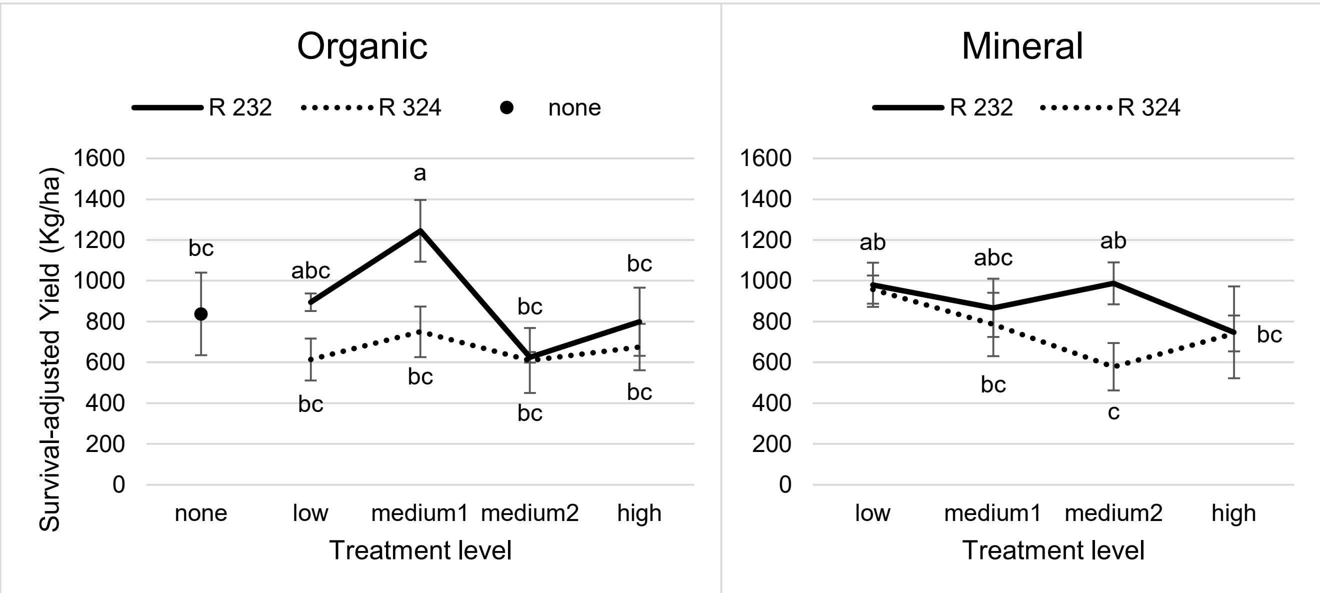

Figure 4.11: Effect of fertilizer type, NPK ratio and treatment application level on survival-adjusted yield at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

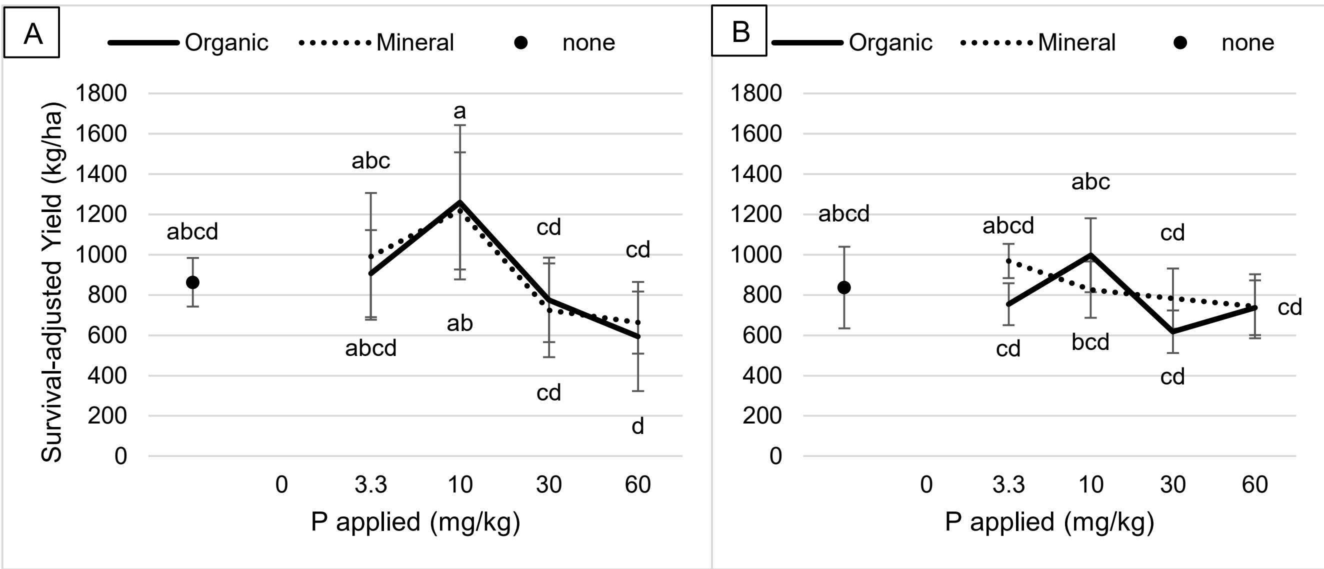

Figure 4.13: Effect of P application on survival-adjusted tea yield in the organic (solid line) and mineral (dotted line) fertilizers in February 2018 at Rogland (A) and Blomfontein (B). Lowercase letters indicate a significant difference at a 95 % confidence interval.

4.4.4 Soil chemical analysis

Soil pH

The factorial effect of fertilizer type, NPK ratio and application rate had a statistically significant effect (3-way ANOVA: p < 0.05) on soil pH (H_2O) at Rogland at harvest in February 2018. A significant increase in soil pH (H_2O) occurred in the organic and mineral 3:1:5 fertilizers at the high treatment level, with the highest occurring in the latter. In the organic fertilizers the application of PO_4^{3-} (bone meal) would have had a liming effect and increased soil pH. Application of higher amounts of N would have also increased pH through hydrolysis of urea which generates alkalinity in the first step of the nitrification process of urea. Application of N showed a significant positive correlation with soil pH (H_2O) in the mineral (R^2 = 0.6587) treatments. Soil pH (H_2O) values in the control treatment were higher at Rogland and similar to those found by Smith (2014) and Lourenco (2018) in the Clanwilliam region.

The effect of fertilizer type, NPK ratio and treatment level had no significant effect (3-way ANOVA: p < 0.05) on soil pH (KCl) at both farms. However at Rogland, treatment level had a significant effect with an increase observed in the organic 3:1:5 and mineral 3:1:5 and 3:2:4 fertilizers at the high treatment level (Fig. 4.14). Application of 60 mg/kg P and above 87 and 110 mg/kg N and K significantly increased soil pH (KCl). NPK ratio and fertilizer type had a significant effect (p < 0.001) with the mineral 3:1:5 fertilizer being significant higher than the control.

Application of N showed a significant positive correlation with soil pH (KCl) in the organic (R^2 = 0.5502) and mineral (R^2 = 0.7253) treatments at Rogland (Fig. 4.15). The increase in soil pH (H_2O and KCl) was only observed at Rogland with treatment type not having a significant effect at Blomfontein with a pH increase only observed in the high treatment levels of the mineral fertilizers.

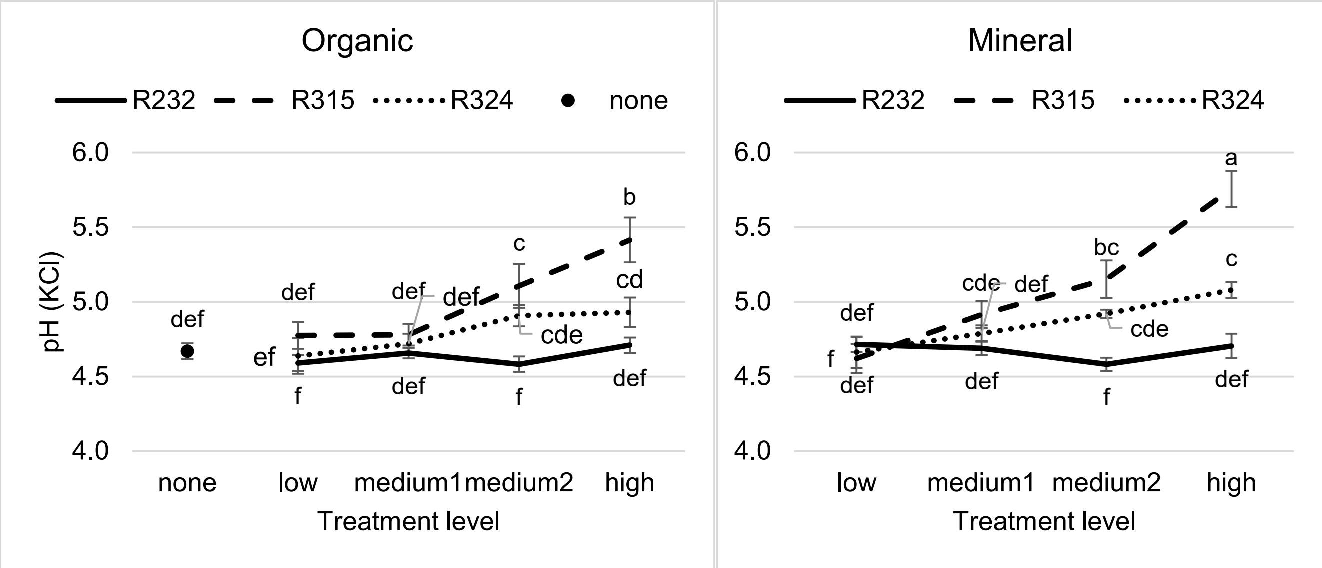

Figure 4.14: Effect of fertilizer type, NPK ratio and treatment application level on soil pH (KCl) at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

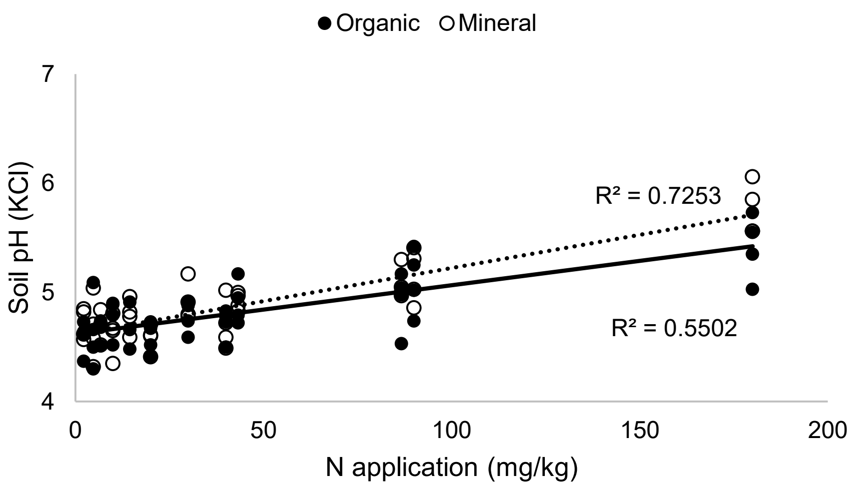

Figure 4.15: Correlation between N application and soil pH (KCl) in organic (solid line) and mineral (dotted line) treatments at Rogland in February 2018.

Electrical Conductivity (EC)

The factorial effect of fertilizer type, NPK ratio and treatment level had no significant effect (3-way ANOVA: $p > 0.05$) on soil EC at both farms. At Rogland, the high treatment level in the organic and mineral 3:1:5 fertilizers significantly increased EC to 305.7 ± 123.2 and 257.8 ± 46.8 μS/cm, respectively from 65.6 ± 20.5 in the control μS/cm (Fig. 4.16). At Blomfontein, a significant increase in EC was observed in the mineral fertilizers with an increase in treatment level (Fig. 4.17).

At Rogland, EC showed a significant positive correlation with soil exchangeable K in the organic (R^2 = 0.7082) and mineral (R^2 = 0.6144) fertilizers (Fig. 4.18), respectively, with positive trends also evident with soil exchangeable Ca, Mg, ECEC and soil N. At Blomfontein, positive trends were observed with soil Ca in the organic and mineral treatments. This indicates the higher dissolved salt content in the soil consists of macronutrients that are beneficial for plant growth.

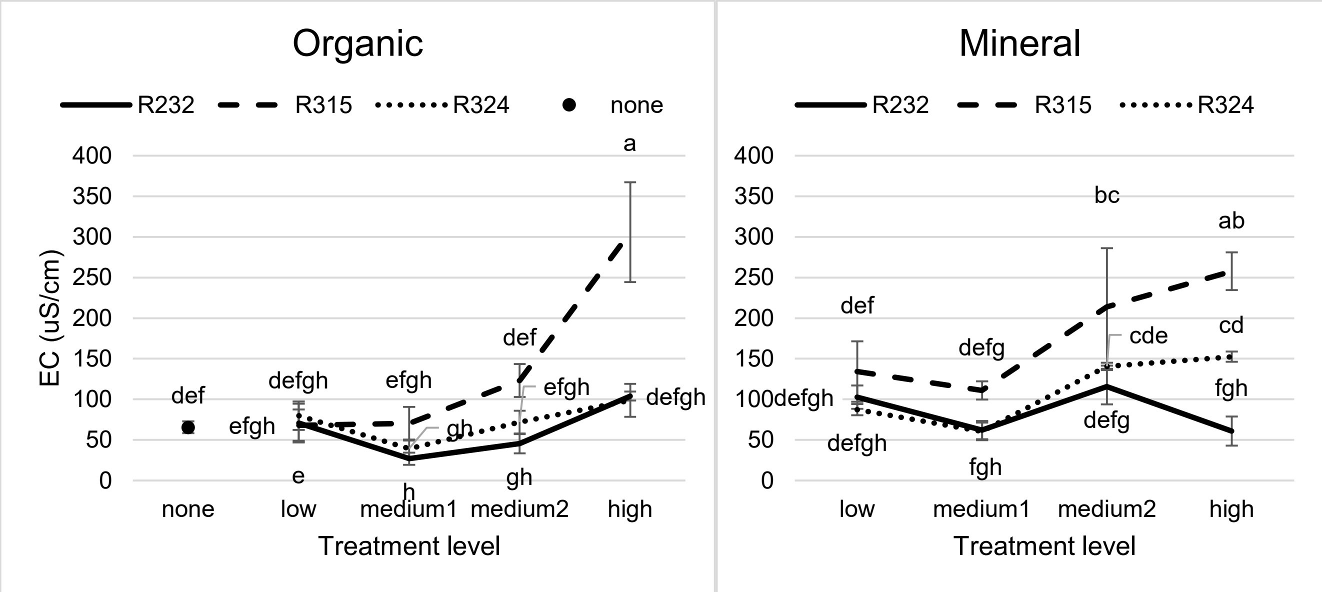

Figure 4.16: Effect of fertilizer type, NPK ratio and treatment application level on soil EC at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

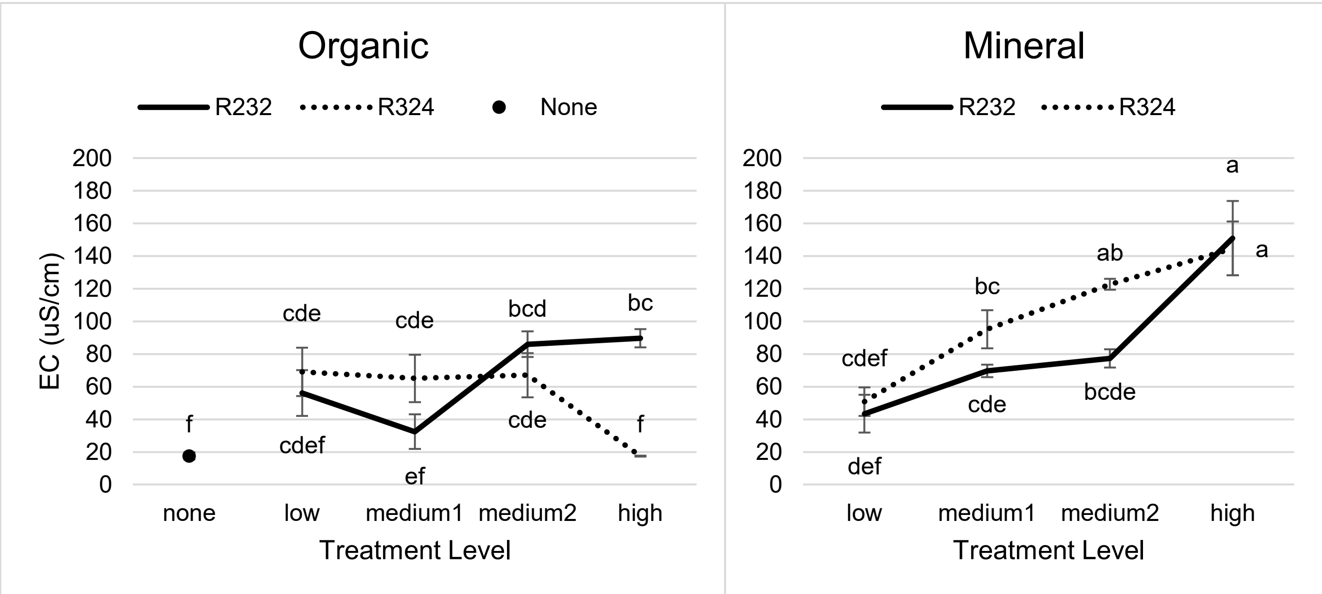

Figure 4.17: Effect of fertilizer type, NPK ratio and treatment application level on soil EC at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

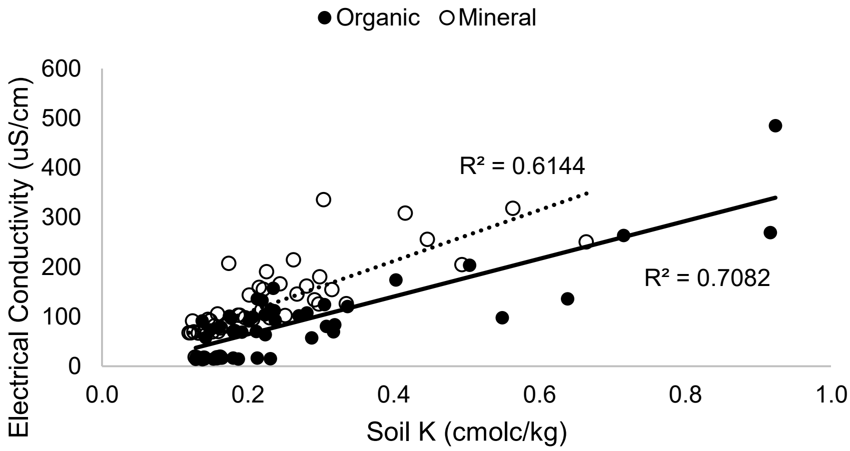

Figure 4.18: Correlation between soil K and EC in the organic (solid line) and mineral (dotted line) treatments at Rogland in February 2018.

Exchangeable acidity

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on exchangeable acidity at both farms. At Rogland, treatment type had a statistically significant ($p < 0.001$) effect on soil exchangeable acidity with the control (0.373 ± 20.5 cmol$_c$/kg) being significantly higher than all organic treatments. This can be due to the increase in soil pH and exchangeable cations (Ca, Mg, Na, K) associated with the applied treatments due to these elements competing for exchange sites on soil particles.

No significant effects were observed for soil exchangeable acidity at Blomfontein, however a general negative trend was evident with an increase in treatment levels (Fig. 4.19) as soil pH increased. Negative trends were observed between exchangeable acidity and soil Ca and Mg in the organic fertilizers. In the mineral fertilizers negative trends were found with soil Ca and K. A significant positive correlation was found with soil ECEC in the mineral (R = 0.5958) fertilizer at Blomfontein.

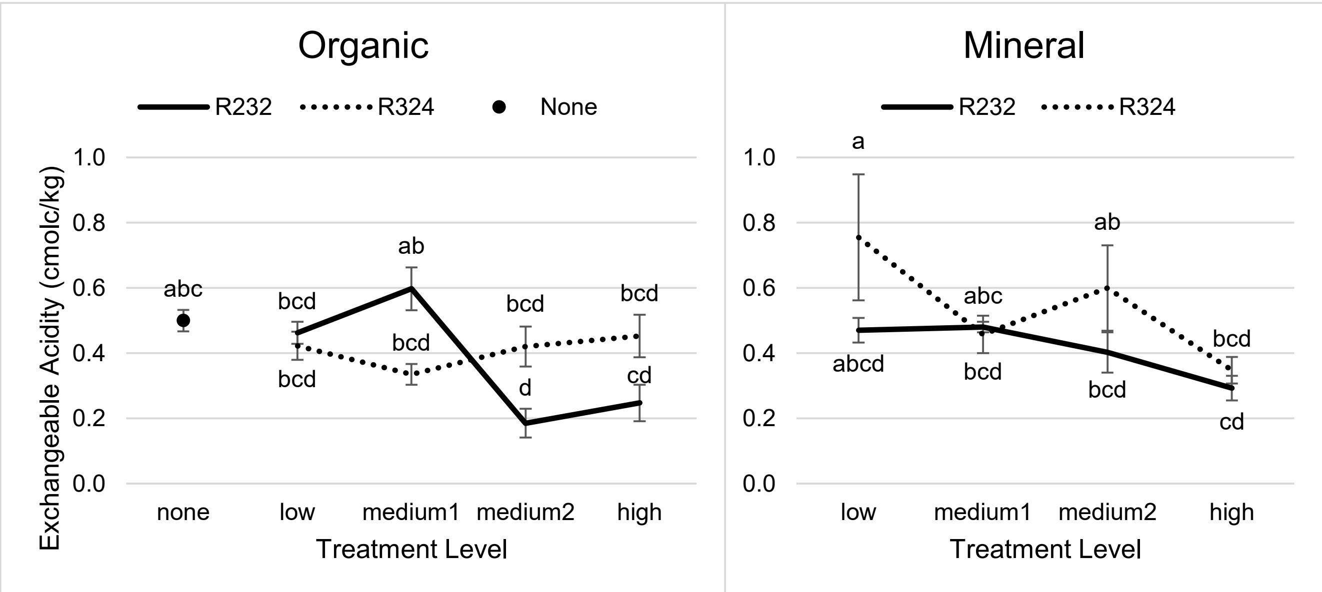

Figure 4.19: Effect of fertilizer type, NPK ratio and treatment application level on soil exchangeable acidity at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Exchangeable Calcium (Ca)

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on exchangeable Ca at both farms. At Rogland, a positive trend was observed in the organic fertilizers with the 2:3:2 at the high (1 ± 0.2 $cmol_c$/kg) and 3:2:4 fertilizers at the two highest treatment levels (0.86 ± 0.2 and 0.88 ± 0.2 $cmol_c$/kg) being significantly higher than the control (0.74 ± 0.2 $cmol_c$/kg) (Fig. 4.20). At all treatment levels, except the highest, the organic 3:2:4 generally had a higher soil Ca level. This is due to the fertilizer being based on chicken manure, which has high levels of Ca. At Blomfontein no general trends were observed, however a significant increase in soil Ca was found in the mineral fertilizers at the high treatment level (Appendix A: Fig. 9.2). The increase is due to the Ca added with the double superphosphate fertilizer.

In the organic fertilizers, a significant positive correlation was found between soil Ca and Mg at Rogland (R^2 = 0.634) (Fig. 4.21) and Blomfontein (R^2 = 0.5873), and with soil C (R^2 = 0.5235) at Rogland.

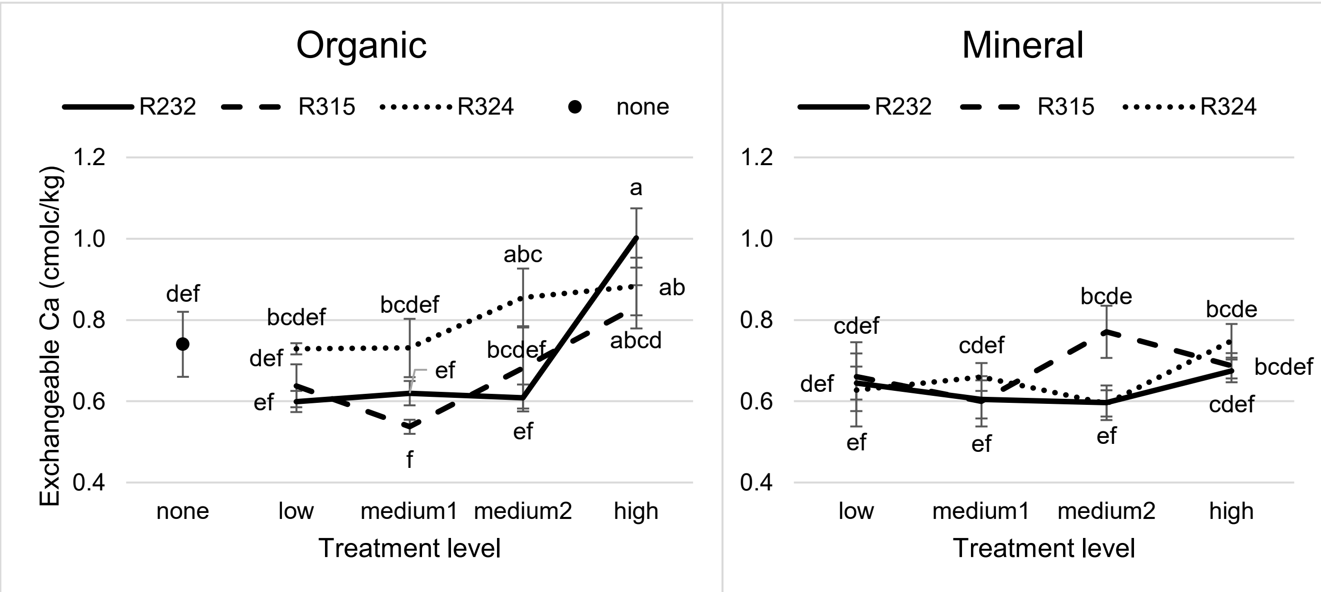

Figure 4.20: Effect of fertilizer type, NPK ratio and treatment application level on soil Ca at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

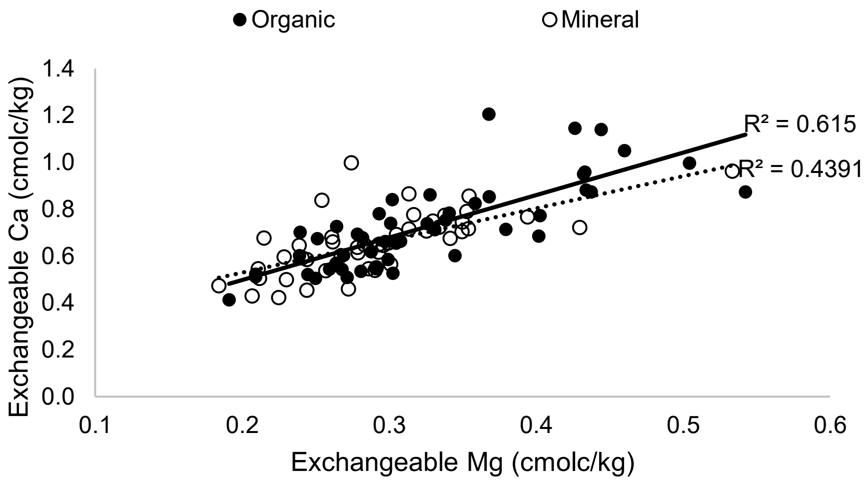

Figure 4.21: Correlation between soil Ca and soil Mg in the organic (solid line) and mineral (dotted line) treatments at Rogland in February 2018

Exchangeable Magnesium (Mg)

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on exchangeable Mg at both farms. At Rogland, treatment type had a statistically significant effect ($p = 0.011$) on exchangeable Mg, however application of nutrients had no significant effect on soil Mg. A positive trend was observed in organic 3:2:4 fertilizer in increasing treatment levels at Rogland only (Fig. 4.22). No general trends were observed at Blomfontein (data not shown).

In the organic fertilizers, a significant positive correlation was found between soil Mg and soil Ca at Rogland ($R^2 = 0.634$) and Blomfontein ($R^2 = 0.5873$).

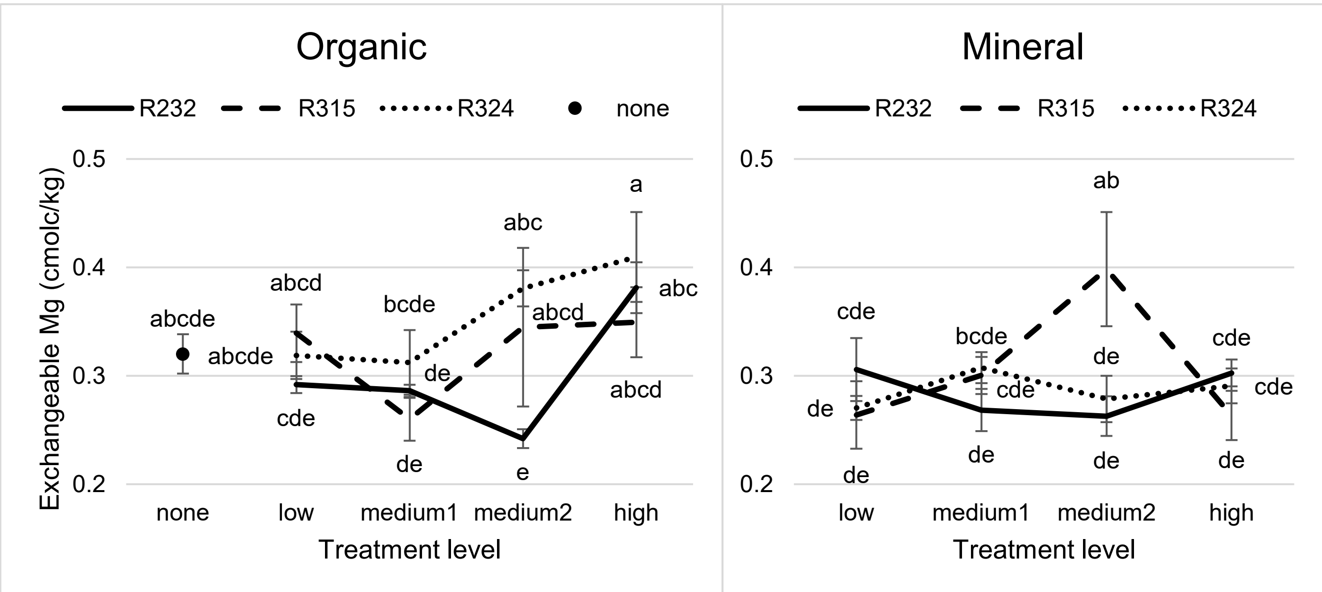

Figure 4.22: Effect of fertilizer type, NPK ratio and treatment application level on soil Mg at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

Exchangeable Sodium (Na)

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on exchangeable Na at both farms. At Rogland, treatment type had a statistically significant effect ($p = 0.001$) on exchangeable Na, however the application of N, P and K had no significant effect on soil Na. A significant increase in soil Na was observed at the high treatment level of the organic 3:2:4 fertilizer at Rogland (Fig. 4.23), however the opposite was found at Blomfontein with a negative trend (Fig. 4.24) which can be due to the addition of Ca in the chicken manure based fertilizer. The decrease in soil Na across all mineral treatments is due to the addition of Ca (double superphosphate) resulting in Na being leached to deeper depths. No significant correlations were found between soil Na and other soil properties at both farms, with only a positive trend with soil Mg across all treatments.

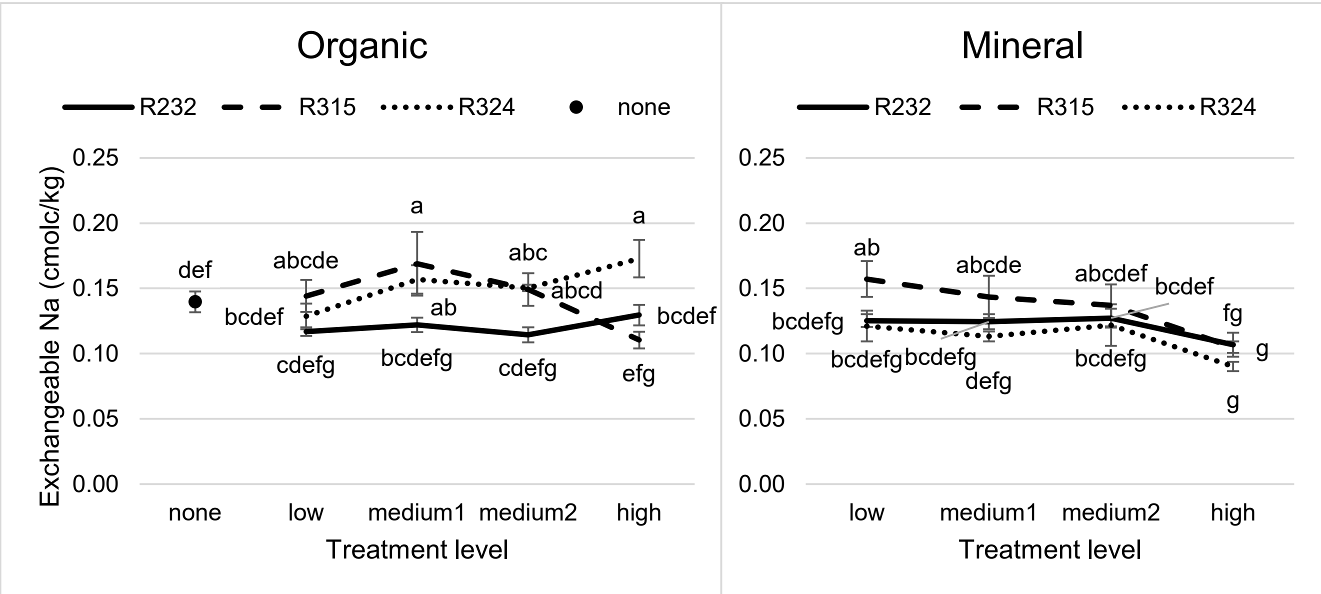

Figure 4.24: Effect of fertilizer type, NPK ratio and treatment application level on soil Na at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

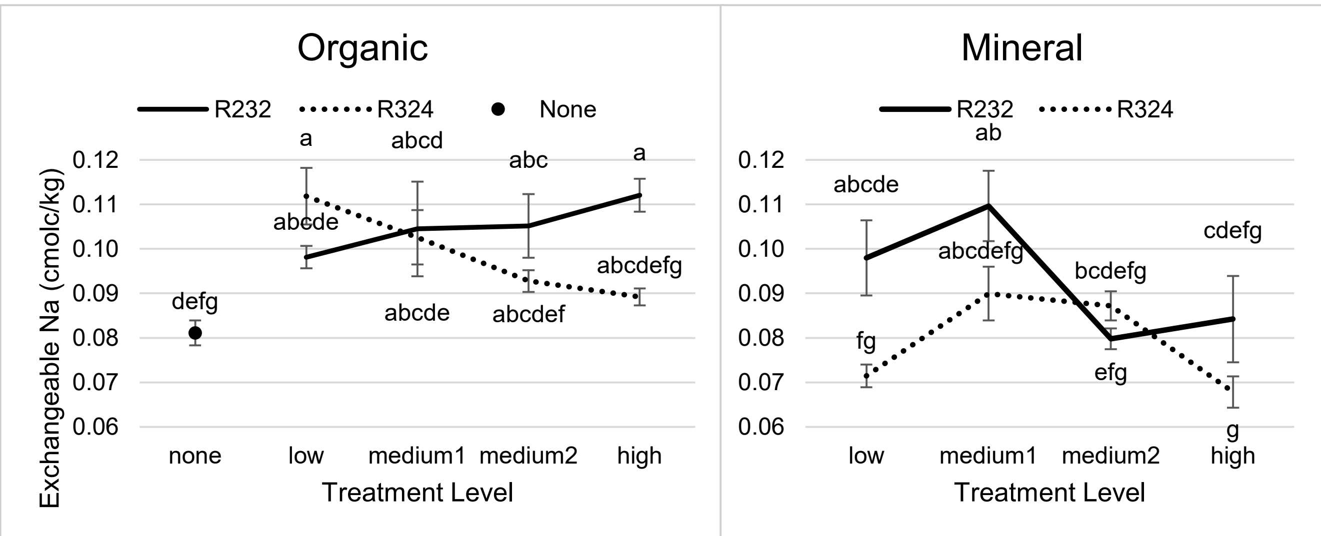

Figure 4.23: Effect of fertilizer type, NPK ratio and treatment application level on soil Na at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Exchangeable Potassium (K)

The factorial effect of fertilizer type, NPK ratio and application rate had a significant effect (3-way ANOVA: $p < 0.05$) on soil exchangeable K at Rogland (Fig. 4.25) and Blomfontein (Fig. 4.26). At Rogland, the high treatment levels of all the organic fertilizers significantly increased soil K from 0.15 ± 0.01 $cmol_c$/kg in the control to 0.26 ± 0.04; 0.25 ± 0.09 and 0.77 ± 0.2 $cmol_c$/kg, in the 2:3:2, 3:2:4 and 3:1:5 treatments, respectively. The second highest treatment level of organic 3:1:5 also significantly increased soil K to 0.47 ± 0.14 $cmol_c$/kg. In the mineral treatments only the two highest levels of the 3:2:4 and 3:1:5 fertilizers significantly increased soil K from 0.15 ± 0.01 to 0.27 ± 0.04 and 0.29 ± 0.04 $cmol_c$/kg in the 3:2:4 treatments; and to 0.27 ± 0.112 and 0.54 ± 0.1 $cmol_c$/kg in the 3:1:5 treatments.

At Blomfontein, no significant change was observed in the organic treatments, while a significant increase was observed in the high treatment level of the mineral 3:2:4 fertilizer to 0.32 ± 0.1 from 0.15 ± 0.03 $cmol_c$/kg in the control. Organic and mineral treatments applied at both farms yielded similar soil K values. The significant higher soil K levels in the organic and mineral fertilizers is due to the higher K applied in the 3:2:4 and 3:1:5 fertilizers. The insignificant increase in soil K among the two lowest treatments can be due to higher leaching or plant uptake associated with mineral K.

A significant positive correlation was found between soil K and K application rate in both fertilizer types at Rogland (Fig. 4.27) and in the mineral fertilizers at Blomfontein ($R^2 = 0.5431$). Significant positive correlations were found with Bray II P in the organic ($R = 0.5638$) and mineral ($R = 0.7002$) fertilizers at Blomfontein (Fig. 4.28).

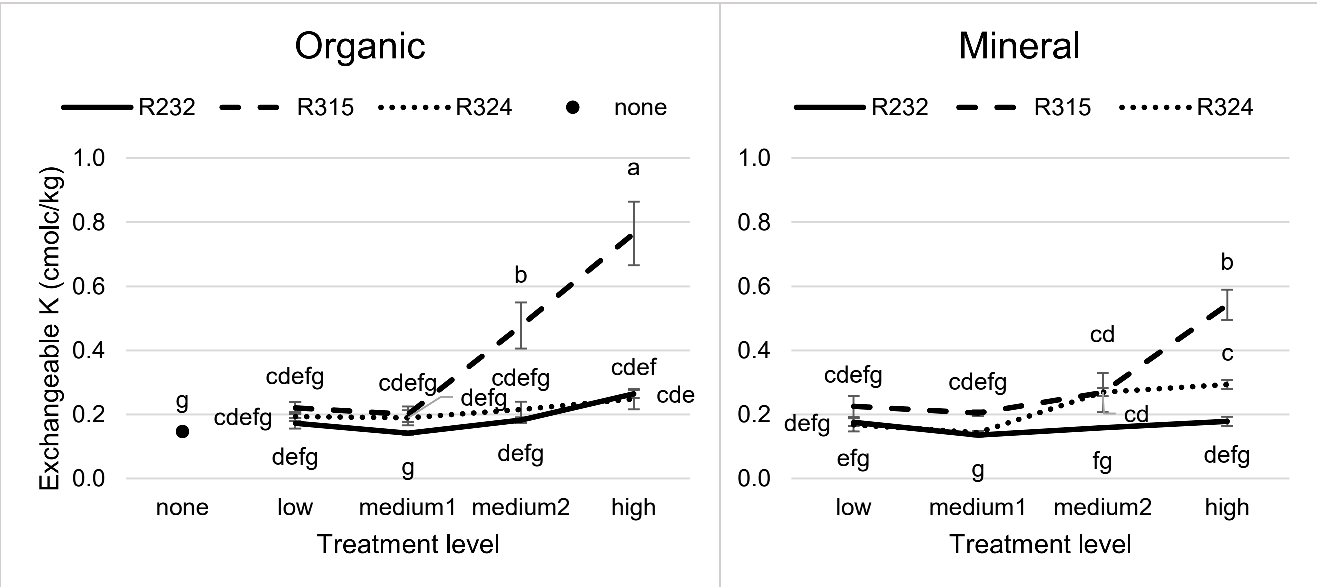

Figure 4.25: Effect of fertilizer type, NPK ratio and treatment application level on soil K at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

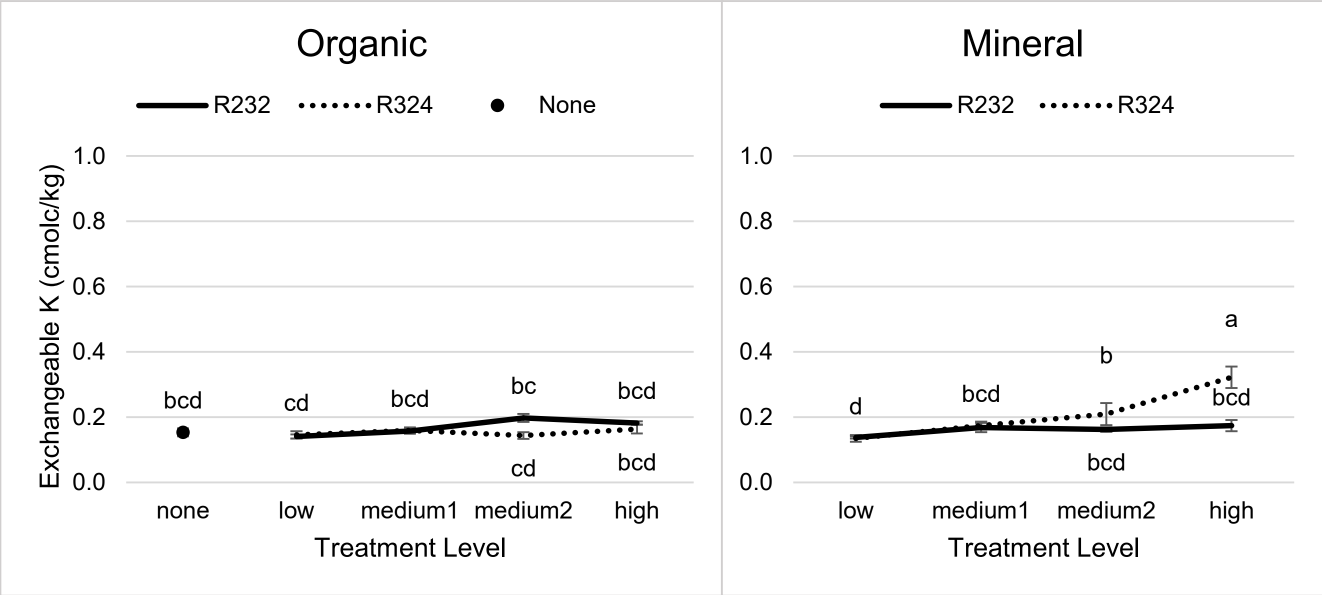

Figure 4.26: Effect of fertilizer type, NPK ratio and treatment application level on soil K at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

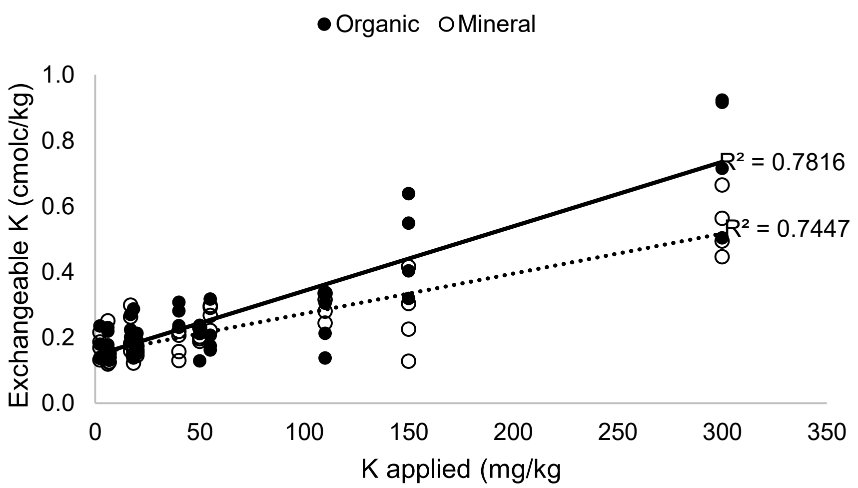

Figure 4.27: Correlation between soil K and K application rate in the organic (solid line) and mineral (dotted line) treatments at Rogland in February 2018

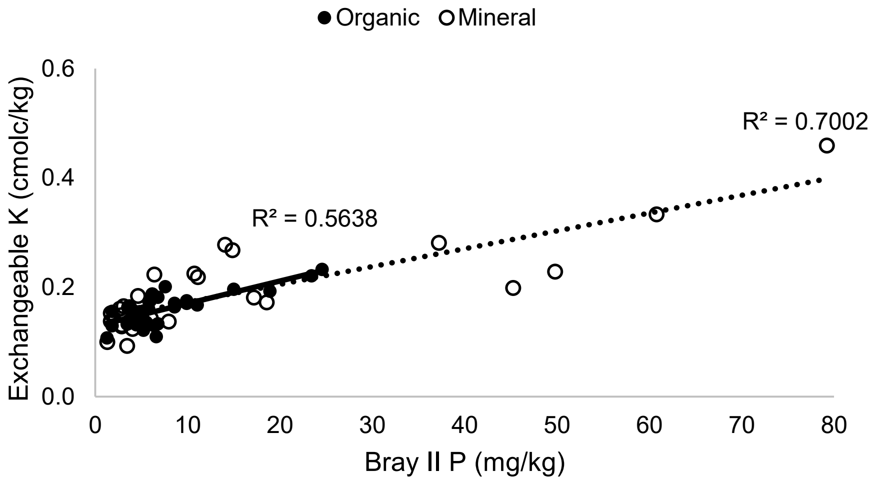

Figure 4.28: Correlation between soil K and Bray II P in the organic (solid line) and mineral (dotted line) treatments at Blomfontein in February 2018

ECEC

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on soil ECEC at both farms. At Rogland, in both the organic and mineral fertilizers the highest ECEC was obtained in the 3:1:5 treatment at the high treatment level (Fig. 4.29). This can be due to the high soluble K level in the soil in the mineral treatments. Therefore in the mineral fertilizers an increase in the treatment level increased ECEC, whereas in the organic fertilizers it did not. Soil ECEC values were relatively low and only started increasing at the higher treatment levels. This is due to the low cation exchange capacity associated with acidic sandy soils (kaolinite). An increase occurred with application rates across all treatments at Rogland, however a negative trend was observed at Blomfontein with an increase in treatment level (Fig. 4.30). The negative trend at Blomfontein can be due to the higher rainfall and soil water content resulting in increased leaching of exchangeable cations from the low CEC soil.

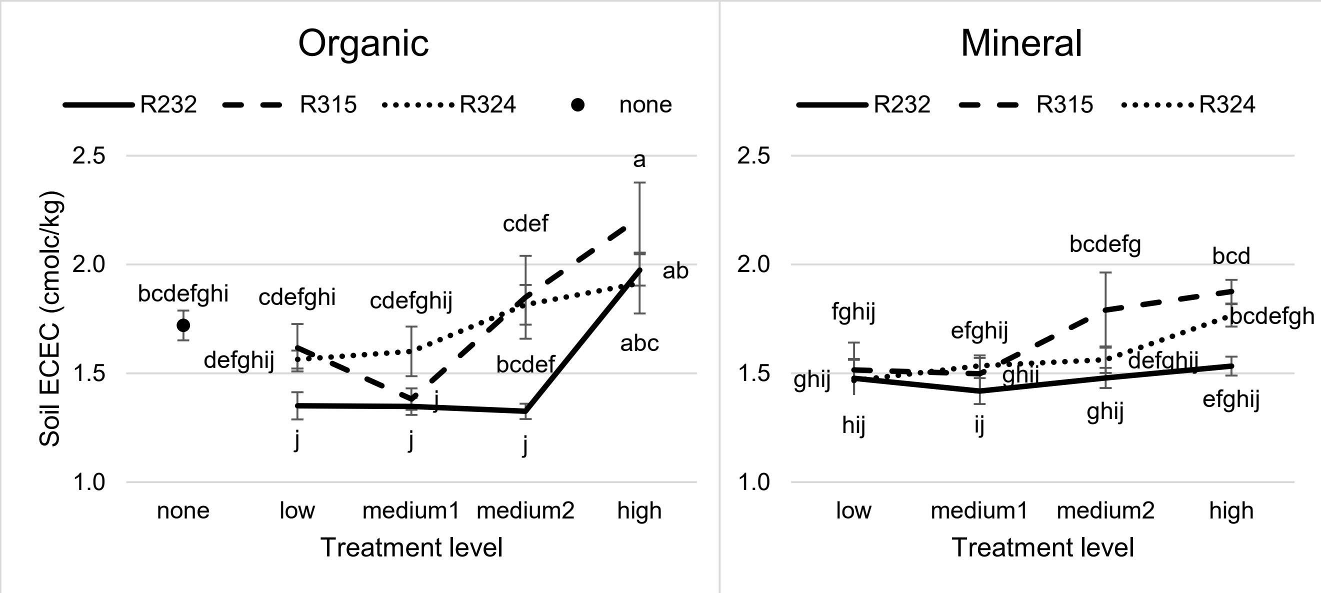

Figure 4.30: Effect of fertilizer type, NPK ratio and treatment application level on soil ECEC at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

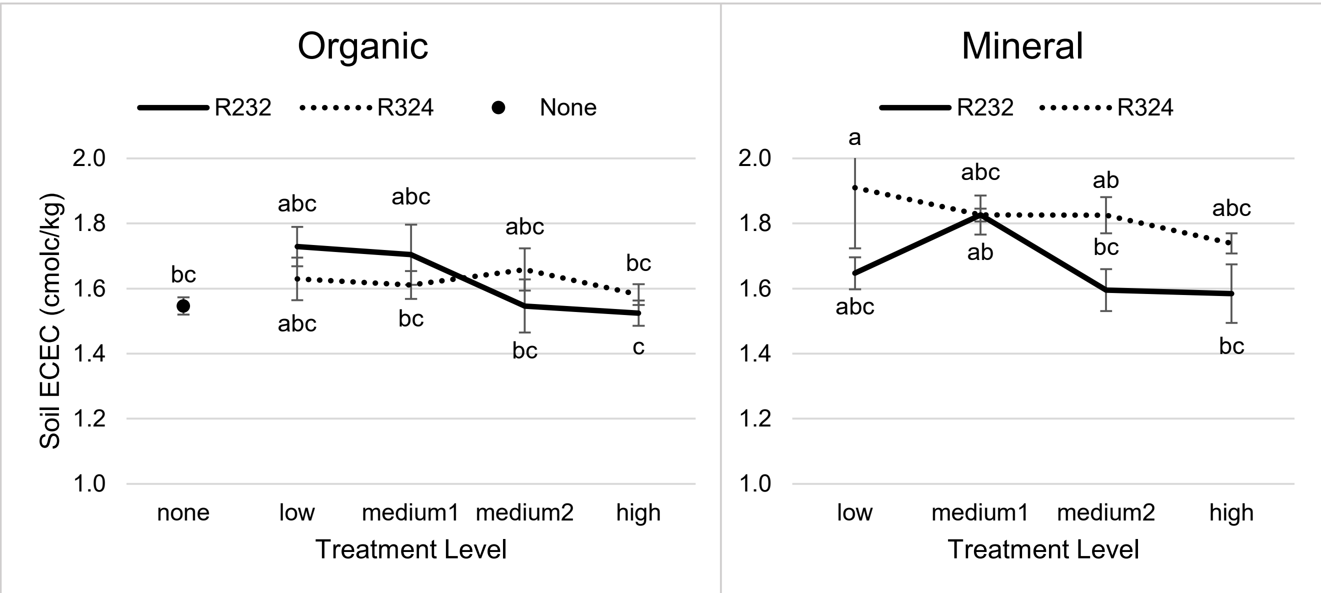

Figure 4.29: Effect of fertilizer type, NPK ratio and treatment application level on soil ECEC at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Bray II P

Fertilizer type and treatment level had a significant effect on soil Bray II P at Rogland (Fig. 4.31) and Blomfontein (Fig. 4.32). NPK ratio of the fertilizers had no significant effect as the P applied was constant across the fertilizers at the different treatment levels. A significant increase was observed in the organic 3:1:5 and all mineral fertilizers at the highest treatment level at Rogland, and at the high treatment level of the mineral fertilizers at Blomfontein.

At Rogland, in both the organic and mineral fertilizers, the 3:1:5 treatments had the highest soil Bray II P of 21.5 ± 14.7 and 31.3 ± 20.7 mg/kg compared to the 4.8 ± 0.8 mg/kg of the control treatment. At Blomfontein, in the mineral fertilizers the high treatment level of the 2:3:2 increased the Bray II P from 2.1 ± 1.2 mg/kg in the control to 26.3 ± 24.6 mg/kg, while in the two highest treatment levels of the 3:2:4 fertilizers increased to 19.5 ± 27.9 and 36.3 ± 30.5 mg/kg, respectively. The organic P fertilizers failed to mineralize effectively and the insignificant increase in Bray II P at the lower treatment levels can be due to P fixation occurring. Comparatively, at the high treatment level the mineral fertilizers had a higher Bray II P level than the organic fertilizers at both farms. Positive trends were observed between soil Bray II P and soil EC, Ca, Mg and K.

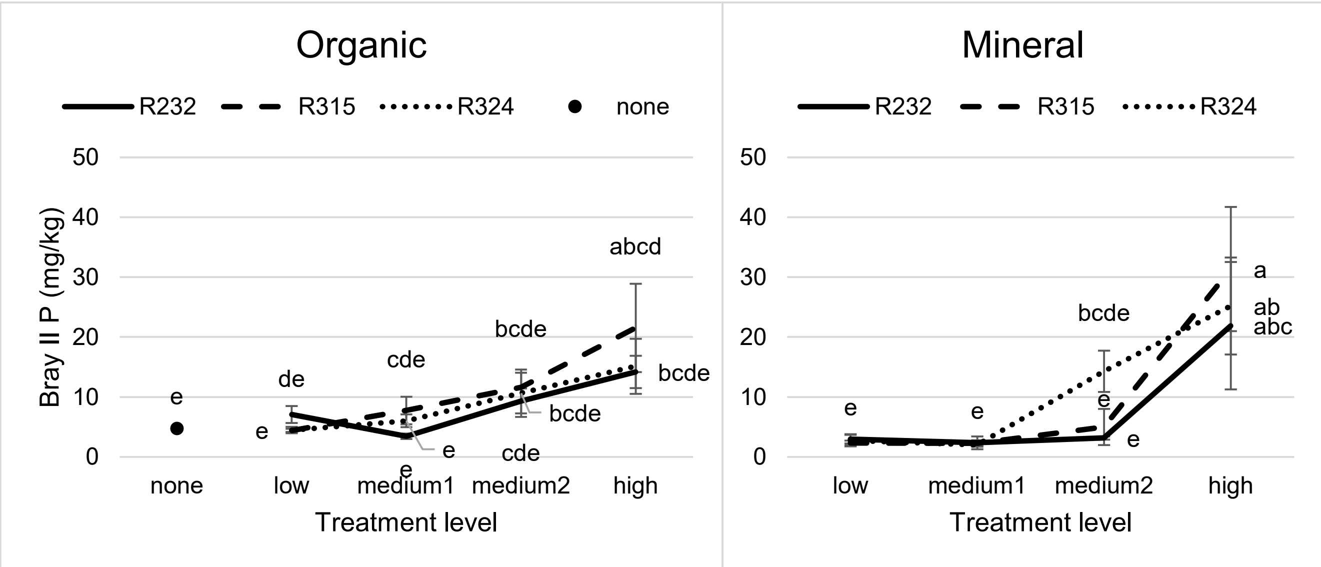

Figure 4.31: Effect of fertilizer type, NPK ratio and treatment application level on soil Bray II P at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

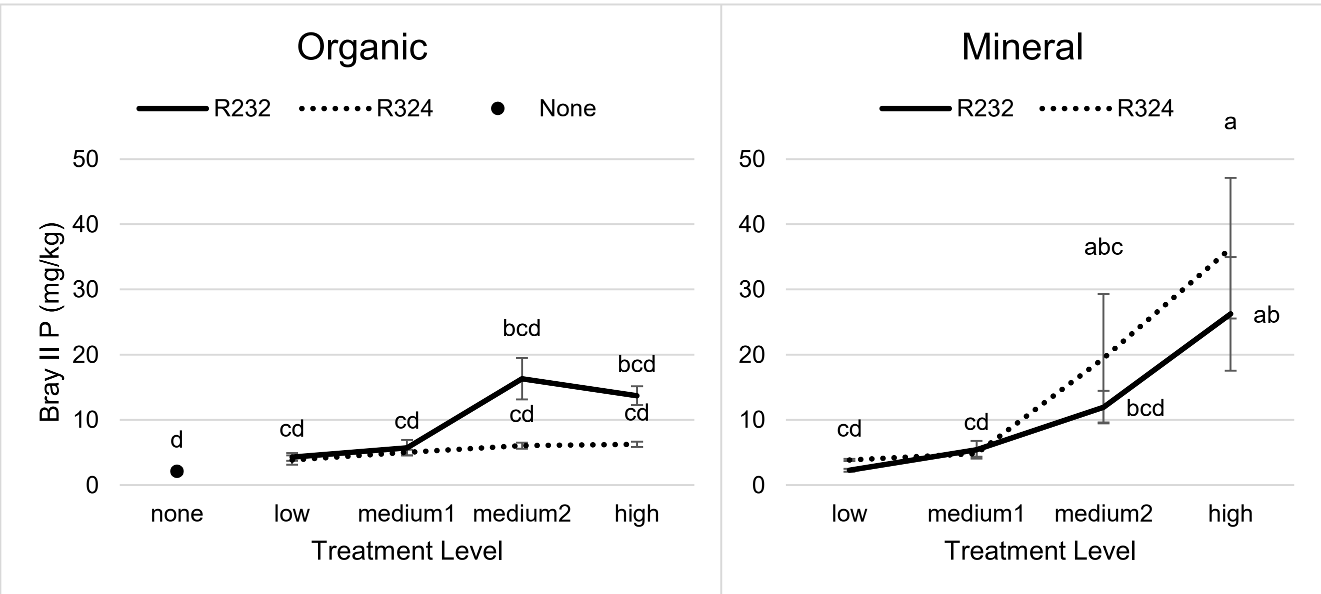

Figure 4.32: Effect of fertilizer type, NPK ratio and treatment application level on soil Bray II P at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Soil Carbon

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on soil C at both farms. No significant trends in soil C were observed with the application of fertilizers at both farms. Positive trends were found between soil C and N in the organic and mineral fertilizers at Rogland, and in the mineral fertilizers at Blomfontein. Soil C was low among all treatments as limited organic matter is added to the soil as plant material is removed through harvesting.

Soil Total Nitrogen

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on soil total N at both farms. At Rogland, a significant increase in soil total N was observed in the organic 3:1:5 fertilizer in the low and high treatment levels (Fig. 4.33), and at Blomfontein an increase was observed in the mineral 3:2:4 treatment (Appendix A: Fig. 9.4). However across all other treatments at both farms no clear trends were identified. The lack of increase in soil total N in the mineral treatments is possibly linked to plant uptake or leaching as mineral N is highly mobile.

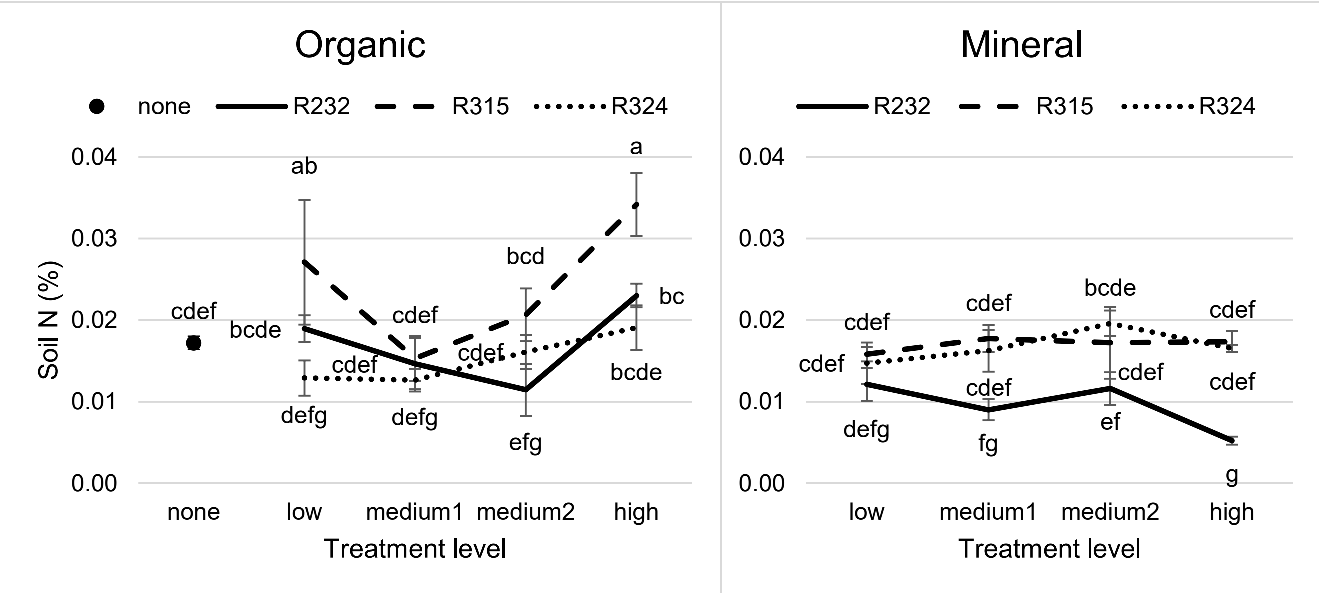

Figure 4.33: Effect of fertilizer type, NPK ratio and treatment application level on soil total N at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

Micro-nutrients (Fe, Cu, Zn and Mn)

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on soil Fe at both farms. Fertilizer type and treatment level had a significant effect on soil Fe with mineral fertilizers having significantly higher values than organic fertilizers at Rogland (Fig. 4.34) and Blomfontein in the highest treatment levels. In the organic fertilizers significant increases were only observed at Rogland, whereas in the mineral fertilizers significant increases were observed at both farms. Blomfontein had a significantly higher inherent soil Fe level of 53.2 ±

23.7 mg/kg compared to 17.5 ± 4.4 mg/kg at Rogland. A positive trend occurred between soil Fe and Cu in the organic treatments at Rogland.

The dissolution of Fe tends to reduce with an increase in pH, however at Rogland a positive trend was found between soil Fe and pH in the organic and mineral treatments. The increase in soil Fe could be due to organic acids released into the soil by the plant (Jones, 1998).

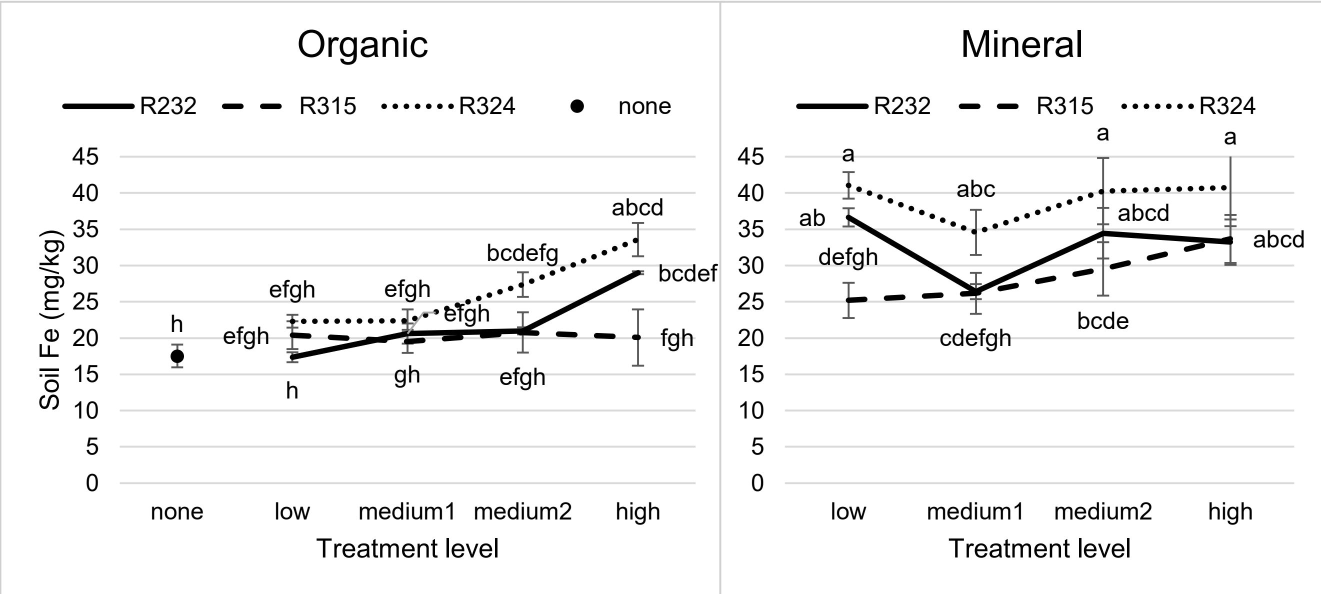

Figure 4.34: Effect of fertilizer type, NPK ratio and treatment application level on soil Fe at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

The factorial effect of fertilizer type, NPK ratio and application rate had a significant effect (3-way ANOVA: $p < 0.05$) on soil Cu at both farms. At Rogland a positive trend was observed in the organic fertilizers with a significant increase in the two highest treatment levels of the 3:2:4 fertilizer (Fig. 4.35). This increase is due to the decomposition of the chicken-manure based fertilizer, therefore increasing the availability of Cu that derived from the fertilizer.

At Blomfontein no general trends were identified in the organic fertilizers, whereas in the mineral fertilizers a positive trend was identified with a significant increase in the 3:2:4 fertilizer at higher treatment levels (Fig. 4.36). In the organic treatments a significant positive correlation was found between soil Cu and Zn (R^2 = 0.689).

In the mineral fertilizers a negative trend was observed in the 3:2:4 fertilizer with soil Cu. This negative trend can be due to plant uptake or the increase in pH at higher treatment levels, which have a negative effect on Cu solubility. However, at Blomfontein an increase in soil Cu with soil pH was observed as pH levels rarely elevated above 5.6, above which Cu forms hydroxides (Qiao & Ho, 1997).

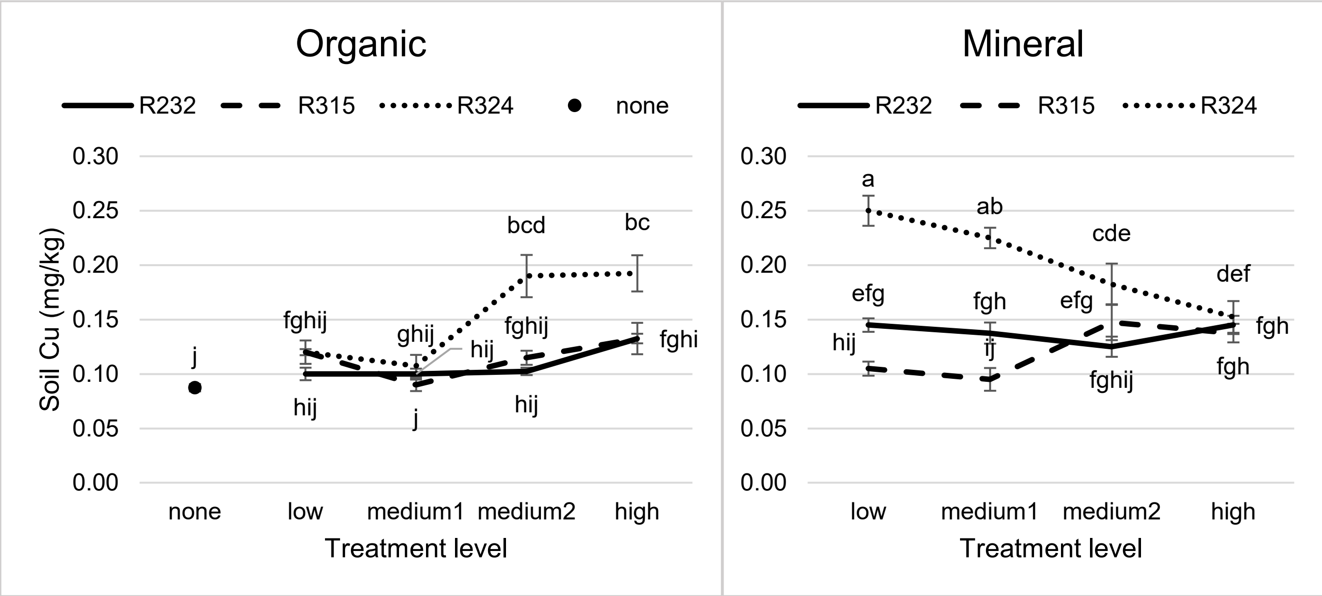

Figure 4.36: Effect of fertilizer type, NPK ratio and treatment application level on soil Cu at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

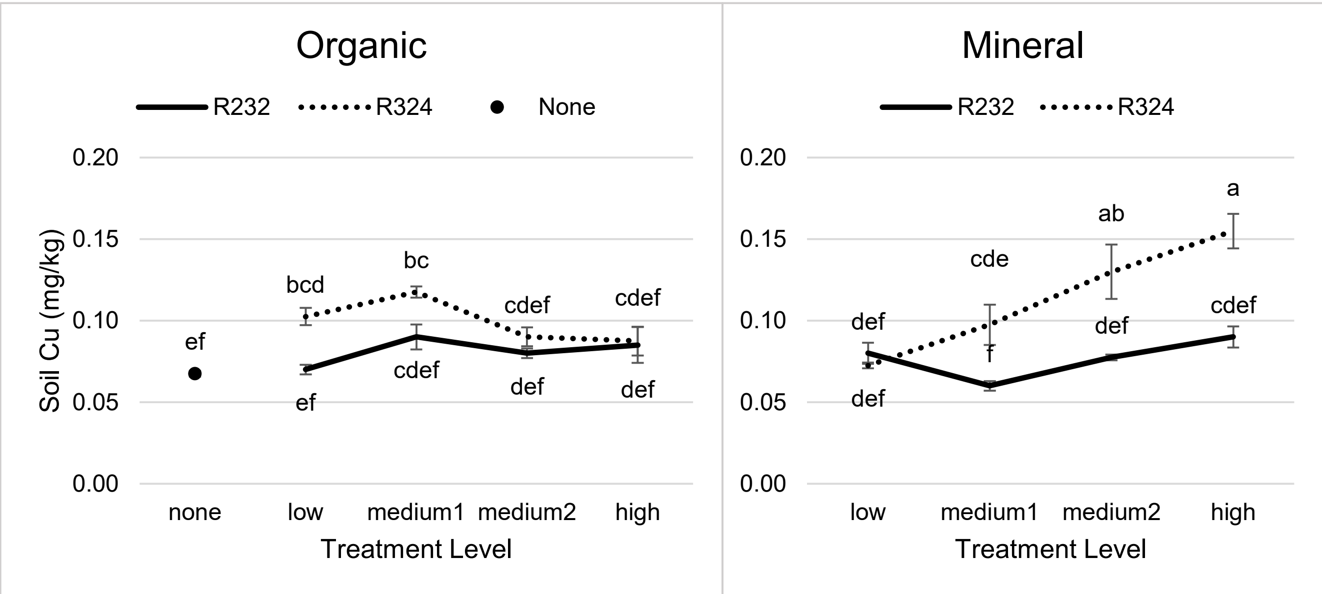

Figure 4.35: Effect of fertilizer type, NPK ratio and treatment application level on soil Cu at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

The factorial effect of fertilizer type, NPK ratio and application rate had a significant effect (3-way ANOVA: $p < 0.05$) on soil Zn at Rogland (Fig. 4.37) while no significant effect was found at Blomfontein. Organic 3:2:4 fertilizers significantly increased soil Zn from 0.24 ± 0.07 mg/kg to 0.62 ± 0.17 and 0.72 ± 0.38 mg/kg, respectively. This significant increase can be attributed to the high Zn levels found in chicken manure fertilizers. A significant positive correlation was found between soil Zn and soil and Cu (R^2 = 0.689). Positive trends were observed between soil Zn and soil Ca, Mg and Na.

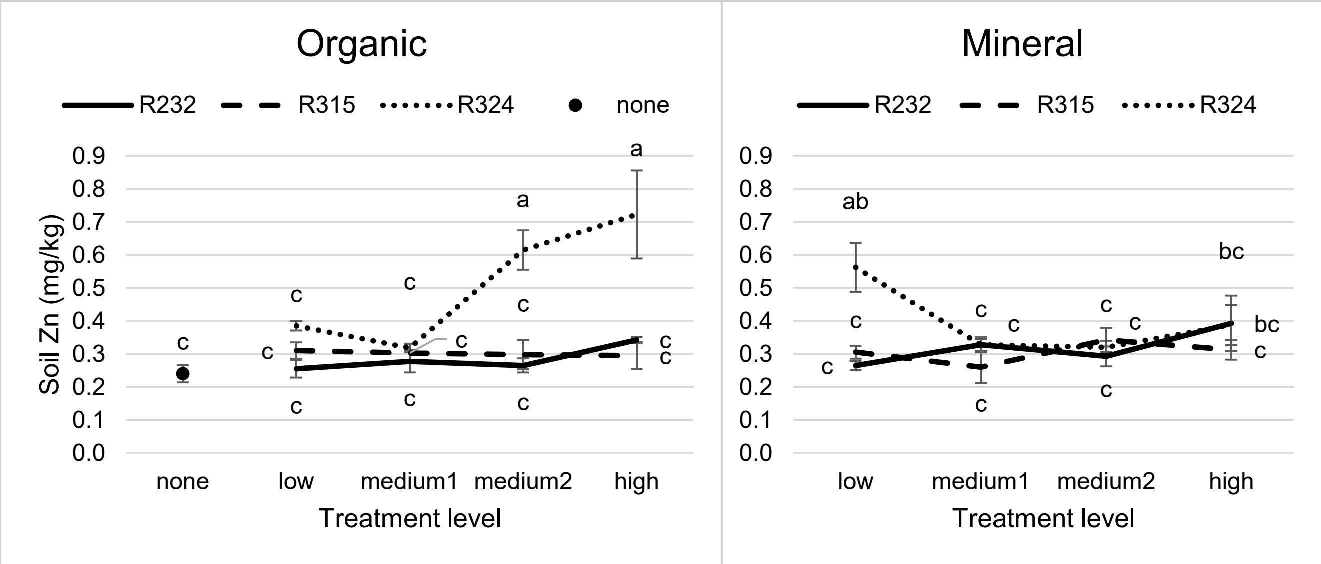

Figure 4.37: Effect of fertilizer type, NPK ratio and treatment application level on soil Zn at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on soil Mn at both farms. No general trends were identified in the organic or mineral fertilizers at both farms for soil Mn. In the organic treatments, soil Mn showed positive trends with soil Fe and soil Cu, whereas in the mineral treatments a positive trend was found with soil Ca. A weak negative trend was observed between soil Mn and increase in soil pH in the organic and mineral treatments due to very little Mn dissolution occurring above pH 5.0 (Jones & Darrah, 1994).

4.4.5 Foliar analysis

Foliar N

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar N at both farms. Treatment type had a statistically significant ($p < 0.05$) effect on foliar N concentration in February 2018 at Rogland. A general increase was found in the 2:3:2 (2.1 ± 0.2 and 2.1 ± 0.3 %) and 3:1:5 (2.0 ± 0.1 and 2.1 ± 0.2 %) treatments, at the high treatment level, in the organic and mineral fertilizers, respectively, however it was not significantly higher than the control (2.1 ± 0.2 %). At Blomfontein no general trends in foliar N were found and all applied treatments were lower than the control treatment (2.0 ± 0.3 %). The insignificant difference in foliar N can be a result of the lack of increased N uptake at higher application rates.

Foliar N showed no correlation with any soil property and only showed a positive and negative trend with foliar Mg and Al, respectively. Foliar N values, at Rogland, were within the range found in the Clanwilliam region in seedlings (Lourenco, 2018). At both farms, values were considerably higher than those found in the Citrusdal (Stassen, 1987), Wuppertal (Lotter, *et al.,* 2014b) and Nieuwoudtville regions (Nieuwoudt, 2017).

Foliar P

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar P at both farms. Fertilizer type had a significant effect with foliar P increasing in the mineral fertilizers (Fig. 4.38). At Rogland in the mineral fertilizers, as found by Lourenco (2018), P application had a significant effect on foliar P content with the increase in P application significantly increasing foliar P. In the two highest treatment levels in all mineral treatments, the increase in foliar P could have contributed to the decline in average tea yield per plant, indicating a possible toxicity effect.

However, at Blomfontein a negative trend was identified in foliar P with an increase in P application. Both farms showed similarity in foliar P values found in one-year old plants by Lourenco (2018), but higher than studies in Citrusdal (Stassen, 1987) on older plants.

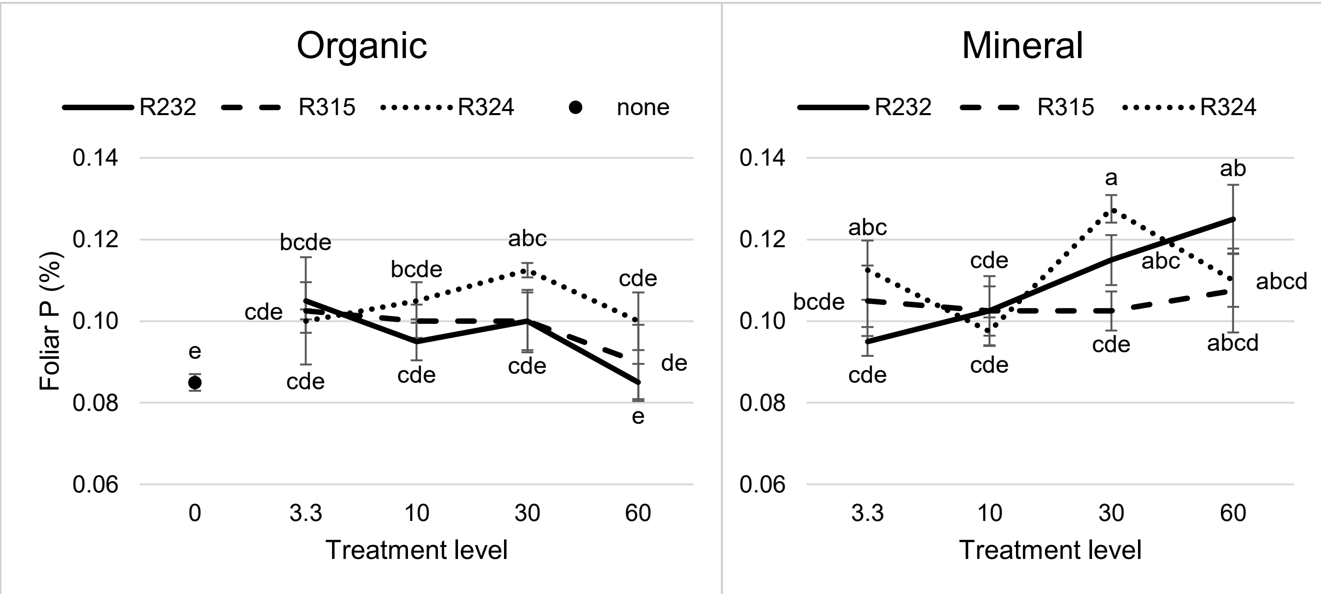

Figure 4.38: Effect of fertilizer type, NPK ratio and P application on foliar P at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

Foliar K

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar K at both farms. The application of K had no statistically significant effect on foliar K content at both sites, with only a positive trend with the increase in treatment levels in the mineral fertilizers (0.7 – 0.75 %) at Rogland. Foliar K values were generally higher at Rogland with the control having a concentration of 0.7 ± 0.1 %, compared to 0.6 ± 0.06 % in the control at Blomfontein. This increase can however be linked to less plant growth, therefore foliar K values were more concentrated. In the organic fertilizers foliar K declined in the high treatment level. This decline is unexpected as plant growth also declined, therefore less dilution of foliar K occurred due to plant growth. Foliar K showed positive trends with foliar P and Ca and a negative trend with foliar Al indicating an antagonism. At Blomfontein no trends in foliar K were identified (data not shown).

At both farms foliar K was considerably higher than values found by Stassen (1987) in Citrusdal and Smith (2014) in the Clanwilliam region.

Foliar Ca

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Ca at both farms. At Roland, a general increasing trend in foliar Ca with treatment level was found in the mineral fertilizers (Fig. 4.39). At Blomfontein, contrasting results were found with foliar Ca decreasing in the organic and increasing in the mineral fertilizers with an increase in treatment level (Fig. 4.40). The increase in the mineral fertilizers can be linked to the increase in soil Ca associated with the application of double superphosphate. Positive trends were found between foliar Ca and foliar P, K and Mg, while negative trends were found with foliar Na indicating an antagonism in plant uptake.

At Rogland and Blomfontein foliar Ca was lower than studies in the Citrusdal (Stassen, 1987) and Clanwilliam areas (Smith, 2014; Lourenco, 2018), but higher than values found by Nieuwoudt (2017) in the Nieuwoudtville region. This indicates that foliar Ca of rooibos in the Nieuwoudtville region is generally lower than other rooibos growing areas. The values fell within the range of 0.1 – 5 %, considered the optimum range for plant growth (Marschner, 1995).

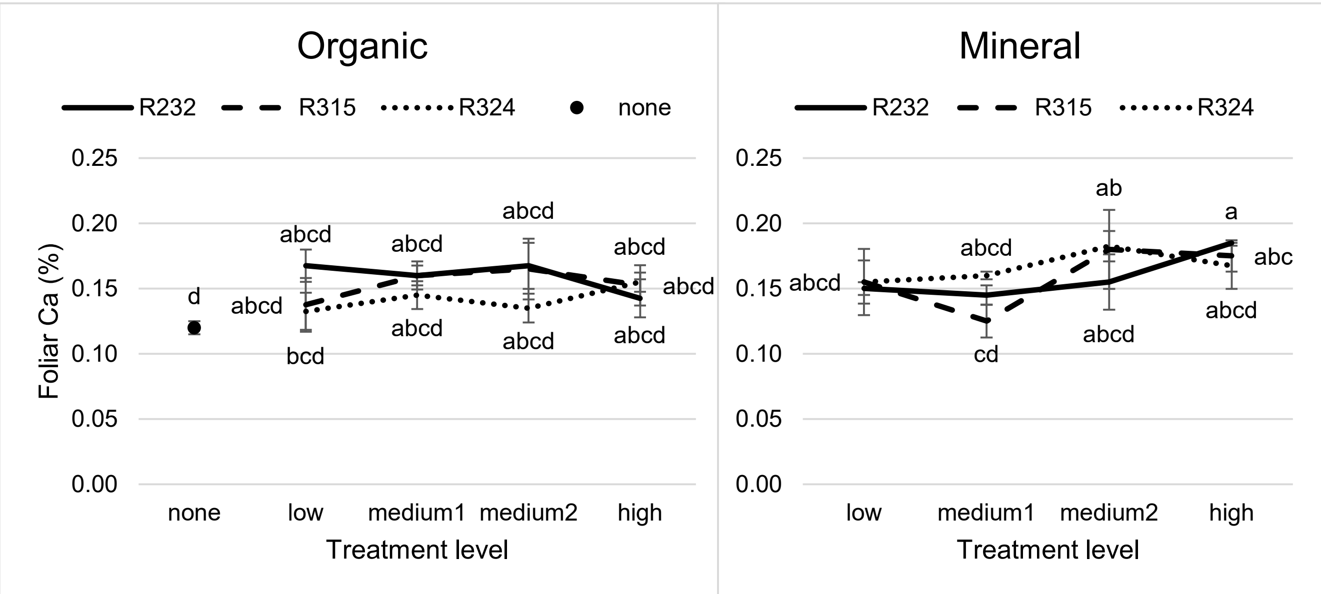

Figure 4.39: Effect of fertilizer type, NPK ratio and P application on foliar Ca at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

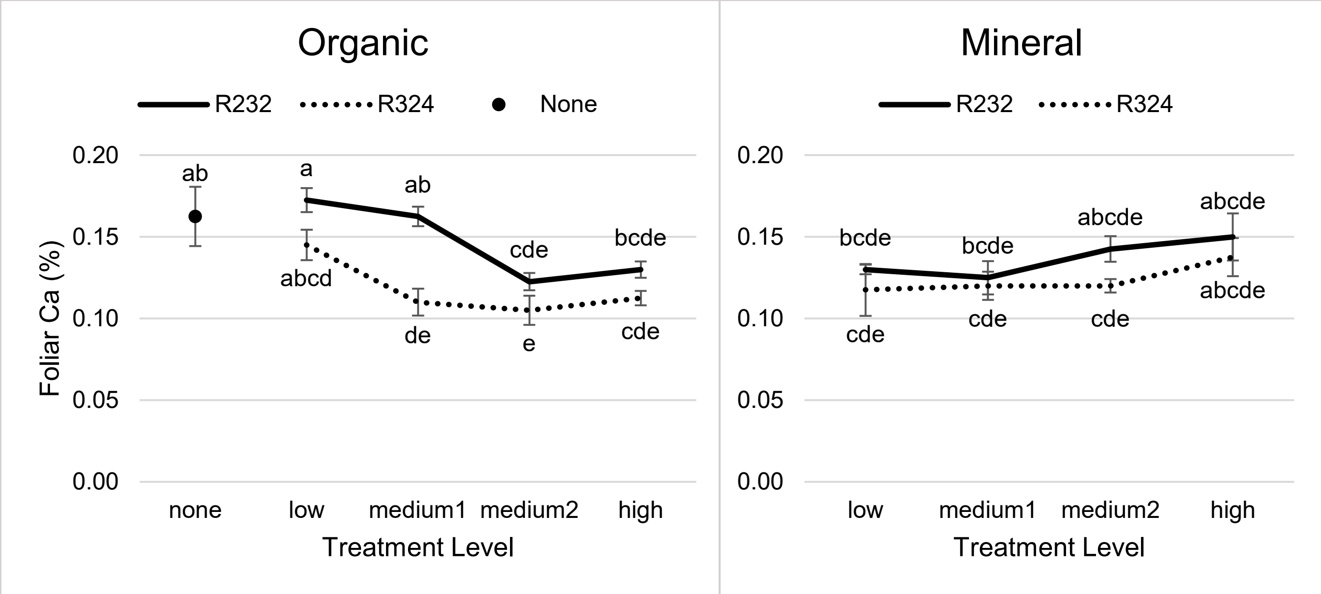

Figure 4.40: Effect of fertilizer type, NPK ratio and P application on foliar Ca at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Foliar Mg

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Mg at both farms. The application of nutrients had a statistically significant effect on foliar Mg at Rogland. In the organic fertilizers no trends were identified, however in the mineral fertilizers foliar Mg declined in the second treatment level, caused by the dilution of increased plant growth at this treatment level. At Blomfontein foliar Mg levels followed the same trend as tea yields per plant in the organic fertilizers, however no significant difference to the control was found. Foliar Mg showed positive trends with foliar Ca, Cu and B and a negative trend with soil and foliar Na indicating a possible antagonism.

At Rogland and Blomfontein foliar Mg values were considerably higher than that found by Stassen (1987); Smith (2014) and Nieuwoudt (2017), but were similar to values found by Lourenco (2018). The values fell within the range of 0.15 – 0.35 %, which is considered the optimum range for plant growth (Marschner, 1995).

Foliar Na

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Na at both farms. At Rogland, a negative trend in foliar Na was identified in the organic fertilizers, with no general trend in the mineral fertilizers. No treatment was significantly higher or lower than the control. At Blomfontein, no trends were observed for fertilizer type or treatment level. No positive correlations were found with any soil properties and only a negative trend with foliar Ca and Mg was identified indicating an antagonism. Foliar Na levels were higher than values found in the Clanwilliam region (Smith, 2014; Lourenco, 2018).

Foliar Fe

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Fe at both farms. At Rogland, no significant changes in foliar Fe was found across all treatments, while at Blomfontein treatment level had a significant effect on foliar Fe. Positive trends in foliar Fe were observed in the organic treatments with the 3:2:4 fertilizers being significantly higher at all treatment levels (Fig. 4.41). This increase can be due to the Fe content associated with chicken-manure based fertilizers. No trends were found in relation to any soil properties with foliar Fe only showing a positive trend with foliar Cu.At both farms foliar Fe values across all treatments were less than the toxicity level of 500 mg/kg. Values are lower than that found in the Clanwilliam region (Smith, 2014; Lourenco, 2018), but slightly higher than that found by Nieuwoudt (2017) in the Nieuwoudtville region.

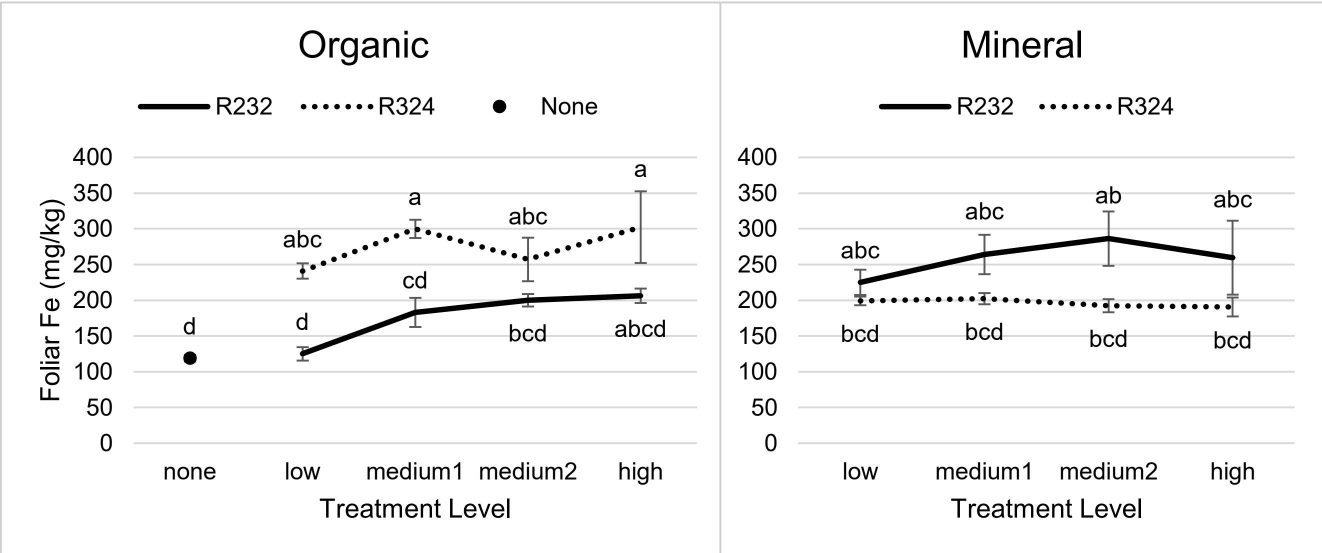

Figure 4.41: Effect of fertilizer type, NPK ratio and P application on foliar Fe at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232 and R324 represents the NPK ratio.

Foliar Cu

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Cu at both farms. At Rogland, treatment level had a significant effect on foliar Cu in the organic fertilizers. A general decrease in foliar Cu was observed, whereas in the mineral fertilizers no trend was found.

A negative trend was found between foliar Cu and soil pH across all treatments indicating that higher soil pH reduced Cu availability and uptake. Positive trends were found between foliar Zn and foliar Ca, Fe and B. Foliar Cu values were below the level of toxicity of 20 – 30 mg/kg (Marschner, 1995). Values are similar to plants in the Citrusdal region (Stassen, 1987), but higher than those in the Clanwilliam region (Smith, 2014; Lourenco, 2018).

Foliar Zn

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Zn at both farms. At Rogland, treatment level had a significant effect on foliar Zn, however no general trends were found, with a decrease at the high treatment level across all fertilizers. At Blomfontein, no general trends were found with no treatment significantly higher or lower than the control. Foliar Zn showed no correlation with any soil property, but a positive trend was found with foliar Mn.

Foliar Zn values were below the toxicity level of 100 – 300 mg/kg and even lower than 15 – 20 mg/kg, which is considered deficient for plant growth (Marschner, 1995). Values were lower than that found by Stassen (1987) and Smith (2014), but higher than values by Nieuwoudt (2017) and Lourenco (2018).

Foliar Mn

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar Mn at both farms. Treatment type had a statistically significant effect on foliar Mn at Rogland, with the highest values found at the second treatment level across all fertilizers, except mineral 3:1:5, which was highest at the third treatment level (Fig. 4.42). The trend of highest foliar Mn at the second treatment level positively correlates with average tea yield and survival-adjusted yield. However, at Blomfontein, varying results were found with the highest foliar Mn values occurring in the high treatment levels across all fertilizers. A positive trend was found with foliar Zn and negative trends with foliar B and Al. Foliar Mn values were above the deficient level of 10 – 20 mg/kg (Marschner, 1995), indicating sufficient uptake for plant growth. At Rogland values were higher than that found by Stassen (1987) and Nieuwoudt (2017), but were similar to values found in the Clanwilliam region (Smith, 2014; Lourenco, 2018). At Blomfontein values were lower than that found in the Clanwilliam region.

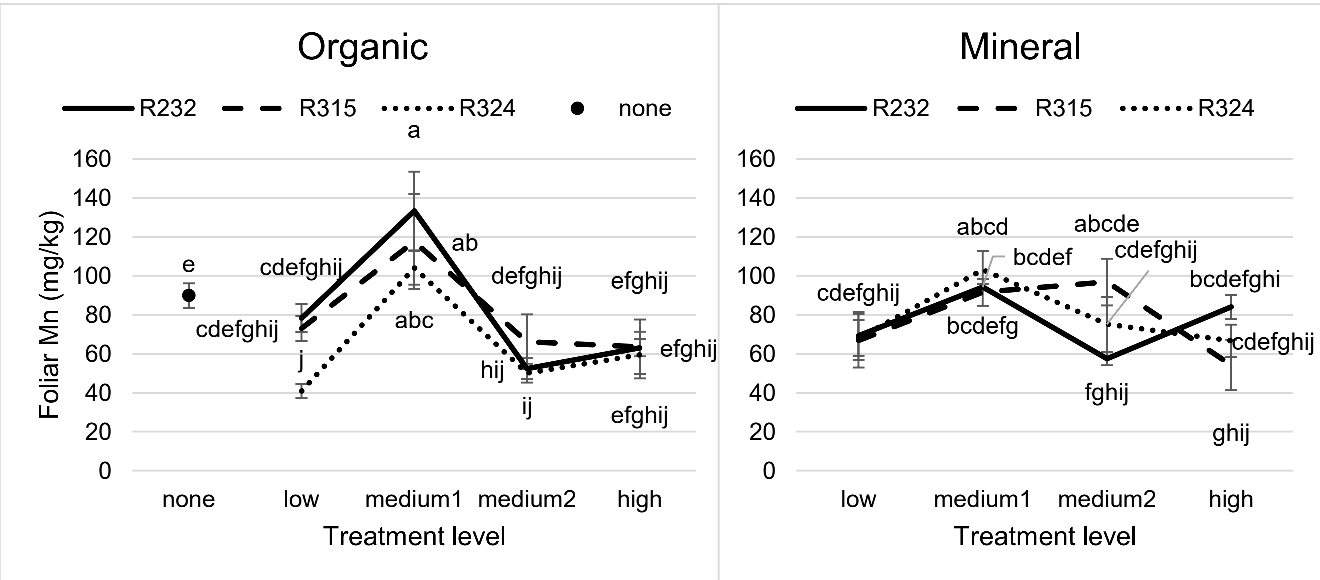

Figure 4.42: Effect of fertilizer type, NPK ratio and P application on foliar Mn at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval. R232, R315 and R324 represents the NPK ratio.

Foliar B

The factorial effect of fertilizer type, NPK ratio and application rate had no significant effect (3-way ANOVA: $p < 0.05$) on foliar B at both farms. At Rogland, treatment type had a statistically significant effect on foliar B, with the lowest values found at the second treatment level. The lower values can be due to nutrient dilution caused by increased plant growth occurring at this treatment level. At Blomfontein treatment type had no significant effect and no general trends were observed in foliar B. A very weak significant positive correlation was found with foliar Mg ($R^2 = 0.278$) and a negative trend with foliar Mn.

Foliar B values were lower than the toxicity level of 400 mg/kg, but higher than the lower level of deficiency of 20 mg/kg (Marschner, 1995). Values were higher than that found in Citrusdal (Stassen, 1987), but similar to Clanwilliam (Lourenco, 2018).

Foliar Al

The factorial effect of fertilizer type, NPK ratio and application rate only had a significant effect (3-way ANOVA: $p < 0.05$) on foliar Al at Rogland. A general positive trend was observed in the organic fertilizers, with only the second treatment level of the mineral 3:1:5 fertilizer being significantly lower than the control. At Blomfontein a negative trend was observed in the mineral fertilizers, however there was no significant change in foliar Al. A negative trend was identified between foliar Al and tea yields across all fertilizers at Rogland and in the mineral fertilizers at Blomfontein. These negative trends indicate a possible toxicity effect of high foliar Al levels. At Rogland foliar Al were similar to values found by Nieuwoudt (2017) in the same region, but was lower than that found in Clanwilliam (Lourenco, 2018). Foliar Al was significantly higher at Blomfontein due to the inherent lower soil pH which increases Al solubility.

4.4.6 Fertilizer Efficiency

Fertilizer efficiency for applied N was significantly higher in the organic and mineral 2:3:2 fertilizer at the lowest application rate (Fig. 4.43). It was significantly higher than other NPK ratio fertilizers at this application rate as less N was applied. However the efficiency levels are extremely high, not necessarily due to nutrient uptake from applied fertilizers but rather the plant being associated with N-fixing bacteria. This causes all efficiency levels to be elevated to unrealistic values. The lower efficiency levels of higher application rates indicate loss of applied N through leaching, however, it is difficult to accurately quantify N uptake from fertilizer as rooibos is associated with biological N-fixing bacteria (Brink, *et al*., 2017).

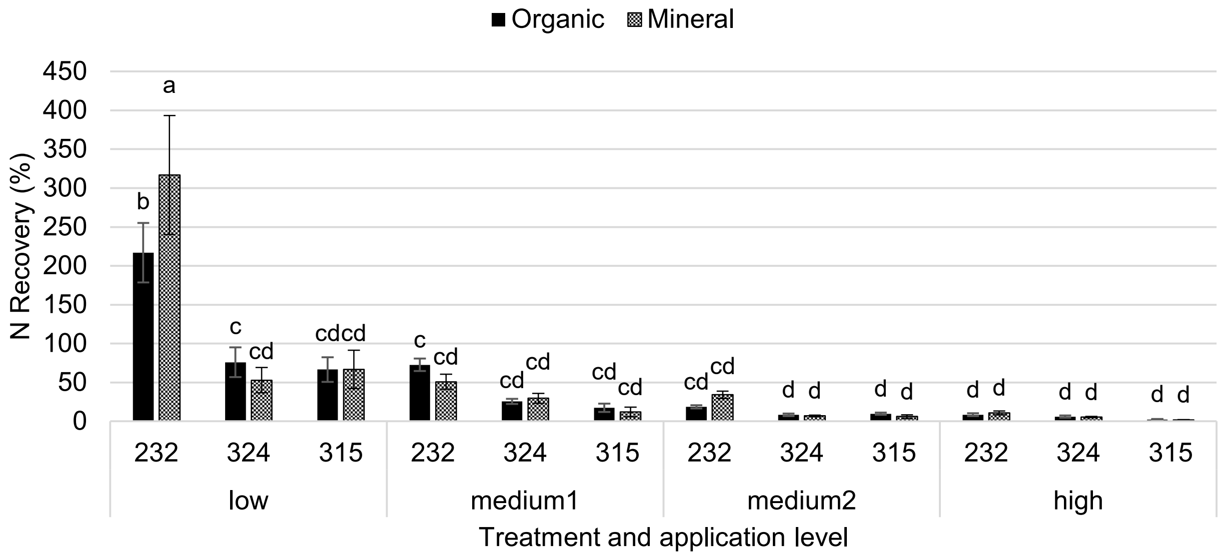

Figure 4.43: N recovery based on foliar nutrient concentration in the organic and mineral fertilizers in February 2018 at Rogland. Lowercase letters indicate a significant difference at a 95 % confidence interval.

All treatments had a very low fertilizer efficiency for P, with the highest P recovery occurring in the lowest application rate of the 2:3:2 and 3:1:5 fertilizers (Fig. 4.44). These low values indicate that P uptake is a slow process, even at low application rates, and that P application should not be done on a regular basis. P efficiency values are more accurate than N efficiency as P is not as mobile in the soil and is only lost through plant uptake or P fixation, but is not leached from the soil.

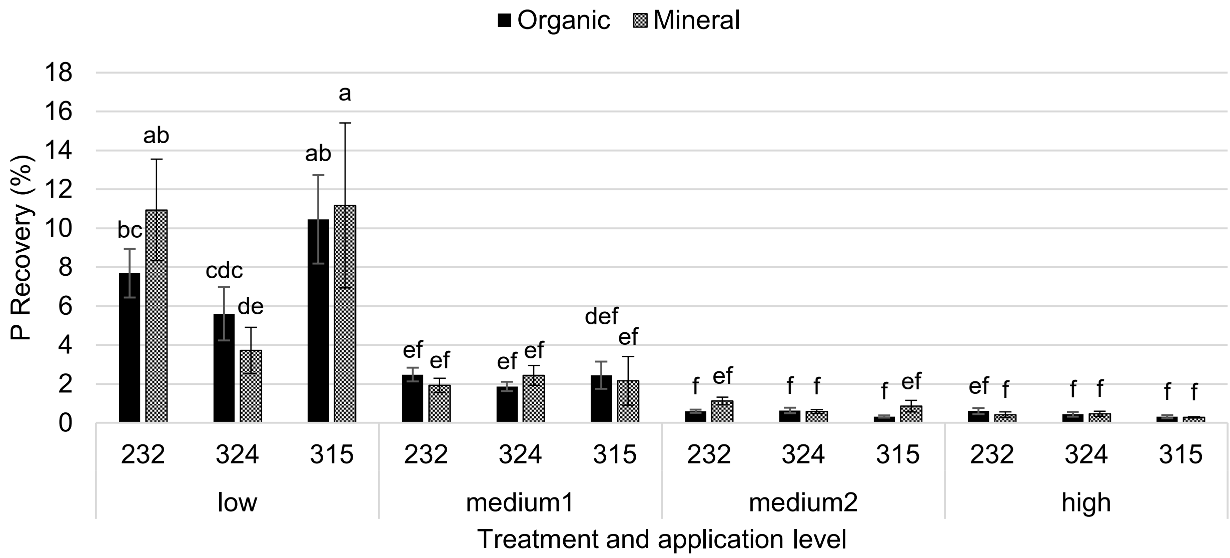

Figure 4.44: P recovery based on foliar nutrient concentration in the organic and mineral fertilizers in February 2018 at Rogland. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Fertilizer efficiency for applied K was significantly higher in in the lowest application rate of the 2:3:2 fertilizer (Fig. 4.45). This significantly higher efficiency is due to the lowest K application occurring in these treatments. The significant low K recovery can be due to leaching in the sandy soil or that the plant is unable to take up high volumes of K.

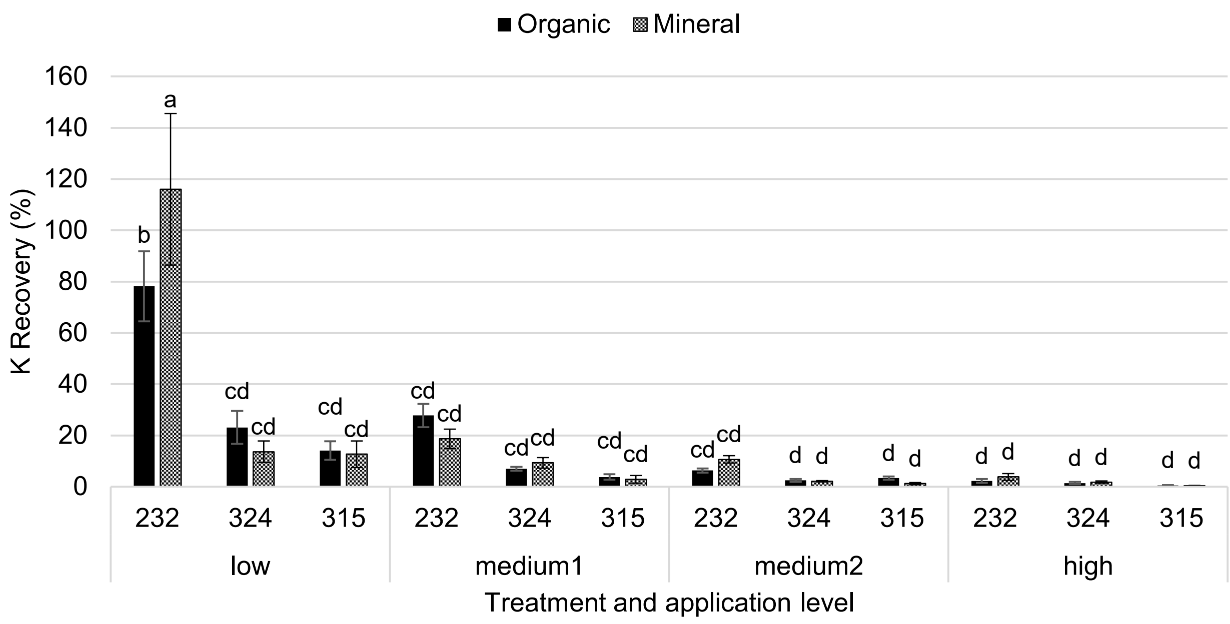

Figure 4.45: K recovery based on foliar nutrient concentration in the organic and mineral fertilizers in February 2018 at Rogland. Lowercase letters indicate a significant difference at a 95 % confidence interval.

4.5 Conclusions

The organic and mineral 3:1:5 fertilizer treatment had a significant effect on soil pH (KCl), EC and soil K. The organic 3:2:4 fertilizer had a noticeable effect on soil micronutrients (Fe, Cu, and Zn) possibly due to the micronutrient contents associated with chicken manure fertilizers. Bray II P increased with treatment levels, however soil P did not did not increase to the intended targets, indicating that a proportion of applied P became unavailable for plant uptake likely through P fixation.

Foliar P generally showed a negative trend with soil P (0 – 15 cm), with only a positive trend found in the mineral fertilizers at Rogland. This contradicts the findings of other studies whereby it was concluded that rooibos plants are unable to regulate P uptake when its supply is more abundant. However, the low soil water content due to the drought conditions could have limited P uptake. At both farms foliar P showed a positive trend with tea yield per plant and survival-adjusted yields in the organic fertilizers, while foliar Mn showed a positive trend at Rogland.

At Rogland, increased P application and soil P increased plant survival in the organic and mineral fertilizers; while at Blomfontein a negative trend was found with soil P in the mineral fertilizers. This indicates that one-year old rooibos plants are more resistant to P application than seedlings. The highest tea yields were obtained at the second treatment level across all organic fertilizers at both farms and in the mineral fertilizers at Rogland without significantly negatively affecting plant survival. This highlights a preferred level of P application by rooibos plants.

The highest tea yield per plant was obtained in the organic 3:2:4 fertilizer, however, due to the lower plant survival rate, the highest survival-adjusted yield was obtained in the second treatment level of the mineral 3:1:5 fertilizer (1420.3 kg/ha) by increasing yield by 64.5 %. Across all fertilizer treatments and both farms the high treatment level negatively affected survival-adjusted yield. However, due to the high variability in the results of treatment replicates the differences were statistically insignificant.

Therefore we can conclude that the application of organic and mineral fertilizers improved soil fertility, however had a limited effect on foliar nutrients. High nutrient applications negatively influenced plant growth, while the application of 10 mg P/kg (36.3 kg P/ha) had a positive effect of tea yields, with N and K application rates not having a significant effect. The low nutrient recovery of the applied P indicates that this application rate should be sufficient to support plant growth for several seasons. Fertilizer efficiency was highest at the low nutrient applications with higher application of N and K lost to leaching. It is therefore recommended that up to 30 N and 50 K mg/kg be applied with 10 mg P/kg to one-year old rooibos plants to increase tea yields.

Further field trials are recommended to study the effect of organic and mineral fertilizers on rooibos tea yields over several years as organic fertilizers are able to start showing significant results after 3 – 5 years after fertilizer application. The effect of a once-off application of 36.3 kg P/ha on one-year old plants and yearly application of low amounts of N (24 - 108 kg/ha) and K (24 - 180 kg/ha) on rooibos tea yields must be researched to further optimize the use of organic and mineral fertilizers. By monitoring plant growth over several seasons will also provide additional information on the effect of rainfall.

5 RESEARCH UNIT 3: EFFECT OF VERMICOMPOST TEA ON ROOIBOS PLANT GROWTH

5.1 Introduction

Vermiculture is a low cost system that involves the process of using earthworms to convert organic waste into finer, more plant available nutrient-rich material (Buchanam, *et al*., 1988). However, it has also been shown to decrease P and micronutrient availability (Pant, *et al*., 2012). Baca, *et al*. (1992) described vermicomposting as the aerobic transformation of an organic by-product into an organic product that has no detrimental effects on crop growth. The recycling and usage of organic waste as a fertilizer minimizes the contamination of the soil and waterways associated with the usage of mineral fertilizers (Theunissen, *et al*., 2010). The earthworms are able to break down organic residues and stimulate microbial activity, increasing the rates of nutrient mineralization (Arancon, *et al*., 2006). Vermicomposts (VC) also contain essential nutrients readily taken up by plants during growth (Edwards & Burrows, 1988). The addition of VC or vermicompost tea (VCT) to soil improves soil fertility (Srivastava, *et al*., 2011) and enhances seedling growth and development, plant growth and productivity (Atiyeh, *et al*., 2000), and root elongation (Padmavathiamma, *et al*., 2008).

VCT has been shown to contain organic acids and result in an increase in soil pH that can affect nutrient availability in the soil (Pant, *et al*., 2012). The increase in soil pH can increase P, Ca and Mg availability in acidic soils, while also reducing the solubility of toxic elements such as Al and Mn. Organic acids increase P dissolution, while reducing Mn and Fe dissolution (Jones & Darrah, 1994). The use of VC increases fertilizer value and therefore decreasing the required dosage per application of fertilizer. VC has been shown to have a significantly higher percentage of N, P and K than conventional compost with an increase of 62, 20 and 38 %, respectively (Padmavathiamma, *et al*., 2008). Atiyeh, *et al*., (2002) and Arancon, *et al*., (2006) found that humic acids extracted from VC significantly increased plant growth. Organic waste with earthworms increased N-content of plant and significantly increased soil available P and K (Garg, *et al*., 2006).

Singh, *et al*., (2010) conducted a study by using VCT as a foliar spray and found that strawberry plant growth and leaf nutrient levels were higher than that of the control. Tejada, *et al*., (2008) conducted a similar study on tomatoes and found that plant growth and fruit yield significantly increased under foliar VCT fertilization. Plants treated with VCT had increased root and shoot growth and N-uptake than that of plants treated with a mineral nutrient solution (Pant, *et al.* 2011). This suggests that VCT provided additional microbial and hormonal compounds that are beneficial for plant growth (Pant, *et al*., 2011).

The symbiotic relationships with soil bacteria play an important role in the survival of rooibos plants (Postma, 2016). Little is known about the bacteria associated with rooibos, with known bacteria occurring in the rhizosphere including species in the *Mesorhizobium* and *Rhizobium* (alpha-Proteobacteria), and *Burkholderia* and *Herbaspirillum* (Beta-Proteobacteria) (Hassen, *et al.,* 2011).

Many factors, including seasonal changes and soil properties, can influence the interaction between plants and bacterial and fungal communities in the soil as warmer temperatures favour bacterial activity (Wang, *et al*., 2003). In the dry season bacterial communities are more diverse in the bulk than the rhizosphere soil (Postma, 2016). A significant difference in the bacterial β-diversity between the dry and wet seasons exists, indicating a possible seasonal effect on plant growth (Postma, 2016).

Slabbert (2008), Postma (2016) and Brink, *et al*., (2017) discuss in their studies the measurement of microbial community diversity and the microbes associated with rooibos plants, but the response to VCT application is unclear.

There is a lack of research on the effect of the usage of VCT, as an organic fertilizer, on crop production under field soil and climatic conditions. Majority of studies are under greenhouse conditions (Garg, *et al*., 2006), using hydroponic solutions or using soilless container (potting) media (Atiyeh, *et al*., 2000; Atiyeh, *et al*., 2002; Arancon, *et al*., 2006). Therefore, the effect of VCT on crop production and microbial diversity and species richness under field soil and climatic conditions remains unclear. The use of VCT solutions in the nutrient poor sandy soils of the fynbos region can lead to soils becoming more productive and enhancing its potential to support agriculturally important plants (Theunissen, *et al*., 2010).

5.2 Objectives

1. To determine the effect of the monthly application of a vermicompost tea solution on plant nutrient uptake and growth of rooibos tea under Northern Cape growing conditions.
2. To determine the effect of vermicompost tea application on rhizosphere bacterial and fungal diversity and species richness.

5.3 Methods and materials

5.3.1 Brewing of vermicompost tea (VCT)

A trial brewer (Growing Solutions Incorporated: Compost Tea System10™) was used to brew the VCT to be used in the field trial. The VC used was obtained from a South African company supplying commercial compost that is derived from plant residue and organic food waste. The guidelines used in the brewing process were provided by the company. In the brewing process 1.5 L of the VC was placed in a sieved net and suspended in 40 L of water. A VCT catalyst (100 ml), consisting of seaweed extract, mineral powder and botanical ingredients was then added to the water. The tea solution was aerated for 24 hours before being diluted to specified treatment concentration and applied to the soil as a soil drench. Teas produced with aeration are found to be more stable and effective than those produced without aeration (Edwards, *et al*., 2006).

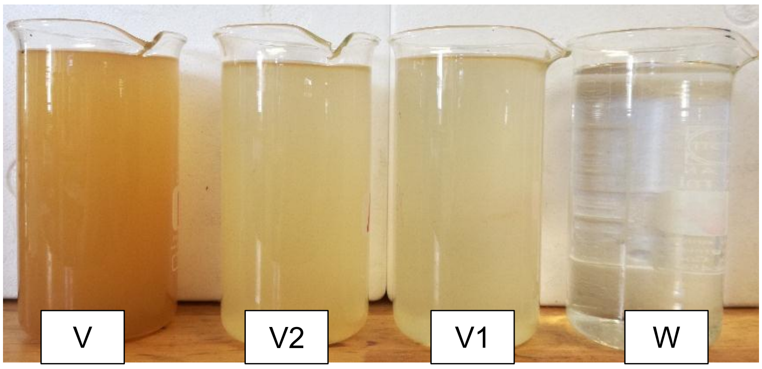

Figure 5.1: Illustration of the colour of the concentrated vermicompost tea (V) and the V2; V1 and Water only (W) treatments.

5.3.2 Layout and Setup

The VCT field trial consisted of two trials, with the first, main trial conducted over a 9-month growing period during the winter rainfall period to summer tea harvest (June 2017 to February 2018). In the first VCT trial, treatments were applied on a monthly basis for six months, from June to November 2017. This coincided with the period of active nutrient uptake by the plant in winter and the start of the growing season in spring. This period of application was performed in accordance to the guidelines of the commercial VCT producer. In the second, short-term VCT trial (April – June 2018), the effect of VCT application on plant soil microbial diversity and species richness within the rhizosphere was determined, to try and further explain the results of the main VCT field trial. The same treatments were applied to new plots within the same field. The plots were moved to ensure that the plants had no previous treatment to accurately monitor the effect of VCT application on the rhizosphere. Treatment application was ceased in June 2018 when the plants and rhizosphere soil was sampled.

Both trials consisted of a control (no applied treatment) and three applied treatments (Table 5.1): i) VCT, inoculated with 5 ml protein hydrolysate, diluted with water at a ratio of 1:110 (V1); ii) VCT, inoculated with 25 ml protein hydrolysate, diluted with water at a ratio of 1:21 (V2); iii) and water (W). The control treatment received no solution so that the effect of the water treatment can also be evaluated as an applied treatment. The V2 treatment was concentrated with VCT at five times more than the recommended concentration of the VCT solution. Each treatment had an application rate of 250 ml/plant per month, to ensure that the applied solution would reach the feeder roots of the rooibos plants. The 1:110 dilution treatment (V1) is according to the VC producer's guidelines for making compost tea. The more concentrated treatment (V2) was selected to determine whether a more concentrated application would have a significant effect on plant growth. Each treatment was replicated four times.

5.3.3 Characterisation of vermicompost tea and its effect on soil reaction

Vermicompost tea nutrient and organic C content

Water and concentrated VCT solutions were analysed for inorganic macro- (N, P, K, Ca, Mg) and micro-nutrients (Fe, Cu, Zn, Mn) to determine if the compost tea provided additional nutrients. The solutions were also analysed for Dissolved Organic Carbon (DOC) to determine if organic acids were applied to the soil. Total macro- and micro-nutrient content and DOC was determined by Bemlab Laboratory (Pty). Ltd., Somerset West.

Table 5.1: Summary of the vermicompost tea experimental treatments and monthly application rates per plant.

Code	Treatment	L/ha	ml/plant	ml/plant
C	Control (no treatment)	0	0	0
V1	Protein Hydrolosate	5	0.11	250
	Vermicompost Tea	100	2.25	
	Water	11006	247.64	
V2	Protein Hydrolosate	25	0.56	250
	Vermicompost Tea	500	11.25	
	Water	10586	238.19	
W	Water	11111	250	250

Soil pH and EC

A laboratory incubation trail was performed to determine the effect of the tap water and VCT application on soil pH and EC, so as to mimic the effect of application in the field. The three treatments of 250 ml were applied to a soil volume based on the bulk density of 1612 $kg.m^{-3}$, application depth of 0.1 m and application radius of 0.04 m, similar to the volume of soil receiving VCT in the field trial. The mass of soil in each pot was therefore 1215.4 g. Soil was sampled after each treatment application and oven-dried before measuring the pH and EC. Each treatment was duplicated and treatments were applied for a total of five times. The pH and EC of the soil was determined in water using a 1:2.5 suspension ratio on a mass basis (Rhoades, 1996; Thomas, 1996).

5.3.4 Plant sampling

Plant survival

The number of living plants were recorded in each treatment replicate at the first VCT application (June 2017 and April 2018) again at harvest (February and June 2018). Plant survival was expressed as the percentage of plants that survived of the original number from plants at the start of the experimental trial.

Tea yield

The rooibos plants were harvested in February 2018 in the first field trial and in June 2018 in the second field trial, and the total biomass yield was determined for each replicate. The number of plants within the replicate was used to determine the average yield per plant (kg). The average number of plants per replicate at the start of the field trial (June 2017) was used to determine the number of plants expected to occur per hectare. This was then used to calculate the expected yield per hectare per treatment replicate (kg/ha).

5.3.5 Plant analyses

Foliar sampling was performed at plant harvest in February and June 2018. The plant samples were rinsed with distilled water, cut into smaller pieces and oven-dried before being analysed. Total macro- and micro-nutrient content of the dried samples was determined using the Kjeldahl method (N), and acid digestion and ICP-MS (P, Ca, Mg, K, Na, Fe, B, Zn, Mn, Cu and Al) by Elsenburg Plant Laboratory.

5.3.6 Soil microbial analysis

Rhizosphere soil was sampled in June 2018 within each treatment replicate to determine bacterial and fungal diversity; species dominance using the Simpson Index (alpha diversity) and beta-diversity between samples. Samples were kept at room temperature and analysed by Sporatec Analytical services using Automated Ribosomal Intergenic Spacer Analysis (ARISA). The ARISA method is an effective and rapid process used to estimate the diversity and composition of bacterial and fungal communities (Slabbert, *et al*., 2010). Alpha diversity is defined as the diversity of a specific group of organisms or communities within a specific location (Slabbert, 2008). The larger the Simpson's index, the higher the chance that two randomly picked species will be the same species. Beta diversity is the variation in the types of species among different sites (Anderson, *et al*., 2011) which is determined by the Bray-Curtis method.

5.3.7 Statistical Analysis

Statistical analyses was performed using Statistica™ Software (Version 13.3, 2018, Dell Software, Tulsa). The data was tested for significant differences between treatments at a 95 % confidence level between the different treatments.

5.4 Results and discussion

5.4.1 Vermicompost tea chemical properties

The VCT solution contained a higher concentration of macronutrients and dissolved organic carbon than the tap water (Fig. 5.3). The higher macronutrient level derives from the compost that was brewed, indicating that VCT is able to provide a higher nutrient level that is already in solution and available for plant uptake. The increase in the dissolved organic carbon in the VCT is due to organic acids associated the organic material. VCT increased P (4.0 mg/l), K (6.45 mg/l), Ca (24.0 mg/l), Mg (7.0 mg/l) and DOC (16.0 mg/l) by 97.5; 64.4; 88.8; 99.1; and 47.5 %, respectively. The concentration of mineral N and micronutrients in the VCT were below detection, supporting Pant, *et al.* (2012) in that VCT does not enhance soil micronutrient availability. Even with the increase in macronutrients in the VCT, once diluted to the application ratios there was only slight differences between applied P, K, Ca and Mg in the V1, V2 and water treatments (Table 5.2).

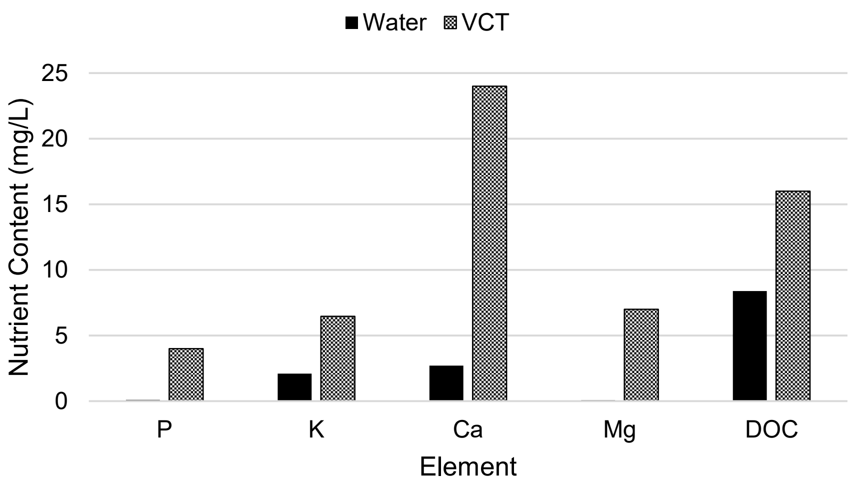

Figure 5.2: Mineral macronutrient and dissolved organic carbon (DOC) content of the water and brewed vermicompost tea solutions.

Table 5.2: Mineral macronutrients added to the soil in the vermicompost tea and water treatments over the course of six months in the first VCT trial at Rogland.

	Treatment		
Mineral Nutrient	V1	V2	Water
	g/ha	g/ha	g/ha
P	1.27	2.71	0.93
K	20.15	22.47	19.6
Ca	27.24	35.87	25.2
Mg	1.15	3.67	0.56

The application of water and VCT had a positive effect on soil pH with a significant increase in the V1 and V2 treatment at the fifth application compared to the control (Fig. 5.3), however this increase was not significantly higher than the water treatment. This indicates that the application of water, and not the VCT, had an effect on soil pH. Positive trends were observed for all treatments but the application of the VCT increased soil pH more than just the water treatment. This increase in the VCT can be attributed to the additional organic acids (Fig. 5.2) that are associated with the brewing of VCT. The application of water and VCT had no significant effect on soil EC with no general trends identified.

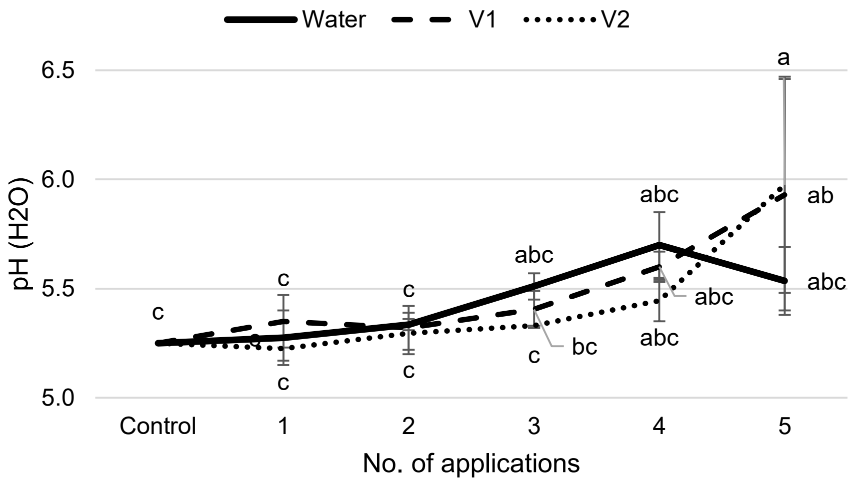

Figure 5.3: Effect of water and vermicompost tea treatments on soil pH (H_2O) of topsoil sampled at Rogland. Lowercase letters indicate a significant difference at a 95 % confidence interval.

5.4.2 Plant analysis

Plant survival

Treatment type had a statistically significant (p = 0.028) effect on plant survival (%) (Fig. 5.4). The application volume of VCT application had no significant effect, whereas the application of water had a statistically significant effect (p = 0.028) on plant survival (%). A significant positive correlation (R^2 = 0.504) was found between plant survival (%) and water application indicating that the addition of water increased plant survival and not the VCT. In the 3-month winter trial plant survival was increased in all applied treatments with a significant increase occurring in the V2 treatment. Plant survival in June 2018 followed the same trend as in February 2018 (Fig. 5.5). This indicates that the application of VCT and water has a positive effect on plant survival regardless of seasonal conditions.

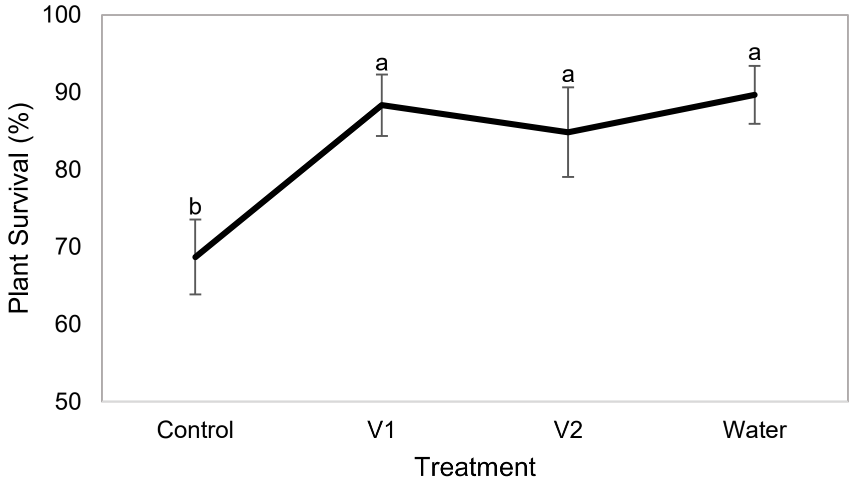

Figure 5.4: The effect of the vermicompost tea and water treatments on plant survival in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence level.

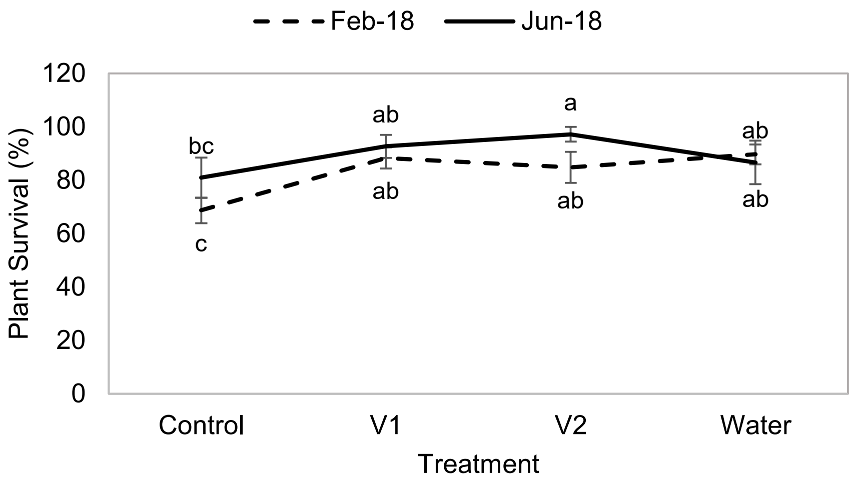

Figure 5.5: Effect of the vermicompost tea and water treatments on plant survival in February and June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

Tea yield per plant

Treatment type had a statistically significant effect (p = 0.004) on average tea yield per plant (Fig. 5.6). The application of VCT had no significant effect, whereas the application of water had a statistically significant effect (p = 0.004). A significant negative correlation (R^2 = 0.539) was found between tea yield and water application. The lower plant survival in the control treatment could have led to less plant competition for soil water and nutrients, resulting in a higher tea yield per plant. No significant correlations were found between foliar nutrients and tea yield per plant.

It is important to note that these tea yields do not consider the effect of plant survival on tea yield per hectare.

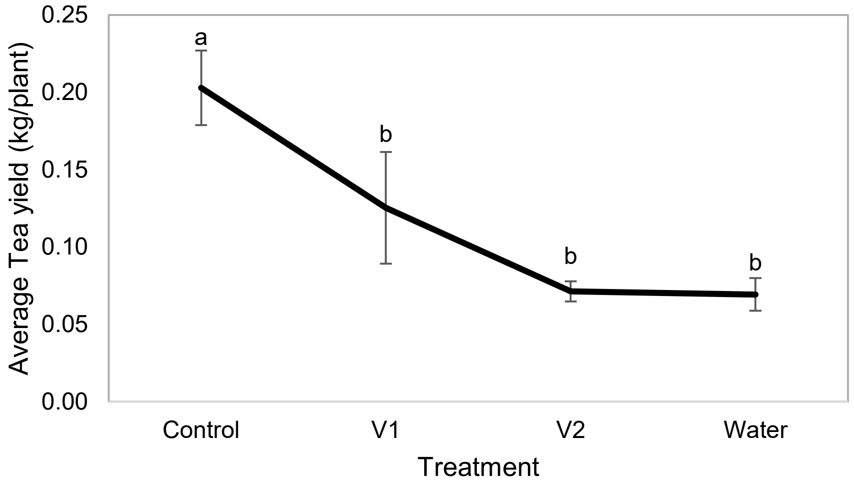

Figure 5.6: The effect of the vermicompost tea and water treatments on average tea yield per plant in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Survival-adjusted tea yield per hectare

Treatment type had a statistically significant effect (p = 0.024) on the survival-adjusted tea yields (Fig. 5.7). In the control treatment the adjusted harvest was significantly lower than the tea yield before being adjusted, indicating the negative effect of the lower plant survival rate. VCT application had no significant effect but a negative trend was evident with increased VCT and water application. In the short-term trial in the cooler months the V2 treatment had a significantly higher yield than the control treatments (Fig. 5.8). This indicated that the applied treatments had the inverse effect on survival-adjusted tea yield than during the spring and summer months. This can possibly be linked to the seasonal effect on the microbial diversity and dominance (Postma, 2016) associated with each treatment which in turn has an effect on rooibos plant growth.

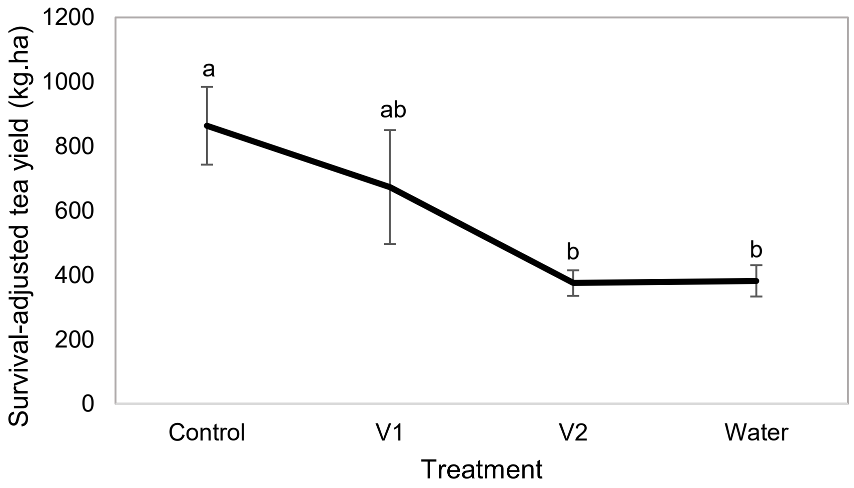

Figure 5.7: The effect of vermicompost tea and water treatments on survival-adjusted tea yield in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

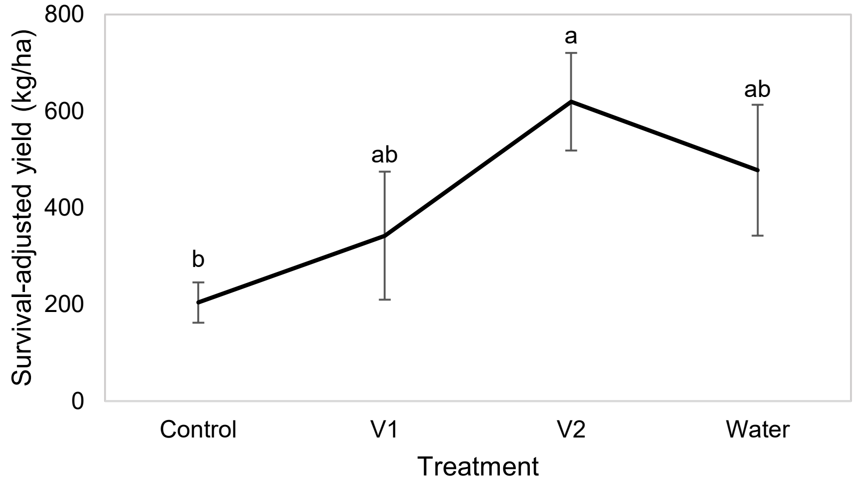

Figure 5.8: Effect of vermicompost tea and water treatments on survival-adjusted tea yields (kg/ha) in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval

5.4.3 Foliar analysis

Foliar N

Treatment type had no significant effect on foliar N concentration, however treatments V1 (1.7 ± 0.2 %) and W (1.65 ± 0.3 %) had a statistically significant negative effect on foliar N compared to the control (2.1 ± 0.2 %) (Fig. 5.9). Foliar N levels were higher than that found in plants of the same age at Clanwilliam (Stassen, 1987) and Nieuwoudtville (Nieuwoudt, 2017), but lower than 2.26 % found in rooibos seedlings (Lourenco, 2018). Water application showed a negative trend with foliar N, while foliar Zn and Mn showed a positive trend. Foliar N was found to have a positive effect on survival-adjusted tea yields, however, a negative effect was observed with plant survival. The higher foliar N in the control treatment cannot be attributed to less dilution due to less plant growth as it had the highest tea yield per plant, neither can it be linked to N-fixation increased at a higher pH as the applied treatments increased soil pH. Therefore the main effect on foliar N is unknown.

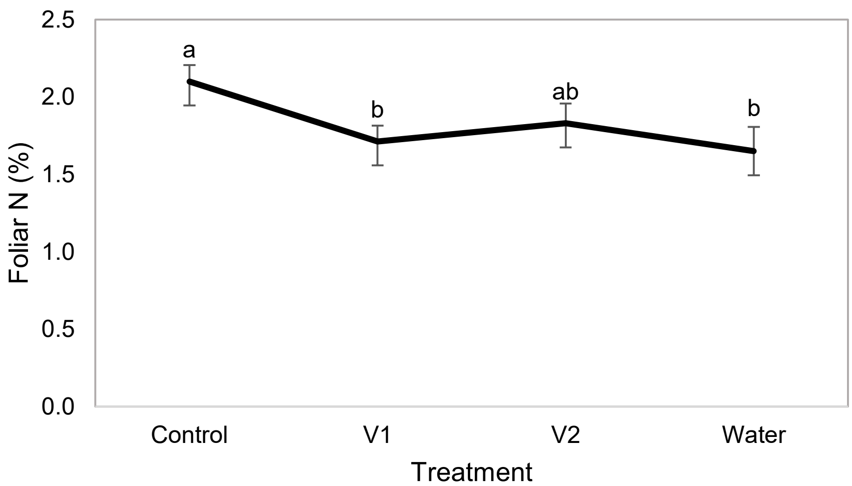

Figure 5.9: Effect of vermicompost tea and water treatments on foliar N concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Foliar P

Treatment type had a statistically significant effect on foliar P levels (Fig. 5.10). VCT treatments V1 and V2 significantly increased foliar P from 0.09 ± 0.01 % in the control to 0.1 ± 0.01 and 0.11 ± 0.01 %, respectively. Foliar P levels were higher among all treatments than that found in plants of a similar age (Stassen, 1987; Nieuwoudt, 2017) and seedlings (Lourenco, 2018). The increase in foliar P in the VCT treatments could be due to the increase in soil pH which increases P solubility and uptake. The increase in foliar P is also associated with an increase in P and DOC in the VCT treatments as the organic acids solubilise inorganic P and increase its availability for plant uptake. During the short winter trial the opposite was found as foliar P decreased in the VCT treatments (Appendix B: Fig. 9.11). This negative effect further highlights the effect of seasonal conditions on microbial communities which in turn can have a varying effect on plant nutrient uptake and growth.

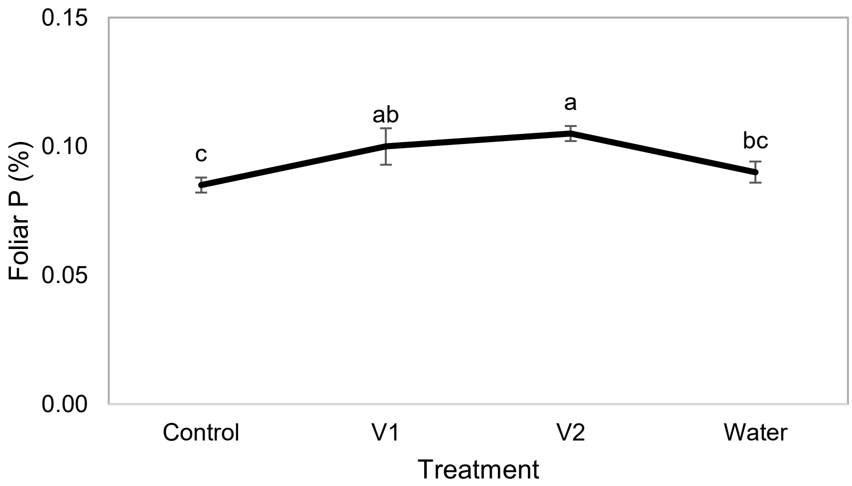

Figure 5.10: Effect of vermicompost tea and water treatments on foliar P concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Foliar basic cations

Treatment type had no significant effect on foliar K, Ca, Mg and Na concentrations (Appendix B: Figs. 9.6 – 9.10). Average foliar K levels ranged between 0.59 – 0.68 % and were higher than that found in similar aged plants by Stassen (1987) and Nieuwoudt (2017). Average foliar Ca levels ranged between 0.12- 0.13 % and were similar to that found by Nieuwoudt (2017) in the same rooibos production region. In the short-term trial the application of VCT showed to have a negative effect on foliar Ca (Appendix B: Fig. 9.12), possibly due to seasonal changes affecting microbial communities and plant nutrient uptake. Average foliar Mg levels ranged between 0.31 – 0.37 % and were similar to that found in seedlings (Lourenco, 2018) and higher than that found in Clanwilliam (Stassen, 1987) and Nieuwoudtville (Nieuwoudt, 2017). A significant positive correlation was found between foliar Mg and foliar B (R^2 = 0.5301). Magnesium has been reported to have a synergistic effect on the uptake of anions such as phosphate and borate (Tisdale & Nelson, 1975). Foliar Na levels were significantly higher than those found by Lourenco (2018) in seedlings, but similar to values found in the same production region by Nieuwoudt (2017).

Foliar Fe

Treatment type had no significant effect on foliar Fe, however a significant increase occurred from 95.6 ± 14.9 mg/kg in the control to 149.5 ± 40.3 and 150.1 ± 26.4 mg/kg in the V1 and water treatments, respectively (Fig. 5.11). Foliar Fe levels among all treatments were higher than that found by Nieuwoudt (2017) in the same production region. The increase in foliar Fe in the applied treatments is not likely due to soil pH increase, as an increase in pH reduces Fe mobilisation from Fe_2O_3 and Fe_3O_4, but rather the lack of the dilution effect associated with increased plant growth. Plant growth was lower in the applied treatments, therefore foliar Fe was more concentrated and at higher levels. Foliar Fe showed a significant positive correlation (R^2 = 0.5748) (Fig. 5.12) with plant survival. However, this is likely due to the reduced plant growth in the applied treatments therefore foliar Fe is more concentrated.

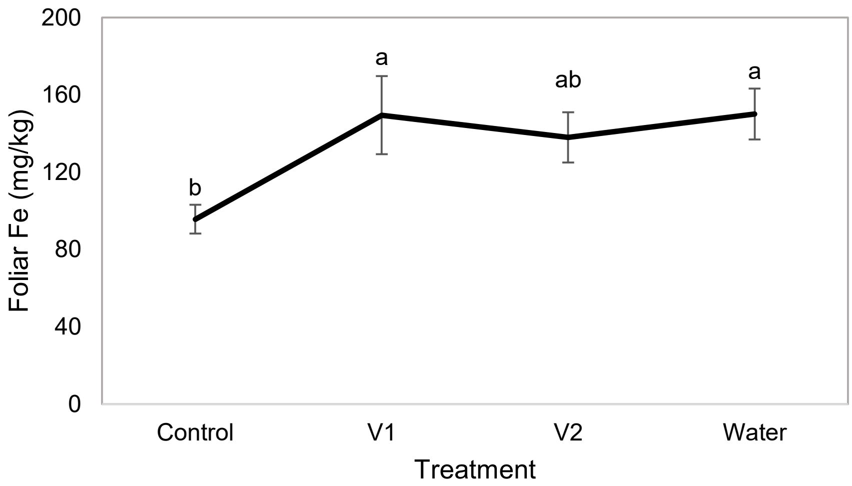

Figure 5.11: Effect of vermicompost tea and water treatments on foliar Fe concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

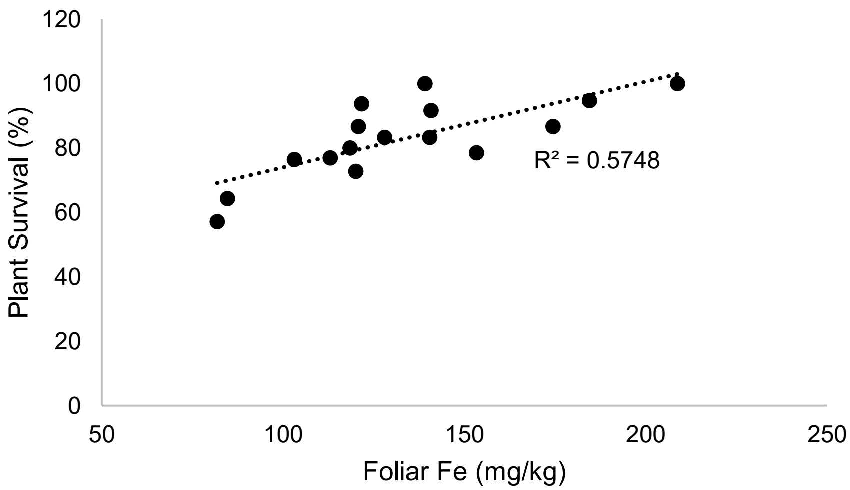

Figure 5.12: Correlation between plant survival and foliar Fe concentration in the first VCT trial in February 2018.

Foliar Cu

Treatment type had no significant effect on foliar Cu levels, however a significant increase from 4.78 ± 0.98 mg/kg in the control to 6.65 ± 0.89 mg/kg in the V1 treatment was found (Fig. 5.13). Foliar Cu showed a positive trend with foliar Fe. In the short-term trial a significant decrease in foliar Cu was found in the V2 treatment (Appendix B: Fig. 9.13).

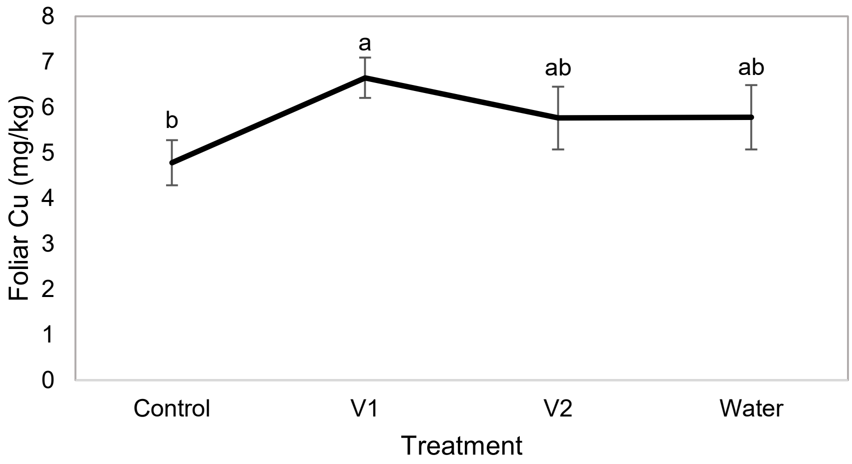

Figure 5.13: Effect of the vermicompost tea and water treatments on the foliar Cu concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Foliar Zn

Treatment type had no significant effect on foliar Zn, however the water treatment (8.3 ± 1.1 mg/kg) had significantly lower foliar Zn than the control (10.9 ± 1.2 mg/kg) (Fig. 5.14). A positive trend was found with foliar N and Zn. Survival-adjusted yield showed a significant positive correlation with foliar Zn (R^2 = 0.5258) (Fig. 5.15). This correlation is likely due to the genetic heterogeneity in rooibos plants as foliar Zn cannot be linked to the VCT or water application. In the short-term trial the V2 treatment had a significant negative effect on foliar Zn (Appendix B: Fig. 9.14).

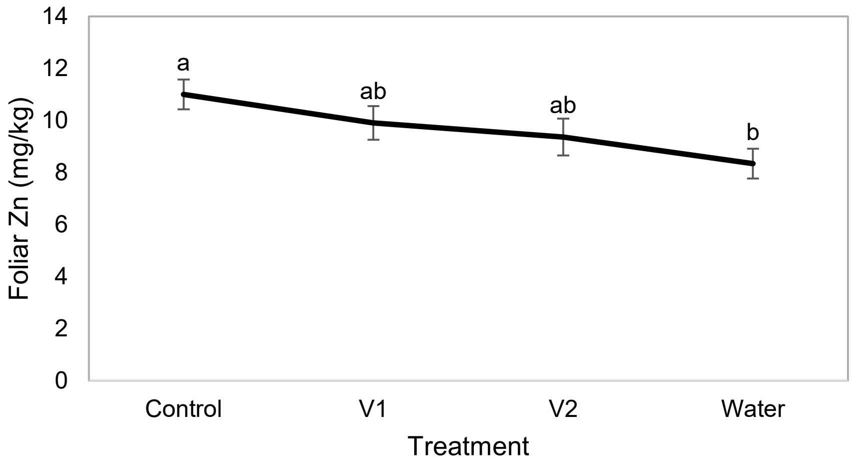

Figure 5.14: Effect of vermicompost tea and water treatments on foliar Zn concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

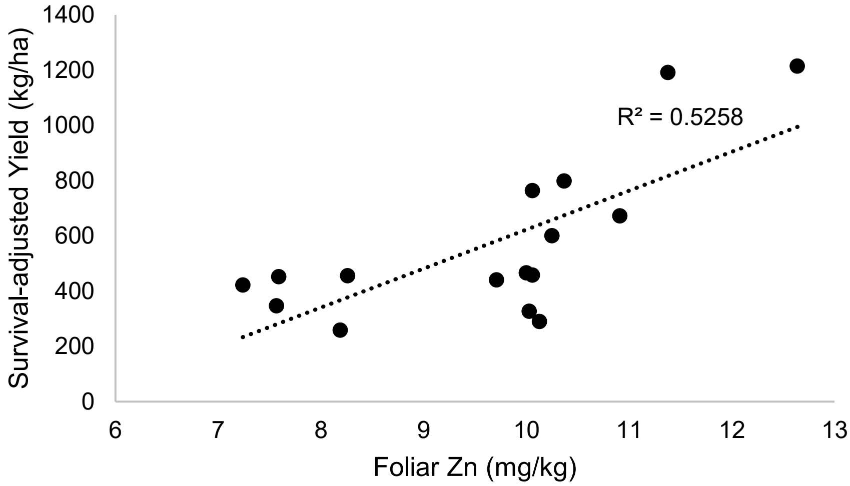

Figure 5.15: Correlation between survival-adjusted yield and foliar Zn concentration in the first VCT trial in February 2018.

Foliar Mn

Treatment type (Fig. 5.16) and water application had a statistically significant (p = 0.003) effect on foliar Mn, while application of VCT had no significant effect. All applied treatments were significantly lower than the control treatment (89.8 ± 17.8 mg/kg) indicating that the application of water negatively influenced foliar Mn. The decrease in foliar Mn can be linked to the increase in soil pH in the applied treatments as an increase in pH reduces the solubility of Mn. Foliar Mn in the applied treatments was lower than the average of 77 mg/kg found over a three-year period by Stassen (1987), likely indicating a deficiency. In Chapter 4 foliar Mn was identified to have a positive effect on tea yield, therefore indicating that the applied treatments had a negative effect on plant growth. A negative trend was found with foliar Fe, while positive trends were found with foliar N.

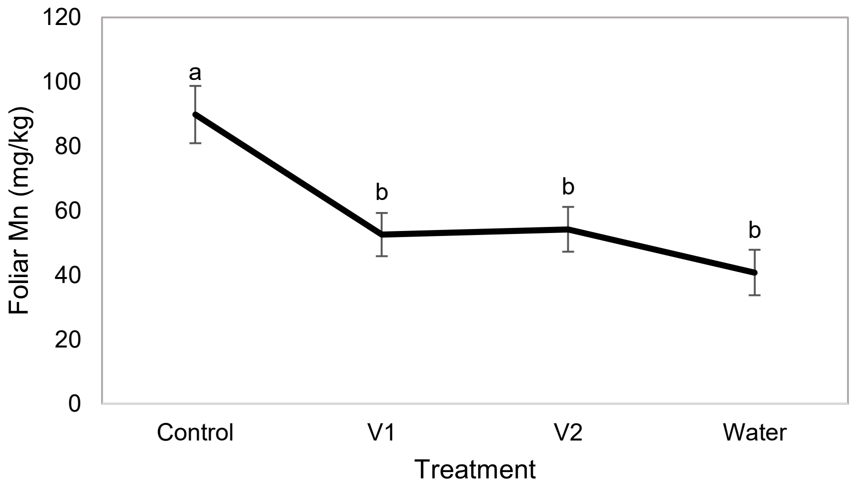

Figure 5.16: Effect of the vermicompost tea and water treatments on foliar Mn concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval

Foliar B

Treatment type had no significant effect on foliar B levels, however a general increase in foliar B was identified in all applied treatments with a significant increase at treatment V1 (Fig. 5.17) to 46.3 ± 5.5 mg/kg from 35 ± 2.3 mg/kg in the control. In the short-term trial the application of both VCT treatments significantly decreased foliar B concentrations (Appendix B: Fig. 9.15), possibly indicating a seasonal effect.

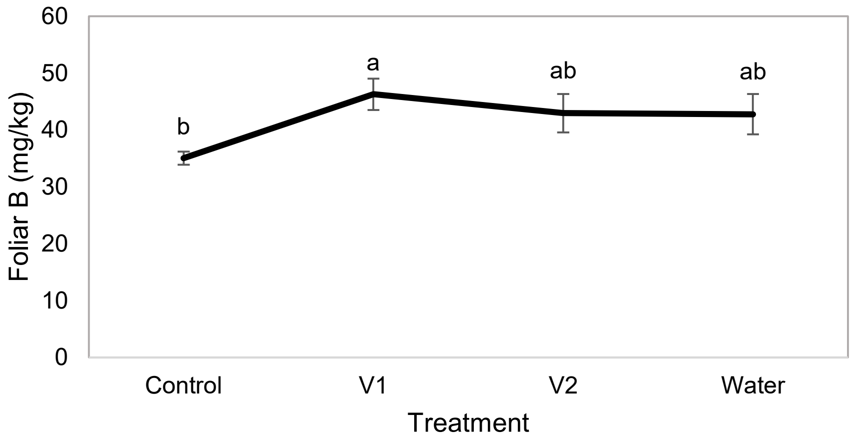

Figure 5.17: Effect of the vermicompost tea and water treatments on foliar B concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Foliar Al

Treatment type (Fig. 5.18), VCT (p = 0.008) and water application (p = 0.025) had a statistically significant effect on foliar Al levels. The application of VCT significantly decreased foliar Al levels to 59.8 ± 8.6 (V1) and 57.5 ± 5.3 mg/kg (V2) in relation to the control (72.4 ± 2.7 mg/kg). The decrease in foliar Al can be linked to the increase in soil pH in the applied treatments as Al solubility decreases with an increase in pH and applied organic acids. Organic acids form Al-organic acid complexes making it unavailable for plant uptake therefore foliar Al concentration decreased in the VCT treatments. Even though foliar Al decreased in the VCT treatments it had no significant effect on tea yields.

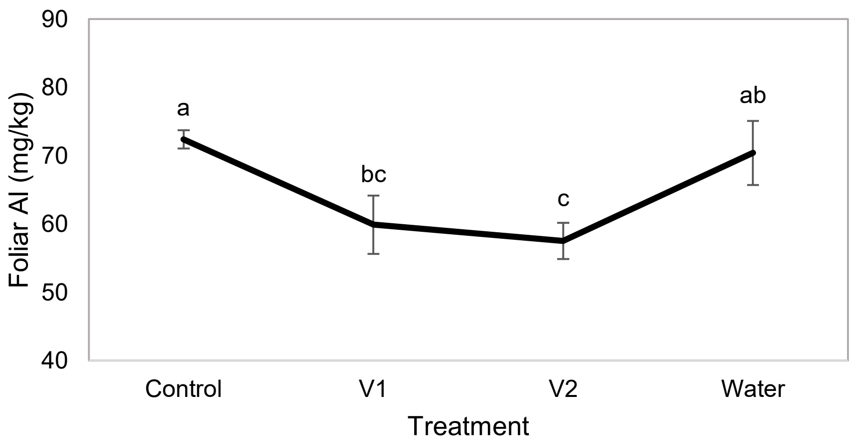

Figure 5.18: Effect of the vermicompost tea and water treatments on foliar Al concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

5.4.4 Rhizosphere Microbial Analysis (Second Trial: April - June 2018)

The soil temperature and water content varied between the warmer and cooler months of the two experimental trials (Fig. 5.19). Warmer soil temperatures were experienced in the summer months, but a higher soil water content occurred in the winter months. This variability in the seasonal climatic conditions has an effect on microbial communities that are influenced by soil temperature and moisture content. Warmer temperatures tend to favour bacterial communities, however soil moisture is required for the organisms to move within the soil.

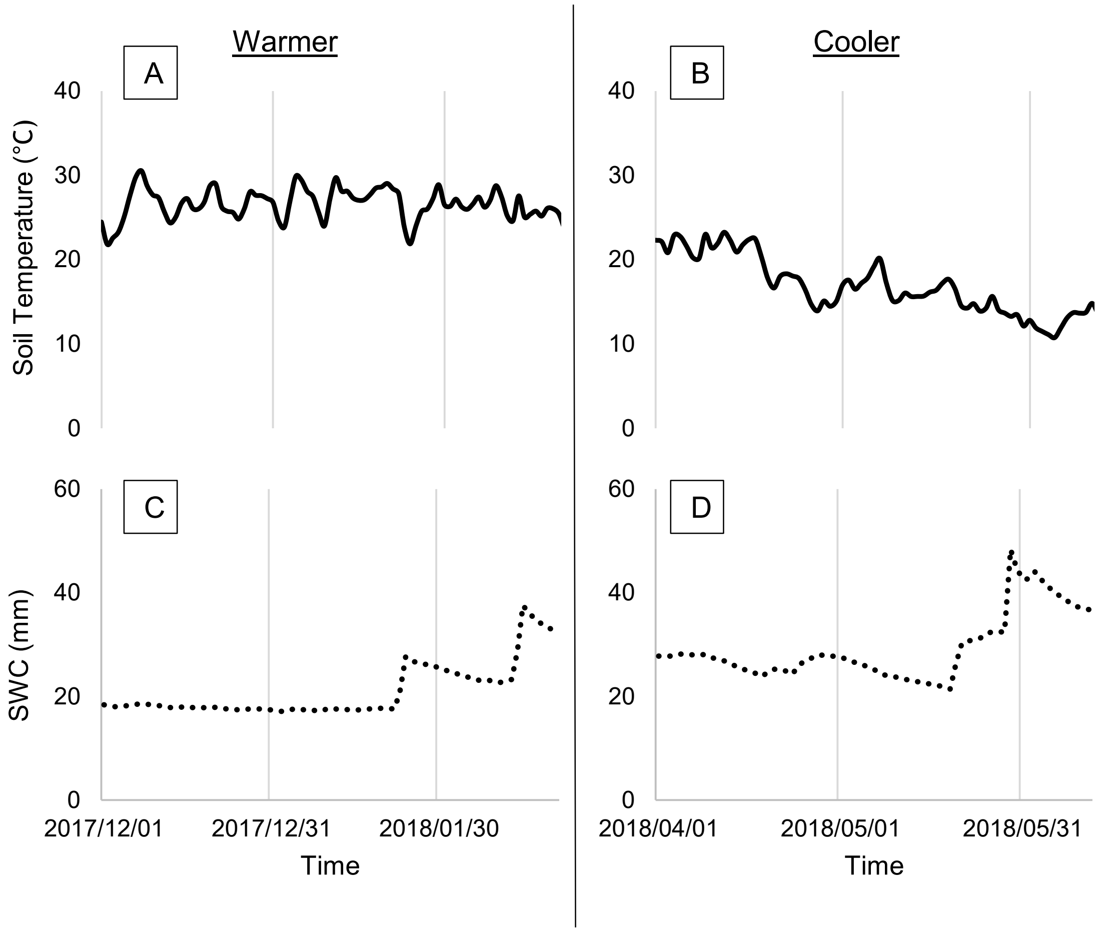

Figure 5.19: Comparison of the average daily soil temperatures at 15 cm depth three months before harvest in the A) Warmer (Dec 2017 – Feb 2018) and B) Cooler months (Apr – Jun 2018); and the total soil water content (SWC) in the soil profile in the C) Warmer and D) Cooler months.

α - Diversity

Treatment type had a significant effect on the bacterial species diversity. An increase in the Simpson Diversity Index (Fig. 5.20) of bacterial species in the VCT treatments indicates a more diverse microbial community, whereas a lower index value in the control and water treatments indicates a higher species dominance. However, treatment type had no significant effect on the bacterial species richness (α-diversity) (Fig. 5.21). There was however a positive trend in bacterial species richness when VCT was applied by increasing from 34 ± 2.6 in the control to 42 ± 6.1 and 39 ± 6.2 in the V1 and V2 treatments, respectively. This increase in the bacterial species richness in the VCT treatments supports the Simpson Index results of a more diverse community.

The bacterial Simpson Index had a positive trend with plant survival and plant biomass production in June 2018. Bacterial species richness had no significant correlations with plant properties but showed a positive trend with plant survival. A negative trend was observed between bacterial species richness and plant biomass, possibly indicating a more negative effect over the long-term. Bacterial species richness showed no significant correlations with foliar nutrient concentrations, but a positive trend was found for foliar N. This positive trend can be due to the increase in N-fixing rhizobium bacteria that is associated with rooibos plants (Masson-Boivin, *et al*., 2009).

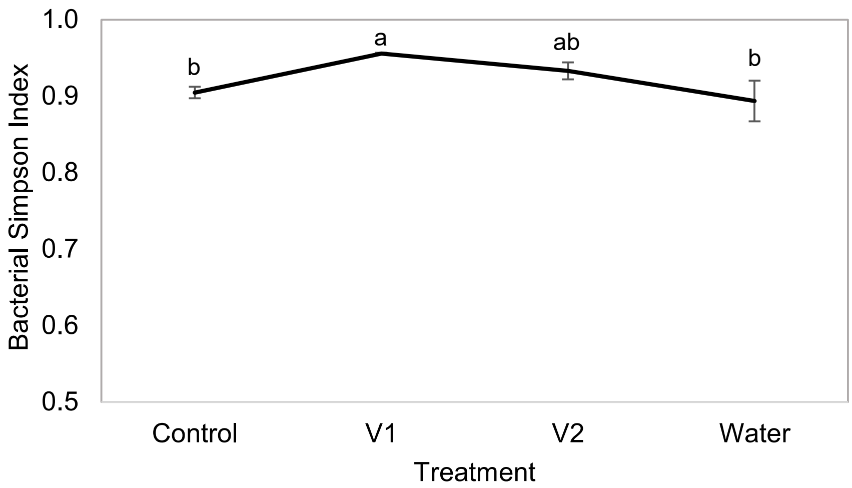

Figure 5.20: Effect on vermicompost tea and water treatments on the bacterial Simpson Diversity Index in second VCT trial in June 2018. Lowercase letters indicate significant difference between treatments a 95 % confidence interval.

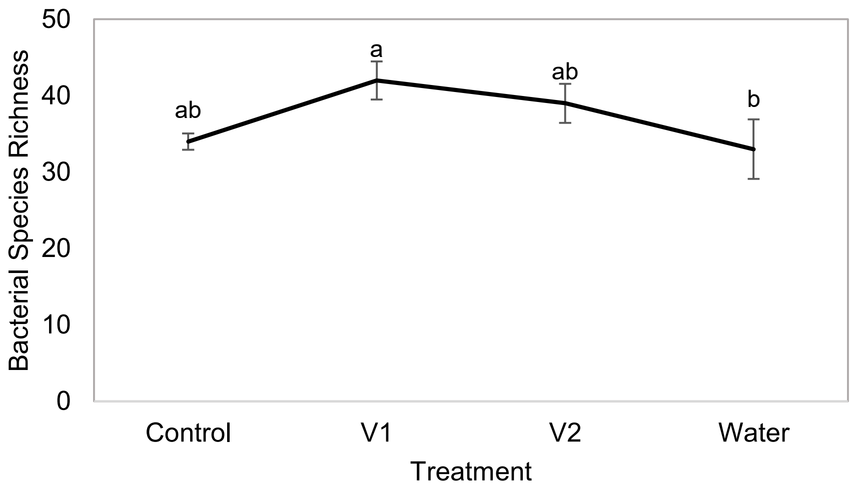

Figure 5.21: Effect of the vermicompost tea and water treatments on the bacterial species richness in second VCT trial in June 2018. Lowercase letters indicate significant differences at a 95 % confidence interval.

The applied treatments had no significant effect on the Simpson Index or species richness of the fungal community (Fig. 5.22). The insignificant change is due to it being more resistant to change than bacterial species. Fungal species diversity and richness showed positive trends with VCT and water application, however showed a negative trend with plant survival. Fungi species richness showed contrasting results to bacterial species richness with a negative trend with foliar N and P.

The contradicting results of fungi species richness and foliar P can be due to increased bacterial species competing with plants for P.

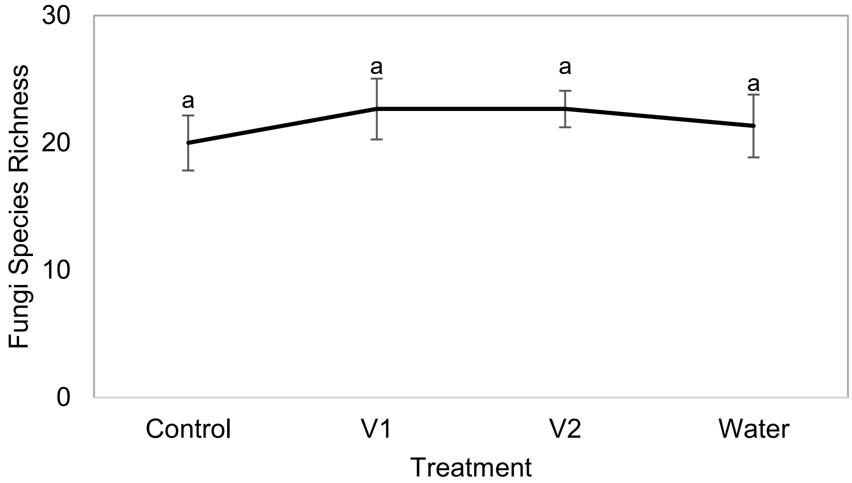

Figure 5.22: Effect of the vermicompost tea and water treatments on the fungi species richness in second VCT trial in June 2018. Lowercase letters indicate significant differences at a 95 % confidence interval.

ß - Diversity

The application of VCT and water had no significant effect on the ß-diversity (PERMANOVA $p > 0.05$) of the rhizosphere soil for bacteria and fungi. This indicates that the type of species occurring in the different rhizosphere's are similar. These results were only for the wet season and could possibly change during the dry season as found by (Postma, 2016) for bacterial species.

5.5 Conclusions

During the spring and summer months the application of VCT had no effect on plant survival and size, but rather that it was the application of water matrix that significantly increased plant survival. Resulting in smaller plants and tea yields due to higher plant density. The addition of water, particularly during the drought conditions contributed positively towards the plants survival. The application of the water and diluted VCT slightly increased soil pH, which was mainly attributed to the near neutral pH of the tap water. The slight increase in the soil pH seemed to negatively affect Mn foliar concentrations, which was shown in Chapter 4 to have a positive effect on tea yields. Only foliar P and Al concentrations were significantly different between the more concentrated VCT (V2) and water treatments. The increase in foliar P and decrease in foliar Al were attributed to the effect of the enhanced soil pH and organic acids in the VCT on enhancing P dissolution by enhancing Al complexation. The concentrated VCT and tap water contributed negligible amounts of plant essential macronutrients such as basic cations and P.

The application of both VCT treatments significantly increased bacterial diversity and species richness, however, by applying more VCT did not increase the rhizosphere bacterial species richness. The type of bacterial species that occurred were unknown making it difficult to conclude that the application of VCT increased beneficial bacterial activity. A negative trend was observed between bacterial species richness and plant biomass, however this experimental trial was during the winter months when plant growth is limited. The application of VCT and water had no effect on fungal species richness and diversity.

Soil temperatures were also low during winter which affects the type of microbial species occurring during that time period. Therefore to determine the effect of VCT on rooibos plants further research is required to investigate the effect of the application of VCT over a longer period of time on microbial communities during the summer season. The effect of VCT on rooibos plants root growth should also be investigated further. Determining root growth and harvesting all roots under field conditions is not always possible, therefore it is suggested to first carry out the experiment in pot trials to accurately determine the effect on rooibos plant root growth.

6 RESEARCH UNIT 4: OPTIMAL FERTILIZER APPLICATION IN TERMS OF INCREASED YIELD AND ECONOMIC FEASIBILITY

6.1 Introduction

In any agricultural system, it must be economically feasible for the farmer to produce a product that results in an income that is higher than the cost to produce that product. If a farmer wants to increase their production output it will be either to increase their profit or to supply produce that is demanded in the market place. In South Africa, the Department of Agriculture, Forestry and Fisheries (DAFF) has been involved in reducing input costs of farmers by providing subsidies and crop production loans (Ramaila, *et al*., 2011). During the mid-1990's the funding for the commercial sector was reduced and funding was used to support small-scale farmers and the upgrading of old infrastructure in developing agricultural areas (Ramaila, *et al*., 2011). Therefore commercial farmers had to improve their agricultural output growth by maintaining or improving yields at lower input costs or by increasing their production area.

The strength of the rooibos industry is based on the increase in global health-conscious markets showing a strong demand for rooibos tea and as a blend with other teas or juices (DAFF, 2015). Rooibos is also registered as a Geographic Indicator, which allows the product to be marketed based on place of origin which can lead to an increase in prices (Bienabe, *et al*., 2009). The slow production of rooibos and the effect of drought also results in the supply of the product to fail to meet the global demand, however, this can be advantageous as it keeps the price for rooibos high (DAFF, 2015). There was a sharp increase in production in 2007 until production peaked in 2009 with approximately 18 000 tonnes produced, thereafter production decreased to approximately 12 500 tonnes in 2013 (DAFF, 2015). The gross value of tea has also increased from below R60 000 in 2010 to over R210 000 in 2013, largely due to the increase in volume of rooibos produced and exported (DAFF, 2015).

However, the cyclic production of rooibos and the distance to markets with high transport costs are a weakness of the industry (DAFF, 2015). South Africa is the only exporter of rooibos tea and exports over 6000 tonnes per year to more than 30 countries (DAFF, 2015). Export volumes and prices are dependent on the harvest size and the exchange rate with the US Dollar, in which world commodities are traded, which is unpredictable due to the fluctuating South African Rand (DAFF, 2015). Approximately 90% of rooibos is exported in bulk to external processors which limits profitability. In the rooibos production area of Nieuwoudtville the expansion of production areas are inhibited due to the protection of natural vegetation types. Prices of produce are out of the control of the farmer and are determined in the market place, therefore the only factor that rooibos farmers can control is their yield growth. The implementation of irrigation systems is not feasible so the only option is the application of fertilizers to enhance yield growth.

The highest fertilizer application may result in the highest yield of rooibos tea, but if one considers the expenses involved in the application of fertilizers then it could result in the farmer making a loss. It is possible that even if yields are high, the net income gain from applying fertilizers may be inefficient due to fixed costs, such as transport and changing methods of production associated with using fertilizers (Duflo, *et al*., 2008). Economic feasibility of fertilizer application is an essential part to improving crop production, however, farmers only adopt a change in their production methods if it is financially rewarding. An example of the economic feasibility of implementing fertilizer in a production system is a study by Selassie (2016). The study consisted of different rates of P fertilization on maize in Ethiopia and found that the highest yield and the highest economic return was not associated with the same treatment. The highest yield was obtained at the treatment of 90 kg/ha P, but once fertilizer cost was considered it was found that the 30 kg/ha P treatment had the highest gross margin.

The total input costs of the production system are based on two categories: fixed and variable costs. Fixed costs are fixed in the short term irrespective of the scale or intensity of the production system and include costs related to permanent labour, machinery, licences, property tax and insurance (DAFF, 2015). Variable costs vary in direct proportion to changes in the scale and intensity of the production system and include costs related to casual labour; seeds and plants; insecticides; fertilizers; transport and fuel (DAFF, 2015).

When most fertilizer trials are conducted the input costs of the farmer are not considered, which could result the findings of the trial being for scientific purposes and the farmer cannot afford to practically implement it. By considering all the input costs researchers and agricultural advisors can recommend fertilizer treatments based on the crop response and economic feasibility for the famer. An improved understanding of factors affecting optimal NPK application in terms of both external (input costs) and internal (soil properties, rainfall) influences will assist farmers in obtaining higher yields that are economically feasible to achieve (Basso, *et al*., 2012).

6.2 Objectives

To determine which organic and mineral fertilizer treatment, and at what application rate, is the most optimum for increased biomass production and economic feasibility.

6.3 Methods and materials

6.3.1 Experimental attributable costs

Experimental attributable costs includes all the costs that are variable within the experimental period. The cost is therefore dependent on the specific treatment within the experimental trial. The costs include: fertilizers; transport of fertilizers; labour for fertilizer application; harvesting labour; and transport of yield to the factory.

Fertilizer treatments that were evaluated are as follows:

1. Control treatment (no fertilizer)
2. Commercial organic 3:1:5 fertilizer applied at 605, 1 813, 5 440 and 10 880 kg/ha.
3. Commercial organic 2:3:2 fertilizer applied at 175.1, 525.5, 1 577 and 3 154 kg/ha.
4. Commercial organic 3:2:4 fertilizer applied at 671, 2 015, 6 045 and 12 090 kg/ha.

5 - 7 Commercial mineral fertilizers blended to the same NPK ratios and applied to match the nutrient supply of the organic fertilizers.

Fertilizer treatment levels are based on a provision of 12.1, 36.3, 108.8 and 217.6 kg P per hectare (3.3; 10; 30 and 60 mg P/kg soil). Each treatment was replicated four times with the organic and mineral 2:3:2 and 3:2:4 treatments duplicated on two farms, Rogland and Blomfontein. Fertilizer was manually applied by hand in June 2017 and tea yields harvested in February 2018.

Fertilizer Labour Input Requirements

Fertilizer was applied through band placement by hand and worked into the soil using a spade. Six labourers were used to complete the action and the time was recorded for the fertilizer to be applied to the field trial area of 0.18 ha and converted to man hours per hectare for the particular action (Eq. 6.1).

$$Labour\ Input\ requirements\ (man\ hours.ha^{-1}) = \frac{\left(\frac{t}{n_{labourers}}\right)}{A_{plot}} \qquad \text{(Eq. 6.1)}$$

Where: t = time required to complete the input (h)

$n_{labourers}$ = number of labourers applying the labour input

A_{plot} = area of experimental plot (ha)

The labour requirement costs are based on the man hours required to perform the input work over a certain area, and the hourly wage for the work done. The farm worker minimum wage, at the time of application, of R15.39 per hour (Ramutloa, 2018) was multiplied with the labour requirement to calculate the cost per hectare of the specific labour input.

Harvesting Labour Input Requirements

The labour cost involved in harvesting was based on a fixed rate of R0.95 per kilogram rooibos tea harvested. Therefore the harvesting labour cost will increase as the yield of the harvest increases. The harvest values used was based on the survival-adjusted tea yields per hectare.

Truck transport cost

Fertilizer transport costs were calculated based on the usage of an eight ton truck to transport the fertilizer from the town to the farm; and the rooibos harvest from the farm to the factory in town. Transport costs from the fertilizer depot to the town was neglected as the co-operative will keep the fertilizer in stock if it is used by the farmers (Thiaart, 2018). The distance (D) from town to the farm Rogland and Blomfontein was 20 and 43.2 km, respectively, and the mean traveling speed was estimated at 80 km.h^{-1}. The costs involved in the truck's operating cost are complex as there are fixed and variable costs associated. Fixed costs include depreciation; interest; insurance and licenses, whereas variable costs include repair and maintenance, fuel usage and tyre repair and replacement (DAFF & KZNDARD, 2016). As this is not an in-depth economic study the fixed costs were ignored, as they are constant across all treatments, and only the repair and maintenance and fuel costs were considered in calculating the truck operation cost. The truck's total operating cost was fixed at R4.94 per km (DAFF & KZNDARD, 2016).

Repair and maintenance costs are difficult to estimate as it depends on the operating conditions, management and local costs, therefore it is calculated as a percentage of the purchase price and the expected lifetime of the truck (Eq. 6.2) (DAFF & KZNDARD, 2016). The purchase price for an eight ton single differential truck was R670 000 with a lifetime of 300 000 km (DAFF & KZNDARD, 2016).

$$Repair\ and\ Maintenance\ cost\ (R\ /km) = \frac{Purchase\ Price\ (R)\ \text{x}\ 50\%}{Life\ period\ (km)} \qquad \text{(Eq. 6.2)}$$

Fuel consumption costs also vary greatly between areas, operators, method of use and fuel price, therefore fuel usage per 100 km is based on figures provided by dealerships and manufacturers (DAFF & KZNDARD, 2016). Fuel cost of R3.83 per km was based on the fuel usage of 30 L per 100 km and a diesel price of R12.75 per litre was used (Eq. 6.3) (DAFF & KZNDARD, 2016).

$$Fuel\ cost\ (R/km) = Fuel\ consumption\ (L\ /km) \text{x}\ Fuel\ Price\ (R\ /L) \qquad \text{(Eq. 6.3)}$$

The cost per km.ton^{-1} is based on the operational cost per km (R4.94) which is then divided by the capacity of the truck (eight tons) (Eq. 6.4).

$$Cost\ /km.ton = \frac{Operating\ Cost\ (R/km)}{Truck\ Capacity\ (ton)} \qquad \text{(Eq. 6.4)}$$

The cost of transport with the truck is then calculated by multiplying the cost per km per ton (R0.62) by the return distance from town to the farm (D); the mass (M) of fertilizer or rooibos harvest and the area to be applied or harvested (Eq. 6.5).

$$Truck\ Cost\ per\ ha = Cost/km.ton\ \text{x}\ D\ (km)\ \text{x}\ M\ (ton)\ \text{x}\ Area\ (ha) \qquad \text{(Eq. 6.5)}$$

Where: D = Return distance from farm to factory (km)

M = Mass transported (ton)

6.3.2 Non-experimental attributable costs

Non-experimental attributable costs are not directly measured during the field trial and are consistent across all experimental treatments. The costs included in the trial are pest and disease control application of insecticides and herbicides.

6.3.3 Gross margin analyses

A simple method that can be used to determine the economic feasibility is by calculating the gross margin. The gross margin is determined by subtracting all the input costs from the financial output of the product produced (Naab, et al., 2009). The input costs consist of variable and fixed costs.

Gross Margin Equation: $GM = (Y \times P) - TC$ (Eq. 6.6)

Where Y is the yield in kg/ha, P the price of the produced product R/kg and TC the total experimental attributable and non-attributable input costs (Rands).

For each treatment the input cost was based on current production cost to produce one kg of rooibos and the cost of the fertilizer treatment per hectare. The survival-adjusted yield (kg/ha) of each treatment was multiplied by the current price for wet rooibos off the land of R30/kg (Thiaart, 2018). The gross margin was calculated for each treatment to determine which treatment is the most economically feasible for the farmer. For this project the gross margin was calculated on the basis of a "farm gate cost", which only includes the cost that are involved in the active production process of rooibos tea.

6.3.4 Statistical analyses.

Statistical analyses were performed using Statistica™ Software (Version 13.3, 2018, Dell Software, Tulsa). The data was tested for significant differences at a 95 % confidence level between the different fertilizer treatments.

6.4 Results and Discussion

6.4.1 Experimental Attributable Costs

Fertilizer Cost

The cost of obtaining the fertilizers varied considerably between the type and application rate within each fertilizer. Organic fertilizer had a considerably higher cost than mineral fertilizers due to the larger quantity required to supply the required nutrients (Fig. 6.1). Between the organic fertilizers the 3:2:4 fertilizer had the lowest cost as it was derived from chicken manure, whereas the other organic fertilizers (3:1:5 and 2:3:2) were based on animal blood and bones with natural mineral deposits. In both the organic and mineral treatments the 3:1:5 fertilizer had the highest cost due to the higher nitrogen and potassium quantities supplied within the fertilizer. On the farm Rogland all fertilizers were used, whereas at Blomfontein only the 2:3:2 and 3:2:4 fertilizers were used.

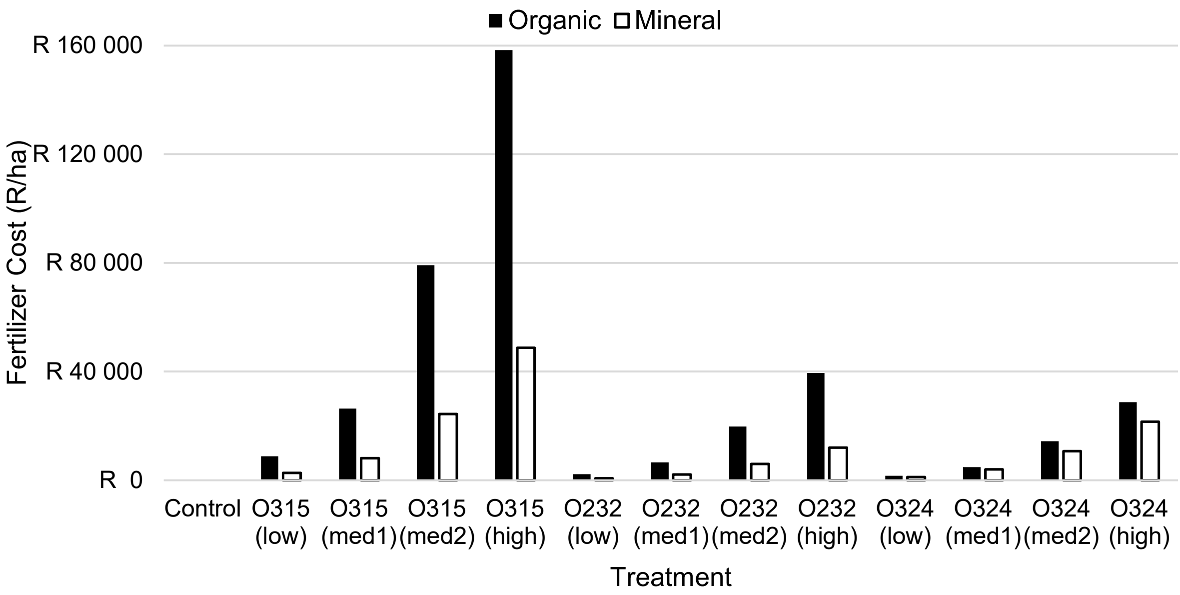

Figure 6.1: Cost of the organic and mineral fertilizers at the four application rates (low - high) applied on the farms Rogland and Blomfontein in June 2017.

Fertilizer Labour Input requirement

It took six labourers two hours to apply the fertilizer to an area of 0.18 ha resulting in 1.85 man hours required per ha for fertilizer application. At application the hourly wage for farmworkers was R15.39 (Ramutloa, 2018) which adds up to a cost of R171 per hectare for fertilizer application with six labourers (Table 6.1). This input cost was constant across all treatments for manual fertilizer application, therefore there was no cost difference between treatments.

Table 6.1: The labour input requirement of fertilizer application on the farms Rogland and Bloemfontein during June 2017.

Action	Time to complete input	No. Labourers	Area	Labour Input	Wage Rate	Cost
	Hours		ha	man hours/ha	R/hour	R/ha
Fertilizer Application	2	6	0.18	1.85	R 15.39	R 171

Harvesting Labour Input requirement

The harvesting labour input requirement was based on the biomass yield produced from each treatment and the harvesting cost of a fixed rate of R0.95 per kg rooibos tea harvested (Thiaart, 2018). Therefore the labour input requirement per treatment was directly proportional to the yield harvested.

At Rogland, for each treatment type, except mineral 3:2:4, the second treatment level of 36.3 kg P/kg (med1) was found to have the highest harvesting costs (Fig. 6.2). The mineral 3:1:5 fertilizer, at the second treatment level, had the highest harvesting cost of R1 349.26/ha across all treatments on the farm Rogland (Table 6.3). No treatment had a harvesting cost significantly higher than the control treatment.

At Blomfontein the same trend was found for the organic treatments with the second treatment level (med1) having the highest harvesting costs of R1 182.38/ha (organic 2:3:2) and R712.27/ha (organic 3:2:4) (Fig. 6.3). However, for the mineral treatments the first treatment level in the mineral 2:3:2 and third in the mineral 3:2:4 fertilizer had the highest harvesting costs per treatment type (Table 6.5). The harvesting cost of the organic 2:3:2 fertilizer at the second treatment level was significantly higher than the control treatment (R795.53/ha) (Fig. 6.3).

The effect of farm, fertilizer NPK ratio and treatment level (3-way ANOVA) had no significant effect ($p > 0.05$) on the harvesting labour input cost.

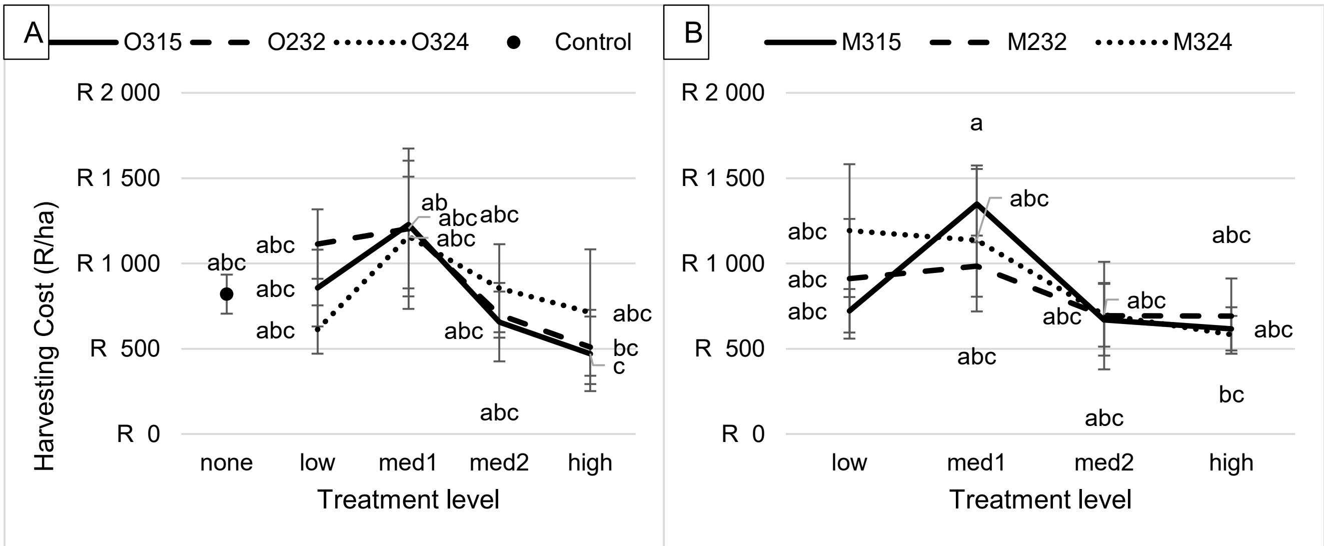

Figure 6.2: Harvesting costs within the organic (A) and mineral (B) fertilizers at the three NPK ratios on the farm Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

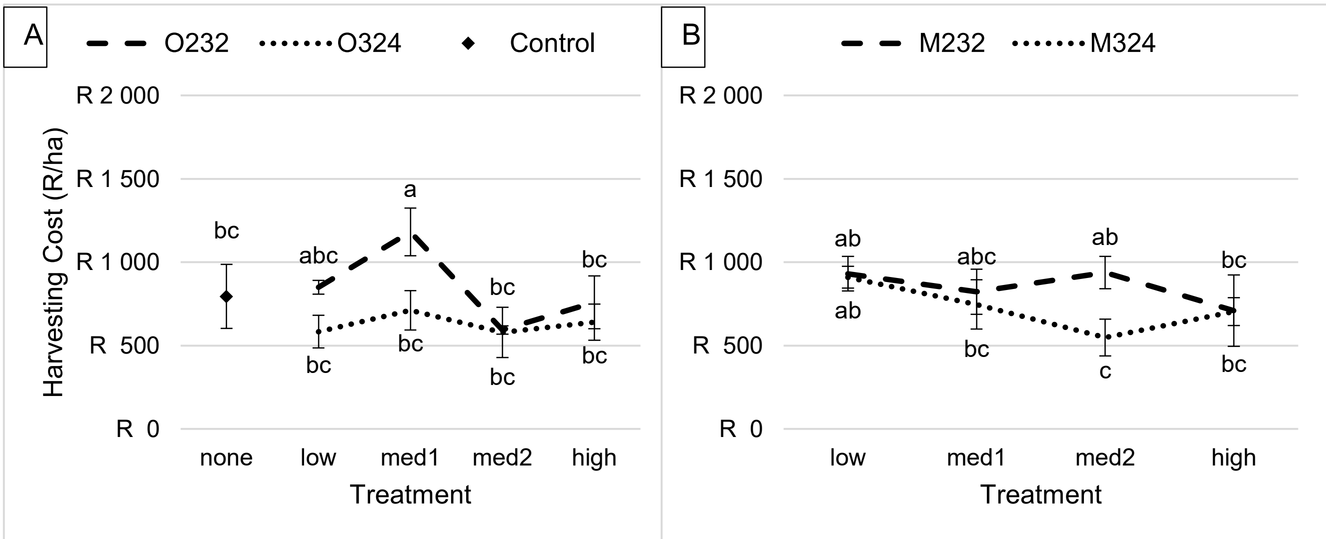

Figure 6.3: Harvesting costs within the organic (A) and mineral (B) fertilizers at the three NPK ratios on the farm Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Truck Transport Costs

Values were used from the Guide for Machinery Costs 2015 – 2016 to calculate the approximate truck transport costs for the fertilizers and the harvested tea. The average purchase price of a single differential 8 ton truck was R670 000 with a life period of 300 000 km and a repair and maintenance percentage of 50 % (DAFF & KZNDARD, 2016). The fuel usage of the truck was set at 30 L per 100 km (DAFF & KZNDARD, 2016). The diesel price at the time of analysis was R12.75 per L. Repair and maintenance costs were R1.12 per km and the fuel cost was R3.83 per km. This equals to R4.94 per km and this cost was constant across all treatments. This value was used to calculate a transport cost per km per ton carried of R0.62 (Eq. 6.4). The cost per km per ton transported varied according to the mass of fertilizer or the harvested tea to be transported (Eq. 6.5).

The two farms varied in the distance from the town, therefore the same treatment and application rate had different transport costs from the town to the farm. This difference, where the transport costs were higher for the more distant farm (Blomfontein) is illustrated in Figure 6.4. To meet the nutrient input requirements a significantly higher mass of organic fertilizer was needed, therefore the organic fertilizers had a higher transport cost than the mineral fertilizers (Fig. 6.5). At both farms, the organic 3:2:4 fertilizer at the high treatment level had the highest fertilizer transport cost, while the mineral 2:3:2 fertilizer at the low treatment level had the lowest (Rogland: Table 6.2 and 6.3; Blomfontein: Table 6.4 and 6.5).

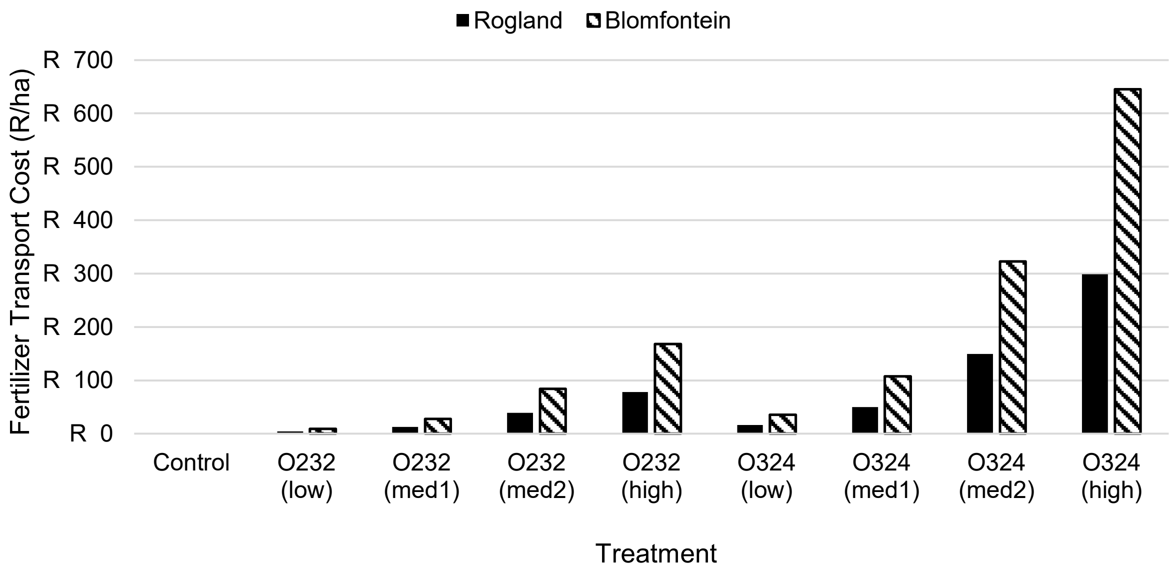

Figure 6.4: Illustration of the comparison of transport costs of the organic fertilizers (O232 and O324) at the four application rates (low – high) to the farms Rogland and Blomfontein in June 2017.

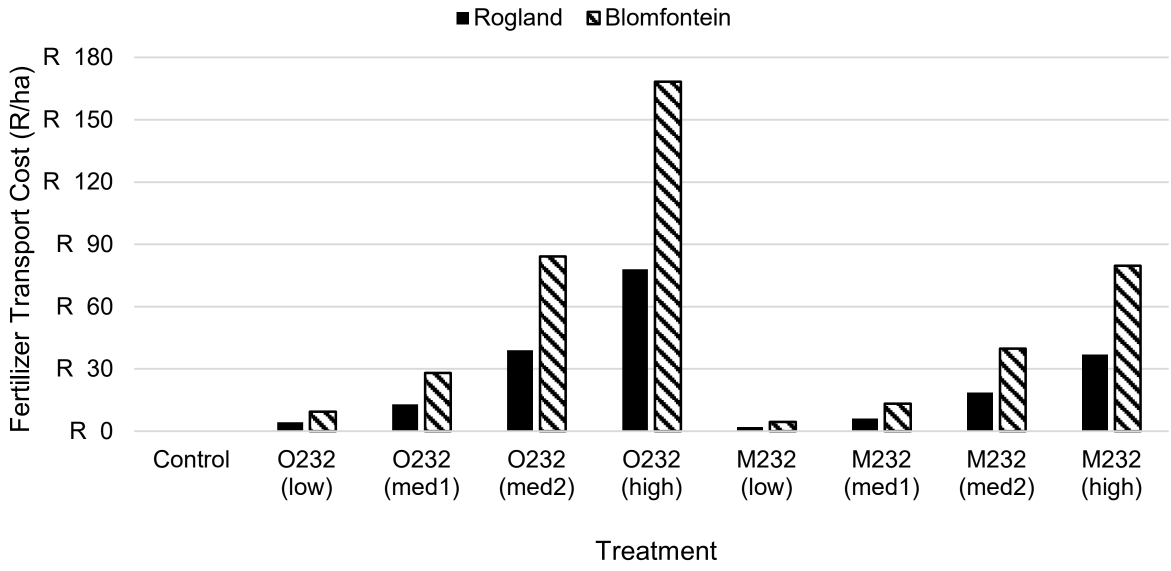

Figure 6.5: Comparison between the transport costs of the organic and mineral 2:3:2 fertilizer at the four application rates (low – high) to Rogland and Blomfontein.

The tea yield transport costs were influenced by the running costs of the truck, distance of the farm to town and the harvested tea yields. At both farms the yield transport costs followed the same trend as the harvesting costs. At Rogland, the second treatment level of all treatments, except the mineral 3:2:4 fertilizer, had the highest yield transport costs; however the treatment yield transport costs were not significantly higher than the control treatment (Fig. 6.6). In the mineral 3:2:4 fertilizer the lowest treatment level had the highest yield transport cost (Table 6.3). At Blomfontein (Fig. 6.7), the second treatment level in the organic treatments had the highest yield transport costs (Table 6.4), whereas in the mineral treatments the third (M232) and first (M324) treatment levels had the highest (Table 6.5).

Total experimental attributable cost

The total experimental attributable costs were significantly higher in the organic than the mineral treatments at the same NPK ratio and treatment level (Fig. 6.8 and 6.9). This significant difference is largely driven by the larger mass of organic fertilizers required to provide the same amount of nutrients as the mineral fertilizers. This larger mass associated with the organic fertilizer significantly increased the cost of fertilizer and transport cost of the fertilizers.

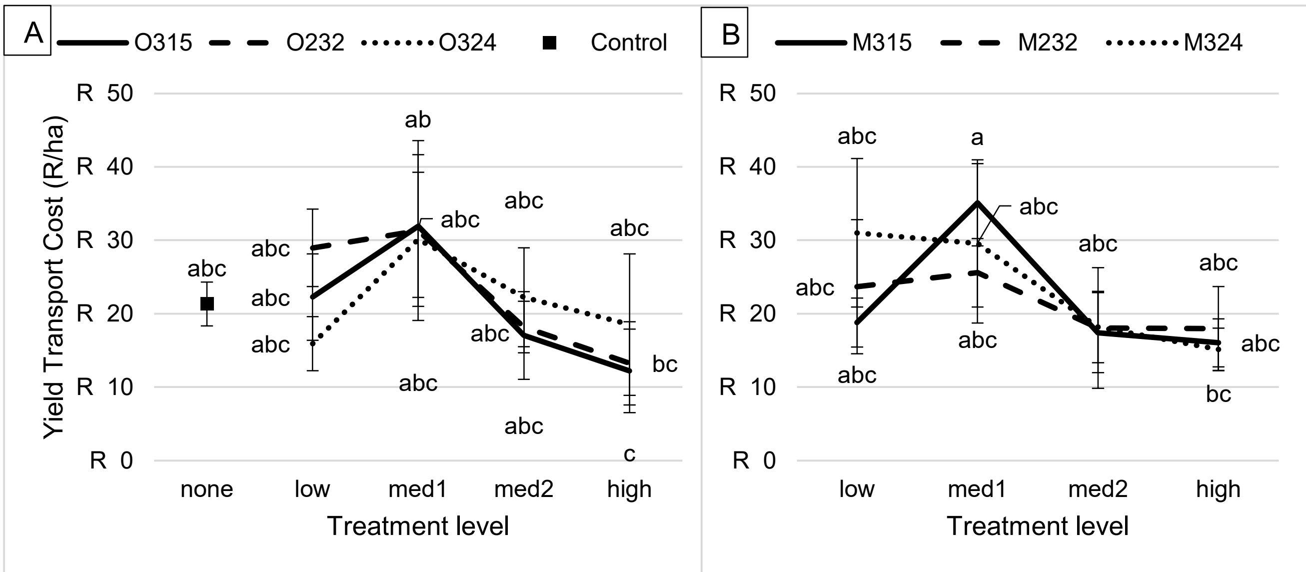

Figure 6.6: Tea yield transport cost within the organic (A) and mineral (B) fertilizers at the three NPK ratios on the farm Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

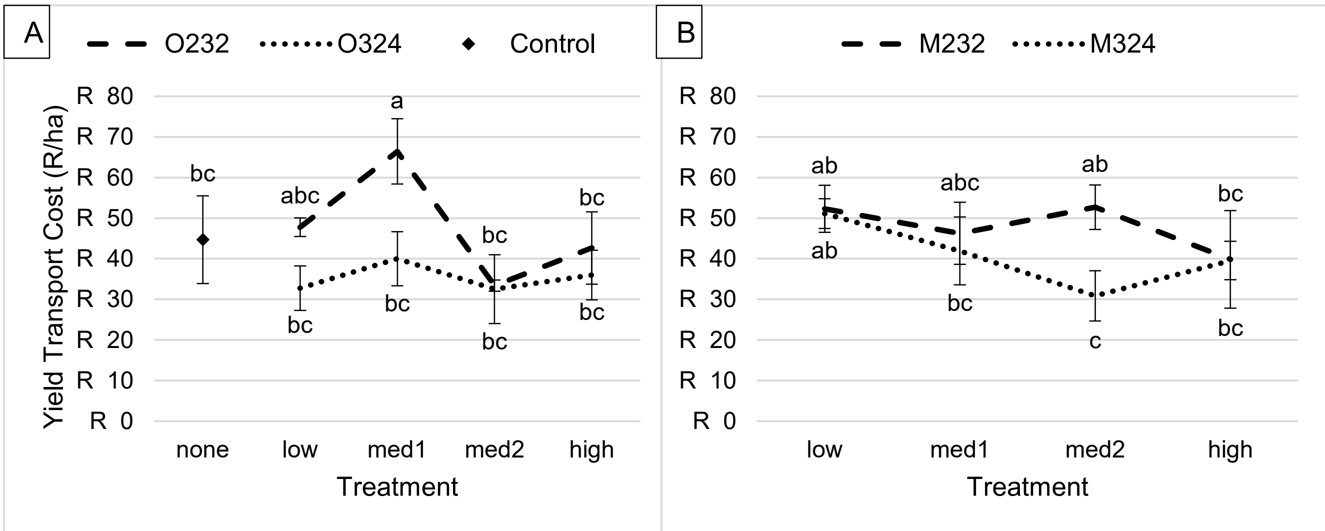

Figure 6.7: Tea yield transport cost within the organic (A) and mineral (B) fertilizers at the three NPK ratios on the farm Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

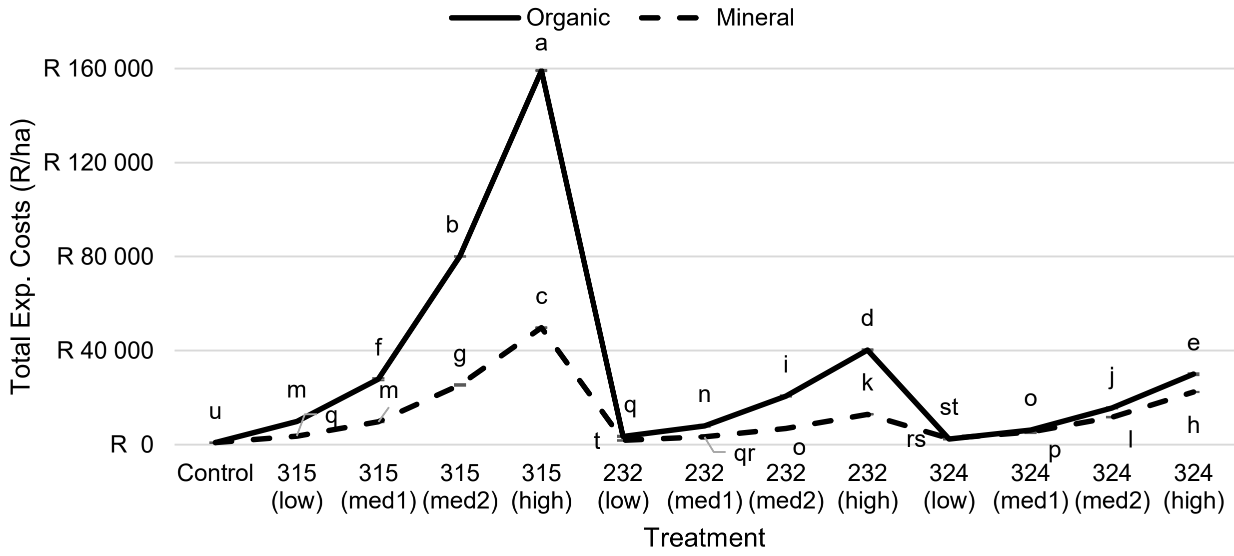

Figure 6.8: Total experimental attributable costs of the organic and mineral fertilizers on the farm Rogland. Lowercase letters indicate a significant difference at a 95 % confidence interval.

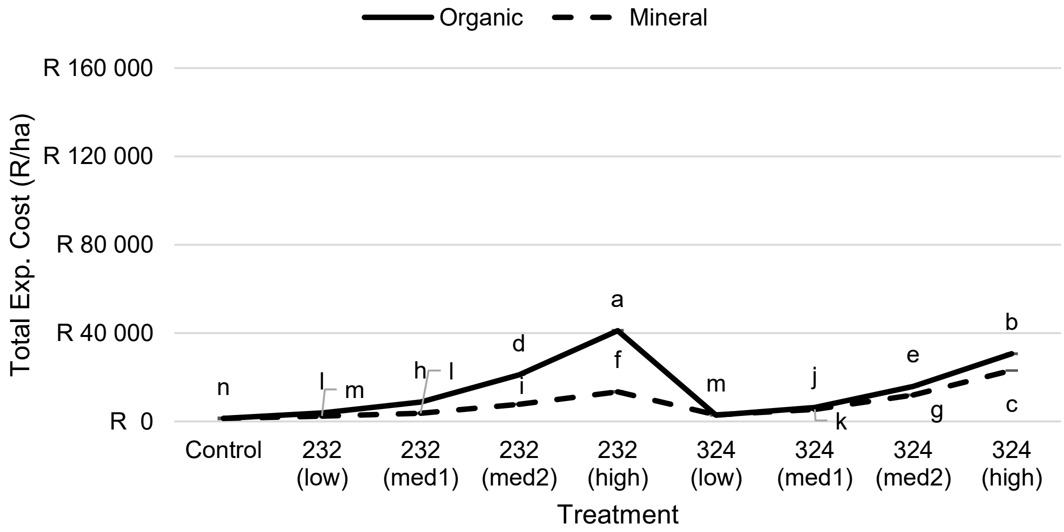

Figure 6.9: Total experimental attributable costs of the organic and mineral fertilizers on the farm Blomfontein. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Table 6.2: The mean experimental attributable costs of the different organic fertilizer treatments during the 2017/18 season on the farm Rogland. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment												
	Control	O3:1:5(1)	O3:1:5 (2)	O3:1:5 (3)	O3:1:5 (4)	O2:3:2 (1)	O2:3:2 (2)	O2:3:2 (3)	O2:3:2 (4)	O3:2:4(1)	O3:2:4 (2)	O3:2:4 (3)	O3:2:4 (4)
Experimental attributable costs (R.ha^{-1})													
Fertilizer	R 0	R8 800	R26 370	R79 125	R158 256	R2 194	R6 583	R19 756	R39 512	R1 597	R4 796	R14 389	R28 778
Fertilizer Transport	R 0	R15	R45	R134	R269	R4	R13	R 39	R78	R17	R50	R149	R299
Fertilizer Labour input	R 0	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171
Harvesting	R820 abc	R856 abc	R1 228 ab	R655 abc	R470 c	R1 114 abc	R1 204 abc	R699 abc	R510 bc	R613 abc	R1 158 abc	R855 abc	R713 abc
Yield Transport	R21 ab	R22 ab	R32 a	R17 ab	R12 b	R29 ab	R31 ab	R18 ab	R13 ab	R16 ab	R30 ab	R22 ab	R19 ab
TOTAL	**R842 m**	**R9 864 h**	**R27 846 e**	**R80 103 b**	**R159 178 a**	**R3 512 k**	**R8 003 i**	**R20 684 f**	**R40 284 c**	**R2 414 l**	**R6 205 j**	**R15 587 g**	**R29 979 d**

Table 6.3: The mean experimental attributable costs of the different mineral fertilizer treatments during the 2017/18 season on the farm Rogland. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment												
	Control	M3:1:5 (1)	M3:1:5 (2)	M3:1:5 (3)	M3:1:5 (4)	M2:3:2 (1)	M2:3:2 (2)	M2:3:2 (3)	M2:3:2 (4)	M3:2:4 (1)	M3:2:4 (2)	M3:2:4 (3)	M3:2:4 (4)
Experimental attributable costs (R.ha^{-1})													
Fertilizer	R 0	R2 713	R8 135	R24 409	R48 819	R661	R2 116	R5 983	R11 966	R1 196	R3 988	R10 767	R21 534
Fertilizer Transport	R 0	R8	R24	R73	R147	R2	R6	R18	R37	R4	R12	R35	R70
Fertilizer Labour input	R 0	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171	R171
Harvesting	R820 ab	R722 ab	R1 349 a	R670 ab	R616 b	R911 ab	R984 ab	R694 ab	R692 ab	R1 193 ab	R1 137 ab	R699 ab	R582 b
Yield Transport	R21 ab	R19 ab	R35 a	R17 ab	R16 b	R24 ab	R26 ab	R18 ab	R18 ab	R31 ab	R30 ab	R18 ab	R15 b
TOTAL	**R842 l**	**R3 633 i**	**R9 715 f**	**R25 340 b**	**R49 769 a**	**R1 768 k**	**R3 303 ij**	**R6 885 g**	**R12 883 d**	**R2 594 j**	**R5 338 h**	**R11 690 e**	**R22 372 c**

Table 6.4: The mean experimental attributable costs of the different organic fertilizer treatments during the 2017/18 season on the farm Blomfontein. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment								
	Control	O2:3:2 (1)	O2:3:2 (2)	O2:3:2 (3)	O2:3:2 (4)	O3:2:4 (1)	O3:2:4 (2)	O3:2:4 (3)	O3:2:4 (4)
Experimental attributable costs (R.ha^{-1})									
Fertilizer	R 0	R2 194	R6 583	R19 756	R39 512	R1 597	R4 796	R14 389	R28 778
Fertilizer Transport	R 0	R9	R28	R84	R168	R36	R108	R323	R645
Fertilizer Labour	R 0	R171	R171	R171	R171	R171	R171	R171	R171
Harvesting	R 796 b	R 850 ab	R 1 182 a	R 594 b	R 759 b	R 583 b	R 712 b	R 579 b	R 641 b
Yield Transport	R 45 b	R 48 ab	R 66 a	R 33 b	R 43 b	R 33 b	R 40 b	R 33 b	R 36 b
TOTAL	**R 840 i**	**R 3 271 g**	**R 8 031 e**	**R 20 639 c**	**R 40 653 a**	**R 2 420 h**	**R 5 827 f**	**R 15 494 d**	**R 30 271 b**

Table 6.5: The mean experimental attributable costs of the different mineral fertilizer treatments during the 2017/18 season on the farm Blomfontein. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment								
	Control	M2:3:2 (1)	M2:3:2 (2)	M2:3:2 (3)	M2:3:2 (4)	M3:2:4 (1)	M3:2:4 (2)	M3:2:4 (3)	M3:2:4 (4)
Experimental attributable costs (R.ha^{-1})									
Fertilizer	R 0	R2 194	R6 583	R19 756	R39 512	R1 597	R4 796	R14 389	R28 778
Fertilizer Transport	R 0	R4	R13	R40	R80	R8	R25	R76	R152
Fertilizer Labour	R 0	R171	R171	R171	R171	R171	R171	R171	R171
Harvesting	R 796 a	R 931 a	R 823 a	R 938 a	R 709 a	R 909 a	R 746 a	R 549 a	R 704 a
Yield Transport	R 45 a	R 52 a	R 46 a	R 53 a	R 40 a	R 51 a	R 42 a	R 31 a	R 40 a
TOTAL	**R 840 i**	**R 1 819 h**	**R 3 169 f**	**R 7 185 d**	**R 12 965 b**	**R 2 336 g**	**R 4 973 e**	**R 11 594 c**	**R 22 601 a**

6.4.2 Non – Experimental Attributable Costs

Non-experimental attributable costs included the use of pesticides that were applied at the same application rate across all treatments. The same total non-experimental attributable costs of R150 per hectare were used for all treatments on both farms (Table 6.6).

Table 6.6: The non-experimental attributable costs for the production of rooibos tea in the Nieuwoudtville area (personal communication: Thiaart, 2018).

Non – experimental attributable costs	
Specific Input	**Cost ($R.ha^{-1}$)**
Acetamiprid (insecticide)	R 50
Spinetoram (insecticide)	R 50
Lamda-cyhalothrin (insecticide)	R 50
Total ($R.ha^{-1}$)	**R 150**

6.4.3 Gross Margin Analysis

At Rogland, the income generated by the survival-adjusted tea yield and price per kilogram for raw rooibos tea was highest at the second treatment level for all fertilizers, except for the mineral 3:2:4 treatment where the first treatment level generated the highest income (Fig. 6.10). The highest income was obtained at the second treatment level of the mineral 3:1:5 fertilizer with an income of R42 608.21/ha. No treatment was significantly higher or lower than the control treatment (Fig. 6.10). There was no significant difference in income between the organic fertilizers (Table 6.7), however a significant difference was found between the mineral fertilizers of 3:1:5 at the second treatment level (R42 608.21/ha) and 3:2:4 at the high treatment level (R18 378.42/ha).

However, when the input costs are considered then the economic feasibility of the treatments produce a different outcome. In the organic fertilizers only the first (R31 510.06/ha) and second (R29 881.65/ha) treatment level of the 2:3:2 and second (R30 215.06/ha) of the 3:2:4 fertilizers generated a positive gross margin higher than the control (R24 910.69) treatment (Fig. 6.11). None of the organic 3:1:5 fertilizers generated a gross margin higher than the control treatment due to the high input costs. In the mineral fertilizers the second (R32 743.46/ha) treatment level of 3:1:5, first (R26 846.63/ha) and second (R27 623.52/ha) of 2:3:2 and first (R34 915.63/ha) and second (R30 423.32/ha) of 3:2:4 generated a positive gross income higher than that of the control (R24 910.69/ha) treatment (Fig. 6.11).

At Blomfontein, the income generated was highest at varying treatment levels across the different fertilizers (Fig. 6.12). In the organic fertilizers only the first (R26 836.07/ha) and second (R37 338.35/ha) treatment level of the 2:3:2 fertilizer generated an income higher than the control (R25 122.12/ha), whereas the first three treatment levels of the mineral 2:3:2 fertilizer (R29 398.36;

R25 995.51; R29 620.85/ha) and first treatment level of the mineral 3:2:4 (R28 714.65/ha) fertilizer generated an income higher than the control. The organic 2:3:2 fertilizer at the second treatment level was the only treatment to generate an income significantly higher than the control treatment (Fig. 6.12).

When the expenses are considered, of the organic fertilizers only the 2:3:2 at the first (R23 414.57/ha) treatment level generated a positive gross margin higher than the control treatment (R24 131.89/ha). None of the organic 3:2:4 fertilizers generated a gross margin higher than the control treatment (Fig. 6.13). In the mineral fertilizers the first (R27 428.98/ha) treatment level of 2:3:2 and the first (R26 228.95/ha) of 3:2:4 generated a gross margin higher than the control treatment (R24 131.89/ha) (Table 6.10).

At both experimental farms the gross margins produced were higher in the mineral fertilizers with a significant difference occurring at the higher treatment levels (Fig. 6.14 and 6.15). The gross margin on both farms followed similar trends with the first or second treatment level within each NPK ratio and fertilizer type yielding the highest result (Fig. 6.16). Across all treatments replicated across both farms, except in the mineral 2:3:2, the highest gross margin values were obtained at Rogland. The mineral 3:2:4 fertilizer at the first treatment level on the farm Rogland yielded the highest gross margin value across all treatments on both farms with a gross margin of R34 915.65/ha (Fig. 6.16).

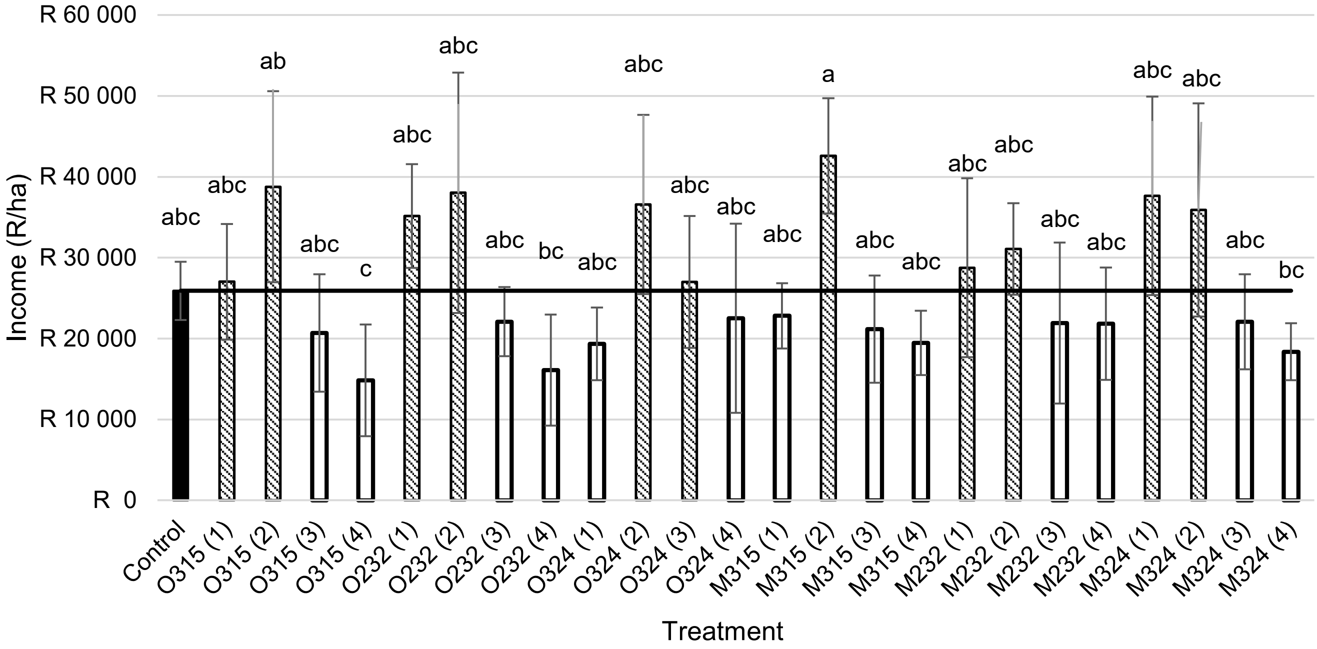

Figure 6.10: Income generated by the organic and mineral fertilizer treatments at the four application rates (1: low, 2: med1, 3: med2, 4: high) that were applied at Rogland. Pattern-filled bars indicate an income higher; and outlined bars indicate an income lower than the control treatment (solid bar). Lowercase letters indicate a significant difference at a 95 % confidence interval.

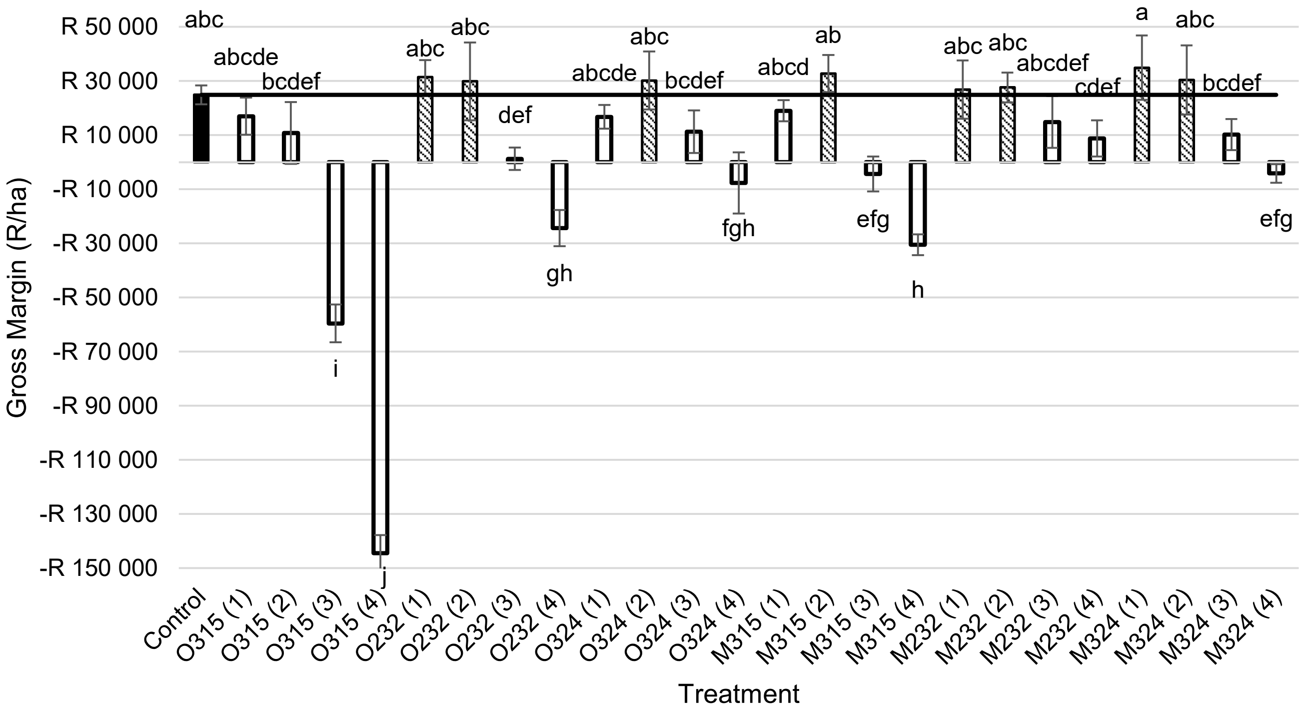

Figure 6.11: Gross margin of the organic and mineral treatments at the four application rates (1: low, 2: med1, 3: med2, 4: high) that were applied on the farm Rogland. Pattern-filled bars indicate a gross margin higher; and outlined bars indicate a gross margin lower than the control treatment (solid bar). Lowercase letters indicate a significant difference at a 95 % confidence interval.

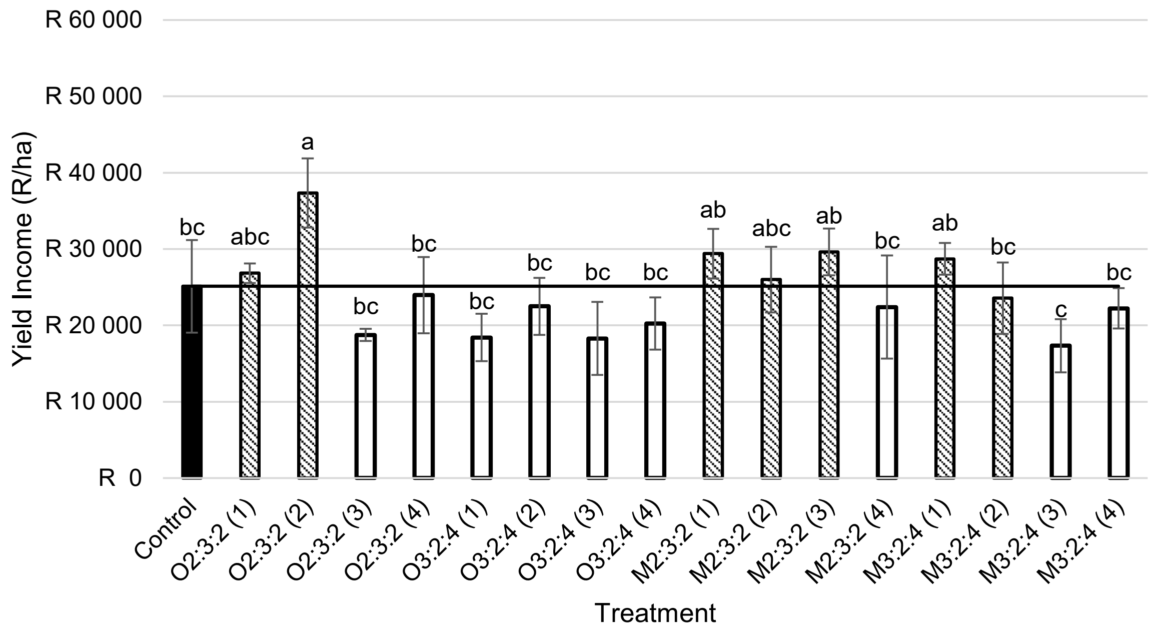

Figure 6.12: Income generated by the organic and mineral fertilizer treatments at the four application rates (1: low, 2: med1, 3: med2, 4: high) that were applied at Blomfontein. Pattern-filled bars indicate an income higher; and outlined bars indicate an income lower than the control treatment (solid bar). Lowercase letters indicate a significant difference at a 95 % confidence interval.

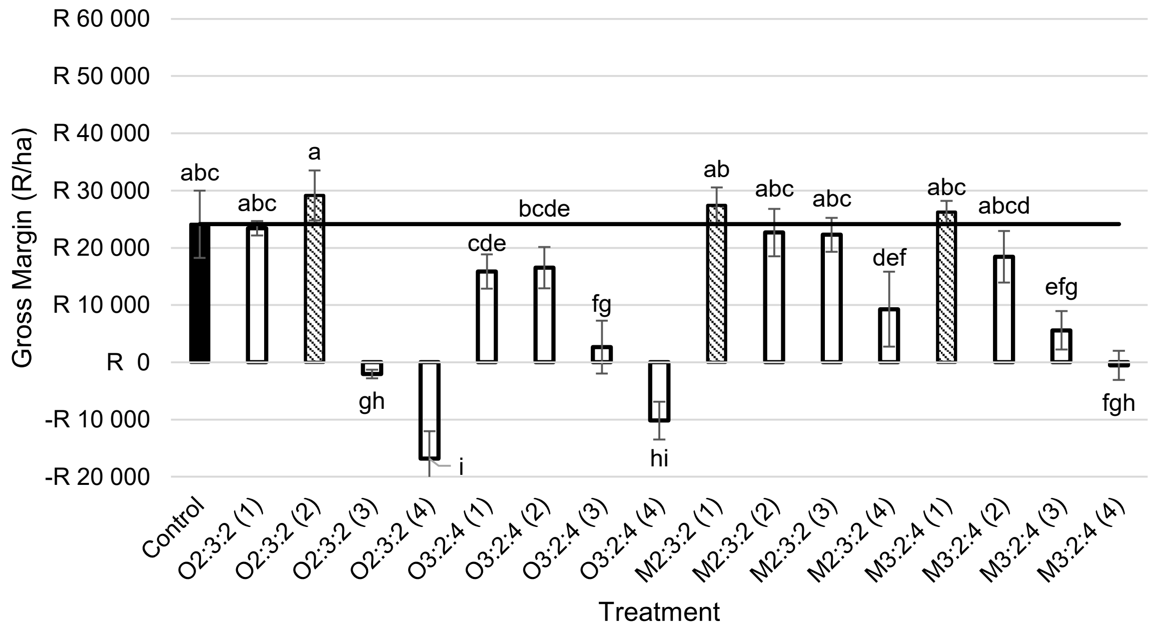

Figure 6.13: Gross margin of the organic and mineral treatments at the four application rates (1: low, 2: med1, 3: med2, 4: high) that were applied on the farm Blomfontein. Pattern-filled bars indicate a gross margin higher; and outlined bars indicate a gross margin lower than the control treatment (solid bar). Lowercase letters indicate a significant difference at a 95 % confidence interval.

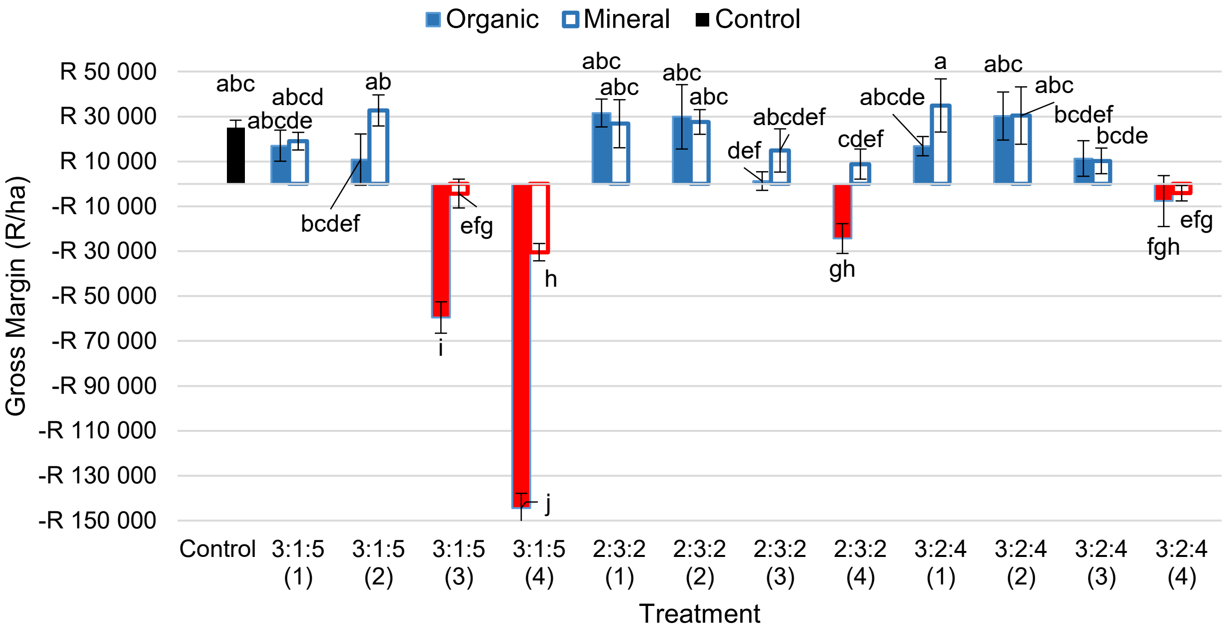

Figure 6.14: Comparison of the gross margin produced by the organic (solid bars) and mineral (outlined bars) treatments at Rogland at the four application rates (1: low, 2: med1, 3: med2, 4: high). Blue bars indicate a positive gross margin and red bars indicate a negative gross margin. Lowercase letters indicate a significant difference at a 95 % confidence interval.

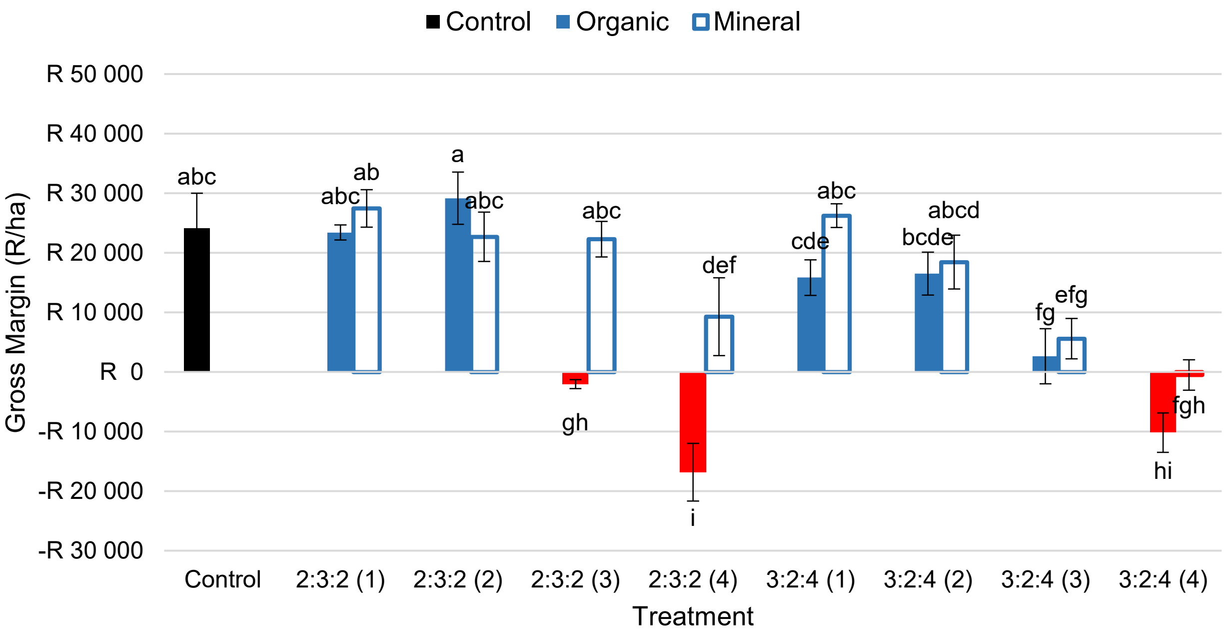

Figure 6.15: Comparison of the gross margin produced by the organic (solid bars) and mineral (outlined bars) treatments at Blomfontein at the four application rates (1: low, 2: med1, 3: med2, 4: high). Blue bars indicate a positive gross margin and red bars indicate a negative gross margin. Lowercase letters indicate a significant difference at a 95 % confidence interval.

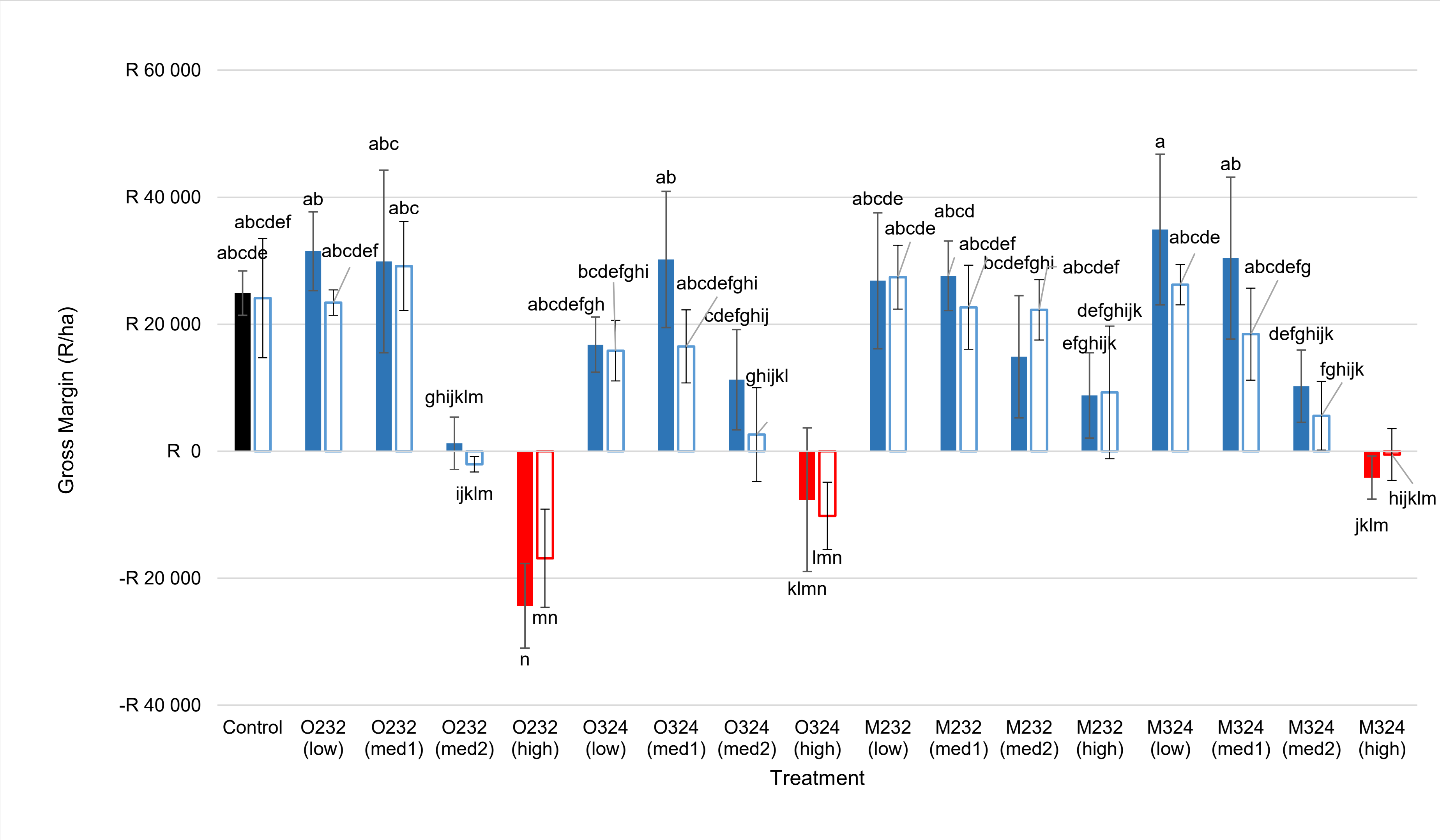

Figure 6.16: Gross margin of the organic and mineral treatments that were applied on both farms, Rogland (solid bars) and Blomfontein (outlined bars). Blue bars indicate a positive gross margin; and red bars indicate a negative gross margin. Lowercase letters indicate a significant difference at a 95 % confidence interval

Table 6.7: The gross margin analysis of the organic fertilizer treatments during the 2017/18 season on the farm Rogland. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment												
	Control	O3:1:5 (1)	O3:1:5 (2)	O3:1:5 (3)	O3:1:5 (4)	O2:3:2 (1)	O2:3:2 (2)	O2:3:2 (3)	O2:3:2 (4)	O3:2:4 (1)	O3:2:4 (2)	O3:2:4 (3)	O3:2:4 (4)
Gross production value (R.ha^{-1})													
Gross Income	R25 902 a	R27 033 a	R38 776 a	R20 699 a	R14 848 a	R35 172 a	R38 035 a	R22 085 a	R16 098 a	R19 351 a	R36 570 a	R27 001 a	R22 500 a
Total experimental attributable costs	R842 m	R9 864 h	R27 846 e	R80 103 b	R159 178 a	R3 512 k	R8 003 i	R20 684 f	R40 284 c	R2 414 l	R6 205 j	R15 587 g	R29 979 d
Total non-experimental attributable costs	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150
Total expenses	R992 m	R10 014 h	R27 996 e	R80 253 b	R159 328 a	R3 662 k	R8 153 i	R20 834 f	R40 434 c	R2 563 l	R6 355 j	R15 737 g	R30 129 d
Gross Margin (R.ha^{-1})	**R 24 911 ab**	**R17 019 ab**	**R10 780 abc**	**-R59 554 e**	**-R144 480 f**	**R31 510 a**	**R29 882 a**	**R1 251 bc**	**-R24 337 d**	**R16 788 ab**	**R30 215 a**	**R11 265 abc**	**-R7 629 cd**

Table 6.8: The gross margin analysis of the mineral fertilizer treatments during the 2017/18 season on the farm Rogland. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment												
	Control	M3:1:5 (1)	M3:1:5 (2)	M3:1:5 (3)	M3:1:5 (4)	M2:3:2 (1)	M2:3:2 (2)	M2:3:2 (3)	M2:3:2 (4)	M3:2:4 (1)	M3:2:4 (2)	M3:2:4 (3)	M3:2:4 (4)
Gross production value (R.ha^{-1})													
Gross Income	R25 902 ab	R 22 815 ab	R 42 608 a	R 21 154 ab	R 19 468 b	R 28 765 ab	R 31 076 ab	R 21 923 ab	R 21 841 ab	R 37 660 ab	R 35 911 ab	R 22 077 ab	R 18 378 b
Total experimental attributable costs	R842 l	R3 633 i	R9 715 f	R25 340 b	R49 769 a	R1 768 k	R3 303 ij	R6 885 g	R12 883 d	R2 594 j	R5 338 h	R11 690 e	R22 372 c
Total non-experimental attributable costs	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150	R150
Total expenses	R992 l	R 3 783 i	R 9 865 f	R 25 490 b	R 49 919 a	R 1 918 k	R 3 453 ij	R 7 035 g	R 13 033 d	R 2 744 j	R 5 488 h	R 11 840 e	R 22 522 c
Gross Margin (R.ha^{-1})	**R 24 911 ab**	**R 19 032 ab**	**R 32 743 a**	**-R 4 336 c**	**-R 30 451 d**	**R 26 847 ab**	**R 27 624 ab**	**R 14 888 abc**	**R 8 808 bc**	**R 34 916 a**	**R 30 423 ab**	**R 10 236 bc**	**-R 4 144 c**

Table 6.9: The gross margin analysis of the organic fertilizer treatments during the 2017/18 season on the farm Blomfontein. Values designated the same letter within each row do not differ significantly (*p* > 0.05).

	Treatment								
	Control	O2:3:2 (1)	O2:3:2 (2)	O2:3:2 (3)	O2:3:2 (4)	O3:2:4 (1)	O3:2:4 (2)	O3:2:4 (3)	O3:2:4 (4)
Gross Production Value (R.ha^{-1})									
Gross Income	R 25 122 b	R 26 836 ab	R 37 338 a	R 18 753 b	R 23 968 b	R 18 416 b	R 22 493 b	R 18 278 b	R 20 240 b
Total experimental attributable costs	R 840 i	R 3 271 g	R 8 031 e	R 20 639 c	R 40 653 a	R 2 420 h	R 5 827 f	R 15 494 d	R 30 271 b
Total non-experimental attributable costs	R 150	R 150	R 150	R 150	R 150	R 150	R 150	R 150	R 150
Total expenses	R 990 i	R 3 421 g	R 8 181 e	R 20 789 c	R 40 803 a	R 2 570 h	R 5 977 f	R 15 644 d	R 30 421 b
Gross Margin (R.ha^{-1})	**R 24 132 ab**	**R 23 415 ab**	**R 29 157 a**	**-R 2 035 cd**	**-R 16 835 e**	**R 15 846 b**	**R 16 516 b**	**R 2 634 c**	**-R 10 182 de**

Table 6.10: The gross margin analysis of the mineral fertilizer treatments during the 2017/18 season on the farm Blomfontein. Values designated the same letter within each row do not differ significantly ($p > 0.05$).

	Treatment								
	Control	M2:3:2 (1)	M2:3:2 (2)	M2:3:2 (3)	M2:3:2 (4)	M3:2:4 (1)	M3:2:4 (2)	M3:2:4 (3)	M3:2:4 (4)
Gross Production Value (R.ha^{-1})									
Gross Income	R 25 122 a	R 29 398 a	R 25 996 a	R 29 621 a	R 22 395 a	R 28 715 a	R 23 568 a	R 17 337 a	R 22 233 a
Total experimental attributable costs	R 840 i	R 1 819 h	R 3 169 f	R 7 185 d	R 12 965 b	R 2 336 g	R 4 973 e	R 11 594 c	R 22 601 a
Total non-experimental attributable costs	R 150	R 150	R 150	R 150	R 150	R 150	R 150	R 150	R 150
Total expenses	R 990 i	R 1 969 h	R 3 319 f	R 7 335 d	R 13 115 b	R 2 486 g	R 5 123 e	R 11 744 c	R 22 751 a
Gross Margin (R.ha^{-1})	**R 24 132 a**	**R 27 429 a**	**R 22 676 a**	**R 22 286 a**	**R 9 280 bc**	**R 26 229 a**	**R 18 445 ab**	**R 5 594 c**	**-R 517 c**

6.5 Conclusions

The highest income produced from the harvested rooibos tea was largely observed in the first and second treatment level of both the organic and mineral fertilizer treatments. This trend indicates a preference of the rooibos plants to lower nutrient applications rates as income values are directly proportional to harvest yields. Across all treatment types the highest gross margin was observed at either the first or second treatment levels. At Rogland, the highest gross margin was obtained in the first treatment level of the mineral 3:2:4 fertilizer (R 34 915.63/ha), while at Blomfontein, the highest gross margin was in the second treatment level of the organic 2:3:2 fertilizer (R 29 157.19/ha). These values represent a 40.2 and 20.8 % increase in the gross margin at the respective farms.

Across both farms a higher gross margin was generally observed at Rogland due to the higher income produced from a higher yields per hectare. In the organic fertilizers, the highest gross margin was produced in the 2:3:2 fertilizer at the first treatment level (R 31 510.06/ha) at Rogland, whereas in the mineral fertilizers the highest was produced at the first treatment level of the 3:2:4 fertilizer (R 34 915.63/ha), also at Rogland. The highest costs observed occurred in the organic 3:1:5 fertilizers due to the high volume of fertilizer transported and applied. The highest loss was in the highest treatment level in the organic 3:1:5 fertilizer with a gross margin of negative R 144 480.15/ha, which is a decline of 680 %.

Based on the results the organic fertilizers produced a lower gross margin than the mineral fertilizers. This is of particular importance as it highlights that organic producers require an incentive, either financially, for social benefit or through market security, to convert to organically producing rooibos tea.

These conclusions are based on one harvest yield that occurred during the prolonged drought experienced by south-western South Africa. Input costs were only calculated based on the year of fertilizer application and would therefore decrease dramatically in the years to follow. To make more accurate conclusions, especially with the use of organic fertilizers where treatment effects can only observed after several years, the yields and costs should be monitored over a longer period of time.

7 GENERAL CONCLUSIONS AND FUTURE RESEARCH PROSPECTS

The main aim of the study was to investigate the effect of three commercial organic and mineral fertilizers on soil fertility, one-year old rooibos plant survival and tea yield production under Northern Cape field conditions. Mineralisation and uptake of applied nutrients were monitored in the wet winter season when plant nutrient uptake occurs. This was used to identify if organic fertilizer mineralisation was effective for plant nutrient accumulation to occur before growth is stimulated in the warm dry spring and summer conditions. Another objective was to determine the effect of the application of vermicompost tea (VCT) solutions in comparison to water on plant growth and rhizosphere microbial diversity within the soil. The economic feasibility of the soil amendments was determined to ensure that the results obtained in the study are beneficial to farmers financially and for increased production.

In the winter mineralisation study it was found that organic fertilizers failed to mineralise effectively due to the cold soil conditions limiting microbial activity. Therefore the addition of mineral fertilizers was more effective in the short-term as it provided plant-available nutrients during the nutrient uptake season of rooibos plants. The addition of mineral fertilizers under drought conditions also ensured that nutrients were more readily available for plant uptake as soon as the soil water content increased. Foliar NPK concentrations peaked in July due to increased soil water content. The prevailing drought conditions reduced the time for nutrient uptake with a decline in foliar nutrient concentration in August due to warmer and drier conditions stimulating plant growth. Foliar NPK concentration was highest in the mineral 3:1:5 fertilizer, indicating that the higher nutrient application increased plant uptake. Nutrient recovery was highest in the mineral 2:3:2 fertilizer with higher application of N and K lost through leaching.

In the main fertilizer study the application of organic and mineral fertilizers improved soil fertility, however had a limited effect on foliar nutrients. The organic and mineral 3:1:5 fertilizer had a significant effect on soil pH (KCl), EC and soil K due to the higher amounts of N and K applied. The organic 3:2:4 fertilizer had an effect on soil micronutrients (Fe, Cu, and Zn) due to the high micronutrient contents associated with chicken manure fertilizers. Bray II P increased with treatment levels, however soil P failed to increase to the intended targets, indicating that a proportion of the applied P became unavailable for plant uptake through P fixation occurring in the acidic sandy soils. Foliar P generally showed a negative trend with soil P (0 – 15 cm) contradicting the findings of previous studies. An increase in plant survival at both farms in the applied fertilizer treatments indicates that one-year old rooibos plants are more resistant to P toxicity than rooibos seedlings. Across all fertilizer treatments and both farms the high treatment level negatively affected survival-adjusted yield with a decrease of 42.7 and 37.8 % occurring in the organic 3:1:5 and 2:3:2 treatments, respectively.

The application of 10 mg P/kg (36.3 kg P/ha) increased tea yields across all organic fertilizers at both farms and in the mineral fertilizers at Rogland without significantly negatively affecting plant survival. The average tea yield per plant was increased by 59.3 and 47.2 % in the organic 3:2:4 (0.32 kg/plant) and mineral 3:1:5 fertilizers (0.3 kg/plant) at Rogland, while at Blomfontein yield increased by 20.9 % in the organic 2:3:2 fertilizer (0.18 kg/plant). The highest survival-adjusted yield was obtained at 10 mg P/kg in the mineral 3:1:5 fertilizer (1420.3 kg/ha) by increasing yield by 64.5 %. Foliar P and Mn showed positive trends with tea yields. Fertilizer efficiency was highest at the low nutrient applications with higher application of N and K lost to leaching. The low nutrient recovery of the applied P indicates that the application of 10 mg P/kg soil should be sufficient to support plant growth for several seasons. It is therefore recommended to that up to 30 N and 50 K mg/kg be applied with 10 mg P/kg to one-year old rooibos plants to increase tea yields.

In the VCT trial, the application of VCT and water increased soil pH and dissolved organic carbon, thereby significantly affecting nutrient availability and plant uptake. The application of VCT had no significant effect on plant properties, but rather the application of water increased plant survival resulting in smaller plants and tea yields due to higher plant density. The application of water reduced foliar Mn to below average values which had a negative effect on plant growth. In the cooler months of the second VCT trial the application of VCT enhanced bacterial species richness and diversity but had no effect on the fungal community. However, the type of bacterial species occurring was unknown therefore determining if the application of VCT is beneficial to the microbes associated with the rooibos plant remains unknown.

The mineral 3:1:5 fertilizer at 10 mg P/kg produced the highest income, however the highest gross margin was achieved in other treatments. At Rogland, the mineral 3:2:4 treatment at the first treatment level and at Blomfontein the organic 2:3:2 treatment at the second treatment level produced the highest gross margin of R34 916/ha and R29 157/ha, respectively. This represents a 40.2 (Rogland) and 20.8 % (Blomfontein) increase in the net income per hectare. Generally a higher gross margin was obtained in the mineral fertilizers emphasizing that producers require an incentive to convert to organically producing rooibos tea.

Future research prospects

Further research is required to determine the effect of VCT on rooibos tea above- and below-ground growth. Effects on components such as microbial community diversity and species richness over varying seasons require determination, as well as the effect of compost quality and type from which the VCT is derived. Determining root growth and harvesting all roots under field conditions is not always possible, therefore it is suggested to first carry out the experiment in pot trials to accurately determine the effect on rooibos root growth. Pot trials must be conducted to investigate the effect on above- and below-ground growth and to determine optimal fertilizer application rate for rooibos plants.

Field trials are recommended to study the effect of organic and mineral fertilizers on rooibos tea yields over several years. The effect of a once-off application of 36.3 kg P/ha on one-year old plants and yearly application of low amounts of N (24 - 108 kg/ha) and K (24 - 180 kg/ha) on rooibos tea yields must be researched to further optimize the use of organic and mineral fertilizers. By monitoring plant growth over several seasons will also provide additional information on the effect of rainfall. Gross margins were only calculated based on the year of fertilizer application and would therefore vary in the years to follow. To make more accurate conclusions, especially with the use of organic fertilizers where treatment effects are only observed after several years, the yields and costs should be monitored over a longer period of time.

8 BIBLIOGRAPHY

Agehara, S. & Warncke, D. D., 2006. Soil Moisture and Temperature Effects on Nitrogen Release from Organic Nitrogen Sources. *Soil Science Society of American Journal,* 69(6), pp. 1844 - 1855.

Anderson, M. J., Crist, T. O. Chase, J. M. *et al*., 2011. Navigating the multiple meanings of B diversity: a roadmap for the practicing ecologist. *Ecology Letters,* Volume 14, pp. 19-28.

Anderson, M. J., Ellingsen, K. E. & McArdle, B. H., 2006. Multivariate dispersion as a measure of beta diversity. *Ecology Letters,* Volume 9, pp. 683-693.

Arancon, N. Q., Edwards, C. A., Atiyeh, R. & Metzger, J. D., 2004. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. *Bioresource Technology,* Volume 93, pp. 139-144.

Arancon, N. Q., Edwards, C. A., Babenko, A., Cannon, J., Galvis, P. & Metzger, J. D., 2008. Influences of vermicomposts, produced by earthworms and microorganisms from cattle manure, food waste and paper waste, on the germination, growth and flowering of petunias in the greenhouse. *Applied Soil Ecology,* Volume 39, pp. 91-99.

Arancon, N. Q., Edwards, C. A., Lee, S. & Byrne, R., 2006. Effects of humic acids from vermicomposts on plant growth. *European Journal of Soil Biology,* Volume 42, pp. S65-S69.

Arancon, N. Q., Lee, S., Edwards, C. A. & Atiyeh, R., 2003. Effects of humic acids derived from cattle, food and paper-waste vermicomposts on growth of greenhouse plants. *Pedobiologia,* Volume 47, pp. 741-744.

Archer, E. R. M., Oettle, N. M., Louw, R. & Tadross, M. A., 2008. 'Farming on the edge' in arid western South Africa: climate change and agriculture in marginal environments. *Geography,* 93(2), pp. 98-107.

Arias, M. E., Gonzalez-Perez, J. A., Gonzalez-Vila, F. J. & Ball, A. S., 2005. Soil health - a new challenge for microbiologists and chemists. *International Microbiology,* Volume 8, pp. 13-21.

Atiyeh, R. M., Lee, S., Edwards, C. A., Arancon, N. Q., & Metzger, J. D., 2002. The influence of humic acids derived from earthworm-processed organic wastes on plant growth. *Bioresource Technology,* Volume 84, pp. 7-14.

Atiyeh, R. M., Subler, S., Edwards, C. A., Bachman, G., Metzger, J. D. & Shuster, W., 2000. Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedo Biologia,* Volume 44, pp. 579-590.

Baca, M. T., Fornasier, F. & De Nobili, M., 1992. Mineralization and Humification Pathways in Two Composting Processes Applied to Cotton Wastes. *Journal of Fermentation and Bioengineering,* 74(3), pp. 179-184.

Basso, B., Sartori, L., Cammanrano, D., *et al*., 2012. Environmental and economic evaluation of N fertilizer rates in a maize crop in Italy: A spatial and temporal analysis using crop models. *Biosystems Engineering,* Volume 113, pp. 103-111.

Bienabe, E., Bramley, C. & Kirsten, J., 2009. An economic analysis of the evolution in intellectual property strategies in the South African agricultural sector: The Rooibos Industry. In: *The economics of intellectual property in South Africa.* s.l.:World Intellectual Property Organization, pp. 56-83.

Blake, G. R. & Hartge, K. H., 1986. Bulk Density. In: *Methods of Soil Analysis: Part 1.* s.l.:s.n., pp. 363-375.

Bowen, G. D., 1981. Coping with low nutrients. In: J. S. Pate & A. J. McComb, eds. *The Biology of Australian Plants.* Western Australia: The University of Western Australia Press, pp. 33-64.

Brink, C., Postma, A. & Jacobs, K., 2017. Rhizobial diversity and function in rooibos (*Aspalathus linearis*) and honeybush (Cyclopia spp.) plants: a review. *South African Journal of Botany,* Volume 110, pp. 80-86.

Broadley, M., Brown, P., Cakmak, I., Rengel, Z. & Zhao, F., 2012. Function of Nutrients: Micronutrients. In: P. Marschner, ed. *Mineral Nutrition of Higher Plants.* 3rd ed. s.l.:Elsevier Ltd, pp. 191-248.

Broadley, M. R., White, P. J., Hammond, J. P., Zelko, I. & Lux, A., 2007. Zinc in plants. *New Phytol,* Volume 173, pp. 677-702.

Buchanam, M. A., Rusell, E. & Block, S. D., 1988. Chemical charaterization and nitrogen mineralization potentials of vermicompost derived from differing organic wastes. In: C. A. Edwards & E. F. Neuhauser, eds. *Earthworms in Environmental and Waste Management.* s.l.:SPB Academic Publishing, The Netherlands, pp. 231-240.

Bulluck III, L. R., Brosius, M., Evanylo, G. K. & Ristaino, J. B., 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. *Applied Soil Ecology,* Volume 19, pp. 147-160.

Cheney, R. & Scholtz, E., 1963. Rooibos Tea, A South African Contribution to World Beverages. *Economic Botany,* 17(3), pp. 186-194.

Chen, J. H., 2006. *The combined use of chemical and organic fertilizers and/or biofertilizer for crop growth and soil fertility,* Bangkok, Thailand: Land Development Department.

Chimphango, S. B. M., Hattas, D. & Oettle, N., 2015. Effect of organic cultivation of rooibos tea plants (*Aspalathus linearis*) on soil nutrient status in Niewoudtville, South Africa. *South African Journal of Plant and Soil,* pp. 1-9.

Coblentz, W., Jokela, W. & Cavadini, J. S., 2016. Production and Nitrogen Use Efficiency of Oat Forages Receiving Slurry or Urea. *Agronomy, Soils, and Environmental Quality,* 108(4), pp. 1390-1404.

Corwin, D. L., 2002. Measurement of solute concentration using soil water extraction: Suction cups. In: J. H. Dane & G. C. Topp, eds. *Methods of soil analysis. Part 4 - Physical Methods.* s.l.:SSSA, pp. 1261-1266.

Corwin, D. L. & Lesch, S. M., 2005. Apparent soil electrical conductivity measurements in agriculture.. *Computers and Electronics in Agriculture,* Volume 46, pp. 11-43.

Daddow, R. L. & Warrington, G. E., 1983. *Growth-limiting soil bulk denisities as influenced by soil texture,* s.l.: Watershed Systems Development Group.

DAFF, 2006. *Crops and Markets: Volume 87, No. 927,* s.l.: Department of Agriculture.

DAFF, 2015. *A Profile of the South African Rooibos Market Value Chain,* s.l.: Department: Agricultural, Forestry and Fisheries.

DAFF, 2016. *A Profile of the South African Rooibos Market Value Chain,* s.l.: Department of Agriculture, Forestry and Fisheries.

DAFF, S.-D. E. A. & KZNDARD, S.-D. A. E., 2016. *Guide to Machinery Costs: Trucks,* s.l.: s.n.

DAFF, S.-D. E. A. & KZNDARD, S.-D. A. E., 2016. *Introduction to the Guide for Machinery Costs 2015 - 2016,* s.l.: s.n.

Dahlgren, R., 1968. Revision of the genus *Aspalathus* II: The species with ericoid and pinoid leaves. 7 subgenus Nortieria. With remarks on Rooibos cultivation. *Botany Notiser,* Volume 121, pp. 165-208.

Dakora, F. D. & Phillips, D. A., 2002. Root exudates as mediators of mineral acquisition in low-nutrient environments. *Plant and Soil,* Volume 245, pp. 35-47.

Drechsel, P., Gyiele, L., Kunze, D. & Cofie, O., 2001. Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. *Ecological Economies,* Volume 38, pp. 251-258.

Drinkwater, L. E., Letourneau, D. K., Workneh, F., van Bruggen, A. H. & Shennan, C., 1995. Fundamental differences between conventional and organic tomato agroecosytems in California. *Applied Ecology,* Volume 5, pp. 1098-1112.

Duflo, E., Kremer, M. & Robinson, J., 2008. How High Are Rates of Return to Fertilizer? Evidence fom Field Experiments in Kenya. *The American Economic Review,* 98(2), pp. 482-488.

Edwards, C. A., Arancon, N. Q. & Greytak, S., 2006. *Effects of Vermicompost Teas on Plant Growth and Disease,* s.l.: BioCycle.

Edwards, C. A. & Burrows, I., 1988. The potential of earthworm composts as plant growth media. In: C. A. Edwards & E. Neuhauser, eds. *Earthworms in Environmental and Waste Management.* The Hague, The Netherlands: SPB Academic Press, pp. 21-32.

Elliot, G. N., Chen, W. M., Bontemps, C., *et al*., 2007. Nodulation of *Cyclopia* spp. (Leguminosae, Papilionidae) by *Burkholderia tuberum*. *Annals of Botany,* Volume 100, pp. 1403-1411.

Evanylo, G., Sherony, C., Spargo, J., Starner, D., Brosius, M. & Haering, K., 2008. Soil and water environmental effects of fertilizer-, manure-, and compost-based fertility practices in an organic vegetable cropping system. *Agriculture, Ecosystems and Environment,* Volume 127, pp. 50-58.

Gardner, W., Barber, D. & Parbery, D., 1983. The acquisition of phosphorus by *Lupinus albus* L. III. The probable mechanism by which phosphorus movement in the soil/root interface is enhanced. *Plant and Soil,* Volume 70, pp. 107-124.

Garg, P., Gupta, A. & Satya, S., 2006. Vermicomposting of different types of waste using *Eisenis foetida*: A comparative study. *Bioresource Technology,* Volume 97, pp. 391-395.

Ge, G., Li, Z., Fan, F., Chu, G., Hou, Z. & Liang, Y., 2010. Soil biological activity and their seasonal variations in response to long-term application of organic and inorganic fertilizers. *Plant Soil,* Volume 326, pp. 31-44.

Gerz, A. & Bienabe, E., 2006. Rooibos tea, South Africa: The challenge of an export boom. In: P. van de Kop, D. Sautier & A. Gerz, eds. *Origin-based Products: Lessons for pro-poor market development.* s.l.:Royal Tropical Institute - CIRAD, pp. 53-63.

Griffin, T. S. & Honeycutt, C. W., 2000. Using growing degree days to predict nitrogen availability from livestock manures. *Soil Science Society of American Journal,* Volume 64, pp. 1876-1882.

Griffiths, B. S., Diaz-Ravina, M., Ritz, K., McNicol, J. W., Ebblewhite, N. & Baath, E., 1997. Community DNA hybridisation and % G + C profiles of microbial communities from heavy metal polluted soils. *FEMS Microbiology Ecology,* Volume 24, pp. 103-112.

Griffiths, B. S., Rits, K., Wheatley, R., *et al*., 2001. An examination of the biodiversity-ecosystem function relationship in arable soil microbial communities. *Soil Biology and Biochemistry,* Volume 33, pp. 1713-1722.

Hassen, A. L., Bopape, F. L. & Habig, J. e. a., 2011. Nodulation of rooibos (*Aspalathus linearis* Burm. f.), an indenous South African legume, by members of both the A-Proteobacteria and B-Proteobacteria. *Biology and Fertility of Soils,* 48(3), pp. 295-303.

Hawkesford, M., Horst, W., Kichey, T., *et a*l., 2012. Functions of Macronutrients. In: P. Marschner, ed. *Mineral Nutrition of Higher Plants.* 3rd ed. s.l.:Elsevier Ltd, pp. 135-189.

Hawkins, H., Hettasch, H., Mesjasz-Przybylowicz, J., Mesjasz-Przybylowicz, W. & Cramer, M., 2008. Phosphorus toxicity in the Proteaceae: A problem in post-agricultural lands. *Scientia Horticulturae,* Volume 117, pp. 357-365.

Hawkins, H.., Malgas, R. & Bienabe, E., 2011. Ecotypes of wild rooibos (*Aspalathus linearis* (Burm. F) Dahlg., Fabaceae) are ecologically distinct. *South African Journal of Botany,* Volume 77, pp. 360-370.

Heeb, A., Lundegardh, B., Savage, G. & Ericsson, T., 2006. Impact of organic and inorganic fertilizers on yield, taste, and nutritional quality of tomatoes. *Journal of Plant Nutrition and Soil Science,* Volume 169, pp. 535-541.

Hobbie, S. E., 1992. Effects of Plant Species on Nutrient Cycling. *TREE,* 7(10), pp. 336-339.

Holford, I. C. R., 1997. Soil phosphorus: its measurement, and its uptake by plants. *Australian Journal of Soil Research,* Volume 35, pp. 227 - 239.

Itoh, S. & Barber, S. A., 1983. Phosphorus uptake by six plant species as related to root hairs. *Agronomy Journal,* Volume 75, pp. 457-461.

Jeschke, W. D. & Pate, J. S., 1995. Mineral nutrition and transport in xylem and phloem of *Banksia prionotes* (Proteaceae), a tree with dimorphic root morphology. *Journal of Experimental Botany,* 46(289), pp. 895-905.

Jones, D. L., 1998. Organic acids in the rhizosphere - a critical review. *Plant and Soil,* Volume 205, pp. 25-44.

Jones, D. L. & Darrah, P. R., 1994. Role of root derived organic-acids in the mobilization of nutrients from the rhizosphere. *Plant and Soil,* Volume 166, pp. 247-257.

Joubert, E. & de Beer, D., 2011. Rooibos (*Aspalathus linearis*) beyond the farm gate: From herbal tea to potential phytopharmaceutical. *South African Journal of Botany,* Volume 77, pp. 869-886.

Joubert, E., Gelderblom, W. C. A., Louw, A. & de Beer, D., 2008. South African herbal teas: *Aspalathus linearis*, *Cyclopia* spp. and *Athrixia phylicoides* - A review. *Journal of Ethnopharmacology,* Volume 119, pp. 376-412.

Joubert, E. & Schulz, H., 2006. Production and quality aspects of rooibos tea and related products. *Journal of Applied Botany and Food Quality,* Volume 80, pp. 138-144.

Joubert, M., Kotze, W. A. G. & du Preez, M., 1987. Voedingsbehoefte van Rooibostee. *Tuinbouwetenskap,* Volume 5, pp. 11-14.

Joubert, R., 2012. *Farmer's Weekly - Putting worms to good use.* [Online]
Available at: www.farmersweekly.co.za/crops/field-crops/putting-worms-to-good-use/
[Accessed 20 July 2018].

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. & Schuman, G. E., 1997. Soil Quality: A Concept, Definition, and Framework for Evaluation. *Soil Science Society of America Journal,* Volume 61, pp. 4-10.

Keerthisinghe, G., Hocking, P. J., Ryan, P. R. & Delhaize, E., 1998. Effect of phosphorus supply on the formation and function of proteoid roots of white lupin (*Lupinus albus* L.). *Plant, Cell and Environment,* Volume 21, pp. 467-478.

Kemper, J., Cowling, R. M. & Richardson, D. M., 1999. Fragmentation of South African renosterveld shrublands: effects on plant community structure and conservation implications. *Biological Conservation,* pp. 103-111.

Kirchmann, H., Johnstone, A. E. J. & Bergstrom, L. F., 2002. Possibilities for reducing nitrate leaching from agricultural land. *Ambio,* Volume 31, pp. 404-408.

Kramer, P. J. & Boyer, J. S., 1995. *Water Relations of Plants and Soils.* London: Academic Press.

Kriel, G., 2008. *Farmer's Weekly - Does compost tea work?.* [Online] Available at: www.farmersweekly.co.za/archive/does-compost-tea-work/ [Accessed 7 July 2018].

Kuo, S., 1996. Phosphorus. In: D. L. Sparks, ed. *Methods of soil analysis: Part 3.* Madison, WI.: SSSA, pp. 869-919.

Lambers, H., Ahmedi, I., Berkowitz, O., *et al*., 2013. Phosphorus nutrition of phosphorus-sensitive Australian native plants: threats to plant communities in a global biodiversity hotspot. *Conservation Physiology,* p. 1.

Lambers, H., Shane, M. W., Cramer, M. D., Pearse, S. J. & Veneklaas, E. J., 2006. Root Structure and Functioning for Efficient Acquisition of Phosphorus: Matching Morphological and Physiological Traits. *Annals of Botany,* Volume 98, pp. 693-713.

Lamont, B., 1982. Mechanisms for Enhancing Nutrient uptake in Plants, with Particular Reference to Mediterranean South Africa and Western Australia. *Botanical Review,* 48(3), pp. 597-689.

Le Clercq, M., Bienabe, E. & Caron, P., 2009. The case of the South African Rooibos: Biodiversity conservation as a collective consensus. *International Symposium Locating the products: a sustainable way to serve the natural and cultural diversity of South Africa*, 9-11 June, p. 7.

Leake, S., 1993. Soil conditions and fertilizers for P sensitive plants. *Unpublished paper, Sydney Environmental & Soil laboratory.*

Lexmond, T. M. & van der Vorm, P. D. J., 1981. the effect of pH on copper toxicity to hydroponically grown maize. *Netherlands Journal of Agricultural Science,* Volume 29, pp. 217-238.

Liu, E., Yan, C., Mei, X., *et al*., 2010. Long-term effect of chemical fertilizer, stra, and manure on soil chemical and biological properties in northwest China. *Geoderma,* Volume 158, pp. 173-180.

Lopez-Perez, A., Casanova, E., Chacon, L. A., Paz, P. M. & Guerrero, J. R., 1990. Residual effect of three phospahte rocks from Tachina (Venezuela) in a greenhouse experiment with maize (*Zea mays* L.) as indicator plant. *Revista-Cientifica-UNET,* Volume 4, pp. 29-48.

Lotter, D., Valentine, A. J., van Garderen, E. A. & Tadross, M., 2014a. Physiological responses of a fynbos legume, *Aspalathus linearis* to drought stress. *South African Journal of Botany,* Volume 94, pp. 218-223.

Lotter, D., van Garderen, E. A., Tadross, M. & Valentine, A. J., 2014b. Seasonal variation in the nitrogen nutrition and carbon assimilation in wild and cultivated *Aspalathus linearis* (rooibos tea). *Australian Journal of Botany,* Volume 62, pp. 65-73.

Lourenco, M. R., 2018. *Effect of NPK application on rooibos (Aspalathus linearis) under Clanwilliam field conditions,* Stellenbosch: M.Sc Thesis. Faculty of AgriSciences. Stellenbosch University.

Louw, R., 2006. *Sustainable harvesting of wild rooibos (Aspalathus linearis) in the Suid Bokkeveld, Northern Cape.,* Cape Town: M.Sc: Botany Department, University of Cape Town.

Low, A. B., Mustart, P. & van der Merwe, H., 2004. *Greater Cedeberg Biodiversity Corridor: Provision of Biodiversity Profiles for Management,* s.l.: Coastec Coastal and Environmental Consultants.

Lynch, J., Lauchli, A. & Epstein, E., 1991. Vegetative growth of the common bean in response to phosphorus nutrition. *Crop Science,* Volume 31, pp. 380-387.

Lynch, J., Marschner, P. & Rengel, Z., 2012. Effect of Internal and External Factors on Root growth and Development. In: P. Marschner, ed. *Mineral Nutrition of Higher Plants.* 3rd ed. s.l.:Elsevier Ltd, pp. 331-346.

Lynch, J. P. & Brown, K. M., 2001. Topsoil foraging - an architetural adaptation of plants to low phosphorus availability. *Plant and Soil,* Volume 237, pp. 225-237.

MacArthur, R. H., 1955. Fluctuations of animal populations and a measure of community stability. *Ecology,* Volume 36, pp. 533-536.

MacLean, A. A. & McRae, K. B., 1987. Rate of hydrolysis and nitrification of urea and implications of its use in potato production. *Canadian Journal of Soil Science,* Volume 67, pp. 679-686.

Maistry, P. M., Cramer, M. D. & Chimphango, S. B. M., 2013. N and P colimitation of N2-fixing and N-supplied fynbos legumes from the Cape Floristic Region. *Plant and Soil,* Volume 373, pp. 217-228.

Maistry, P. M., Musaya, A. M., Valentine, A. J. & Chimphango, S. B. M., 2015. Increasing nitrogen supply stimulates phosphorus azquisition mechanisms in the fynbos species *Aspalathus linearis*. *Functional Plant Biology,* Volume 42, pp. 52-62.

Malgas, R. R., Potts, A. J., Oettle, N. M., *et al*., 2010. Distribution, quantitative morphological variation and preliminary molecular analysis of different growth forms of wild rooibos (*Aspalathus linearis*) in the northern Cederberg and on the Bokkeveld Plateau. *South African Journal of Botany,* Volume 76, pp. 72-81.

Manning, J. & Goldblatt, P., 1997. *Niewoudtville, Bokkevel Plateau and Hantam: South African Wildflower Guide No. 9.* Cape Town: Botanical Society of South Africa.

Marschner, H., 1995. *Mineral Nutrition of Higher Plants.* 2nd ed. London: Academic Press Limited.

Marschner, H. & Cakmak, I., 1989. High light intensity enhances chlorosis and necrosis in leaves of zinc, potassium, and magnesium deficient bean (*Phaseolus vulgaris*) plant. *Journal of Plant Physiology,* Volume 134, pp. 308-315.

Masson-Boivin, C., Giraud, E. & Perret, X. e. a., 2009. Establishing nitrogen-fixing symbiosis with legumes: how many rhizobium recipes?. *Trends in Microbiology,* 17(10), pp. 458-466.

McGechan, M. B., Moir, S. E., Sym, G. & Castle, K., 2005. estimating Inorganic and Organic Nitrogen Transformation Rates in a model of a Constructed Wetland Purification System for Filute Farm Effluents. *Biosystems Engineering,* Volume 91, pp. 61-75.

Meng, L., Ding, W. & Cai, Z., 2005. Long-term application of organic manure and nitrogen fertilizer on N2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biology and Biochemistry,* Volume 37, pp. 2037-2045.

Mooney, H. A. & Rundel, P. W., 1979. Nutrient relations of the evergreen shrub, *Adenostoma fasciculatum*, in the Californian Chaparral. *Botanical Gazette,* 140(1), pp. 109-113.

Morton, J. F., 1983. Rooibos Tea, *Aspalathus linearis*, a Caffeineless, Low-Tanin Beverage. *Economic Botany,* 37(2), pp. 164-173.

Moyo, C. C., Kissel, D. E. & Cabrera, M. L., 1989. Temperature Effects on Soil Urease Acitivity. *Soil Biology and Biochemistry,* 21(7), pp. 935-938.

Muofhe, M. L. & Dakora, F. D., 1998. Bradyrhizobium species isolated from indigenous legumes of the Western Cape exhibit high tolerance of low pH. In: C. Elmerich, A. Kondorosi & W. E. Newton, eds. *Biological nitrogen fixation for the 21st century.* Dordrecht: Kluwer Academic Publishers, p. 519.

Muofhe, M. L. & Dakora, F. D., 2000. Modification of rhizosphere pH by the symbiotic legume *Aspalathus linearis* growing in a sandy acidic soil. *Australian Journal of Plant Physiology,* Volume 27, pp. 1169-1173.

Muofhe, M. L. & Dakora, F. L., 1999. Symbiotic response of the African tea legume *Aspalathus linearis* (rooibos tea) to nutrient supply under glasshouse conditions. *Symbiosis,* Volume 27, pp. 279-292.

Naab, J. B., Seini, S. S., Gyasi, K. O., *et al.*, 2009. Groundnut yield response and economic benefits of fungicide and phosphorus application in farmer-managed trials in northern Ghana. *Experimental Agriculture,* Volume 45, pp. 385-399.

Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G. & Renella, G., 2003. Microbial diversity and soil functions. *European Journal of Soil Science,* Volume 54, pp. 655-670.

Newborn, R., 2017. *Information about vermicompost tea product* [Interview] (25 April 2017).

Nieuwoudt, S. F., 2017. *The effect of residue management on the nutrient cycle in the production of rooibos (Aspalathus linearis) at Nieuwoudtville, Northern Cape,* Stellenbosch: M.Sc Thesis: Faculty of AgriSciences, Stellenbosch University.

O'Donoghue, R. & Fox, H., 2009. *Rooibos: A Biodiversity Economy ar Risk.* s.l.:Share-net.

O'Farrell, P. J., Donaldson, J. S. & Hoffman, M. T., 2007. The influence of ecosystem goods and services on livestock management practices on the Bokkeveld Plateau, South Africa. *Agriculture, Ecosystems and Environment,* Volume 122, pp. 312-324.

Padmavathiamma, P. K., Li, L. Y. & Kumari, U. R., 2008. An experimental study of vermi-biowaste composting for agricultural soil improvement. *Bioresource Technology,* Volume 99, pp. 1672-1681.

Pant, A. P., Rodovich, T. J. K., Hue, N. V. & Paull, R. E., 2012. Biochemical properties of compost tea associated with compost quality and effects on pak choi growth. *Scientia Horticulture,* Volume 148, pp. 138-146.

Pant, A., Radovich, T. J. K., Hue, N. V. & Arancon, N. Q., 2011. effects of Vermicompost Tea (Aqueous Extract) on Pak Choi Yield, Quality, and on Soil Biological Properties. *Compost Science and Utilization,* 19(4), pp. 279-292.

Parks, S. E., Haigh, A. M. & Cresswell, G. C., 2000. Stem tissue phosphorus an an index of the phosphorus status of *Banksia ericifolia* L. f.. *Plant and Soil,* Volume 227, pp. 59-65.

Parr, J. F., Pappendick, R. I., Hornick, S. B. & Meyer, R. E., 1992. Soil quality: attributes and relationship to alternative and sustainable agriculture. *American Journal of Alternative Agriculture,* Volume 7, pp. 5-11.

Pienaar, C. & du Plessis, D., 2007. *Vermiculture,* Bloemfontein: UFS Centre for Agricultural Management.

Postma, A., 2016. *Soil microbial communities associated with two commercially important plant species indigenous to the fynbos region of South Africa: Cyclopia spp. (honeybush) and Aspalathus linearis (rooibos),* s.l.: PhD Dissertation: Faculty of Science, Stellenbosch University.

Pretorius, G., 2007. *Rooibos Biodiversity Initiative (RBI): Biodiversity Best Practice Guidelines for the Sustainable Production of Rooibos ,* Malmesbury: Natura Libra Environmental Consultants.

Pretorius, G., Harley, V. & Ryser, L., 2011. *Handbook for Implementing Rooibos Sustainability Standards.* s.l.:s.n.

Qiao, L. & Ho, G., 1997. the effects of clay amendment and composting on metal speciation in digested sludge. *Water Research,* Volume 31, pp. 951-964.

Ramaila, M., Mahlangu, S. & du Toit, D., 2011. *Agricultural Productivity in South Africa: Literature Review,* s.l.: Directorate: Economic Services Production Economics Unit.

Ramutloa, L., 2018. *Republic of South Africa Department: Labour.* [Online]
Available at: www.labour.gov.za
[Accessed 18 April 2018].

Raven, J. A., Franco, A. A., de Jesus, E. L. & Jacob-Neto, J., 1990. H^+ extrusion and organic-acid synthesis in N_2-fixing symbioses involving vascular plants. *New Phytologist,* Volume 114, pp. 369-389.

Reddell, P., Yun, Y. & Shipton, W. A., 1997. Cluster roots and mycorrhizae in *Casuarina cunninghamiana*: Their occurrence and formation in relation to phosphorus supply. *Australian Journal of Botany,* Volume 45, pp. 41-51.

Reganold, J. P., 1988. Cpmparison of soil properties as influenced by organic and conventional farming systems. *American Journal of Alternative Agriculture,* Volume 3, pp. 144-155.

Rhoades, 1996. Salinity: Electrical Conductivity and Total Dissolved Solids. In: D. L. Sparks, ed. *Methods of Soil Analysis: Part 3 - Chemical Methods.* s.l.:Soil Science Society of America, Inc., pp. 417-435.

Robinson, D., 1994. The responses of plants to non-uniform supplies of nutrients. *New Phytol,* Volume 172, pp. 635-674.

Roper, M. M., 1985. Straw decomposition and nitogenase activity (C_2H_2 reduction): effects of soil moisture and temperature. *Soil Biology and Biochemistry,* Volume 17, pp. 65-71.

Saha, S., Prakash, V., Kundu, S., Kumar, N. & Mina, B. L., 2008. Soil enzymatic activity as affected by long term application of farm yard manure and mineral fertilizer under a rainfed soybean-wheat system in N-W Himalaya. *European Journal of Soil Biology,* Volume 44, pp. 309-315.

SARC, 2016. *Rooibos Council: Rooibos Industry Fact Sheet,* s.l.: s.n.

Selassie, Y. G., 2016. Response and economic feasibility of maize (*Zea mays* L.) to P fertilization in acidic Alfisols of North-western Ethiopia. *Environmental Systems Research,* 5(3).

Shane, M. W., de Vos, M., de Roock, S., Cawthray, G. R. & Lambers, H., 2003. Effects of external phosphorus supply on internal phosphorus concentration and the initiation, growth and exudation of cluster roots in *Hakea prostrata* R.Br.. *Plant and Soil,* Volume 248, pp. 209-219.

Shane, M. W., McCully, M. E. & Lambers, H., 2004a. Tissue and cellular phosphorus storage during development of phosphorus toxicity in *Hakea protrata* (Proteaceae). *Journal of Experimental Botany,* Volume 55, pp. 1033-1044.

Shane, M. W., Szota, C. & Lambers, H., 2004b. A root trait accounting for the extreme phosphorus sensitivity of *Hakea protrata* (Proteaceae). *Plant, Cell and Environment,* Volume 27, pp. 991-1004.

Shannon, C. E., 1948. A mathematical theory of communication. *Bell System Technical Journal,* Volume 27, pp. 379-423.

Shenker, M., Plessner, O. E. & Tel Or, E., 2004. Naganese nutrition effects on tomato growth, chlorophyll concentration, and superoxide dimutase activity. *Journal of Plant Physiology,* Volume 161, pp. 197-202.

Simpson, E. H., 1949. Measurement of Diversity. *Nature,* Volume 163, pp. 688-688.

Singh, R., Gupta, R. K., Patil, R. T., *et al*., 2010. Sequential foliar application of vermicompost leachates improves marketable fruit yield and quality of strawberry (*Fragaria x ananassa* Duch.). *Scientia Horticulture,* Volume 124, pp. 34-39.

Slabbert, E., 2008. *Microbial diversity of soils of the Sand fynbos,* s.l.: M.Sc Thesis: Faculty of Science, Stellenbosch University.

Slabbert, E., van Heerden, C. J. & Jacobs, K., 2010. Optimisation of Automated Ribosomal Intergenic Spacer Analysis for the Estimation of Microbial Diversity in Fynbos Soil. *South African Journal of Science,* 106(7).

Smith, J., Botha, B. & Hardie, A., 2018. Role of soil quality in declining rooibos (*Aspalathus linearis*) tea yields in the Clanwilliam area,South Africa. *Soil Research,* Volume 56, pp. 252-263.

Smith, J. F. N., 2014. *Investigation of soil quality in the commercial production of rooibos tea in the Western Cape, South Africa,* Stellenbosch: M.Sc Thesis: Faculty of AgriScience, Stellenbosch University.

Smith, S. E. & Read, D. J., 2008. *Mycorrhizal Symbiosis.* 3rd ed. s.l.:Academic Press and Elsevier.

Soil Classification Working Group, 1991. *Soil Classification: A Taxonomic System for South Africa.* s.l.:Department of Agricultural Development.

Srivastava, P. K., Singh, P. C., Gupta, M., *et al*., 2011. Influence of earthworm culture on fertilization potential and biological activities of vermicomposts prepared from different plant wastes. *Journal of Plant Nutrition and Soil Science,* Volume 174, pp. 420-429.

Stamatiadis, S., Werner, M. & Buchanan, M., 1999. Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). *Applied Soil Ecology,* Volume 12, pp. 217-225.

Stassen, P. J. C., 1987. *Aspalathus linearis (Rooibostee): die invloed van oespraktyke op sekere vegetatiewe en fisiologgiese aspekte.,* Pretoria: D.Sc: Faculty of AgriScience, University of Pretoria.

Subler, S., Edwards, C. & Metzger, J., 1998. Comparing Vermicomposts and Composts. *BioCycle,* 39(7), pp. 63-65.

Sumner, M. E. & Miller, W. P., 1996. Cation Exchange Capacity and Exchange Coefficients. In: D. L. Sparks, ed. *Methods of Soil Analysis: Part 3 - Chemical Methods.* s.l.:Soil Science Society of America, Inc., pp. 1201-1229.

Tejada, M., Gonzalez, J. L., Hernandez, M. T. & Garcia, C., 2008. Agricultural ise of leachates obtained from two different vermicomposting processes. *Bioresource Technology,* Volume 99, pp. 6228-6232.

The World Bank Group, 2016. *The World Bank.* [Online]
Available at: http://go.worldbank.org/1DHIV39O50
[Accessed 8 March 2017].

Theunissen, J., Ndakidemi, P. A. & Laubscher, C. P., 2010. Potential of vermicompost produced from plant waste on the grwoth and nutreint status in vegetable production. *International Journal of the Physical Sciences,* 5(13), pp. 1964-1973.

Thiaart, A., 2018. *Rooibos Cultivation* [Interview] (1 March 2018).

Thomas, G., 1996. Soil pH and Soil Acidity. In: D. L. Sparks, ed. *Methods of Soil Analysis: Part 3 - Chemical Methods.* s.l.:Soil Science Society of America, Inc., pp. 475-490.

Tisdale, S. L. & Nelson, W. L., 1975. *Soil Fertility and Fertilizers.* 3rd ed. New York: Macmillan Publishing Co., Inc.

Tregurtha, N. & Vink, N., 2002. *B2B E-Commerce and the South African Horticultural Export Industry: current status and future directions,* s.l.: University of Stellenbosch, South Africa.

van Bruggen, A. H. C. & Semenov, A. M., 2000. In search of biological indicators for soil health and disease suppression. *Applied Soil Ecology,* Volume 15, pp. 13-24.

van Heerden, F. R., van Wyk, B. E., Viljoen, A. M. & Steenkamp, P. A., 2003. Phenolic variation in wild populations of *Aspalathus linearis* (rooibos). *Biochemical Systematics and Ecology,* 31(8), pp. 885-895.

Vitousek, P. M., Porder, S., Houlton, B. Z. & Chadwick, O. A., 2010. Terrestrial phosphorus limitation: mechanisms, implications, and nitrogen - phosphorus interactions. *Ecological Appliations,* 20(1), pp. 5-15.

Wang, W. J., Dalal, R. C., Moody, P. W. & Smith, C. J., 2003. Relationships of soil respiration to microbial biomass, substrate availability and clay content. *Soil Biology and Biochemistry,* Volume 35, pp. 273-284.

Weiss, R. G., 1961. South Africa's Indigenous Tea in Short Supply. In: *Farmers Weekly (July).* Bloemfontein: s.n., pp. 23-25.

Westerman, R. & Mickelson, S., 1990. *Soil Testing and Plant Analysis.* 3rd ed. s.l.:s.n.

Witkowski, E. T. F. & Mitchell, D. T., 1987. Variations in Soil Phosphorus in the Fynbos Biome, South Africa. *British Ecological Society,* 75(4), pp. 1159-1171.

9 APPENDICES

Appendix A: Chapter 4 Supplementary data

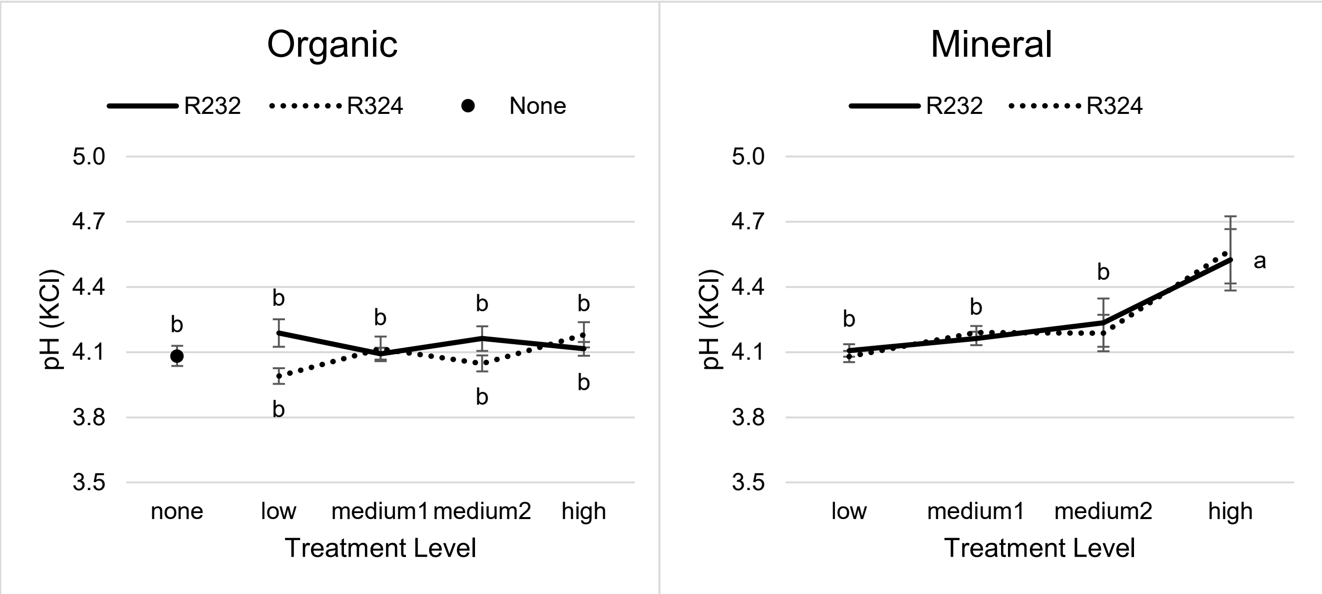

Figure 9.1: Effect of fertilizer type, NPK ratio and treatment application level on soil pH (KCl) at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

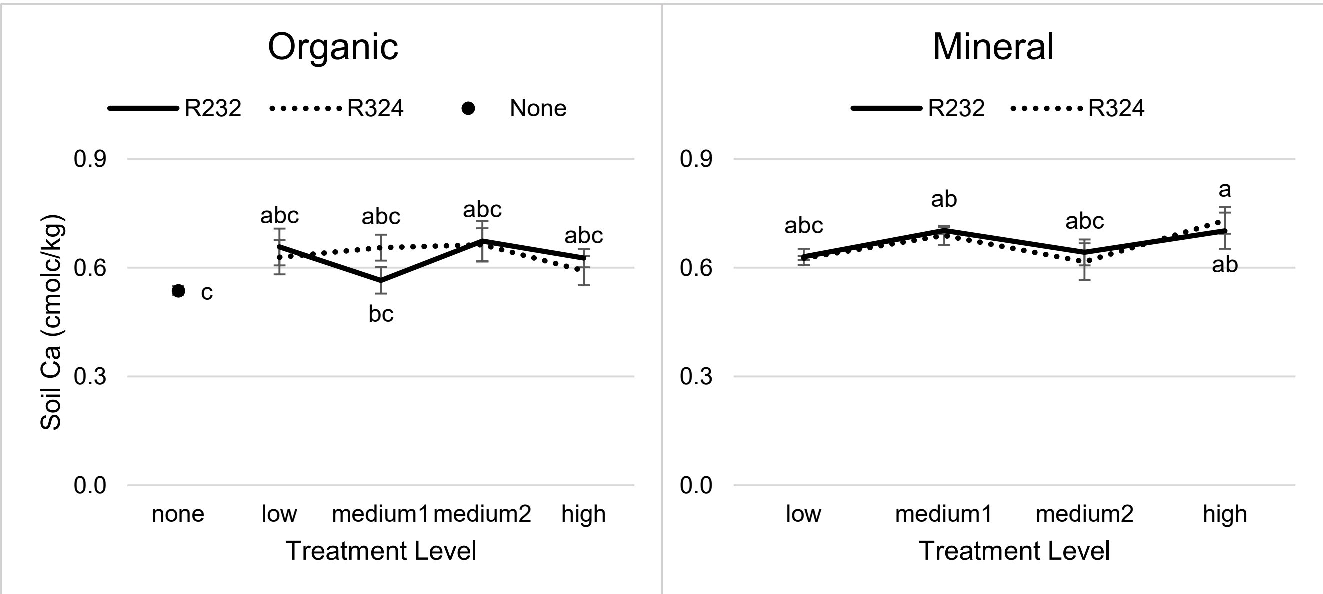

Figure 9.2: Effect of fertilizer type, NPK ratio and treatment application level on soil Ca at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

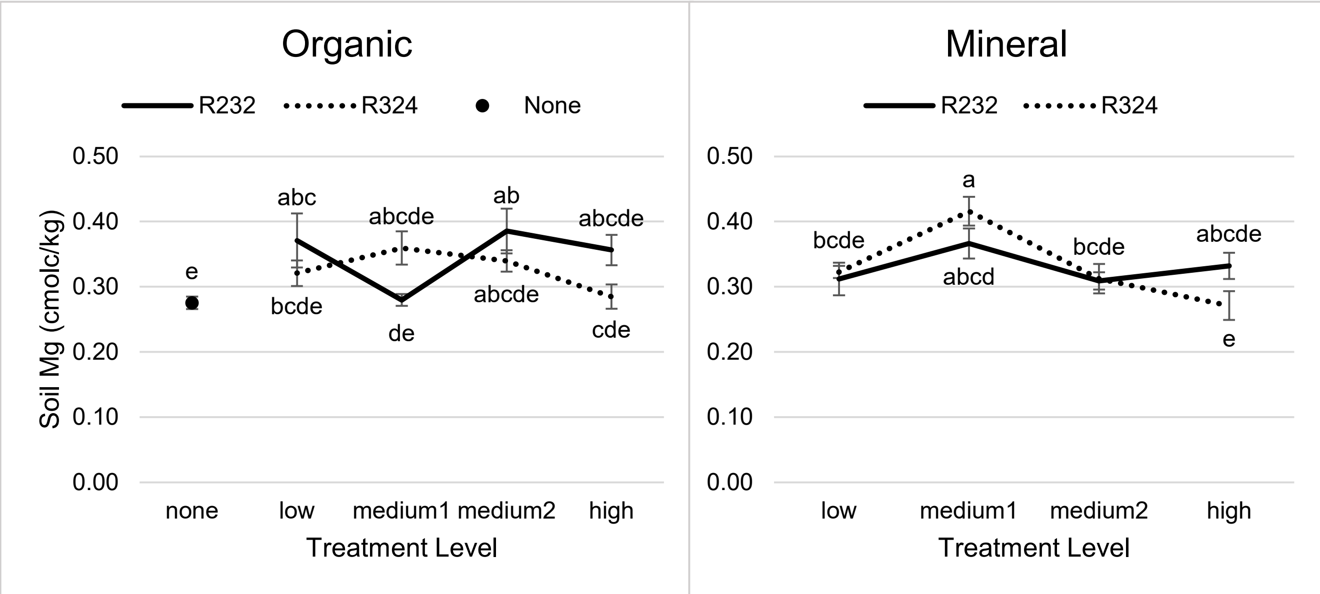

Figure 9.3: Effect of fertilizer type, NPK ratio and treatment application level on soil Mg at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

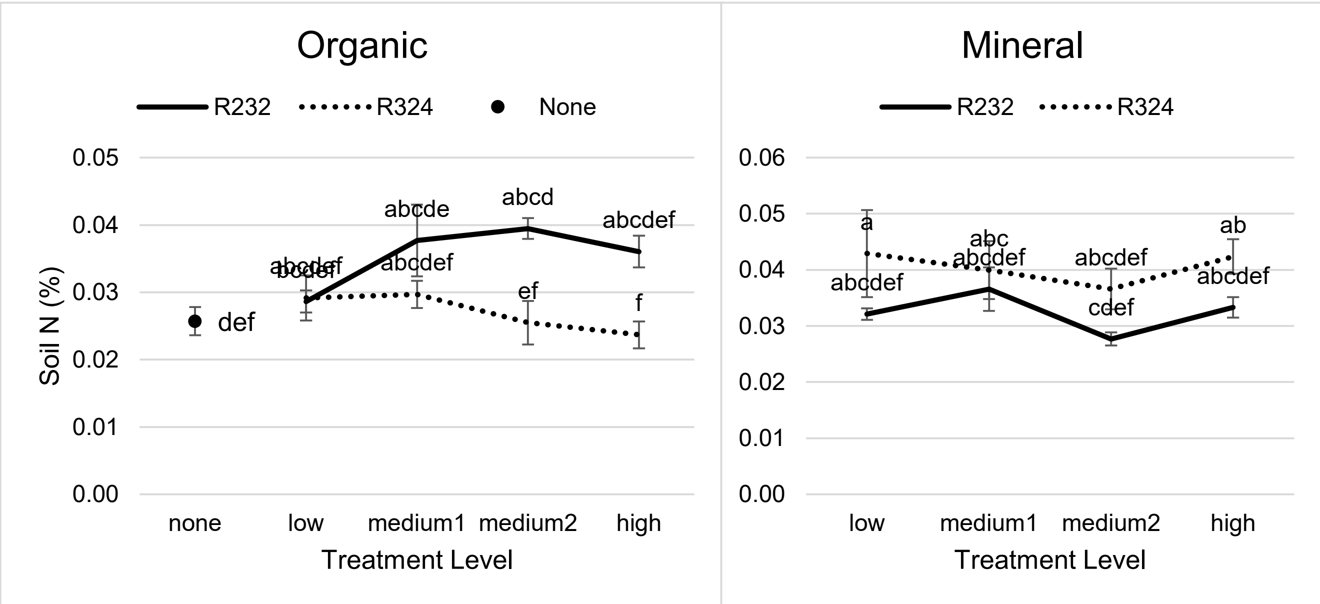

Figure 9.4: Effect of fertilizer type, NPK ratio and treatment application level on soil N at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

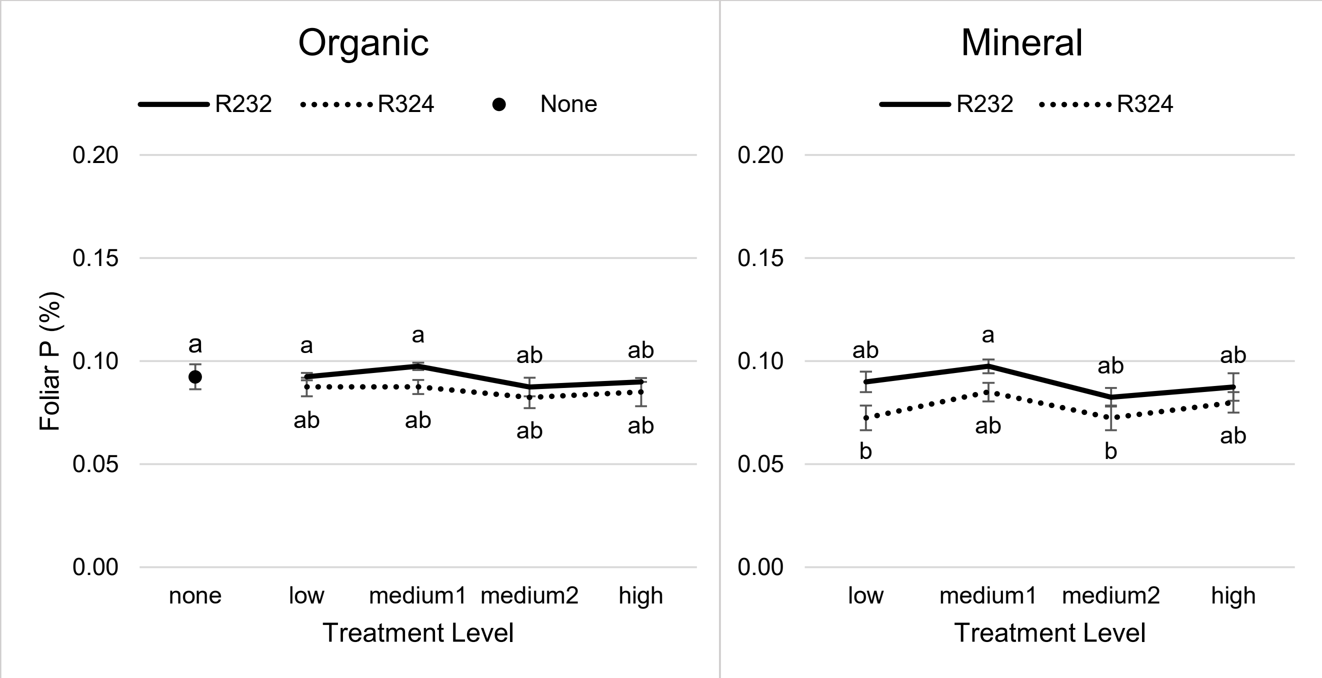

Figure 9.5: Effect of fertilizer type, NPK ratio and P application on foliar P at Blomfontein in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

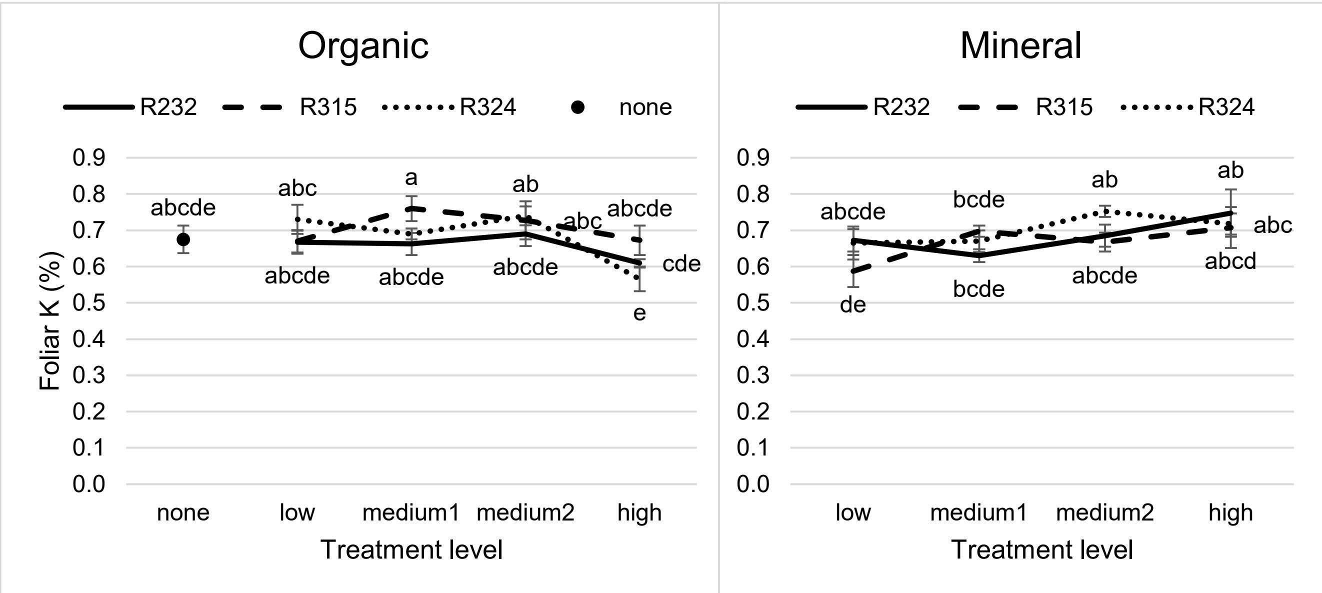

Figure 9.6: Effect of fertilizer type, NPK ratio and P application on foliar K at Rogland in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

Appendix B: Chapter 5 Supplementary data

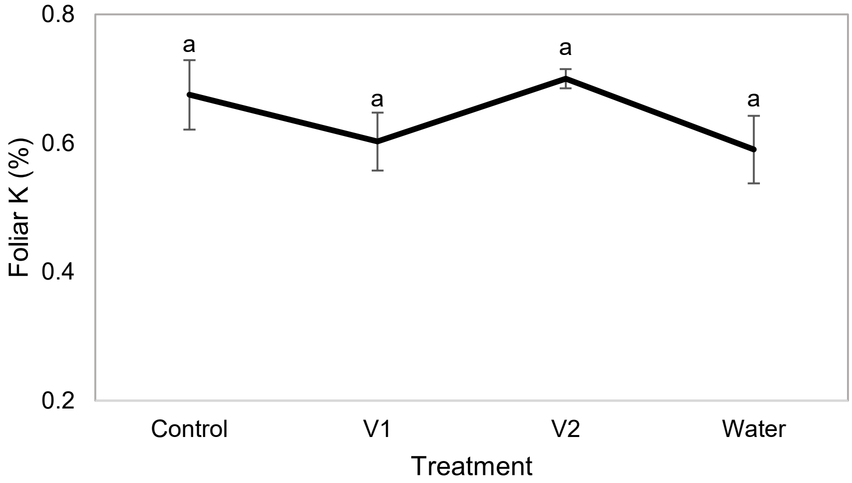

Figure 9.7: Effect of vermicompost tea and water treatments on foliar K concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

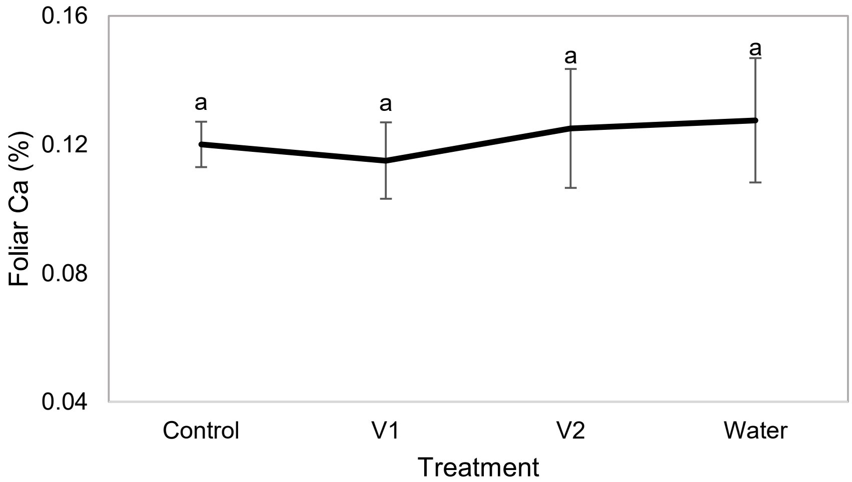

Figure 9.8: Effect of the vermicompost tea and water treatments on foliar Ca concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

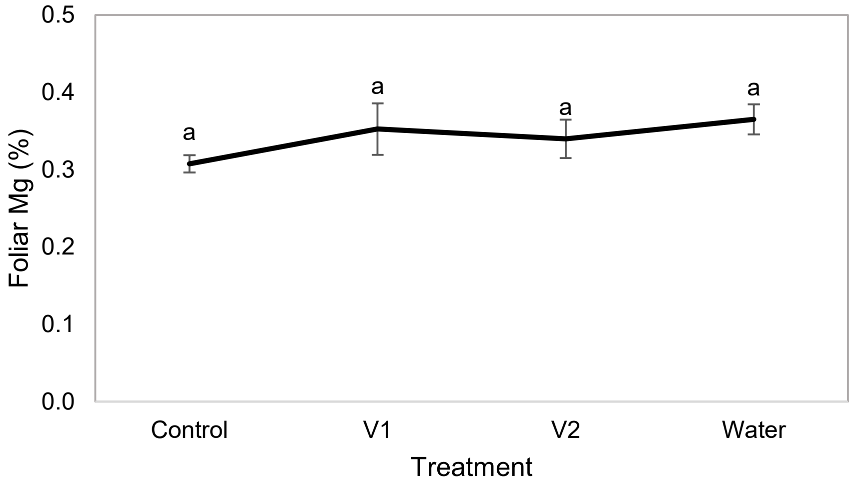

Figure 9.9: Effect of vermicompost tea and water treatments on foliar Mg concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

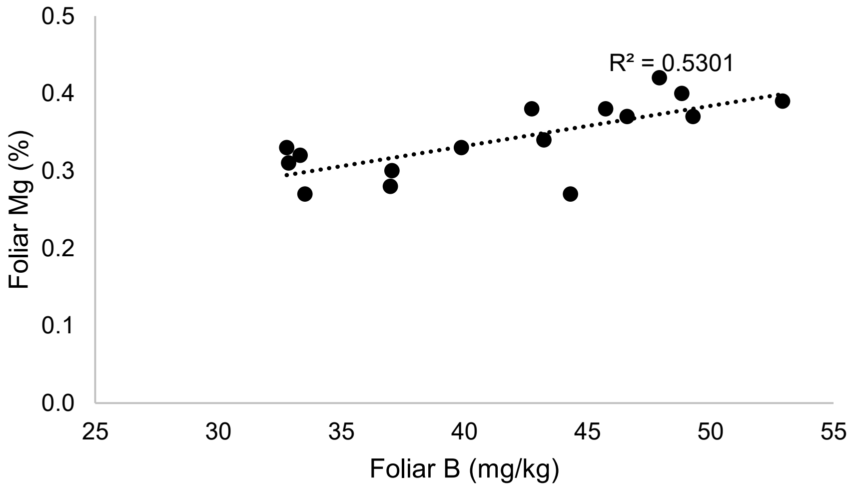

Figure 9.10: Correlation between foliar Mg and B concentrations in first VCT trial in February 2018.

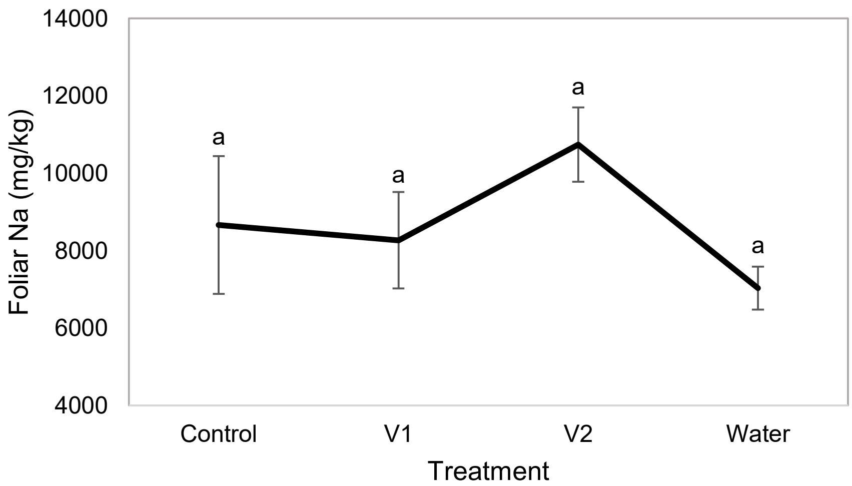

Figure 9.11: Effect of the vermicompost tea and water treatments on foliar Na concentration in first VCT trial in February 2018. Lowercase letters indicate a significant difference at a 95 % confidence interval.

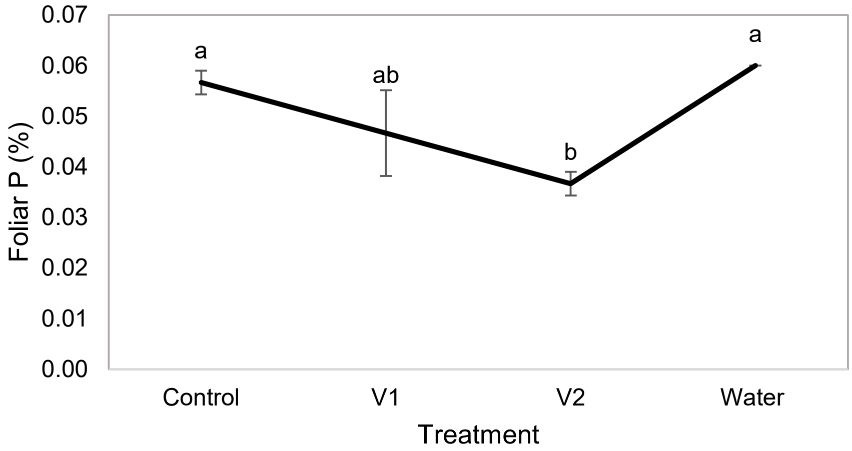

Figure 9.12: Effect of vermicompost tea and water treatments on foliar P in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

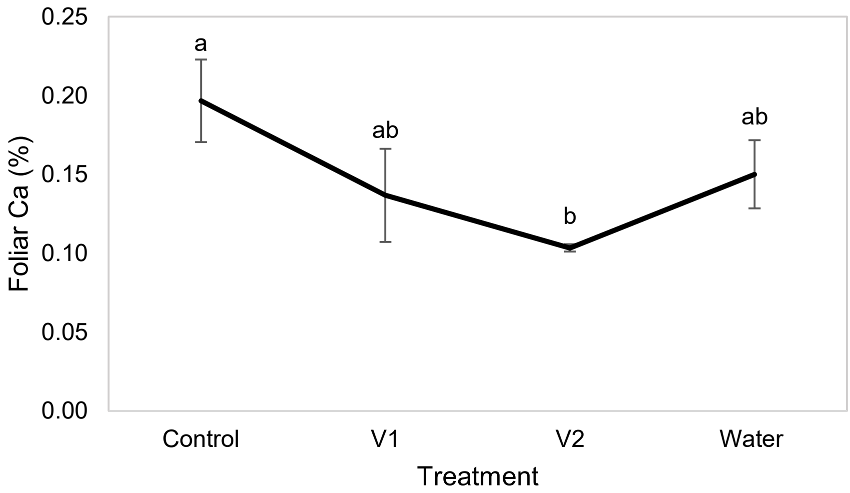

Figure 9.13: Effect of vermicompost tea and water treatments on foliar Ca in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

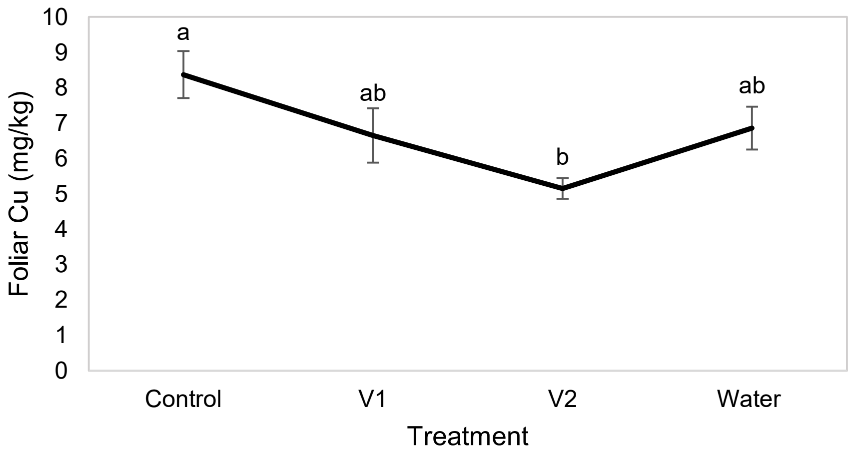

Figure 9.14: Effect of vermicompost tea and water treatments on foliar Cu in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

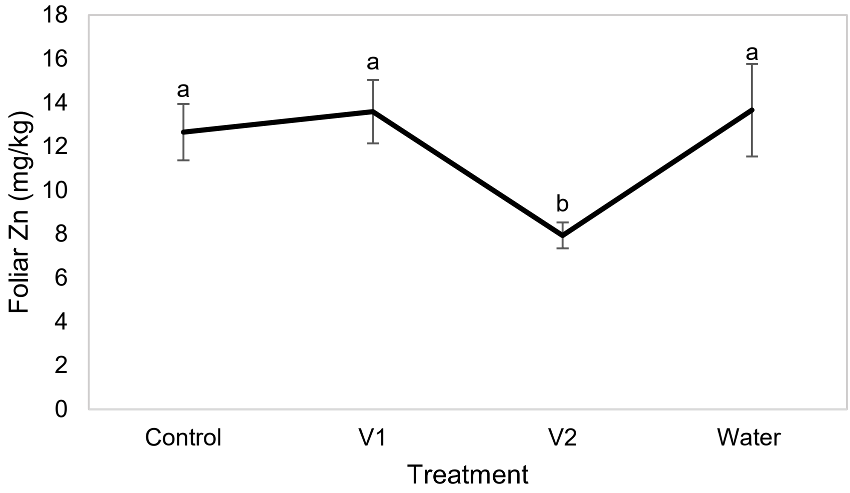

Figure 9.15: Effect of vermicompost tea and water treatments on foliar Zn in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

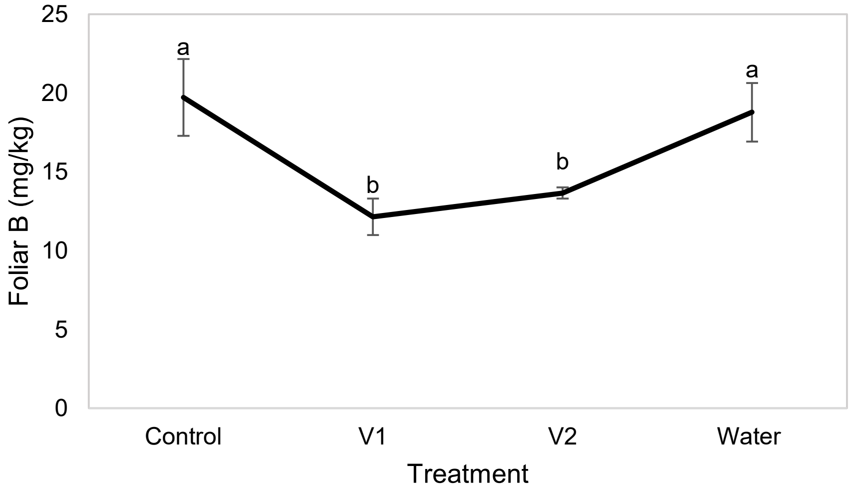

Figure 9.16: Effect of vermicompost tea and water treatments on foliar B in second VCT trial in June 2018. Lowercase letters indicate significant difference at a 95 % confidence interval.

Appendix C: Statistical Data

Table 9.1: Correlation between average tea yields per plant and the different soil and plant factors influencing it across all fertilizer treatments at both farms.

	Rogland		Blomfontein	
	P - value	Effect	P - value	Effect
pH (H2O)	P = 0.554		P = 0.546	
pH (KCl)	P = 0.072		P = 0.211	
EC (uS/cm)	P = 0.074		P = 0.068	
Ex. Acidity (cmolc/kg)	P = 0.873		P = 0.240	
Ca (cmolc/kg)	P = 0.008	- Effect	P = 0.14	
Mg (cmolc/kg)	P = 0.209		P = 0.006	- Effect
Na (cmolc/kg)	P = 0.03	+ Effect	P = 0.237	
K (cmolc/kg)	P = 0.012	- Effect	P = 0.526	
ECEC (cmolc/kg)	P = 0.004	- Effect	P = 0.523	
Bray II P (mg/kg)	P = 0.059		P = 0.321	
Soil Fe (mg/kg)	P = 0.508		P = 0.088	
Soil Cu (mg/kg)	P = 0.891		P = 0.170	
Soil Zn (mg/kg)	P = 0.244		P = 0.183	
Soil Mn (mg/kg)	P = 0.158		P = 0.027	+ Effect
Soil C (%)	P = 0.059		P = 0.353	
Soil N (%)	P = 0.04	- Effect	P = 0.984	
NH4 (%)	P = 0.177		P = 0.492	
P (%)	P = 0.114		P = 0.015	+ Effect
K (%)	P = 0.417		P = 0.110	
Ca (%)	P = 0.173		P = 0.382	
Mg (%)	P = 0.101		P = 0.180	
Na (mg/kg)	P = 0.383		P = 0.391	
Foliar Fe (mg/kg)	P = 0.273		P = 0.231	
Foliar Cu (mg/kg)	P = 0.473		P = 0.133	
Foliar Zn (mg/kg)	P = 0.530		P = 0.368	
Foliar Mn (Mg/kg)	P < 0.001	+ Effect	P = 0.773	
Foliar B (mg/kg)	P = 0.016	- Effect	P = 0.880	
Foliar Al (mg/kg)	P = 0.011	- Effect	P = 0.631	

Table 9.2: Correlation between survival-adjusted yield per hectare and the different soil and plant factors influencing it across all fertilizer treatments at both farms.

	Rogland		Blomfontein	
	P - value	Effect	P - value	Effect
pH (H2O)	P = 0.50		P = 0.399	
pH (KCl)	P = 0.114		P = 0.144	
EC (uS/cm)	P = 0.201		P = 0.036	- Effect
Ex. Acidity (cmolc/kg)	P = 0.867		P = 0.281	
Ca (cmolc/kg)	P = 0.005	- Effect	P = 0.232	
Mg (cmolc/kg)	P = 0.245		P = 0.087	
Na (cmolc/kg)	P = 0.022	+ Effect	P = 0.482	
K (cmolc/kg)	P = 0.052		P = 0.178	
ECEC (cmolc/kg)	P = 0.01	- Effect	P =0.667	
Bray II P (mg/kg)	P = 0.306		P = 0.061	
Soil Fe (mg/kg)	P = 0.676		P = 0.101	
Soil Cu (mg/kg)	P = 0.674		P = 0.093	
Soil Zn (mg/kg)	P = 0.113		P = 0.078	
Soil Mn (mg/kg)	P = 0.288		P = 0.101	
Soil C (%)	P = 0.05	- Effect	P = 0.123	
Soil N (%)	P = 0.140		P = 0.670	
NH4 (%)	P = 0.044	+ Effect	P = 0.781	
P (%)	P = 0.072		P = 0.012	+ Effect
K (%)	P = 0.206		P = 0.144	
Ca (%)	P = 0.275		P = 0.868	
Mg (%)	P = 0.326		P = 0.485	
Na (mg/kg)	P = 0.545		P = 0.250	
Foliar Fe (mg/kg)	P = 0.523		P = 0.125	
Foliar Cu (mg/kg)	P = 0.424		P = 0.114	
Foliar Zn (mg/kg)	P = 0.920		P = 0.380	
Foliar Mn (Mg/kg)	P < 0.001	+ Effect	P = 0.564	
Foliar B (mg/kg)	P = 0.138		P = 0.805	
Foliar Al (mg/kg)	P = 0.002	- Effect	P = 0.608	