Evaluating the effect of living mulch species as sustainable practice on soil dynamics in perennial orchards in South Africa

By

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DECLARATION

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SUMMARY

Two plant (weed) species were investigated for their potential as suitable living mulch species in two perennial fruit orchards in two different climatic regions in South Africa. *Tradescantia fluminensis* Vell. (*Tradescantia*) is a perennial herb, well established in a 'Palmer' navel orange orchard (*Citrus sinensis* L.) in the Sundays river valley, in the Eastern Cape, while *Bromus diandrus (Ripgut)* is a winter annual grass species partially established in a 'Sunkiss' plum orchard, Villiersdorp, in the Western Cape.

A literature review was conducted to determine the effect of cover crops on soil health and fertility and their role in building more sustainable, low input production systems, as well as the role of living mulches in applying these principles directly in the tree row, as opposed to between tree rows as in conventional cover cropping practices in perennial orchards.

The effects of *Tradescantia* and *Ripgut* on soil-plant dynamics were quantified using soil water-holding capacity (WHC), soil temperature (ST), soil moisture (SM), microbial biomass (MB), weed suppression (WC) and tree root counts and distribution (RC). For the citrus orchard, an orchard containing *Tradescantia* (TO treatment) was compared to an adjacent orchard with no mulch and conventional chemical weed to maintain a bare orchard floor (BO treatment). For the plum orchard, measurements were taken in the areas containing the *Ripgut* mulch (RM treatment), as well as in areas with no *Ripgut* (CC treatment), where chemical methods are used to control weeds.

In the citrus orchards, the WHC was higher in the TO treatment in autumn (5.95 %) and winter (9.68 %). The ST fluctuated less in the TO treatment, especially at shallow depths. The microbial respiration (ppm C), calculated MB, as well as estimated potential mineralisable nitrogen (PMN) was higher in the TO treatment. Weed numbers for the TO treatment were 0.67 per m^2 compared to 6 per m^2 in the BO treatment. The TO treatment generally displayed higher root concentrations at deeper soil levels compared to the BO treatment, probably due to competition from the *Tradescantia* in the upper soil layers.

In the plum orchard, the WHC was significantly higher in the RM treatment for both the autumn (1.87 %) and winter (1.58 %) samples. The SM was higher in the RM treatment at most soil depths, suggesting improved water infiltration throughout the soil profile. The ST fluctuated less in the RM treatment due to the *Ripgut*'s buffering effect. There was no significant difference between the treatments for microbial respiration, calculated MB and estimated PMN. Weed numbers were significantly lower in the RM treatment (2.17 weeds per m^2) compared to the CC treatment (11.17 weeds per m^2). Root numbers were higher in the RM treatment, however, the presence of *Ripgut* roots in the top 20 cm made it difficult to accurately quantify root counts in this region.

Both *Tradescantia* and *Ripgut* influenced soil health and water dynamics positively, while providing sufficient weed suppression. However, further investigations are recommended to quantify the threats posed by the invasive nature of these plants before commercial implementation.

OPSOMMING

Twee onkruid spesies is ondersoek vir hul potensiaal as gepaste lewende deklae in meerjarige vrugteboorde in twee areas met verskillende klimaatstoestande, in Suid-Afrika. *Tradescantia fluminensis* Vell. (*Tradescantia*) is ‘n meerjarige kruid, wat goed gevestig is in ‘n ‘Palmer’ nawel lemoenboord (*Citrus sinensis* L.) in die Sondagsriviervallei, Oos-Kaap, terwyl *Bromus diandrus (Ripgut),* ‘n eenjarige wintergras spesie is wat gedeeltelik gevestig is in ‘n ‘Sunkiss’ pruimboord, Villliersdorp, in die Weskaap.

‘n Literatuurstudie het die effek van lewende deklae op grondgesondheid en –vrugbaarheid in die bou van meer volhoubare, lae inset produksie sisteme ondersoek, sowel as die bydra van hierdie beginsels direk in die boomry, in plaas van die konvensionele trekkerrye, in meerjarig boorde.

Die effekte van hierdie spesies as lewende deklae op grond-plant-dinamika is ondersoek deur grondgesondheidsmerkers, onkruidbeheer en die moontlike effek van kompetisie op boom wortelverspreiding te gekwantifiseer. Aanwysers was grondwaterhouvermoë (WHC), grondtemperatuur (ST), grondvog (SM), mikrobiese biomassa (MB), onkruid onderdrukking (WC) en wortel hoeveelheid en verspreiding (RC). ‘n Sitrusboord met *Tradescantia* (TO behandeling) is vergelyk met ‘n naasliggende boord met geen lewende deklae (BO behandeling) nie. In die pruimboord, is *Ripgut* (RM behandeling) vergelyk met areas sonder *Ripgut* (CC behandeling) en chemiese onkruidbeheer.

In die sitrusboord, was die WHC hoër in die TO behandeling in beide herfs (5.95 %) en winter (9.68 %). Die ST het minder gevarieër in die TO behandeling, veral by vlak grond. Mikrobiese respirasie (ppm C) bepaal mikrobiese biomassa en voorspel ook die moontlike potensieël mineraliseerbare stikstof en was hoër in die TO behandeling, wat dui op hoër grondvrugbaarheid. Onkruidtellings in die TO behandeling was 0.67 per m^2 in vergelyking met 6 per m^2, in die BO behandeling. Die TO behandeling het hoër wortelkonsentrasies by dieper grondvlakke getoon, in verglyking met die BO behandeling, wat moontlik verklaar word deur kompetisie van die *Tradescantia* in die boonste grond lae.

In die pruimboord, was die waterhouvermoë beduidend hoër in herfs (1.87 %) en winter (1.58 %) in die RM behandeling Die grondvog was ook hoër in die RM behandeling by die meeste grond dieptes. Die hoër waterhouvermoeë en grondvog in die RM behandeling impliseer dat water infiltrasie deur die hele grondprofiel verbeter is deur *Ripgut*. Die grondtemperatuur het minder gevarieër in die RM behandeling en die *Ripgut* het die boonste lae van die grond beskerm teen temperatuur uiterstes. Daar was geen beduidende verskille tussen die behandelings in terme van mikrobiese respirasie, berekende mikrobiese biomass en potensieël mineraliseerbare stikstof nie. Onkruid getalle was beduidend minder in die RM- (2.17 plante per m^2) vergeleke met die CC behandeling (11.17 plante per m^2). Die totale worteltellings was hoër in die RM behandeling, maar die teenwoordigheid van *Ripgut* wortels in die boonste 20 cm het akkurate kwantifisering van die wortels in hierdie area bemoeilik.

Beide *Tradescantia* en *Ripgut* het ‘n positiewe invloed op grondgesondheid en –waterdinamika, terwyl dit ook onkruidgroei onderdruk. Verdere studies word voorgestel om die impak van die indringende natuur van hierdie plante te ondersoek voor kommersiële implimentering.

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CHAPTER 1

General Introduction

1. Overview/Background

The role of increased vegetative cover in perennial orchards as sustainable practice in commercial agriculture (cover crops and mulches) was investigated. Cover cropping in particular, shows great promise as a practical means to sequester carbon (C) successfully (Poeplau and Don 2015). The fundamental principle of a cover crop is to provide vegetative cover on soil surfaces that would otherwise be bare. In the context of a cash cropping system, cover crops are sown in the winter fallow period to provide ground cover between main crops (Hartwig and Ammon 2002), whereas for perennial orchards, cover crops are typically grown on bare soil in between tree rows (Hammermeister 2016). Cover crops first received attention when farmers became concerned with soil erosion during the 'Dust Bowl' era of the 1930's in the U.S. (Hartwig and Ammon 2002). However, more recent research has unveiled that cover cropping may provide many more benefits in addition to erosion control (Hartwig and Ammon 2002). Soil organic carbon (SOC) levels tend to be significantly higher in cover cropping systems, compared to non-cover cropping systems (Poeplau and Don 2015). Subsequently, increases in SOC levels may significantly improve crop yields (Lal 2004), especially under extreme weather conditions such as floods and droughts (Leu 2007), making production systems more resilient.

In addition, improved SOC levels have a cascading effect on other soil properties such as restoring soil fertility, reduced erosion and leaching, improved soil structure, increased biodiversity, improved soil aeration, disease suppression, greater nutrient availability and enhanced water-holding capacity and water use efficiency of soils (Jones 2008; Lal 2004; Leu 2007; McKenzie 2010). Therefore, the optimization of cover cropping systems may play an unprecedented role in the evolution of agricultural systems that, are (1) more resilient to climate change, (2) sequester atmospheric CO_2, and (3) require fewer inputs and are more resource efficient (Leu 2007). Such systems are more sustainable from both an economic and environmental standpoint and may even have long-term positive impacts on social sustainability (Jones 2008).

Mulching is the practice of maintaining a layer of material (usually non-living) on the soil surface in contrast to maintaining a bare surface between plants or crop rotation. Mulches can conserve resources such as available soil and water (Kader et al. 2017; Granatstein and Mullinix 2008; Prosdocimi et al. 2016; Lötze 2014) in addition to providing partial chemical-free weed control and buffering soil temperature fluctuations (Lötze 2014; Chakraborty et al. 2008). In contrast to organic or inert mulches, a living mulch vegetation maintained on otherwise bare soil, is similar to cover crops in their functionality, but differ in application (Hartwig and Ammon 2002). Since living mulches and cover crops both comprise the maintenance of living plants, they affect soil properties in similar ways, but living mulches are applied like conventional mulches, subsequently acting as a buffer between the soil and atmosphere (Hartwig and Ammon 2002). Living mulches, therefore, combine conventional mulching and cover cropping principles, but have to be evaluated as a different sustainable option to quantify the benefits under specific production systems, as it may interfere with the main crop and may comprise different plant species currently used for cover crops.

'Sustainable' suggests a system in a stable state (Edwards et al. 1990), often reflected in natural ecosystems, as their energy and nutrient flow is stabilized by self-regulation (Paine and Harrison 1993). Agricultural systems should therefore strive to mimic such natural ecosystems in the pursuit of developing resilient, low-input, sustainable production systems (Paine and Harrison 1993). The application of living mulches may add the necessary complexity to production systems, making them more resilient, robust, efficient and sustainable (Paine and Harrison 1993). However, establishing living mulch systems is challenging, as successful application depends on numerous factors such as the physiological characteristics of the mulch species, local climate, the cultivated crop, production goals and resource availability and potential competition with the main crop (Paine and Harrison 1993).

1.2 Aims

Research aimed at identifying novel species (including weeds and native vegetation) as potential living mulches for specific conditions, may contribute to more effective implementation and understanding of this practice in commercial, perennial crops. The aim of this study was therefore to investigate two established invasive weed species in commercial orchards for their mulching capabilities, in two different types of fruit orchards, in different climates within South Africa, and evaluate their potential to contribute towards a more sustainable management approach.

Two case studies were conducted in which two invasive weed species, *Tradescantia fluminensis* (*Tradescantia*) and *Bromus diandrus* (*Ripgut*), were established as living mulches in perennial fruit orchards in South Africa. *Tradescantia* was used as a living mulch, in a navel orange citrus orchard in the Sundays River valley, in the Eastern Cape, while *Ripgut* was used in a plum orchard, near Villiersdorp, in the Mediterranean climate of the Western Cape. In the study, several soil health indicators were quantified between treatments that contained the living mulch and treatments where no mulch was established. These indicators included water-holding capacity, soil moisture and temperature levels and microbial biomass. Other indicators such as weed control and tree root distribution were also included. Together, these indicators gave a holistic representation of the overall effects of these living mulch species on the soil-plant dynamics within the respective orchards.

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CHAPTER 2

Literature Review

2.1 Role of cover crops in sustainable fruit production

Sustainable agriculture is commonly perceived as a vague concept and therefore, often misunderstood or ill defined. However, the philosophy is comprehensively defined by as "The ability to meet the demands of the present without compromising the ability of future generations to meet their own demand" (Lichtfouse et al. 2010). Already at the 1992 Earth Summit in Rio de Janeiro, the United Nations formally familiarised all global spheres of influence with the concept of 'Sustainable Development' and the urgency thereof (Lichtfouse et al. 2009). Although this ideal has been widely accepted by the public, it is an elusive goal met with widespread dissonance as to how to best achieve it practically, and this is of course no different in the field of agriculture (Lichtfouse et al. 2009).

Agricultural systems are complex systems, often intertwined with and codependent on many other complex systems such as intricate ecosystems, social systems, economic systems, climatic systems and even political systems (Edwards et al. 1990). Thus, intervention in such a system with the explicit intention to produce a desired outcome is extremely complex, as these systems are defined by many different components and varying degrees of self-organisation (Wu and David 2002). This complexity resulted in much debate over prioritization of indicators in pursuit of sustainable agricultural systems, since it requires constant management of trade-offs between aspects such as food security, food quality, environmental protection, resilience, flexibility and socio-economic factors (Lichtfouse et al. 2009). Nonetheless, the sustainability of our global agricultural- and food systems is arguably the most important challenge faced by society today (Edwards et al. 1990). Solving this challenge will therefore require a trans-disciplinary and systems thinking approach (Lichtfouse et al. 2009).

In the 1960's, the major agricultural concern was that of low productivity and food security, as natural resources were not seen as finite at that stage (Edwards et al. 1990). Consequently, the 'green revolution' (fueled by high population growth and improvements in infrastructure and technology) drove commercial agriculture into adopting reductionist, high-input/high output systems (Horrigan et al. 2002). Although this resulted in dramatic increases in food production in the short term (decades), it was accompanied by a high price, including desertification, soil erosion, deforestation, biodiversity loss and the accumulation of toxic chemicals in soils and fresh water sources in the vicinity of these production regions (Horrigan et al. 2002; Edwards et al. 1990). This included the radical conversion of complex natural ecosystems that have evolved over millions of years into simplified vast monoculture systems, in a matter of decades, and the destablishment of natural mineral cycles such as the C, nitrogen (N) and phosphorus (P) cycles (Edwards et al. 1990). In more recent years, discoveries indicated that the expansion of commercial agriculture played a major role in the acceleration of global warming and climate change (Ceschia et al. 2010; Lal & Kinble 1997). Many commercial practices such as fallow lands, burning, deforestation and tillage not only lead to massive losses of fertile topsoil via erosion, but also result in substantial fluxes of C from the soil pool to the atmospheric pool (Lal and Kinble 1997). Compared to soils under natural vegetation, conventional cultivation may reduce soil organic carbon (SOC) levels by up to 40% (Poeplau and Don 2015). This is a significant amount of C considering that soils store more C than the atmosphere and terrestrial biota combined (Lal & Kinble 1997; Lal 2004).

However, agriculture may play a crucial role in reversing this phenomenon through a process known as the 'liquid carbon pathway' (Jones 2008), a process that starts with photosynthesis and ends with humification (Leu 2007). Living plants sequester C by absorbing excess CO_2 from the atmosphere and binding it in stable organic forms such as biomass and humus (Jones 2008; Leu 2007). It is estimated that a mere 0.5% increase in SOC levels in only 2% of Australia's total agricultural land would offset the entire country's annual C emissions (Jones 2008). Thus, the most effective method of increasing SOC is by maintaining as much vegetation on the soil surface, for prolonged periods throughout the year (Jones 2008; Leu 2007). By adopting regenerative practices such as conservation tillage, maintenance of crop residues, improved grazing management, organic fertilizer, improved crop rotations and cover cropping on fallow ground (Farina et al. 2017; Lal 2004), agricultural land may be converted into carbon sinks in a relatively short time period (Poeplau and Don 2015).

2.2 The history of cover crops

The use of cover crops is not a new concept and it has been used for centuries (Hartwig and Ammon 2002). Before the 1930's in the U.S., land and natural resources were cheap and abundant, which meant that farmers were not fully aware of the finite nature of these resources, and thus conservation practices such as soil preservation, were not a priority (Hartwig and Ammon 2002). In the 1930's the U.S. experienced what became known as the "dust bowl era", which was characterised by severe dust storms on the great plains that turned out to be one of the greatest environmental catastrophes in the U.S. in the 20^{th} century, (Baumhardt 2003). This phenomenon was the result of vast strips of land being left exposed due to overgrazing and outdated tillage practices, followed by severe droughts and winds over the following decade (Baumhardt 2003). Because of this event, both the U.S. government and farmers became concerned about soil erosion, and started looking at ways to address this issue, one of which being the reintroduction of cover crops (Hartwig and Ammon 2002).

However, with the discovery of chemical herbicides and fertilisers in the late 1940's, as well as technological advances, agriculture was revolutionised, allowing for large scale intensification and mechanisation of production systems, which meant that priorities once again shifted, and production came at the expense of conservation (Hartwig and Ammon 2002). It was not until the 1970's that concern about resource overexploitation and subsequent scarcity in conjunction with the sustainability of commercial agriculture grew big enough to encourage experimentation and exploration into more sustainable practices, as well as the optimization thereof (Hartwig and Ammon 2002). Moreover, climate change is forcing farmers to investigate ways to improve the resilience and resource-use efficiency of production systems, and cover crops are once again being explored with renewed vigour (Jones 2008). Moreover, the discovery that the expansion of commercial agriculture has largely contributed to climate change has reinforced this notion (Ceschia et al. 2010; Lal & Kinble 1997). However, it was also discovered that regenerative agricultural practices can play an important role in reversing climate change (Leu 2007), and cover cropping in particular, shows great promise as a practical means to sequester carbon successfully (Poeplau and Don 2015).

2.3 What are Cover crops?

The fundamental principle of a cover crop is to provide vegetative cover on soil surfaces that would otherwise be bare. Thus, in the context of a cash cropping system, cover crops are sown in the winter fallow period to provide ground cover between main crops (Hartwig and Ammon 2002; Sarrantonio and Gallandt 2008). However, in perennial orchards cover crops are applied differently. Perennial fruit orchards are typically planted in rows, and they make up three distinct zones namely the planting row (tree row), the area adjacent to the planting row, and the space between tree rows known as the work row or alley (which serves as the space for equipment such as tractors to pass through) (Hammermeister 2016). In such orchards, cover crops are typically planted in the work row (Sarrantonio and Gallandt 2008). Planting cover crops between tree rows is a fairly common practice in a number of fruit production systems (Lehmann et al. 2000). Cover crops are typically either grasses or legumes, and may also be annual, biennial or perennial in the case of perennial orchards (Hammermeister 2016).

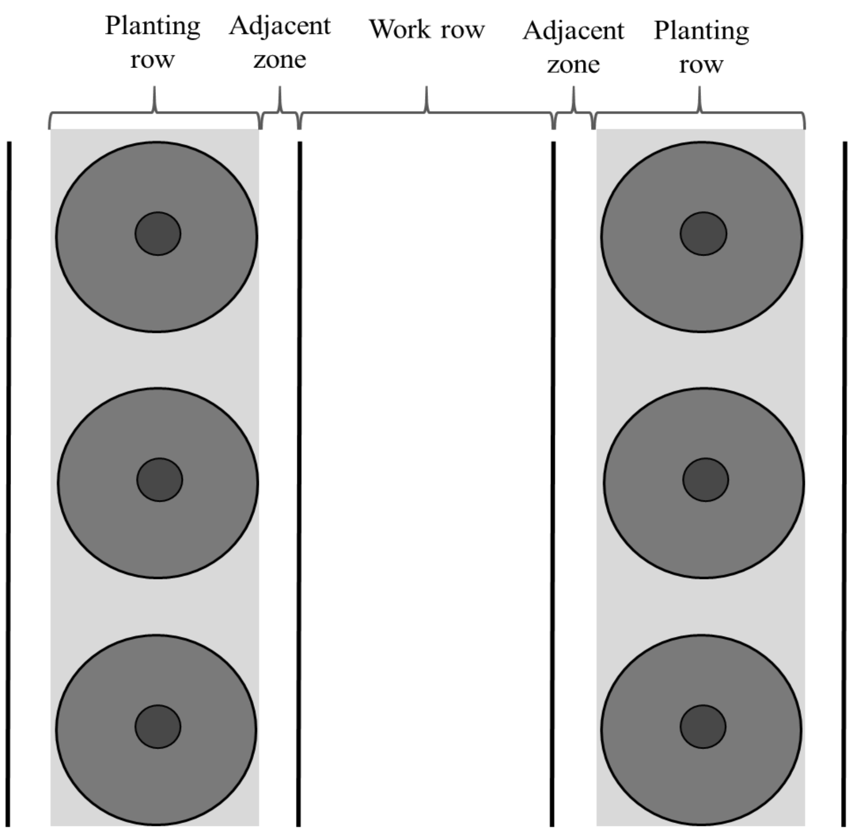

Figure 1. Illustration of the different zones in a typical fruit orchard. The trees are represented by the circles.

Initially cover crops were mainly associated with reducing soil erosion, however, more recent research has unveiled that cover cropping may provide many additional benefits (Hartwig and Ammon 2002). In a meta-analysis study involving 139 plots, Poeplau & Don (2015) found that SOC levels were significantly higher in cover cropping systems compared to non-cover cropping systems and that the SOC levels were directly correlated to the amount of time since introduction of cover crops. Not only do cover crops hold promise for dealing with soil erosion and climate change, but the increased SOC levels may significantly improve subsequent crop yields (Lal 2004), especially under extreme weather conditions such as floods and droughts (Leu 2007). This naturally improves the resilience of production systems. Furthermore, improved SOC levels have a cascading effect on other properties such as restoring soil fertility, reduced erosion and leaching, improved soil structure, increased biodiversity, improved soil aeration, disease suppression, greater nutrient availability, and enhanced water-holding capacity (WHC) and water use efficiency (WUE) of soils (Jones 2008; Lal 2004; Leu 2007; McKenzie 2010). Therefore, the optimization of cover cropping systems may play an unprecedented role in the evolution of agricultural systems that, are (1) more resilient to climate change, (2) sequester atmospheric CO_2 and (3), require fewer inputs and are more resource efficient (Leu 2007). Such systems are more sustainable from both and economic and environmental standpoint and may even have long term positive impacts on social sustainability (Jones 2008).

2.4 Advantages of cover crops

2.4.1 Erosion and Runoff

Soil erosion is influenced by various factors such as slope, soil properties, rainfall amount and intensity and vegetative cover, and can be significantly promoted by changes in land use (Montgomery 2007). Many of these contributing factors (such as rainfall) are beyond our control, however we have control over the land use and vegetative cover of land to some extent. By managing these factors appropriately, soil erosion can be reduced to a point where it is not threatening to the long term productivity of the soil. Soil erosion reduces water infiltration, WHC, SOC and causes losses of nutrients and microbial biomass, and also results in crust formation (Zuazo and Pleguezuelo 2008). However, one of the most effective ways to reduce and reverse this process is the establishment of vegetation on exposed soil (Zuazo and Pleguezuelo 2008), such as cover cropping. Erosion reduction is one of the most well documented benefits of cover crops (Chavarría et al. 2016; Hartwig and Ammon 2002; Horrigan et al. 2002; Langdale et al. 1967) as the introduction of vegetative cover reduces the impact of water droplets on the soil surface, and it also improves water infiltration and WHC, thus reducing runoff and further erosion (Zuazo and Pleguezuelo 2008). The roots of the plants also hold the soil particles together and restrict the flow of runoff water (De Baets et al. 2011).

De Baets et al. (2011) examined the erosion-reducing efficiency of six common cover crop species during concentrated flow erosion (erosion caused by heavy water flow), based on their root density and structure. These included *Sinapis alba* (white mustard), *Phacelia tanacetifoli* (phacelia), *Lolium perenne* (ryegrass), *Avena sativa* (oat), *Secale cereale* (rye) and *Raphanus sativus subsp. oleiferus* (fodder radish). They found that the crops with fibrous root systems (rye, oats and ryegrass) were more effective at reducing erosion than the crops with taproots and/or bulbous root systems (fodder radish, phacelia and white mustard) (De Baets et al. 2011). Derpsch et al. (1986) found that a number of studies done on oxisols, in Brazil between 1977 and 1984 found cover cropping integrated with no tillage systems to be the most effective method of reducing runoff and erosion and improving water infiltration, while increasing yields of the subsequent main crops, in some species, but not in others.

A number of studies done in perennial orchards have also found a number of cover crop species to be very effective as a means of reducing runoff and erosion. Raya et al. (2006) found that thyme cover crop reduced soil loss by 97 %, and runoff by 91 %, in an almond orchard situated on a steep slope in Spain, while barley reduced soil loss by 87 % and runoff by 59 %. In an experiment comparing different floor management regimes in a newly established apple orchard in New York state, it was demonstrated that pre-emergence herbicide and tillage treatments resulted in higher runoff and erosion rates compared to various vegetative cover treatments, while also yielding lower water infiltration rates and saturated hydraulic conductivity (Merwin and Stiles, 1994). Vegetative treatments included mowed sod grass, chemically growth-regulated sod grass, crown vetch, and straw mulch (Merwin and Stiles 1994). Similar results were found in an olive orchard in southern Spain, where Gomez et al. (2009) compared a barley cover crop system with a conventional tillage, and a no-tillage system kept bare using herbicides, over a seven year period. It was found that the cover crop treatment resulted in the lowest soil losses of (0.8 t ha^{-1} $year^{-1}$), compared to the herbicide treatment, which had the highest (6.9 t ha^{-1} $year^{-1}$), and the tillage treatment in-between (2.9 t ha^{-1} $year^{-1}$). The runoff coefficients were 1.2 % for the cover crop treatment and 11.9 % and 3.1 % for the herbicide and tillage treatments, respectively, meaning that the cover crop greatly reduced both erosion and runoff. This is corroborated by earlier findings where similarly cover crops were the most effective method of reducing soil loss in sloped olive orchards in Spain, followed by conventional tillage and herbicide use (Gomez et al., 2003).

Cover cropping seems to be the superior orchard floor management tool for reducing erosion and runoff, and while doing this it may provide additional benefits that further improve soil fertility and nutrient cycling, such as increased SOC (Pardini et al. 2002). Not only is cover cropping the most effective, but also more sustainable in that it affords ecosystem services with additional benefits and reduces the need for external inputs (Pardini et al. 2002).

2.4.2 Soil Organic Carbon (SOC) content

In continuous cropping systems such as a perennial orchard, it is crucial to maintain and increase SOC content in order to ensure long term productivity of that soil (Reeves 1997). It is perhaps the most important indicator of soil quality due to its cascading effect on other chemical, physical and biological soil quality indicators (Reeves 1997). Thus, by increasing SOC content, one can improve other soil characteristics such as the WHC, soil porosity, microbial activity, nutrient supply capacity and cover crops have shown the potential to do this (Snapp et al. 2005).

The meta-analysis by Poeplau and Don (2015), involving 139 plots, found that cover cropping systems had significantly higher SOC levels, without reducing yields, and SOC levels were also directly correlated to the time since introduction of the cover crops. Although winter cover cropping in Brazilian oxisols with both grass and legume species significantly increased SOC stocks, legumes (blue lupin and hairy vetch) tended to be more effective than wheat, black oat and radish (Balota et al. 2014). Sainju et al. (2005) also found that cover winter cropping systems with a vetch-rye bi-culture yielded greater biomass and soil C than respective monocultures. However, these studies all comprised of winter crops in cash cropping systems. Land use plays a great role in CO_2 flux at the soil horizon, as found by a previous study that the annual CO_2 flux due to respiration from an apple orchard was 12% higher than that of a field planted with wheat, suggesting that cover crops may have an important role to play in managing C exchange in perennial fruit orchards (Wang et al. 2018).

In semi-arid almond orchards in Spain, Ramos et al. (2010) found that cover cropping with both oat (*Avena sativa* L.) and vetch (*Vicia sativa* L.) significantly increased SOC, as well as overall soil fertility, compared to frequent tillage systems. Qian et al. (2015) found that total organic carbon (TOC) was 16-44% greater under white clover, crown vetch and perennial ryegrass, compared to the control, in Chinese apple orchards. In apple orchards, Zheng et al. (2018) found that cover crops grown from March, and mowed in late July, increased SOC by 15% compared to a conventional herbicide controlled system. In addition, leaving mowed cover crop residues of five perennial legume species on the soil surface was reported to be more effective at increasing SOC, as opposed to removing mowed residues (Duda et al. 2003). In a local study on chardonnay vineyards near Stellenbosch, Fourie et al. (2007) found that soil organic matter (SOM) was increased in all cover crop treatments (which included cereals and five legumes) over a period of five seasons, while decreasing by 16% in the control, where weeds were mechanically controlled in the work row, and chemically in the vine row. It is apparent that farming practices in orchards play an important role in managing the C status of the soil and the orchard overall and cover crops in particular, hold great potential in improving SOC levels, as well as turning orchards into net C sinks (Farina et al. 2017; Leu 2007; Sarrantonio and Gallandt, 2008).

As plants photosynthesize, they convert atmospheric CO_2 into organic compounds or biomass. Between 30% and 60% of the CO_2 absorbed by plants is deposited in the soil as organic matter (Leu 2007). Some of these C based compounds make up the plant structure itself (sugars, starches, and fiber) and some (such as sugars), are exuded into the soil through the roots to form soil humus, which is incorporated into aggregates (Jones, 2008; Leu 2007; McKenzie, 2010). This is known as humification and it is the primary process through which topsoil is formed - the conversion of atmospheric CO_2 into soil humus (Jones 2008; Leu 2007). Soil aggregates are secondary particles consisting of organic substances, minerals, and other inorganic compounds, and the degree of aggregation is a good indicator of soil structure and quality (Bronick and Lal 2005). SOC plays a very important role in maintaining and improving soil structure, as it acts as the binding agent in aggregation (Bronick and Lal 2005) and it further facilitates improvements in soil quality and fertility such as improved nutrient cycling and soil-water dynamics (Lal 2004). The complex and interconnected nature of soil-plant dynamics means that many improvements, such as increased SOC levels, have cascading effects on other soil properties, as depicted in Figure 2.

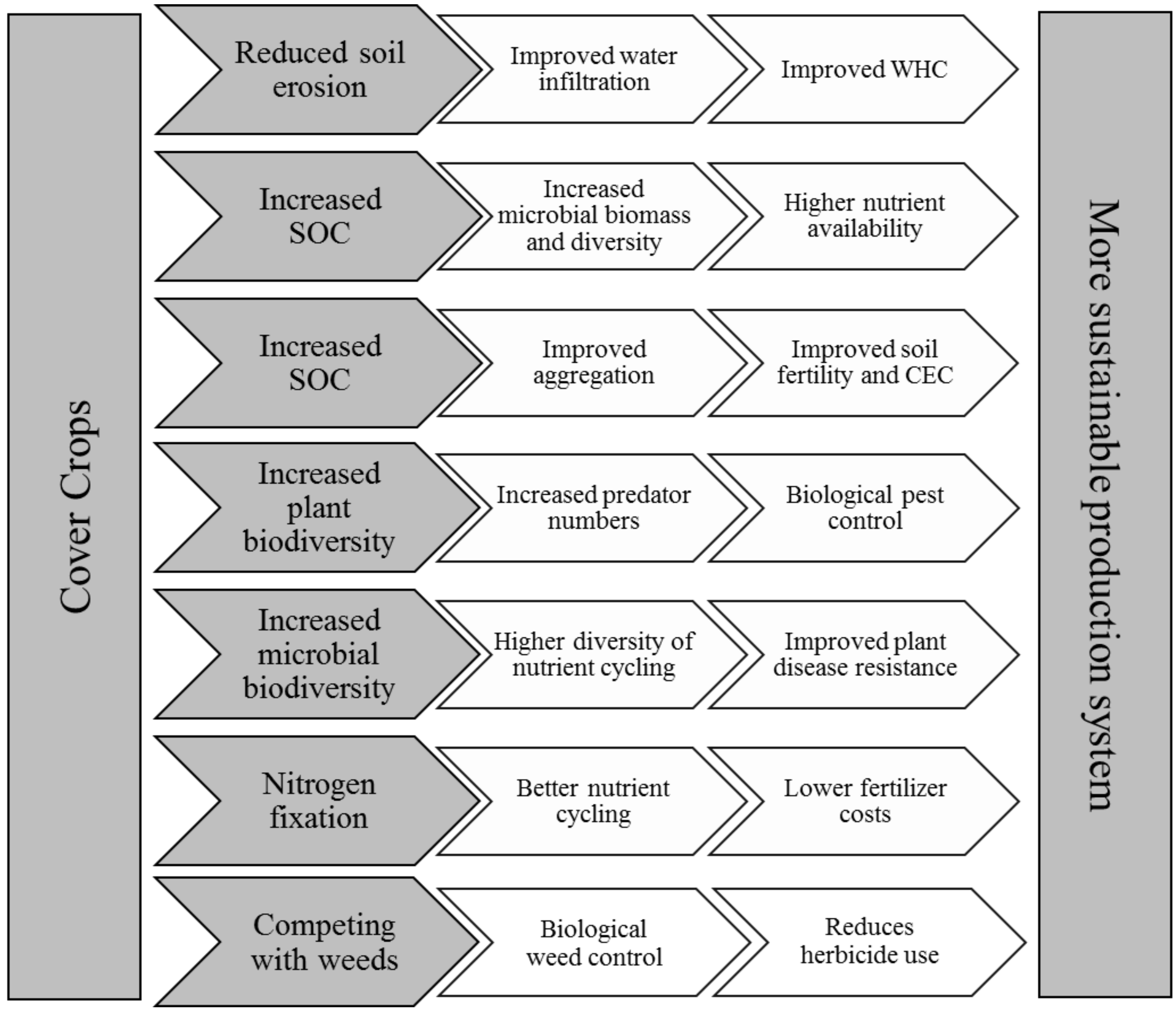

Figure 2. Illustration of the cascading effects that cover crops bring to production systems, which ultimately lead to a reduction in the need for external inputs, leading to more sustainable and resilient production systems.

2.4.3 Nutrient cycling

Cover crops enhance nutrient cycling in soils, which subsequently reduces the need for fertilizer application, therefore cutting input costs (Snapp et al. 2005). It also reduces nutrient loss through leaching and increases nutrient concentrations in the topsoil (Lehmann et al. 2000). As cover crops improve soil aggregation and humification in soils, they improve various other soil characteristics, since soils with higher humus contents have a higher nutrient availability (Leu 2007). Humus has many sites to bind minerals and can store up to 95% of soil nitrogen (N) and up to 80% of phosphorous (P) (Leu 2007). Humus also reduces nutrient leaching, buffers pH and drastically increases nutrient availability (Leu 2007).

Phosphorus, in particular could become fixed by forming chemical bonds with other elements, like aluminum (Al) or calcium (Ca), rendering them unavailable to plants (Jones 2001). The elevated levels of organic C stimulate microbial growth, which is essential for nutrient cycling as they produce the necessary enzymes that unlock these fixed minerals, e.g. P and make them available to plants (Jones 2008). The most notable contribution of cover crops in this regard is the ability of legumes to facilitate dinitrogen (N_2) fixation and increase soil N levels as well as availability (Lehmann et al. 2000). This may greatly reduce the need for N fertilizer (Hartwig and Ammon 2002), however the N fixing efficiency of each species depends largely on soil type and climatic conditions (Sarrantonio and Gallandt 2008). For example: for most clovers it ranges from 70-150 kg N ha^{-1}, while for hairy vetch it can reach up to 250 kg N ha^{-1} (Sarrantonio and Gallandt 2008). Grasses and brassicas, on the other hand, can be used to utilise excess N before it leaches (Dabney et al. 2001).

Various studies indicated N availability to crops can be increased with the use of cover crops. Fourie et al. (2007) found that total inorganic N was significantly higher in treatments with two *Medicago* species and subterranean clover. In an orange orchard in Sicily, five different cover crop sequences were tested over a three-year period, all of which improved N and P availability, though the most favourable sequence was that of *Medicago-Avena-Lolium* (Mauro et al. 2015). Similar results were found by Stagno et al. (2008), in which substrate-induced respiration (SIR), and potentially mineralisable nitrogen (PMN) were higher in plots with legume cover crops, especially subterranean clover. Herencia (2017) found that SOC, N and microbial biomass were higher in Mediterranean organic olive orchards, which included vetch cover crops. In a tomato production system in which hairy vetch and subterranean clover were grown as winter cover crops, mowed in spring and residues used as a mulch, tomato yields were increased by up to 28% compared to a conventional system, with and without N fertilisation, due to its N supplementation (Campiglia et al. 2010). Qian et al. (2015) found that total N was 50% greater under white clover and crown vetch in Chinese apple orchards, while perennial ryegrass had no effect on total N. However, all three treatments improved bacterial metabolic activity and community diversity, and subsequently improved P and potassium (K) availability. Chavarría et al. (2016) found that cover crop mixtures of oat, vetch and radish all improved soil bacterial phospholipid fatty acid (PLFA) levels by 6.8% on average, compared to the control. Soil enzyme activities (including esterase, dehydrogenase and acid phosphatase) were 20% higher under cover crop treatments, while total N was significantly higher in treatments that included vetch. Another 3 year study in organic olive orchards in Spain found that bitter vetch (*Vicia ervilia)* was the most suited cover crop for providing trees with N and thus reducing fertilisation needs (Ordóñez-Fernández et al. 2018).

Although the biggest potential nutrient cycling benefits of cover crops lie with the ability of legumes to supply N, the improved microbial biomass and metabolic activity associated with most species may further improve the availability of other nutrients such as P and K (Qian et al. 2015). Increases in microbial biomass and diversity are often associated with higher levels of enzyme production, which stimulates higher N, P and K availability (Chavarría et al. 2016). Therefore, cover crops may ensure nutrient supplementation, higher nutrient availability and more efficient nutrient utilisation, which ultimately reduces the need for fertilisation, and reduces input costs in a sustainable manner (Wittwer et al. 2017).

2.4.4 Weed Control

Weeds that establish from seed have limited energy available in the seed for early growth and young seedlings are therefore at a very vulnerable stage (Hammermeister, 2016). During this stage, weeds can be controlled either through uprooting, damaging the seedlings, preventing them from germinating, or by depriving the seedling of sunlight or other resources (Hammermeister 2016). Cover crops mostly suppress weeds through the latter two aforementioned modes. Weeds are mostly pioneer species, which means that they prefer soil that is barren or recently disturbed and experience little competition for water and nutrients (Hammermeister 2016). Cover crops restrict the amount of sunlight reaching the soil surface and also compete for nutrients, thus depriving the weed seedlings of resources when they are at their most vulnerable.

Cover crops may also restrict weed growth through allelopathy, which is when the growth and development of plants in close proximity to the cover crops are suppressed by toxic chemicals released into the environment by the particular cover plant (Creamer et al. 1996). Cover crops have also been found to restrict weed propagation by promoting seed decay (Snapp et al. 2005). Cover crop residues, which are left on the soil surface, may alter the soil surface environment (light intensity, temperature, and moisture), which may affect weed seed germination and/or seedling growth (Creamer et al. 1996).

In a tomato production system, oat, hairy vetch and subterranean clover were grown as winter cover crops and mowed in spring, after which residues were used as a mulch. Oat was more effective in suppressing weeds compared to hairy vetch and subterranean clover, but resulted in the lowest tomato yield, while the legumes increased yield; yet, still providing some weed control (Campiglia et al. 2010). Brainard et al. (2012) concluded that cereal rye provided partial weed control while improving soil quality. However, it tended to compete with the main crop in an asparagus production system (Brainard et al., 2012). In no-till summer maize/winter wheat rotation systems in Michigan, U.S.A., burr medic, barrel medic, medium red clover and berseem clover all reduced perennial weeds by 35-75 %, while reducing winter annual weeds by 41-78 % in (Fisk et al. 2001).

In local wine grape vineyards near Robertson, Fourie (2010) evaluated eight cover crop treatments over a 12-year period and found that the treatments varied greatly in their weed suppression abilities. Weed suppression compared favourably to the control for triticale, vetch and a mixture of rye and faba bean (Fourie 2010). In the semi-arid region of Oudtshoorn, South Africa, vetch and wimmera ryegrass were grown as cover crops in colombar vineyard and it was concluded to be a very effective method of weed control, especially when mowed and used as a mulch (Van Huyssteen et al. 1984). In dryland vineyards in Northern California, both weed control and grape yield were either similar or greater in the cover cropping systems compared to conventional systems where tillage and chemical weed control were implemented (Steinmaus et al. 2005). The cover crop treatments included oat, and an oat-vetch mixture, which were planted in the work row, and mowed and mulched, while subterranean clover was planted in the vine row as a subplot, all of which provided sufficient weed control (Steinmaus et al. 2005).

Caamal-maldonado et al. (2001) evaluated the allelopathic properties of four legume species including velvet bean, jack bean, jumbie bean and wild tamarind in a greenhouse experiment. Leachates from all four species significantly suppressed radical growth of tested plant species with velvet bean providing the most effective weed control as a living cover crop (68 %) (Caamal-maldonado et al. 2001). A cover cropping sequence of *Vicia faba-Avena-Avena* was found to be the most effective combination for weed control, with up to 92 % efficacy, in orange orchards in Sicily (Mauro et al. 2015).

The weed control efficiency of cover crops vary among different species and conditions, e.g. allelopathic species such as rye grass (*Secale cereale* L.) and subterranean clover (*Trifolium subterraneum* L.) are more effective in suppressing weed growth (Hammermeister, 2016; Hartwig and Ammon 2002). However, even where weed reduction through cover crops is not as effective as conventional chemical methods, it can significantly reduce herbicide use and subsequently, lower production costs (Snapp et al. 2005), as well as reducing the environmental effects thereof (Mauro et al. 2015). Furthermore, it may provide sufficient weed control, while simultaneously providing other ecosystem services and improving soil fertility and nutrient cycling, unlike conventional weed control methods (Sarrantonio and Gallandt 2008). The downside of weed control with cover crops is that it may compete with the crop for water and nutrients, especially when planted in the tree row, or in areas where water is a limiting resource (Steinmaus et al. 2005; Van Huyssteen et al. 1984).

2.4.5 Biodiversity

Cover crops increase both the above- and belowground biodiversity (Hartwig and Ammon 2002). Agricultural systems with higher biodiversity levels are more resilient to adverse conditions, are less vulnerable to flooding and droughts, and have a greater capacity to suppress pest outbreaks and disease spread (Lin 2011). Incorporating different species into a cropping system not only increases the plant biodiversity, but also attracts different insect species (predators and pollinators) as new habitats and food sources are available (Lin 2011). Cover crops also increase the species diversity and biomass of soil microbes, which results in higher nutrient availability in soils (Qian et al. 2015). If perennial cover crops are used, they provide a continuous supply of organic compounds via the ‘liquid carbon pathway’, which creates an ideal environment for mycorrhizal fungi to thrive in and that plays an extremely important role in making nutrients (especially P) available to plants (Jones 2008).

Although cover crops are commonly used for a variety of benefits, their ability to influence soil microbial communities is poorly understood (Vukicevich et al. 2016). Due to the fact that perennial orchards are commonly cultivated as monocultures, it is plausible they maintain relatively low levels of biodiversity. However, this may be improved through selecting specific combinations of cover crop species (Vukicevich et al. 2016). Cui et al. (2015) found that cover cropping systems in subtropical red soil with *Paspalum natatu* and *Stylosanthes guianensis*, both significantly increased bacterial metabolic activity and diversity, especially when inoculated with arbuscular mycorrhizal fungi (AMF). According to Qian et al. (2015), crown vetch, white clover and perennial ryegrass all resulted in increased soil bacterial diversity and over metabolic activity in apple orchards in China. Similar results were also reported in organic olive orchards in the Mediterranean, especially with legumes (Herencia 2017). Thus, it was concluded that increasing plant species and functional group diversity in perennial orchards may increase soil microbial diversity, which may subsequently suppress pathogenic bacteria and soil-borne diseases, while promoting beneficial microbial communities, although more research is needed to better understand the functionality of these phenomena (Vukicevich et al., 2016).

In terms of above ground biodiversity, the larger the number of cover crop species are used, the greater the vegetative biodiversity becomes, which has subsequent effects on insect biodiversity. Not many studies have focused on successfully increasing native biodiversity in perennial orchards through the use of native cover crop species, and most of them yielded inconclusive results. Fourie (2014) conducted a study in which ten perennial and three annual broadleaf indigenous plant species were evaluated as cover crops over four years in a wine grape vineyard near Stellenbosch, South Africa. Although these species may have improved the overall vegetative biodiversity and resilience of the vineyard, they proved unsuccessful at suppressing weed growth (Fourie 2014). In a greenhouse experiment, Perry et al. (2009) also tested four native cover crop species (Canada goldenrod, little leaf pussy toes, common sunflower and annual ragweed) for their ability to suppress four invasive grasses, which yielded mixed results.

The expansion of intensive agricultural systems is one of the leading causes of global biodiversity loss, which is an alarming issue for agriculture itself since its sustainability relies on natural biodiversity (Scherr and McNeely 2001). Clearing of natural vegetation and replacing it with monocultures is the most common cause of local biodiversity loss, whereas runoff of agrichemicals such as pesticides and fertilisers also cause biodiversity loss, often in remote locations such as rivers and lakes (Scherr and McNeely 2001). Cover crops are not only able to increase biodiversity on the farm itself, but also reduce the need for intensive chemical inputs, which may cause biodiversity loss elsewhere (Scherr and McNeely 2001). If cover crops are well implemented and managed, they may substantially reduce the need for heavy pesticide and insecticide usage, which may not only reduce on-farm costs and improve on-farm biodiversity, but also has far reaching positive effects on biodiversity and ecological and environmental benefits (Pimentel et al. 1993).

2.4.6 Disease and Pest management

Another benefit of cover crops is their ability to provide natural pest and disease control. Cover crops hold particular promise in this regard for horticulture, and may substantially reduce the reliance on chemical-based pest control (Bone et al. 2009). A number of studies have shown that introducing cover crops increases natural enemies and predators, providing biological pest control as an ecosystem service (Tscharntke et al. 2005). This increase in predator numbers is facilitated by the provision of habitat and shelter from human activities, as well as additional food sources for certain predator species that also utilise nectar and other plant constituents (Bone et al. 2009).

Losey and Denno (1998), who reported that cover crops increased ladybird numbers, found that foraging ladybirds caused aphids to fall to the ground, where they could then be utilised by carabid beetles – an example of positive species interactions among predator species known as complementarity (Tscharntke et al. 2005). Altieri et al. (2005) also reported that succeeding winter cover crops with summer cover crops in California vineyards increased the control of thrip and leafhopper numbers, by providing habitat extensions into vineyards from surrounding forest ecosystems and corridors for natural predators. Altieri and Schmidt (1986) found that in a number of Californian apple orchards, with a variety of cover crop species and mixtures, showed lower numbers of aphids, codling moth, and leafhoppers compared to orchards without cover crops and they also had higher numbers of individuals and species of predatory arthropods on the soil surface. In apple orchards in Australia, a number of cover crop treatments were examined which included fenugreek, white mustard, buckwheat, as well as mixtures of Queen Anne’s lace/fennel and chicory/yarrow (Bone et al. 2009). However, no significant difference in predator numbers were found, and some treatments presented production problems and even increased pest problems (Bone et al. 2009).

Biofumigation is the suppression of soil-borne diseases and pests via the release of certain organic compounds during the decomposition of certain plant species, a process that has played an important role in integrated pest management (IPM) against pests and diseases, particularly with regards to nematodes (Kruger et al. 2013). The main active compound involved in this process is a group of anions known as glucosinolates (GSLs), which are found in a number of cover crop species including white mustard, Indian mustard, canola and salad rocket (Kruger et al. 2013). Cover cropping systems that are able to successfully integrate plant species such as these and harness the services they provide, may greatly reduce the need for chemical pest and disease control, reducing the prevalence of chemical residues both within the production system itself and in surrounding ecosystems, while also reducing input costs.

The plant-parasitic nematode suppression abilities of *Crotalaria* species have been well studied for many years, and it can be utilised in different production systems (Wang et al. 2002). Sunn hemp (*C. juncea*) in particular provides good ground cover, weed suppression, is hardy and drought resistant and is also capable of N fixation (Wang et al. 2002). A large number of studies on a number of *Crotalaria* species have yielded varying results for a wide range of cropping systems and crops, with results being mostly positive and the best nematode control achieved with integrated management strategies (Wang et al. 2002). In local studies, ten cover crop species were tested in Saltanina vineyards in South Africa, where ‘Saia’ oats, ‘Midmar’ ryegrass and ‘Paraggio’ medic were poor hosts for root-knot nematodes, whereas ‘Overberg’ oats was a poor host for ring nematodes (Addison and Fourie 2008).

Cover crops may enhance disease resistance through the improvement of crop immune systems (Jones 2001). This is facilitated by increased levels of soil humus and microbial activity and diversity, and thus higher nutrient and trace element availability, some of which are essential in building the plant’s immune system but are often unavailable to the plant (Jones 2001). The increasing occurrence of insecticide and pesticide resistance, and environmental concerns regarding these chemicals have forced producers to seek alternative ways to successfully manage IPM programs, and cover crops have played an integral part in this process (Kruger et al. 2013).

2.5 Disadvantages of Cover crops

2.5.1 Competition

One of the biggest and most obvious concerns and limitations of cover crops is that they often compete for resources with the main crops, which may result in yield reductions (Zhang et al. 2007). This is especially problematic with intercropping in cash cropping systems, or when cover crops share the same root space with the primary crop in perennial orchards and vineyards (Paine and Harrison 1993). This may also be a particular problem in areas where water is a limiting resource, or where production is dependent on rainfall, as cover crops will utilise water that could otherwise have been utilised by the main crop (Van Huyssteen et al. 1984).

Reported studies yielded mixed results, as some reported yield increases under cover crops, while others have resulted in significant decreases, while some long term studies report initial decreases followed by long term increases. Tesic et al. (2007) tested three vineyard floor management regimes in Australian chardonnay vineyards, in two different climatic regions and reported that complete ground cover (weeds left intact) with mowing significantly reduced yields when compared to partial and completely bare treatments using chemical herbicides. This was more pronounced in the study site in a dry hot climate compared to the mild climate study site, as water was much more of a limiting resource and evaporation rates were higher (Tesic et al. 2007). A meta-analysis by Tonitto et al. (2006) compared studies, which involved three types of cash cropping systems - these included, i) winter bare fallow systems with added fertiliser, ii) winter legume cover cropping with no additional N fertiliser and iii) non-legume winter cover crops with additional fertiliser. The legume cover crop systems had a 10% lower yield than conventional bare fallow system on average, whereas nitrate leaching was 40% lower in the legume systems. Yields in non-legume cover crop systems with fertiliser were not significantly different from conventional fallow systems, but they did significantly reduce nutrient leaching (70%) (Tonitto et al. 2006).

In light of these varying results, it is apparent that many factors play a role in determining yield and cover cropping success and these include the cover crop species, climate, management, main crop and soil type (Lehmann et al. 2000). Many of these are not within the control of producers, therefore site-specific species selection and sound management may be the main factors determining yield, since the negative and positive effects need to be balanced out in order to achieve desired outcomes (Lehmann et al. 2000).

2.5.2 Costs

Costs associated with establishment and maintenance of cover crops is another hurdle faced by producers looking to implement this practice. This is especially true in the case of legumes, as legumes can cost up to ten times more to establish than grasses (Snapp et al. 2005). Competition provided by cover crops, both in intercropping and perennial systems, may reduce yield, resulting in monetary losses for the producer (Zhang et al. 2007). Cover crops may also interfere with the main crop, causing difficulties in a practical sense, such as winter cover crops displaying unwanted vigour when the main crop is sown, thus acting as weeds, which may require chemical control (Snapp et al. 2005). Often, cover crops must be killed off at certain dates in order to establish the main crop (Alonso-Ayuso et al. 2014). This may be done either through chemical (herbicide) or mechanical (ploughing or disking) methods, both of which may be expensive.

However, if managed properly, the costs of establishing and maintaining cover crops may be offset by both the reduction of other inputs such as herbicides, pesticides and fertiliser, and in some cases the increased yield associated with certain cover cropping systems. Steinmaus et al. (2005) reported that, in an experiment in California vineyards, cover cropping systems yielded higher profit margins compared to the conventional tillage systems, by an average of Euros (€) 794 ha^{-1}, in two different locations. Therefore, although cover crops may have substantial costs associated with them, their ability to save costs in other respects may outweigh the input costs, if the system is optimally managed (Steinmaus et al. 2005).

2.5.3 Management

A number of characteristics of cover crops may provide obstacles in terms of the management of the cover crop itself, as well as possible hindrance to standard production practices concerning the main crop. One of the biggest concerns in this regard is that cover crops often causes delayed warming of the soil after winter, resulting in slowed N release, especially with non-legume cover crop species (Snapp et al. 2005). However, slowed soil warming is not necessarily a negative outcome since it can be beneficial in warmer regions and is mostly a problem in colder climates (Snapp et al. 2005). Certain cover crop species may become overly vigorous and become difficult to control, especially when they are allowed to reach the seedling stage, as this may lead to a seedbank build-up that could result in unwanted germination and cover crop growth (Snapp et al. 2005), in which case they may have to be controlled through either chemical or mechanical weed control methods. If not managed properly, cover crops may also cause build-up of diseases and may suppress seed germination of the main crop (Alonso-Ayuso et al. 2014). The termination date of cover crops is therefore arguably the most important management aspect governing cover crop success, as it has been found to significantly influence soil moisture conservation, nutrient leaching and competition for water and N with the primary crop (Alonso-Ayuso et al. 2014). Thus, species selection and killing date are two of the most important factors that determine the success of cover cropping systems, both from a practical and economic standpoint (Alonso-Ayuso et al. 2014).

2.6 Living Mulches

2.6.1 What is Mulching?

Mulching refers to the management practice of leaving any material on the soil surface with the aim of providing various benefits to crop production (Prosdocimi et al. 2016). The main purpose of mulch is to provide protective cover on the soil surface to assist mainly in soil and water conservation, however it may also bring various other benefits (Prosdocimi et al. 2016). The mulch layer on the soil surface acts as a buffer between the soil and the atmosphere, as opposed to being integrated into the soil like compost for example (Kader et al. 2017).

A wide range of materials can be used as mulch and their functions vary (Prosdocimi et al. 2016). A mulch can be either living or inert, meaning that it can consist of either living plants acting as a living mulch layer, or non-living material acting as a mulch layer (Paine and Harrison 1993). Inert mulches can be either organic or inorganic. Organic mulching materials may include straw, wood chips, manure, paper, cover crop or weed residues, pips, husks and prunings, most of which decompose over time (Granatstein and Mullinix, 2008; Lötze 2014; Prosdocimi et al. 2016). Inorganic mulching materials may include materials such as stones, gravel, geotextiles and plastic films, all of which do not decompose over time (Lötze 2014; Quintanilla-Tornel et al. 2016).

Living mulches are often also referred to as companion crops and are similar to cover crops in many ways, but differ in their mode of application (Paine and Harrison 1993). In cash cropping systems, the fundamental difference between cover crops and living mulches is that a living mulch and main crop are planted together, where the living mulch would be planted between crop rows, and is often left intact after harvesting the primary crop, whereas cover crops are usually planted in an alternating fashion with main crops, although they may overlap at either the start or end of the growing season (Paine and Harrison 1993). Definitions of living mulches in perennial orchards have differed between authors, however the fundamental difference is that cover crops are typically grown between tree rows (in the work row), often consisting of annual species, whereas living mulches are planted in the tree or vine row, or throughout the entire orchard floor (Hartwig and Ammon 2002; Qian et al. 2015). Living mulch species may include legumes, grasses, annuals and perennials, and often provide soil cover throughout the year (Hammermeister 2016). Examples of species commonly used as living mulches include perennial rye grass (*Lolium perenne* L.), crown vetch (*Coronilla varia* L.) and white clover (*Trifolium repens* L.) (Qian et al. 2015), including several others.

2.6.2 Advantages of Living Mulches

Some living mulch species (often perennials or self-seeding annuals) may provide soil cover all year round and do not need to be re-established every year (Hartwig and Ammon 2002). They may provide nearly all the benefits that inert mulches do, as well as additional ecosystem services that inert mulches cannot (or not as effectively), which include some of the benefits associated with cover crops. Living mulches exude liquid C through their roots, which stimulates soil microbes, enhance nutrient cycling and, in the case of legumes, it may serve as a valuable source of N through fixation (Granatstein and Mullinix 2008). They also reduce soil compaction, nutrient cycling and SOM (Brainard et al. 2012). It has been found that leguminous living mulches may play a significant role increasing microbial C and N, total organic C and N, as well as organic C fractions and overall soil fertility (Qian et al. 2015). Using subterranean clover (*Trifolium subterraneum* L.) as living mulch has been proven to be more effective than conventional tillage-herbicide methods in controlling weeds, without significantly affecting crop yield (Ilnicki and Enache 1992).

To fully understand and holistically utilise living mulches may be difficult, as each species may require unique soil and climatic conditions, as well as different management regimes to thrive, (Qian et al. 2015). Each species may have different effects on the soil and primary crop, and may provide a different set of challenges and problems (Qian et al. 2015). The main problem associated with living mulches is that they may compete with the main crop for water and nutrients, which could have negative impacts on production (Granatstein and Mullinix 2008).

Extensive research has been done on living mulches in Switzerland. Switzerland is a mountainous country with high annual rainfall, thus soil erosion is a big problem where vines and orchards are established on steep slopes (Hartwig and Ammon 2002). They have developed what is known as the Swiss sandwich system, which entails the maintenance of living mulch in the tree row, while using conventional tillage to keep the adjacent zone free of any vegetation (Stefanelli et al. 2009).

Most living mulch studies focused on erosion and soil moisture, while there is limited information available on the how living mulches impact soil microbial diversity and activity, and subsequent soil quality, although it shows great potential in this regard (Duda et al. 2003; Qian et al. 2015). Living mulches, like cover crops, are able to induce many positive effects on the soil environment. However, with living mulches these principles can be applied in the tree row, where it is more directly accessible to tree roots (Paine and Harrison 1993).

2.6.3 Disadvantages of Living Mulches

One of the biggest challenges with living mulches is that they may provide direct competition to the trees for nutrients and water (Brainard et al. 2012). In order for a living mulch to be successful, it must provide as little competition as possible (Paine and Harrison 1993), while providing a number of benefits that may offset the costs of competition (Hartwig and Ammon 2002).

The success of different living mulch species may be very specific to circumstances such as climate, soil type, cropping system and thus, each species may have a very specific niche within which it can have a net beneficial effect on production and soil fertility (Qian et al. 2015). This makes species selection difficult when looking to implement living mulch systems on a commercial scale for different crops, across different soil types and climates. Studies on living mulches have largely looked at typical crop and/or cover crop species, including legumes such as different vetch and clover species, and non-legumes such as various grass species (Paine and Harrison 1993). In 1987, Ray William from Oregon State University summarised the desirable characteristics of a living mulch species, which included hardiness and adaptability, drought resistance and low fertility, rapid establishment to suppress weeds and control of soil erosion, reducing input costs such as fertiliser, herbicide and mowing costs and improving crop yields

(Paine and Harrison 1993). They further identified 139 species (grasses and legumes) with some of these characteristics for further testing (Paine and Harrison 1993). Autonomous re-seeding legume species have been said to be the most suited species for cover cropping in Mediterranean climates, which are often used as living mulches as well, since they are capable of N-fixation, thus reducing fertiliser costs, while they require little maintenance and do not need to be sown every season (Ordóñez-Fernández et al. 2018).

However, in more recent years, very little research has focused on screening of novel species for living mulches. Since the success of living mulches is very niche specific, perhaps more research is needed to identify hardy plants that are well adapted for specific climates and that require minimal maintenance. Indigenous species have been tested as cover crops by several researchers (Fourie 2014; Perry et al. 2009); however, no known research on such species as mulches was found. Many weed species are hardy and adaptable, and it has been suggested that certain weed species may offer ecosystem services when managed correctly as living mulches (Hartwig and Ammon 2002).

2.7 Conclusions

The benefits of incorporating cover crops into the floor and soil management regimes in perennial orchards stretch across the domains of environmental, economic and human health and this has been well documented. Although extensive research has been done on the topic, many grey areas and limitations remain. The management of ecosystems, such as orchards, is complex in nature, which often requires a more holistic approach rather than a reductionist one, especially when applied in the field where unpredictable external factors may also play a role.

One of the limitations of cover crops is that they function in the work row where tree roots are sparsely populated. Mulching, with its limitations, offers many benefits in the tree row where they are more accessible to tree roots. Living mulches offer exciting prospects of combining the biological ecosystem services and the local precision of mulching, bringing the advantages of having living roots in the soil directly to the tree row. Knowledge about the effects of living mulches on soil ecology, nutrient cycling, and overall soil health is still relatively limited, as it varies greatly between species, climates and crops. There is also limited literature on suitable species to be used as living mulch, especially with regards to adaptability to different climates, management requirements, and compatibility with different crops. There is also little knowledge about the extent to which different living mulch species compete with perennial crops, or possible interactions that may lead to complimentary effects that may offset the costs of competition.

Research aimed at identifying novel species (including weeds and native vegetation) as potential living mulches for specific conditions, may contribute to more effective implementation and understanding of this practice. Better understanding and harnessing of practices such as cover crops and living mulches may reduce the reliance of commercial fruit production on chemical inputs, which may ultimately aid in achieving incremental improvement of the sustainability and resilience within commercial perennial fruit orchards.

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CHAPTER 3

Investigating the potential of *Tradescantia fluminensis* vell. as a living mulch in citrus orchards in the Eastern Cape of South Africa

3.1 Abstract

The effects of *Tradescantia fluminensis* Vell. (*Tradescantia*) on soil-plant dynamics, in a Palmer navel orange orchard (*Citrus sinensis* L.) in the Eastern Cape of South Africa were investigated to determine its suitability as a novel living mulch species. Using living mulches in commercial fruit orchards may provide many ecosystems services, reducing the need for inorganic inputs and improving the resilience and sustainability of these systems. The success of living mulches are determined by many factors, but there is limited literature available on the potential of novel species, such as weeds and native vegetation, as living mulches. Multiple indicators were compared between an orchard containing the *Tradescantia* mulch (TO treatment) and an adjacent orchard with no mulch (BO treatment), which served as the control. Measurements included water-holding capacity (WHC), soil moisture (SM), soil temperature (ST), and microbial biomass (MB), weed control (WC) and root count and distribution (RC). The WHC was significantly greater in the TO treatment, while SM was greater at most soil depths, especially between 20-30 cm. Soil moisture in the TO treatment was less at 10 cm depth, as a proportion of SM in this region was utilized by the mulch. Soil temperature fluctuations were lower in the TO treatment at shallow soil depths. CO_2 respiration and MB were nearly three times greater in the TO compared to the BO treatment, as well as estimated potential mineralizable nitrogen (PMN). Weed counts were significantly lower in the TO treatment and *Tradescantia* provided effective WC. There was great variation in RC within treatments, however the BO treatment yielded slightly higher overall root counts. The vertical root distribution between the treatments differed slightly, with the BO treatment having higher root concentrations in the upper soil layers, and the TO treatment having higher concentrations at deeper soil levels, likely caused by competition from the mulch at shallow soil depths, although this data was inconclusive. *Tradescantia* therefore provides some ecosystem services that may improve soil fertility and soil-water dynamics, increase soil C and MB, provide chemical-free weed control, lower the need for inputs, and improve the overall resilience and

sustainability of citrus orchards. Although it holds many benefits, the invasive status of this plant may yet present problems, and it is not currently allowed to be propagated.

Key words: Living mulch; *Tradescantia fluminensis*; Perennial orchard; Ecosystem services; Resilience; Sustainability

3.2 Introduction

In perennial orchards, a living mulch is best defined as a companion crop or plant that is maintained in either the tree row alone, or throughout the entire orchard floor, with the goal of providing permanent ground cover (Hartwig and Ammon 2002). Mulching practices are known to bring many benefits to a production system, many of which are associated with improving the sustainability and resilience thereof (Paine and Harrison 1993). Moreover, from an agro-ecological perspective, living mulches provide ecosystem services that, if harnessed effectively, may offer sustainable alternative practices in commercial landscapes (Altieri 1995). Living mulches may be perennial or annual plant species, so long as it provides some form of ground cover throughout the year (Paine and Harrison 1993).

One of the major challenges regarding living mulches is that, unlike inert mulches, their viability and efficacy may be highly variable among different growing conditions such as different soil types, climates, production goals and the type of production system and crops (Paine and Harrison 1993). Typically, in evergreen orchards such as citrus orchards in the Eastern Cape, the ideal living mulch is defined as follows: a perennial plant species with the potential to provide year round weed suppression, alter the soil moisture regime and microbial activity, reduce soil erosion, improve soil fertility, while the shallow roots may offer little competition for trees (Hartwig and Ammon 2002). It is challenging to determine the suitability of a particular plant species to serve as a living mulch, since both the technical and practical aspects need to be considered before the plant can be recommended for commercial application. Plant species with the desired physiological character profile may not necessarily be suitable as a living mulch under commercial agricultural practices and in all climatic regions (Paine and Harrison 1993).

The advantages of cover crops are well known and can be used as a reference to determine characteristics for living mulches that will benefit crops. However, in most perennial orchards such as citrus, cover crops are localised in the work row, and consist mostly of annual species (Muma 1961). The main crop therefore does not receive the majority of these benefits in the planting row, nor throughout the year.

Standard mulching practices on the other hand, focus on enhancing soil conditions in the planting row of perennial crops. Benefits of mulches include reduced erosion (Prosdocimi et al. 2016), reduced evaporation and water conservation (Kader et al. 2017), chemical-free weed control (Granatstein and Mullinix 2008), reduced soil temperature fluctuations (Kader et al. 2017) and pest suppression (Quintanilla-Tornel et al. 2016). In most cases, mulching materials are inert and can include both organic and inorganic materials (Lötze 2014). Inert mulches are unable to induce certain biological services that cover crops are capable of. In contrast, with a living mulch, root exudates excreted by living plants will play a significant role in stimulating and maintaining soil microbial activity (Chavarría et al. 2016), as well as facilitating humification (Jones 2008) and increasing the C:N ratio in soils (Demestihas et al. 2017) that are similar to advantages on soil conditions of a living, cover crop. Thus, living mulches have the potential to combine the biological advantages of cover crops and the localized benefits of mulching, addressing the shortcomings and limitations each on its own.

The biggest concern with a living mulch however, is that it may compete directly with trees for water and nutrients, since their root systems share the same soil space (Liedgens et al. 2004). Fundamentally, the most important function of living mulches is therefore to improve soil fertility without negatively impacting yield through competition. The ideal living mulch should thus have a shallow root system (to minimize competition), provide effective weed control (possibly through allelopathy), and provide uniform ground cover (to effectively reduce erosion and improve soil properties) (Hartwig and Ammon 2002). Moreover, a living mulch should require little maintenance, and should be hardy and adaptable.

A number of plant species may be successful as living mulches for a number of different purposes. Legumes such as white clover (*Trifolium repens* L.) and crown vetch (*Coronilla varia* L) have been found to increase total N and microbial diversity and biomass in apple orchards (Qian et al. 2015), and subterranean clover (*Trifolium subterraneum* L.) provided successful weed control without reducing yield in a number of vegetable systems (Ilnicki and Enache 1992). Grasses may also provide good weed control and improve microbial activity, such as perennial ryegrass (*Lolium perenne* L.) in apple orchards (Qian et al. 2015) and winter rye (*Secale cereale* L.) in asparagus systems (Brainard et al. 2012). While most of these species have been found to be very effective for weed control, legume species are generally associated with higher yields compared to grasses (Hartwig and Ammon 2002). Literature regarding living mulches primarily pertains to traditional crop or cover crop species and very little attention focused on alternative plant species. It has been suggested that perhaps certain weed species may be suitable living mulches (Hartwig and Ammon 2002); yet, little research has been done on the mulching potential of weed species.

Tradescantia fluminensis Vell. (*Tradescantia*) belongs to the genus *Tradescantia Rupp. ex* L., the subtribe Tradescantiinae, tribe Tradescantieae and subfamily Commelinoideae of the family Commelinaceae (Eminağaoğlu et al. 2012). It is commonly known by a number of names including the wandering jew, small-leaf spiderwort, trad, wandering willie and inch plant (Macedo et al. 2016; Seitz and Clark 2016). *Tradescantia* plants have broad, green, waxy leaves and reproduce vegetatively (Seitz and Clark 2016). Each plant typically includes an unbranched, leaf baring, vertical stem reaching up to 60 cm in length, as well as a leafless horizontal stem (30-150 cm in length) with tiny roots at each node anchoring it to the ground (Seitz and Clark 2016). The thin horizontal stems (approximately 3 mm in diameter) form dense intertwined mats (Fig. 1) from which the vertical leaf baring stems grow (Standish et al. 2004).

Tradescantia is a sub succulent perennial herb native to South America, more specifically the subtropical and tropical parts of Brazil and Argentina (Seitz and Clark 2016). It grows most vigorously in humid, shaded areas such as forest remnants, gardens, parks and river banks (Eminağaoğlu et al. 2012). *Tradescantia* has been introduced to roughly 13 other countries, where it is considered an invasive species (Seitz and Clark 2016) and in its native Brazil, it is considered a common agricultural weed (Kelly and Skipworth 1984). In South Africa, *Tradescantia* is classified as a category 1b invasive plant, which means that the propagation, selling or planting of it is strictly prohibited (NEMBA 2014). Most notably, it has invaded lowland forest remnants in

Florida, eastern Australia and New Zealand, where it prevents regeneration of degraded forest ecosystems (Standish et al. 2004). Hence, in most countries, this plant species has a negative connotation. Nevertheless, the horizontal mat-like growth pattern of *Tradescantia* may be a suitable characteristic for a living mulch from a practical perspective, since it provides dense, homogenous ground cover without interfering with trees. The microclimate created underneath the dense *Tradescantia* mats were reported to alter the moisture regime, as well as insect and microbial populations (Standish et al. 2004; Toft et al. 2001). Furthermore, *Tradescantia* prevented forest regeneration by disturbing the natural regeneration cycle and suppressing native seed germination and seedling growth (Maule et al. 1995), a characteristic with potential weed suppressing abilities.

A number of the characteristics of this invasive weed species corresponds with the requirements of a suitable living mulch for a commercial orchard in the Eastern Cape. Therefore, the aim of this study was to i), investigate the potential and viability of the *Tradescantia* weed as a living mulch in citrus orchards in the Eastern Cape of South Africa, without establishing the plant and with the full understanding of the invasive nature thereof. At no time the intention was to recommend planting it, but rather to ii), investigate its effects on the soil-plant dynamics where it has already established itself and iii), quantify some of the positive contributions towards organic production claimed by the producer.

3.3 Materials and Methods

3.3.1 Study Site

The study was conducted on a Citrus farm in the Sundays River Valley, Kirkwood in the Eastern Cape of South Africa (33°24'16.6"S; 25°23'57.6"E). The annual precipitation for this region is 372 mm, most of which occurs during the summer months (South African Weather Service 2010). In summer, maximum temperatures can reach up to 45 °C and in winter, the minimum temperatures often drop below 0 °C (South African Weather Service 2010). The study was conducted over a three-month period, from 15 April 2018 to 15 July 2018.

The *Tradescantia* site (TO) is a Palmer navel orange orchard (*Citrus sinensis* L.), planted in 1976 on Troyer Citrange (*Poncirus trifoliata* × *Citrus sinensis*) rootstock, in an East-West orientation.

Trees spacing is 3 m in the row, with 5 m between rows. Trees are irrigated using micro-sprinklers that are suspended along a wire, approximately 50 cm above the ground, with sprinkler heads spaced 1.5 m apart. The *Tradescantia* was first introduced into this orchard in 2006, after which it required approximately three years to reach complete (current) establishment (Fig. 2) (Potgieter, 2018, personal communication). There was no cover crop cultivated in the work row, and weeds in the work row were left intact where the *Tradescantia* does not reach (Potgieter, 2018, personal communication). This producer follows an organic approach with minimum chemical intervention summarised in Table 1.

Directly adjacent to the *Tradescantia* site, a non-*Tradescantia* site (BO) was selected as control. This Palmer navel orange orchard was planted in 1984 on Troyer Citrange (*Poncirus trifoliata* × *Citrus sinensis*) rootstock, in a North-South orientation. The orchard floor is kept bare through conventional chemical weed control methods, and no cover crop was cultivated in the work row. Trees spacing is 2.5 m in the row, with 5 m between rows. The irrigation system consists of micro-sprinklers attached to a mainline, which runs along the ground down the tree row. Each sprinkler head is attached to a peg in the ground next to each respective tree, with a small pipe connecting it to the mainline. This orchard is managed as a conventional orchard and management practices include a strong chemical approach, summarised in Table 1.

This study focused on quantifying changes in soil properties, weed control and root distribution as follows:

3.3.2 Water-Holding Capacity (WHC)

To determine the WHC of the soil, one composite soil sample was collected from three randomly selected trees in each orchard (thus three samples per treatment). Using a clean spade, samples were collected from the top 30 cm of soil, 50 cm south of the tree trunks, and contained no visible plant matter or stones. After collection, the samples were immediately placed in plastic bags and stored in a cool, dark place before, during, and after transportation. The plastic bags were sealed to reduce moisture loss. Samples were collected two to four days after a rain event to ensure an even distribution of precipitation throughout the orchards, while allowing enough time for some degree of drainage to occur in order to avoid drenched soil.

The samples were weighed out into glass beakers at 100 g each, after which they were placed in an oven to dry at 105 °C for 24 h. After 24 h, the samples were removed from the oven and cooled down for 5 min. The samples were weighed, where the weight difference before and after drying represented soil moisture lost during drying. This was used to calculate the soil moisture content as a percentage of total soil weight before drying, giving an indication of the WHC of the soil. This procedure was done twice, once in April, and again in July. This is a variation of the method used by Priha and Smolander (1999), where soil samples are drenched for two hours and then drained for two hours. This method was altered in order to avoid soil structural disruptions that may alter the WHC.

3.3.3 Soil temperature (ST) and soil moisture (SM)

Continuous logging probes were used to determine the SM and ST at different soil depths (DFM Technologies, 124 Fairview Road, Penhill, Eerste River, 7100). The probes were installed on 12 April 2018. Soil moisture and ST were recorded at 10 cm intervals from the soil surface, ranging from 0 cm to 60 cm. Measurements were recorded at hourly intervals over a three-month period (15 April 2018 – 15 July 2018). These probes have been widely accepted as a reliable measuring tool that is durable and easy to use and the probes are appropriately sensitive to measure the parameters in question, SM (0.002– 0.05 $m^3 m^{-3}$) and ST (absolute errors = ± 1.28 °C) with a great degree of precision (99 % and SD = 0.15 – 1.08 °C, respectively) (Mjanyelwa et al. 2016).

Two probes were installed in two adjacent rows, roughly 5 m apart. One probe was placed in the ground under the living mulch (Fig. 3), while the other was placed in a bare patch (Fig. 4) where the living mulch was cleared the day before the probe was installed (11 April). Both probes were subjected to the same irrigation cycles as well as precipitation throughout the duration of the study.

3.3.4 Microbial Biomass (MB)

Microbial activities and biological fertility of the soil at the study site were assessed by the Solvita® CO_2-burst method (Haney et al. 2008). The Solvita® CO_2-burst method, which measures the CO_2 respiration in soil over a 24 h period, is a simple, affordable method that can be used to determine the microbial activity in soils with reasonable accuracy (Haney et al. 2008). By exploiting a phenomenon called CO_2-burst, Solvita® was accepted as a commercial soil lab testing method in 2006 (Brinton and Laboratories 2017). This method allowed more rapid soil testing as opposed to the previously used 72 h or 7 day tests (Brinton and Laboratories 2017). The Solvita® CO_2-Burst test was used (Groenfontein Farm, c/o R 44 and Anyswortelrug Rd, Klapmuts) to quantify microbial biomass.

Three trees were randomly selected from each orchard, and from each a composite soil sample was taken. Each composite sample comprised three subsamples collected from the top 30 cm of soil, evenly spaced apart within a 60 cm radius from the tree trunk. Samples were sealed in plastic bags and stored in cool, dark conditions before, during and after transport. The samples were free of any visible organic or inorganic material and were collected with a spade. The spade was cleaned in between the collection of each composite sample by sticking it into the ground three to five times on the corner of the orchard, in order to avoid cross contamination.

The samples were taken to a commercial laboratory, Soil Health Solutions (Groenfontein Farm, c/o R 44 and Anyswortelrug Rd, Klapmuts) where the Solvita® CO_2-burst tests were performed. Samples were dried, sieved and weighed out in beakers, after which they were remoistened. The remoistening causes a microbial respiratory response resulting in a sudden burst of CO_2 (Brinton and Laboratories 2017). A gel paddle is placed in the beaker with the soil and is sealed for 24 h. The gel paddle changes colour in response to the amount of CO_2 released, which is then measured using a digital colour reader (DCR) (Haney et al. 2008).

3.3.5 Weed Control (WC)

The weed control capabilities of *Tradescantia* was measured by placing a 1 m × 1 m grid (made of thin steel rods) on the ground at three randomly selected sites within each orchard. The number of weeds (other than *Tradescantia*) within the square was then counted according to Nicholson (2012). The grid was placed in the tree row, directly in the middle between, two randomly selected trees (Fig. 5).

3.3.6 Destructive Root Analysis (RC)

A destructive root analysis was performed on three randomly selected trees within each orchard to quantify the number and distribution of tree roots (Böhm 1979). A 1 m^3 hole was dug 50 cm from the tree trunk on 8 April 2018 and the root analysis was conducted during the following two days. The 1 m × 1 m grid was fitted to the roots of the tree along the tree row. The roots were left intact as much as possible and removed after the grid had been placed against the wall, leaving 1-5 cm of the roots protruding through the grid (Fig. 6).

Roots were categorised according to diameter and the number of roots per size category within each block were counted. A visual representation of the root distribution, or a root map, was constructed. The roots within different size categories were visually represented using a series of symbols (Table 1). The number of roots within each block that were smaller than 2 mm (smallest category) in diameter, were represented using a colour scale (Table 2). Furthermore, the root profile was analyzed in terms of the vertical distribution, thus the number of roots were quantified per row in order to determine if the living mulch roots affected the tree root distribution through competition for space, water and nutrients.

3.4 Results

3.4.1 Water-Holding Capacity (WHC)

The winter samples yielded a higher average WHC than the autumn samples for both treatments, and in both cases the TO treatment showed a higher WHC compared to the BO treatment (Fig. 7). For the autumn samples, the average water content was 15.84% (SE ± 4.57) for the TO treatment and 9.89% (SE ± 0.39) for the BO treatment. For the winter samples, the average water content for the respective treatments TO and BO was 24.09% (SE +/-1.68) and 14.41% (SE +/- 0.44).

3.4.2 Soil Temperature (ST)

At 10 cm depth, the TO treatment exhibited less fluctuation in soil temperature, and this pattern was displayed throughout the study period (Figs. 8, 9, 10). Thus, the daily maximum temperatures were often lower in the TO treatment compared to the BO treatment, and the daily minimum temperatures were always higher in the TO treatment, although these differences varied in magnitude. The most pronounced differences were seen at the minimum daily temperatures, where the temperature was often more than 1 °C higher in the TO treatment at 10 cm depth. The biggest differences in minimum temperatures were seen at shallow depths, between 10 cm and 30 cm, and the smallest differences, at soil levels deeper than 30 cm (Figs. 11, 12). On most days the minimum temperature was recorded at 08:00 in the morning and the average temperature at this time over the three-month trial period was 0.8 °C higher in the TO compared to the BO treatment at a soil depth of 10 cm. On most days the maximum temperature was recorded at 16:00 in the afternoon and the average temperature at this time was 0.11 °C lower in the TO compared to the BO treatment.

3.4.3 Soil Moisture (SM)

Soil moisture for treatments are depicted in Fig. 13. At a soil depth of 10 cm, the mean SM content was 10.75% lower in the TO compared to the BO treatment (ns). In contrast, at soil depths of 20 cm and 30 cm, the mean SM content was 20%, and 23% higher in the TO respectively, compared to that of the BO treatment. At 40 cm, the SM content of the TO was 16.38% lower than that of the BO treatment. In contrast, at 50 cm and 60 cm, the TO treatment again had a SM content, which was 11.15% and 7.6% higher than that of the BO treatment, respectively.

3.4.4 Microbial Biomass (MB)

The Solvita® CO_2-Burst test showed that the mean C released through respiration in the TO treatment was 90.83 ppm (SE ± 25.04) compared to 32.73 ppm (SE ± 8.66) in the BO treatment, nearly three times higher. The estimated PMN for the TO treatment was 76kg ha^{-1} compared to 43.05 kg ha^{-1} in the BO treatment. Finally, the calculated MB was 3851.12 kg ha^{-1} in the TO treatment, more than double that of that of the BO treatment (1686.42 kg/ha) (Table 3).

3.4.5 Weed Control (WC)

The average WC in the TO treatment was 0.67 m^{-2} (SE ± 0.33) compared to 6 m^{-2} (SE ± 1.46) in the BO treatment. Although there was much variation in the BO treatment, with some plots containing as few weeds as some of the TO treatment plots, some plots contained up to 11 weeds per m^2.

3.4.6 Destructive Root Analysis (RC)

The mean root count (which includes all root sizes) was 657 for the TO treatment and 702.67 for the BO treatment. The BO treatment contained a higher number of small roots (0-20 mm), whereas the TO treatment contained more big roots (>20 mm), especially in the >50 mm category (Fig. 14).

Although the root profiles between the two treatments were very similar, the area of densest root concentration occurred at different depths between the two treatments (Fig. 9). Root concentration in the top 10 cm was similar for both orchards, while the biggest differences could be seen at 10-20 cm, 30-40 cm, and 50-60 cm, where the BO treatment had higher root concentrations (Fig. 15). In spite of the variation between replicates, the overall root count was slightly higher in the BO treatment. The largest concentration of roots for the TO treatment was between 40-50 cm, while the largest root concentration for the BO treatment was between 30-40 cm. The TO treatment also yielded much higher root counts at the deepest levels, between 80-90 cm. Although root counts were similar between 0-10 cm, the BO treatment had a much higher count at 10-20 cm.

3.5 Discussion

3.5.1 Water-Holding Capacity (WHC)

The WHC was significantly higher in the TO treatment, both in autumn and winter (Fig. 7). However, both treatments yielded a higher WHC in winter, compared to autumn. This may be largely attributed to the fact that the winter samples were collected two days after a rain event, which resulted in higher overall water content of the soil. The higher WHC for the TO treatment is possibly a result of the anatomy and growth pattern of *Tradescantia*, that formed a dense mat (or stands) that completely covered the soil surface. Bare soil surfaces are vulnerable to crusting, which can be caused by impact of droplets and runoff and that lowers water infiltration rate and hydraulic conductance of the soil (Zuazo and Pleguezuelo, 2008). Therefore, this thick vegetative mat may have facilitated improved water dynamics in the topsoil by reducing droplet impact, runoff and crusting, and improving water infiltration and water storage capacity of the soil (Merwin and Stiles 1994; Zuazo and Pleguezuelo 2008). Maintaining plant cover on the soil surface also increases SOC and humus levels (Jones 2008; Leu 2007; McKenzie 2010), which improves soil structure, and subsequently, water infiltration and retention (Bronick and Lal 2005; Leu 2007). Results from the continuous logging probes show substantially higher SM levels in the TO treatment, at depths of 20 cm and 30 cm (Fig. 13). This supports the findings of higher WHC in the TO treatment, as samples were collected from the top 30 cm of soil. Soils with a higher WHC are more water efficient than soils with a lower WHC, simply because they are able to store water in the root zone of the crop for a longer period of time, which may allow farmers to reduce the amount of irrigation water given to trees.

3.5.2 Soil Temperature (ST)

The fluctuation in the ST was notably less in the TO treatment (Figs. 8, 9, 10). On most days, the maximum temperatures in the TO treatment were lower and the minimum temperatures, higher compared to the BO treatment. This was more prevalent in the upper soil layers, whereas at deeper levels, the soil temperature barely fluctuated within a 24 h cycle (Fig. 11, 12). The largest daily fluctuations in both treatments occurred at a depth of 10 cm, and this is where the *Tradescantia* seemingly had the greatest buffering effect. The study was conducted during the colder months of the year, thus the buffering ability of *Tradescantia* against maximum summer temperatures was not available. Under high temperature conditions, living mulches are able to reduce evaporation compared to bare soil (Qian et al. 2015). Since summer temperatures may reach up to 45 °C, the ability of *Tradescantia* to lower the temperature at the soil surface may play an important role in regulating the soil moisture regime and reducing water loss through evaporation (Standish et al. 2004). Thus, it is plausible that the temperature buffering capabilities of *Tradescantia* are potentially higher than what was found in this study. This is due to the fact that the density of the *Tradescantia* mat was unintentionally reduced around the DFM probe, due to regular inspection of the probe by humans. Since *Tradescantia* is easily damaged by physical force, the thickness of the mulch layer may have been substantially reduced over the three-month study period.

3.5.3 Soil Moisture (SM)

Since the patterns of SM content in the two respective treatments were consistent throughout the study period (Fig. 13), *Tradescantia* may have influenced the SM regime (Standish et al. 2004). In the top 10 cm of soil, the *Tradescantia* roots may be utilizing a considerable amount of water for growth, accounting for the lower SM content at this depth in the TO treatment. In addition, some moisture could have been lost to the atmosphere through evapotranspiration. However, *Tradescantia* roots are tiny and are unable to reach beyond 10 cm in depth, thus they would very unlikely be able to utilize soil moisture beyond this depth. Yet, it may be able to enhance water infiltration in the deeper levels of the soil profile, even beyond the reach of its roots (Zuazo and Pleguezuelo 2008). This possibly explains the significant higher SM content at depths of 20 cm and 30 cm in the TO treatment. A larger proportion of water infiltrates the soil to depths beyond the reach of the *Tradescantia* roots where it may be utilized by the tree roots. At depths of 50 cm and 60 cm, the SM was also greater in the TO treatment; however, the reason for the sharp decrease in SM in the TO treatment at 40 cm is unclear. The higher WHC in the top 30 cm of the soil profile in the TO treatment supports the higher apparent SM content in this same region.

3.5.4 Microbial Biomass (MB)

The amount of C and subsequent calculated MB was significantly higher in the TO treatment (Table 5). A number of contributing factors may be responsible for this observation. Firstly, the living roots of the *Tradescantia* exude simple carbohydrates, increasing SOC levels via the 'liquid carbon pathway', and supporting increased levels of microbial activity (Jones 2008; Qian et al. 2015). Secondly, the specific microclimate created underneath the dense *Tradescantia* mats may alter the moisture regime, as well as insect and microbial populations (Standish et al. 2004; Toft et al. 2001). Toft et al. (2001) found that *Tradescantia* mats were associated with reduced species richness for both beetles and fungus gnats, when compared with native forest floor cover. This was accredited to the reduced plant species richness in areas where *Tradescantia* has established (Toft et al. 2001). Although *Tradescantia* mats reduce the microbial and insect species richness compared to native ground cover, the findings of Standish et al. (2004) suggest that these changes in community composition may facilitate greater decomposition of organic matter, which in the context of a Citrus orchard may lead to a desirable outcome. In addition, although the species richness and microbial diversity under *Tradescantia* mats may be lower compared to a native ecosystem, it may compare favorably when compared to bare soil.

The estimated PMN was also significantly higher in the TO treatment. According to Qian et al. (2015) living mulches may influence soil nutrient availability in three ways, including (1) decreasing soil nutrient availability by absorbing soil nutrients (2), increasing soil nutrients by, stimulating soil microbial activity, which releases nutrients via mineralisation and (3), by increasing available nutrients through root exudates, which enhance soluble compounds in the soil. Under high NO_3^- conditions, NO_3^- accumulates in *Tradescantia* shoots without compromising growth. This stored NO_3^- is used for growth when soil N levels are low (Maule et al. 1995). Plant growth has been found to increase as soil NO_3^- concentrations increase from 0.1 to 5.0 $mol.m^{-3}$, after which it slows down (Maule et al. 1995). Plant growth was similar for plants supplied with low concentrations (0.1 to 1 $mol.m^{-3}$) of NH_4^+ and NO_3^-, whilst at higher concentrations (5.0 $mol.m^{-3}$) plants supplied with NO_3^- showed greater growth compared to the ones supplied with NH_4^+. The plants supplied with NH_4^+ also displayed leaf damage and therefore *Tradescantia* shows no abnormal ability to utilize NH_4^+ compared to most other plant species, and displays comparative sensitivity (Maule et al. 1995).

Tradescantia had a significant effect on litter decomposition and nutrient availability in forest remnants in New Zealand. The *Tradescantia* mats trap leaf litter directly underneath it, which is then penetrated by the roots, thus altering the natural decomposition process and nutrient cycles (Standish et al. 2004). Floor litter under *Tradescantia* mats was found to decompose at nearly twice the decomposition rate of litter outside of these mats (Standish et al. 2004). Moreover, available soil N under *Tradescantia* mats was more than double that of the non-*Tradescantia* plots (Standish et al. 2004). Some of the contributing factors included the fact that *Tradescantia* litter has a high N content due to its ability to accumulate NO_3^- in its shoots (Standish et al. 2004). In addition, the decomposition rate of *Tradescantia* litter is higher than that of native forest litter due to the fact that it has lower C:N and lignin:N ratios, which are good indicators of decomposition rate (Standish et al. 2004). Interestingly, the total length and dry weight of individual shoots were found to be similar at the beginning and end of a two-year period, despite the overall stem growth rate of 60-70 $cm.year^{-1}$ (Maule et al. 1995). The rate of apical growth on the vertical stem is equal to the rate of decay at the base of the horizontal stem, a self-pruning mechanism believed to be associated with coping with high light attenuation (Maule et al. 1995). This rapid growth- and decomposition rate suggests that *Tradescantia* may increase the rate of nutrient cycling, especially for N and C.

3.5.5 Weed Control (WC)

The weed counts were significantly lower in the TO treatment, despite the great variability in the BO treatment (Table 6). Since the TO treatment was not subject to any method of WC, the reduced weed counts are accredited to the mulching abilities of *Tradescantia*. *Tradescantia* is known for preventing native forest regeneration where it has invaded lowland forest remnants in Florida, eastern Australia, and New Zealand (Standish et al. 2004). *Tradescantia* thrives in such moist areas and forms dense, smothering mats along the ground of up to 60 cm thick, thus disturbing the natural regeneration cycle by suppressing native seed germination and seedling growth (Maule et al. 1995). Thus, these characteristics may be the main mechanism through which *Tradescantia* is able to suppress weed growth, rather than allelopathy. *Tradescantia* also has a remarkably high shoot to root ratio (S:R), with shoot dry weight (DW) always making up more than 95% of total DW regardless of irradiance levels (Maule et al. 1995). Therefore, it likely prevents weed seedlings from reaching maturity, not by competition for water and resources (since roots are very small), but by reducing irradiance levels on the soil surface. In a study analyzing the ability of plant species to suppress and tolerate competitors based on root characteristics, it was found that plants with shallow, horizontally spread root systems are better at suppressing other plants, but not as effective at resisting competition, while plants with deeper vertical root systems were less effective at suppressing other plants, but offered greater resistance to competition (Semchenko et al., 2018). Therefore, the coexistence of *Tradescantia* (shallow roots) and citrus trees (deep roots) may result in efficient weed suppression without the tree being negatively affected by the competition.

Tradescantia is predominantly known as a shade plant, however through most of the year it has been found to grow at irradiance levels from 1% to 90% normal daylight (Maule et al. 1995). The growth of *Tradescantia* is thus limited to shaded areas (such as the shade of the citrus trees), which acts a self-control mechanism, preventing it from spreading beyond control, into neighboring orchards or natural vegetation. It is likely that this high S:R is the primary factor limiting

Tradescantia to shaded areas, as this will result in excess water loss in areas with irradiance levels above 90 % (Maule et al. 1995). It is also vulnerable to physical force, and the movement of machinery through the work row prevents it from establishing there.

3.5.6 Destructive Root Analysis (RC)

The region of highest root concentration for the TO treatment occurred at deeper soil depths compared to the BO treatment. The TO treatment also displayed higher overall root concentrations in the deeper soil levels, and lower root concentrations in the upper soil levels compared to the BO treatment. The lower root concentrations in the upper soil layers in the TO treatment may be due to the competition provided by the *Tradescantia*. This is supported by the findings of Dawson et al. (2001), in which cherry (*Prunus avium* L.) tree roots displayed higher concentrations at deeper levels due to competition by grasses in the upper soil layers, in an agroforestry system. Fernandez et al. (2008) also found that grasses and pine trees in an agroforestry system displayed some degree of complementarity in soil water usage, as the trees utilized water deeper down the soil profile, compared to trees in a monoculture system. Based on the different root systems of *Tradescantia* and citrus trees, the coexistence of the two species may result in sufficient weed control by *Tradescantia*, and minimal negative impact on the citrus trees in terms of competition, since the citrus roots are tolerant of the competition by the shallow *Tradescantia* roots (Semchenko et al. 2018).

3.6 Conclusions

Using *Tradescantia* as a living mulch increased the WHC of the soil, probably by improving water infiltration throughout the soil profile. Although the *Tradescantia* mulch utilizes some of the soil water for its own growth, this mainly occurs in the top 10 cm of soil, and had a net positive effect on the overall SM content of the majority of the rest of the soil profile.

The root distribution of trees was slightly altered, as the TO treatment generally had higher root concentrations at deeper soil levels, while the BO treatment generally had higher root concentrations at shallower depths. This is probably because in the TO treatment, trees utilized deeper soil water due to the competition of the *Tradescantia* in the upper soil layers.

Tradescantia also provides relatively effective chemical-free WC, but the effect of *Tradescantia* on nutrient competition was not quantified in this study. Furthermore, it also provides buffering against temperature fluctuations, particularly in the top 10 cm depth. The *Tradescantia* mulch also nearly tripled the amount of C released from soil via microbial respiration, and subsequently MB was also nearly three times greater compared to the BO treatment. The ability of *Tradescantia* to substantially increase soil C levels means that it can positively contribute toward C sequestration, and improving the C footprint of perennial orchards.

Based on the above, *Tradescantia* as living mulch may improve the overall sustainability and resilience of citrus production systems, as far as soil health is concerned. However, due to the invasive status of this plant, and the threat it poses to the longevity of certain natural ecosystems, it may present problems if it is not carefully managed. Thus, the propagation of this plant is not allowed. This study merely investigated the possible benefits thereof when applied to a citrus production system as a living mulch, and the commercial use of this plant at this stage is ill advised.

3.6 References

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APPENDIX A

Table 1. Key used for classification of roots according to diameter. Roots within each category are represented by the corresponding symbol in the root map, to visually illustrate the root distribution.

Root Diameter	Symbol
< 2 mm	Colour scale
2 mm - 10 mm	·
10 mm - 20 mm	∘
20 mm - 50 mm	○
> 50 mm	◯

Table 2. Colour scale used to represent the number of roots smaller than 2 mm in diameter within each block. Each block was assigned a shade of grey that corresponds with the number of roots (< 2 mm) within it. This method was used instead of symbols due to the large number of roots smaller than 2 mm.

Number of roots	Shade
0	
1-9 roots	
10-19 roots	
20-29 roots	
30-40 roots	

Table 3. Root maps of three randomly selected trees in the TO treatment (*Tradescantia* mulch). The different shades of grey represent the corresponding number of small roots (< 2 mm) (Table 2). The symbols each represent one root within the corresponding size category (Table 1).

Tree 1

	Profile width (cm)									
	10	20	30	40	50	60	70	80	90	100
10		▪▪▪▪▪								
20				▪▪▪▪	▪▪▪▪▪▪▪∘		▪	▪▪	▪▪▪	▪▪▪▪
30			▪▪▪▪	▪▪	▪▪▪▪▪▪▪▪▪▪	▪▪▪▪	▪▪▪▪	▪▪	▪▪	▪
40	▪	▪		▪	▪▪	▪▪	▪	▪▪∘	▪▪	
50	▪▪▪▪	▪	▪∘	∘	○	○	▪▪▪	▪▪▪∘	▪	
60		○			▪▪▪○	▪▪▪○	▪	▪▪▪▪▪	▪▪	
70	▪∘	▪		∘ ◯				▪▪		
80	▪∘		▪	▪				▪		
90										

Tree 2

	Profile width (cm)									
	10	20	30	40	50	60	70	80	90	100
10										
20										
30			∘	▪ ◯	▪					
40	▪		▪	∘		▪○				◯
50	∘			▪			∘		◯	
60			∘	▪▪∘	○		∘			
70				▪○	▪▪					
80				▪	▪▪		▪			▪
90										

Tree 3

	Profile width (cm)									
	10	20	30	40	50	60	70	80	90	100
10										
20								▪		
30	∘		▪▪∘		▪	▪	▪▪	▪▪	▪	
40	▪▪○	▪	▪	▪		▪▪	▪▪▪ ◯	○	▪▪∘	▪▪
50			▪▪		▪	▪▪	▪▪ ◯	▪▪▪▪	◯	▪▪▪∘∘
60		▪∘	▪▪		▪▪▪	▪▪	▪▪▪	▪	▪▪▪▪▪	
70		▪		▪	▪▪				○	▪∘
80						▪▪			▪	
90			▪	▪						

Table 4. Root maps of three randomly selected trees in the TO treatment (*Tradescantia* mulch). The different shades of grey represent the corresponding number of small roots (< 2 mm) (Table 2). The symbols each represent one root within the corresponding size category (Table 1).

Tree 1										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10									∘	
20	▪				▪▪	▪▪○			○	▪
30	▪▪▪		∘∘	▪	▪▪▪▪	▪▪▪▪○	∘○	▪▪		∘
40	▪▪▪▪∘	▪▪▪	▪▪▪∘	▪▪▪▪▪∘	▪▪▪▪	▪▪▪		▪▪▪	▪▪▪	
50	▪▪	▪▪	▪▪▪▪▪▪	▪	▪▪	▪▪▪▪	▪	▪	▪▪	▪∘
60	▪▪			▪				▪	▪	▪▪▪
70	▪∘		▪	▪		▪	▪▪∘		▪	▪▪▪
80									▪▪	▪
90	▪		▪		▪		▪	▪		

Tree 2										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10	▪									▪
20	▪	▪▪		∘		▪▪▪∘			∘	
30	▪▪▪	▪∘∘○		▪▪∘	▪▪∘∘∘∘		▪∘	▪∘		▪∘
40		▪▪▪▪	▪▪▪	▪▪	▪▪○	▪▪▪∘	▪▪▪∘	▪▪▪▪∘	▪▪▪	▪
50	◯		▪▪				▪	▪		▪
60			▪		▪▪		▪		▪▪▪∘	▪▪▪
70	▪	▪▪	▪	▪▪	▪		▪▪	▪		
80			▪▪							
90										

Tree 3										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10	▪				▪					
20	▪	▪	▪∘		▪	▪▪	▪▪▪∘∘		▪	
30		▪○	▪▪∘	▪∘∘	▪			∘○	▪	
40		◯						○		
50		∘		∘	▪▪	▪		▪		
60	∘		▪▪▪				∘	▪	▪▪	▪▪▪
70			▪	▪				▪▪∘	▪	▪
80		▪			▪				▪	▪
90										

Table 5. Results of the Solvita CO_2-Burst test. The amount of carbon released as CO_2, through microbial respiration, is shown in ppm C. The estimated potential mineralizable nitrogen is shown as estimated PMN (kg/ha), and the calculated microbial biomass (MB) in $kg.ha^{-1}$.

	CO_2 released (ppm C)	Estimated PMN ($Kg.ha^{-1}$)	Calculated microbial biomass ($Kg.ha^{-1}$)	Number of weeds per m^2
TO	90.83 ± 25.04	76.54 ± 12.67	3851.12 ± 1290.26	0.67 ± 0.33
BO	32.73 ± 8.66	43.05 ± 7.32	1686.42 ± 445.99	6 ± 1.46

Fig. 1. *Tradescantia* mat in the tree row with the irrigation system suspended above the ground along a wire from one tree to another.

Fig. 2. Mats of *Tradescantia* that are well established in a Navel orange orchard.

Fig. 3. DFM® continuous logging probe placed in the *Tradescantia* mulch (TO treatment).

Fig. 4. DFM® continuous logging probe placed on a bare patch where the *Tradescantia* mulch has been cleared (BO treatment).

Fig. 5. Weed count conducted to quantify the weed control capabilities of *Tradescantia with a* 1 m × 1 m grid.

Fig. 6. Destructive root analysis being performed in the *Tradescantia* orchard using a 1 m × 1 m grid.

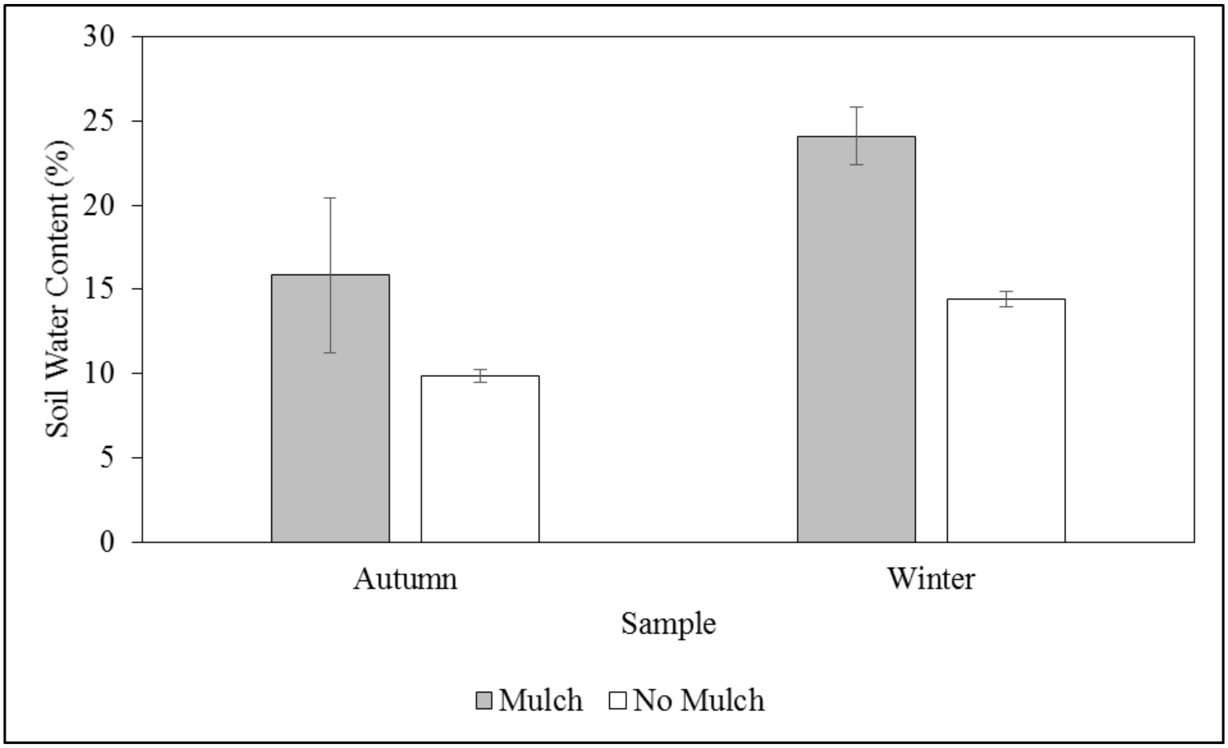

Fig. 7. Mean WHC for the autumn and winter measurements, for both the TO (Mulch) and BO (No Mulch) treatments. Values indicate means with standard errors.

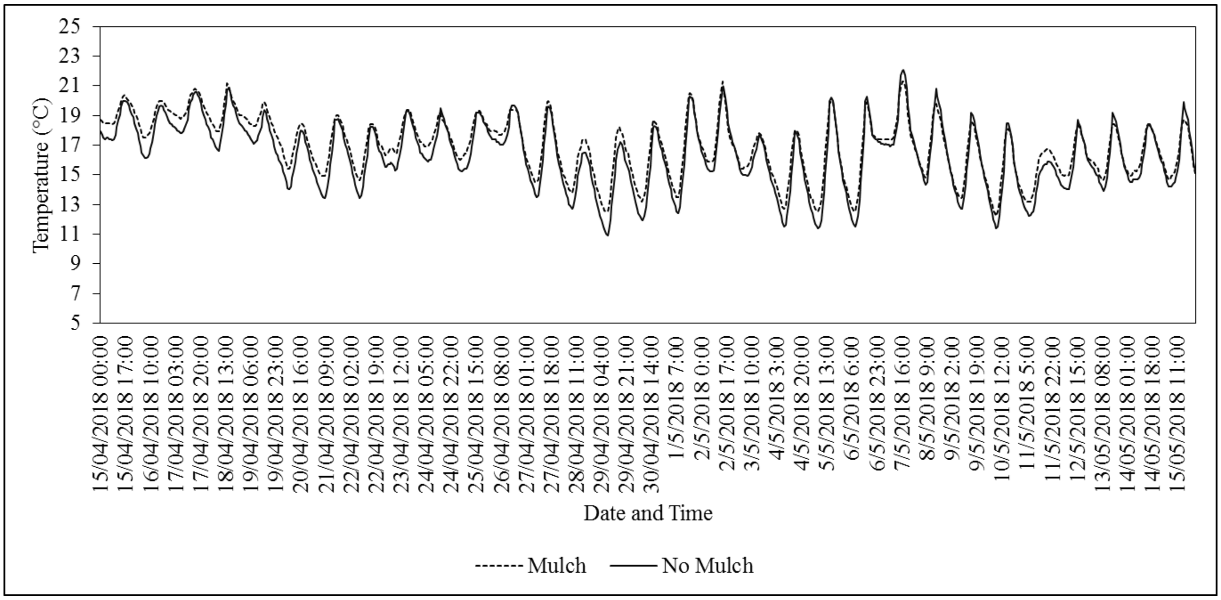

Fig. 8. Soil temperatures for both the TO treatment (Mulch) and BO treatment (No Mulch), at 10 cm soil depth, from 15 April to 15 May. Soil temperature was measured using DFM continuous logging probes.

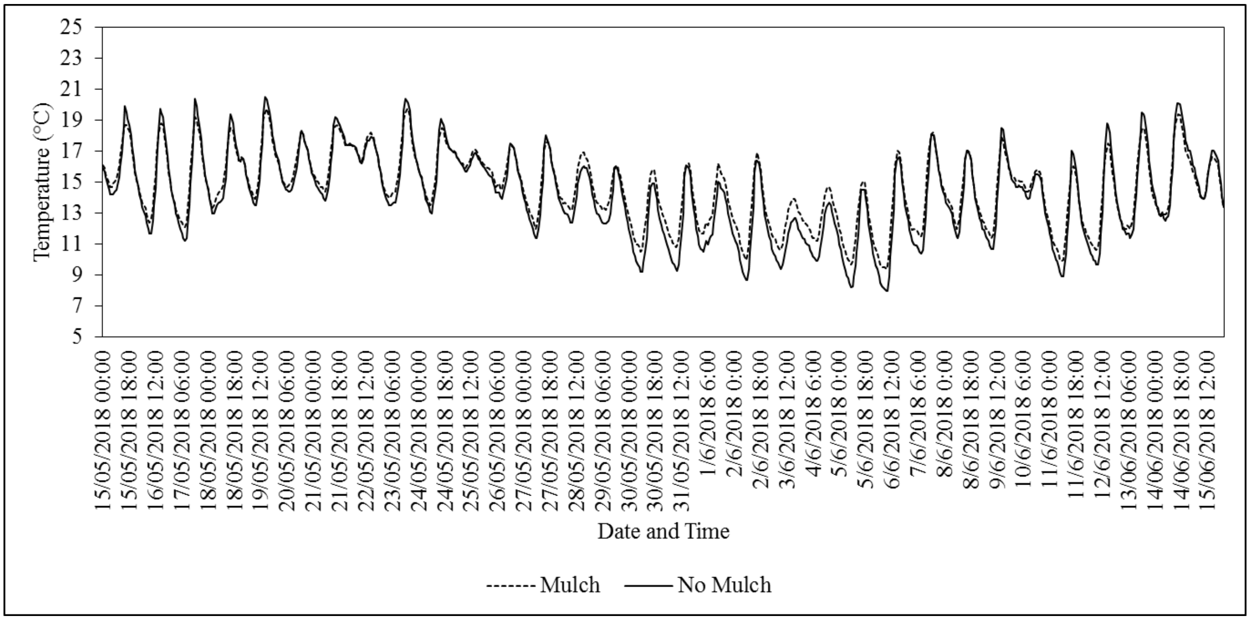

Fig. 9. Soil temperatures for both the TO treatment (Mulch) and BO treatment (No Mulch), at 10 cm soil depth, from 15 May to 15 June. Soil temperature was measured using DFM continuous logging probes.

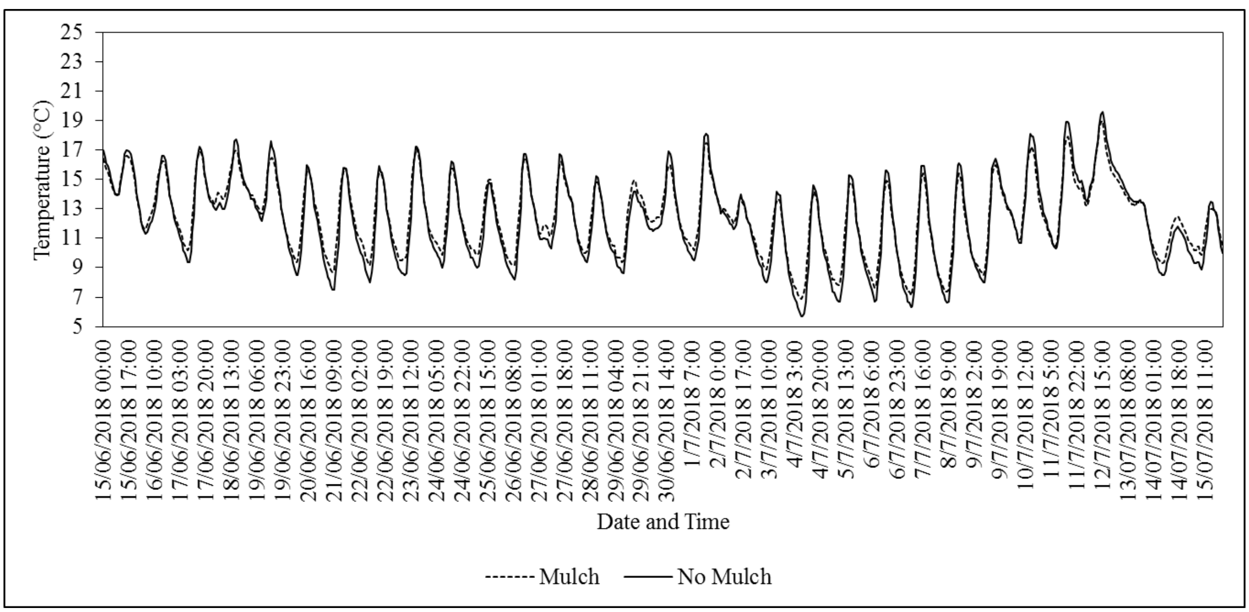

Fig. 10. Soil temperatures for both the TO treatment (Mulch) and BO treatment (No Mulch), at 10 cm soil depth, from 15 June to 15 July. Soil temperature was measured using DFM continuous logging probes.

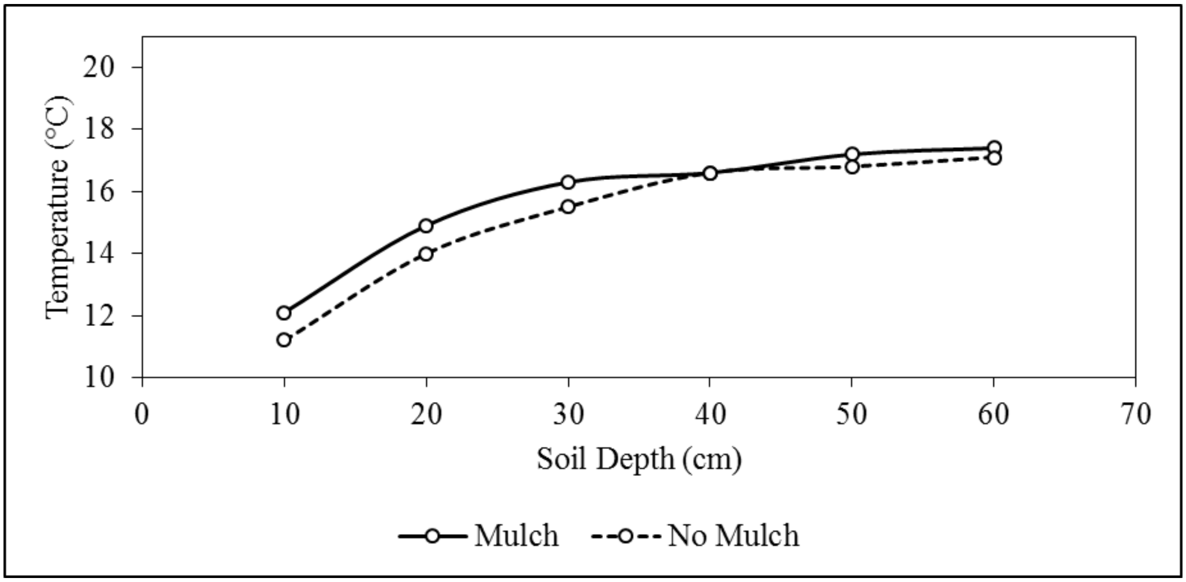

Fig. 11. Soil temperatures for both the TO treatment (Mulch) and the BO treatment (No Mulch) at different soil depths, at 08:00 h on 17 May 2018. The minimum temperature at 10 cm soil depth was recorded at 08:00 h on most days.

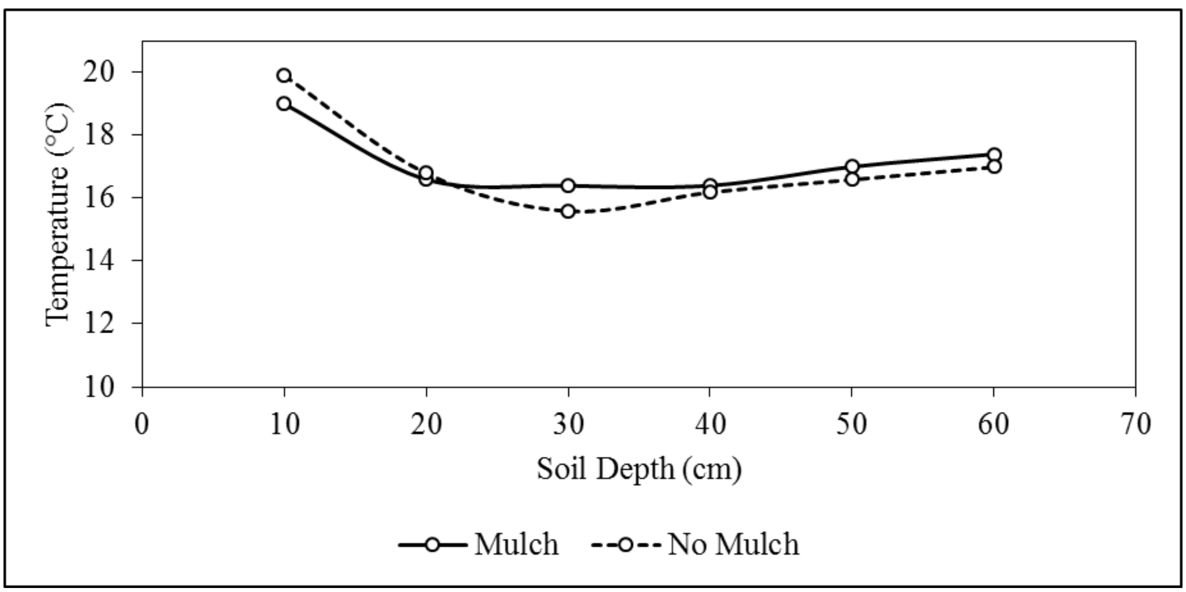

Fig. 12. Soil temperatures for both the TO treatment (Mulch) and the BO treatment (No Mulch) at different soil depths, at 16:00h on 17 May 2018. The maximum temperature at 10cm soil depth was recorder at 16:00h on most days.

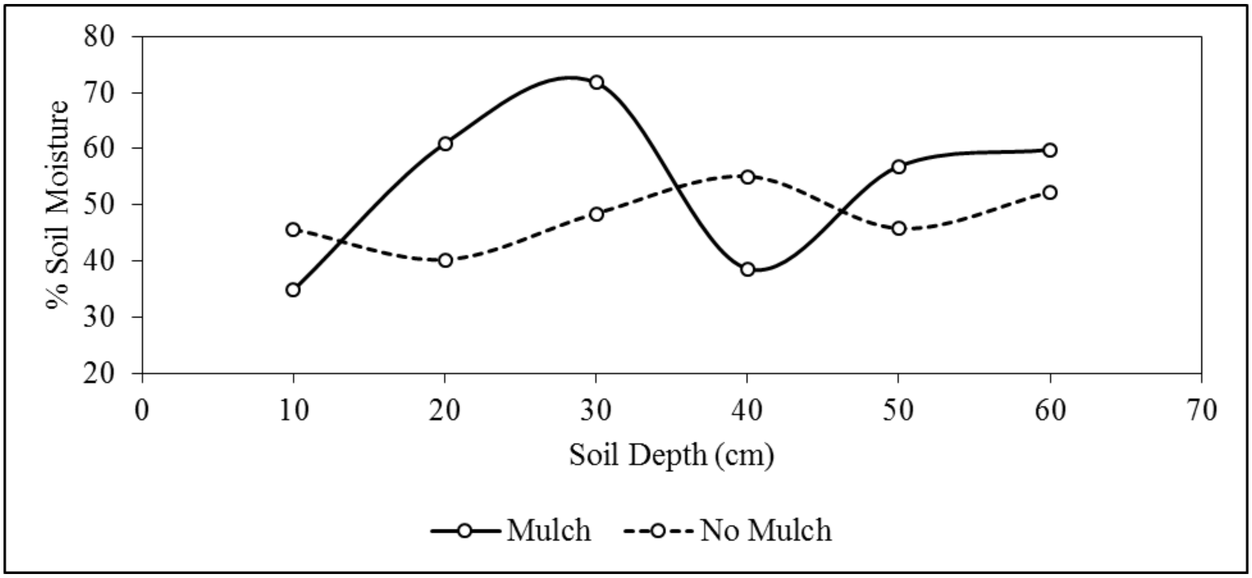

Fig. 13. Average soil moisture (SM) content (%) at different soil depths from 15 April to 15 July 2018, for both the TO (Mulch) and BO (No Mulch) treatments. Soil moisture was measured using DFM continuous logging probes.

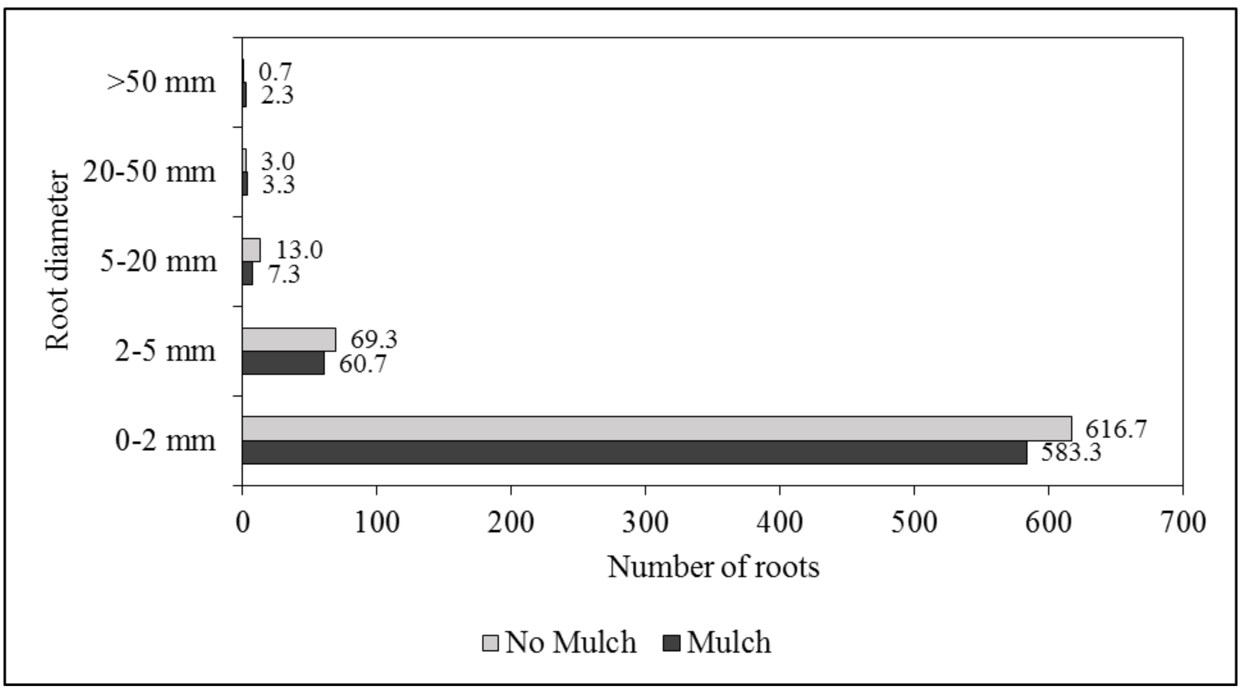

Fig. 14. Mean number of roots within each size category for both TO (Mulch) and BO (No Mulch) treatments.

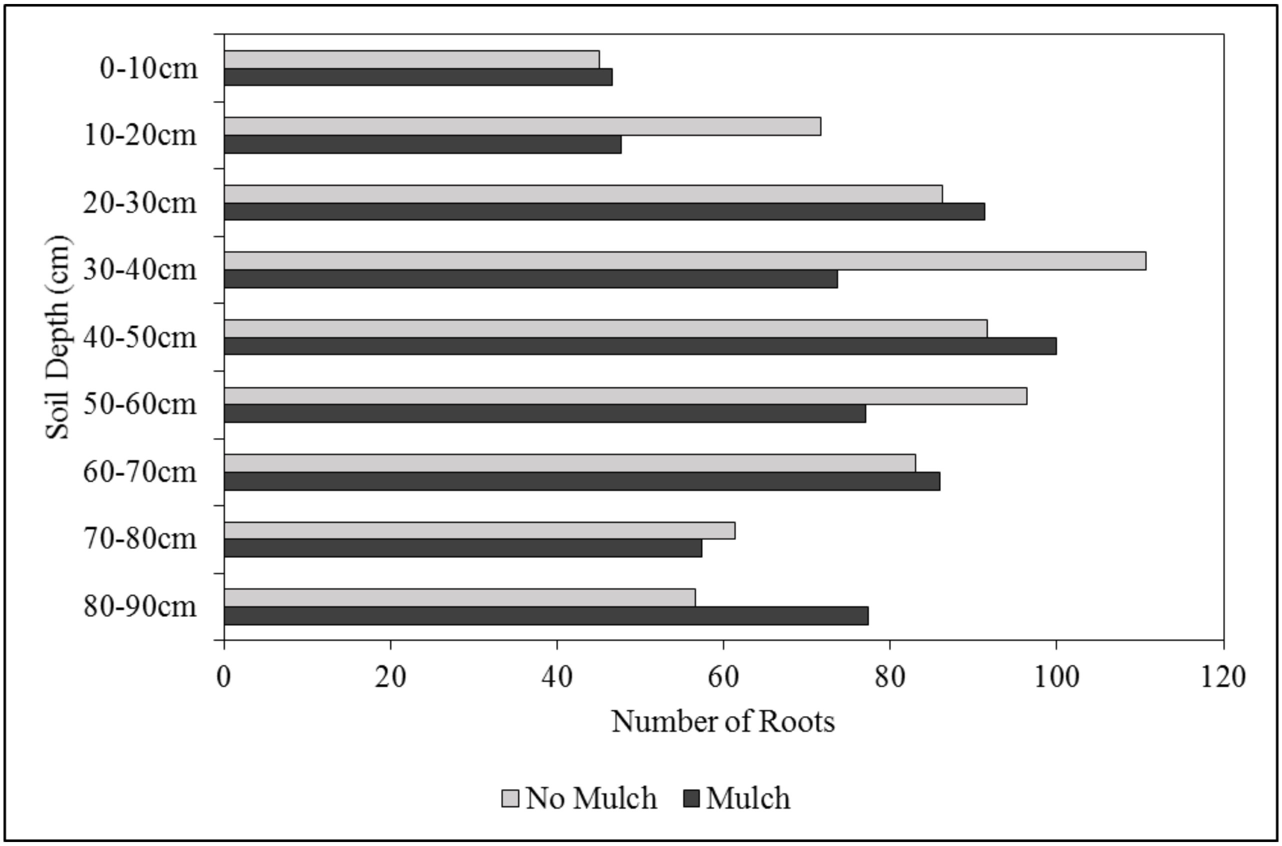

Fig. 15. Graph showing the mean number of roots at different soil depths for both TO (Mulch) and BO (No Mulch) treatments.

CHAPTER 4

Investigating the potential of *Bromus diandrus* as a living mulch in a plum orchard in the Western Cape, South Africa

4.1 Abstract

The suitability of *Bromus diandrus* (*Ripgut*) as a novel living mulch species was investigated by quantifying its effect on soil-plant dynamics in a ‘Sunkiss’ plum (on Mariana rootstock) orchard, in the Western Cape, South Africa. This region has experienced one of the worst droughts in history, leading to substantial losses in the agricultural sector. There is thus a need for agro-ecological innovation in order to improve the resilience, resource efficiency and sustainability of fruit production systems. In this study, various indicators including soil water-holding capacity (WHC), soil temperature (ST), soil moisture (SM) and soil microbial biomass (MB), weed control (WC) and root distribution of trees (RC) were compared between areas where *Ripgut* was well established (RM treatment) and herbicides were applied for clean cultivation (CC treatment). Results indicated higher WHC and SM levels in the RM treatments, possibly due to improved water infiltration throughout the soil profile. ST showed less fluctuation in the RM treatment, as daily maximum temperatures were consistently lower and daily minimum temperatures were higher, compared to the CC treatment. This was especially prevalent at shallow soil depths. Microbial biomass was unchanged between the two treatments. However, there may be a link between MB and the growth cycle of *Ripgut*. *Ripgut* also provided sufficient WC as weed numbers were significantly lower in the RM treatment. Tree root distribution was similar in both treatments, although trees in the RM treatment had a higher average root count, especially for roots < 1 mm in the top 20 cm of the soil profile. Under these commercial conditions, *Ripgut* contributed as living mulch towards ecosystem services that may positively influence the resource efficiency of plum orchards, especially with regards to water, as well as improved resiliency and sustainability within these systems.

Key words: *Bromus diandrus*; Perennial orchard; Sustainability; Resilience; Water-holding capacity.

4.2 Introduction

Southern Africa, in particular the Western Cape region, has been subject to an increase in extreme weather events since 1970, especially with reference to precipitation (Fauchereau et al. 2003). Climate change, in particular the increased probability and severity of droughts, is believed to be one of the greatest threats to future agricultural sustainability and food security in southern Africa (Müller et al. 2011). Indeed, Western Cape producers have endured one of the worst droughts in history in the 2017 season, which has forced farmers to look at novel ways to ensure efficient use of the limited supply of irrigation water (Beerwinkel 2017). Since 2017, the Western Cape Agricultural sector has reduced its water usage by 60%, resulting in subsequent monetary losses of R5.9 billion, approximately 30 000 job losses and a decline in exports of up to 20% (Roux, 2018). The Western Cape is the biggest exporter of agricultural commodities in South Africa, and with current climate change trends expected to continue, drastic innovation is needed in order to secure a sustainable future for Western Cape fruit producers (Roux 2018).

The Western Cape has a Mediterranean climate and is thus a strictly winter rainfall area, receiving 66% (558 mm) of its annual rainfall (843 mm) from May to August (South African Weather Service 2010). In perennial orchards, water mostly becomes a limiting factor during the hot, dry summer months, when crops are dependent on irrigation water (Beerwinkel 2017). Since maximum temperatures may reach up to 45 °C in summer (South African Weather Service 2010), it is imperative that producers adopt orchard floor management practices that maximize water use efficiency by reducing water losses through evaporation, runoff, and poor infiltration. Cover cropping and mulching may address this issue, along with a number of additional benefits pertaining to conservation agriculture and sustainable resource use (Granatstein and Mullinix 2008; Hartwig et al. 2002; Paine and Harrison 1993).

Mulching, including the application of inorganic materials such as gravel, stones, polyethylene plastic films and geotextiles (Lötze 2014; Prosdocimi et al. 2016), or organic materials such as prunings, bark chips, fruit pips and vegetative material like straw (Kader et al. 2017; Lötze 2014), is applied in the tree row in perennial orchards, while cover crops are typically grown in the work row (alley) (Hammermeister 2016). These two strategies differ not only in locality, but also in functionality, since living plant roots of cover crops may influence soil dynamics in ways that inert mulches can't (Leu 2007). Although living mulches are a less commercially popular method, it combines the functional properties of cover crops with the localised benefits of mulching, which can be applied directly in the tree row, thus leading to improved soil fertility and resource use efficiency in the root zone of trees (Hartwig et al. 2002; Qian et al. 2015).

In apple orchards, a number of living mulch species significantly increased soil microbial diversity and biomass, soil organic carbon (SOC) levels, as well as nitrogen levels in the case of legumes (Qian et al. 2015). Without negatively affecting yield, subterranean clover (*Trifolium subterraneum* L.) has also been shown to be an excellent method of chemical-free weed control in five different vegetable crops, (Ilnicki and Enache 1992), while mowed Sunn hemp (*Crotalaria juncea*) was able to suppress above- and belowground pests in green onions, (Quintanilla-Tornel et al. 2016). Furthermore, many living mulches may greatly reduce soil erosion and improve water infiltration in the root zone (Hartwig et al. 2002). The major concern with living mulches is that they may compete directly with crops for soil resources (principally water and nutrients), as they share the same root space (Paine and Harrison 1993). Limiting this competition is therefore of paramount importance to the successful implementation of this practice on a commercial scale (Paine and Harrison 1993).

Limited research has been carried out to identify novel plants as potential living mulches. Studies have focused on a limited number of species, typically other crops and cover crop species such as clovers (Ilnicki and Enache 1992), vetch species (Qian et al. 2015) and grasses (Liedgens et al. 2004). In 1982, 139 grass and legume species were identified as potential living mulches (Paine and Harrison 1993). Locally, Fourie (2014) conducted a study on fynbos and renosterveld species as cover crops in Western Cape vineyards. Fynbos and renosterveld form part of the indigenous flora of the Greater Cape Floristic Region (GCFR), which is considered a global biodiversity hotspot (Fourie 2014). These species may be well adapted to local conditions and may provide less competition for resources and require less maintenance (Perry et al. 2009). However, Fourie (2014) found that these native species were unsuccessful at suppressing weeds. Hartwig et al. (2002) suggested that certain weed species could be suitable as living mulches, since weeds are hardy and adaptable to adverse conditions, while they may be competitive enough to suppress other weeds. However, very little is known about the mulching abilities of different weed species.

Since the Western Cape is a winter rainfall area, the ideal living mulch may be a winter annual that can utilize water from the winter rains during its growth phase, and die off in late spring when rainfall declines, to avoid competition during the dry period (Alonso-Ayuso et al. 2014). Theoretically, this will result in a layer of dead vegetative material on the surface of the soil, which may function as an inert mulch during the hot, dry summer months, conserving soil moisture and promoting more effective use of irrigation water (Paine and Harrison 1993). Intact root systems may also promote improved infiltration and reduced erosion throughout the year without actively competing for water and nutrients (Zuazo and Pleguezuelo 2008). Ideally, these species should also have a shallow root system in order to limit the depth competition with tree roots during its growing season (Dawson et al. 2001).

The species *Bromus diandrus* (hereafter referred to as *Ripgut*) belongs to the class *Monocotyledonae*, the order *Cyperales*, the family *Poaceae* and the genus *Bromus*. It is commonly known as Ripgut brome, Brome grass, Ripgut grass, Jabbers, Spear grass, or Sterile brome (Quattrocchi 2006). In current literature, *Bromus rigidus* is considered a subspecies of *Bromus diandrus*. *Ripgut* is a winter annual grass that is native to the Mediterranean, but it has been naturalized in many countries around the world, most notably in California and Australia, where it has replaced many of the native grasses (Kon and Blacklow 1988). It is often found along roadsides, fences, grasslands, woodlands, disturbed landscapes, riverbanks and cultivated lands (Quattrocchi 2006). *Ripgut* is a notorious weed in cereal crops in southern Australia that may lead to significant reductions in yield (Malone et al. 2016). Herbicides provide ineffective control of *Ripgut* (García et al. 2014). Indeed, there are two *Ripgut* populations that have exhibited resistance to glyphosate, the most commonly used herbicide globally (Malone et al. 2016). In areas of invasion, *Ripgut* has been found to affect the seedling germination of native species, mostly due to the formation of a thick layer of litter that causes a physical barrier, rather than allelopathy (Chen et al. 2018). *Ripgut* seeds, however, require dark conditions for germination and therefore readily germinate under the mulch layer with the first big rains in late autumn (Kleemann and Gill 2013).

The character profile of *Ripgut* may render it a suitable living mulch for plum orchards in the Western Cape. It is well adapted to Mediterranean climates and its growth cycle coincides with the rainfall patterns and water availability in the region. It may thus utilize the excess rainwater in the winter months for its growth phase, while providing a dead litter layer that acts as an inert mulch during the dry summer period, when water is a scarce resource. Furthermore, it may potentially improve soil properties and soil fertility, while reducing soil erosion and providing chemical-free weed control.

Although *Ripgut* is a grass with invasive tendencies, it has been largely naturalized in South Africa and is not officially classified as a weed (Milton 2004). Although it may negatively impact native vegetation in some parts of the world, its possible advantageous functions on disturbed land, such as orchards, still needs to be fully elucidated (Milton 2004). Thus, contrary to conventional thinking, in the context of man-made landscapes such as intensive agricultural systems, adaptable alien species such as *Ripgut* may yet positively contribute toward more sustainable use of natural resources, more resilient agricultural systems, and future food security. The aim of this study was to investigate the potential of *Ripgut* as a living mulch in a plum orchard in the Western Cape region of South Africa, focusing on changes in soil health as a measurement of sustainable management practices.

4.3 Materials and Methods

4.3.1 Study Site

This study was conducted in a plum orchard, situated North-East of Villiersdorp, in the Western Cape region of South Africa (33°56'30.9"S; 19°21'31.1"E). The annual precipitation is 840 mm, mainly occurring between May and August. The driest period of the year is from December to March, and maximum temperatures may reach 45 °C (South African Weather Service 2010).

The orchard comprises 15-year-old ‘Sunkiss’ trees on Mariana rootstock under drip irrigation. Trees were trained as a V-trellis on a ridge of 0.5 m x 1.0 m (Fig. 1). The distance between trees within the row is 2 m, and between opposite trees, 0.5 m (Fig. 2). The dripper lines run down the middle between the two rows of trees along the top of the ridge. There are no cover crops cultivated in the work rows (alleys). *Ripgut* was introduced in 2010 and is now established with varying densities in the orchard, mostly in the planting row, covering the ridges on which the trees are planted, as well as large parts of the work row (Fig. 1, 2). Site-specific chemical weed control was still applied to control other weed species that establish themselves where the *Ripgut* is not fully established.

In this pilot study, multiple measurements were conducted to quantify changes in soil properties after the introduction of *Ripgut* as a living mulch. These indicators included: water-holding capacity (WHC), soil moisture (SM) and temperature (ST), microbial biomass (MB), weed control (WC) and root distribution and counts of trees (RC). These measurements were performed in the areas where the *Ripgut* was well established (RM), as well as in areas where the *Ripgut* was not established yet (CC) and herbicides were applied.

4.3.2 Water-Holding Capacity (WHC)

To determine the WHC of the soil, one soil sample was collected from three randomly selected trees each, both from the *Ripgut* (RM) and non-*Ripgut* (control) treatments (CC). Using a clean spade, samples were collected from the top 30 cm of soil, midway up the side of the planting ridge, roughly 60 cm from the tree trunks on the North-Eastern side of the trees. Samples contained no obvious plant material or stones. After collection, the samples were immediately placed in plastic bags and stored in a cool, dark place before, during, and after transportation. The bags were sealed to ensure no moisture was lost. Samples were collected a two days after a rain event to ensure an even distribution of precipitation throughout the orchards and to allow some time for a certain amount of drainage to occur to avoid waterlogged samples. For quantification of the WHC, a variation of the method used by Priha and Smolander (1999) was used. In the original method, soil samples were drenched for two hours and then drained for two hours, after which samples were weighed to determine how much moisture was retained (Priha and Smolander 1999). This method was altered to avoid potentially compromising the WHC by disturbing the soil structure. A 100 g of each sample was weighed into a glass beaker, after which they were oven-dried at 105 °C for 24 h. After drying, the samples were weighed once more to determine the difference in weight, which was used to calculate the water content of the wet samples as a percentage of total weight. These measurements were carried out twice (once in April, and once in July) in order to obtain representative data for both the autumn and winter seasons.

4.3.3 Soil Temperature (ST) and Soil Moisture (SM)

To simultaneously measure ST and SM, continuous logging probes (DFM Technologies, 124 Fairview Road, Penhill, Eerste River, 7100) were installed on 25 April 2018. Measurements were made at 10 cm intervals, from 10 cm to 60 cm in depth, at hourly time intervals, over a three-month period, i.e. from the start of May to the end of July.

Two probes were placed in the same tree row, roughly 4 m apart. One probe was placed in a section containing the *Ripgut*, and the other was placed in an adjacent patch where the *Ripgut* had been cleared mechanically for the experiment (Fig. 3). Both probes were subjected to the same amount of irrigation and rain throughout the study period.

4.3.4 Microbial Biomass (MB)

The effect of *Ripgut* on the microbial populations in the soil was investigated using the Solvita® CO_2-Burst test. Three trees, in both treatments, were randomly selected for composite sample collection. Each sample comprised three sub-samples taken around the selected trees, within a 60 cm radius from the tree trunk. Samples were obtained from the top 30 cm of soil. Each composite sample was immediately placed in the respective plastic bag which was sealed and stored in a cool place until delivery at the laboratory. There were no stones or obvious plant material present in the samples, and they were collected using a spade, which was cleaned between sampling to avoid cross contamination of samples.

The Solvita® CO_2-burst method quantifies soil respiration by measuring CO_2 output over a 24 h period (Haney et al. 2008). The degree of CO_2 respiration of soil serves as a good indicator of the microbial activity present in that soil, and can be used to formulate estimations of microbial biomass with a fair amount of accuracy (Haney et al. 2008). The Solvita® CO_2-burst method was commercially accepted as a laboratory testing method for determining soil microbial biomass in 2006 (Brinton and Laboratories 2017). This method allowed for more rapid testing as it only requires 24 h, where previous tests required up to seven days (Brinton and Laboratories 2017).

The samples were analysed at a commercial soil testing lab - Soil Health Solutions (Groenfontein Farm, c/o R 44 and Anyswortelrug Rd, Klapmuts). The process involves the drying, sieving and weighing of samples into beakers, after which samples are remoistened, releasing a burst of CO_2

which is the result of a microbial respiratory response (Brinton and Laboratories 2017). A gel paddle which is placed in the closed beaker along with the soil sample, changes colour according to the amount of CO_2 released, which is placed into a digital color reader that assigns it a score (Haney et al. 2008).

4.3.5 Weed Control (WC)

The ability of *Ripgut* to provide sound WC was quantified by comparing the weed quantities in the RM and CC treatments, using a 1 m × 1 m grid placed on the surface of the soil in the vicinity of a randomly selected tree in each of the respective areas (Nicholson 2012). Grids were placed on the slope of the embankment on which the trees are planted, on the North-Eastern side of the trees, roughly 30 cm from the tree trunks. The number of weeds within each square was counted and the means were used to calculate the standard errors.

4.3.6 Destructive Root Analysis (RC)

To determine whether the *Ripgut* had an influence on the development and distribution of tree roots, destructive root analyses were carried out on three randomly selected trees per treatment. This was performed by making a 1 m^3 hole on the north-eastern side of the trees, roughly 30 cm from the tree trunks. A 1 m × 1 m grid was placed in the hole, against the vertical wall closest to the tree (Fig. 4). The grid comprised one hundred smaller squares, each covering an area of 10 cm^2. The roots protruded through the grid and were counted per block (Böhm 1979). Roots were also categorized according to diameter and the number of roots that fell within each category was counted. The bottom row of the grid was disregarded due to practical reasons. As such, grid dimensions were essentially 100 cm × 90 cm. The number of roots per row was quantified to verify any changes in root depth and vertical distribution. This should give an indication of the root-soil dynamics in an environment where the tree roots have to compete with *Ripgut* roots for space and resources.

A visual representation of the root distribution was constructed using a series of symbols, which represented the number of roots from the respective size categories within each block. A key was used to assign a symbol to each root category greater than 1 mm in diameter (Table 1). The number of roots smaller than 1 mm within each block were too high to represent using symbols, and thus a colour key (using different shades of grey) was used to represent the number of roots smaller than 1 mm in diameter within each block (Table 2).

4.4 Results

4.4.1 Water-Holding Capacity (WHC)

The WHC was recorded twice, once in April and once in July. For the autumn samples, the WHC of the RM treatment was 4.88 % (SE = 1.04) compared to 3.01 % (SE = 0.39) in the CC treatment. For the winter recording, it was 5.39 % (SE = 0.29) for the RM treatment, and 3.81 % (SE = 0.25) for the CC treatment (Fig. 5).

4.4.2 Soil Temperature (ST)

Temperature fluctuation was higher in the CC treatment compared to the RM treatment and this pattern was consistent throughout the three-month study period (Fig. 6, 7, 8). For the RM treatment, overall, the daily minimum temperatures were higher, and the maximum temperatures, lower. The biggest effects could be seen on days with extreme fluctuations, with the biggest differences between the two treatments often observed at daily minimum temperatures. The average daily minimum temperature at 10 cm soil depth for the RM treatment was 12.9 °C (SE = 0.18) compared to 10.5 °C (SE = 0.26) in the CC treatment, a difference of 2.4 °C. The average midday temperatures at 10 cm soil depth for the RM treatment was 15.39 °C (SE = 0.2) compared to 16.61 °C (SE = 0.29) in the CC treatment, a difference of 1.22 °C. Temperature fluctuations were most prevalent in the top 20 cm of soil, whilst soil temperatures were more stable at deeper soil levels (Fig. 9, 10).

4.4.3 Soil Moisture (SM)

The SM distribution for the RM and CC treatments displayed a distinct pattern that was consistent throughout most of the study period. The differences in mean SM content for the different soil depths over the study period are depicted in Fig. 11. Similarly, Figs. 12, 13, and 14 show the change in SM content at different soil depths for both RM and CC treatments over a three-day precipitation event. During precipitation events, the SM content was significantly higher in the RM treatment compared to the CC treatment between depths of 20 cm and 50 cm, while the SM remained similar at 10 cm and 60 cm depths. In the RM treatment, SM was greatly increased during the rain event throughout all depths (Fig. 15), while for the CC treatment SM was affected mostly at shallower depths, between 10 cm and 30 cm, and remained relatively unchanged at depths between 40 cm and 60 cm (Fig. 16).

4.4.4 Microbial Biomass (MB)

The CO_2 respiration rate was not significantly different between the two treatments (Table 5). The mean C output (measured as ppm C) was 14.2 (SE = 2.5) for the RM treatment and 14.83 (SE = 3.03) for the CC treatment. Subsequently, the differences in estimated PMN and calculated MB between the two treatments were marginal. The estimated PMN ($kg.ha^{-1}$) was 24.29 (SE = 3.09) for the RM treatment and 24.99 (SE = 3.81) for the CC treatment, and the calculated MB ($kg.ha^{-1}$) was 731.58 (SE = 128.8) and 764.21 (SE = 156.28), respectively for each treatment.

4.4.5 Weed Control (WC)

The mean weed numbers differed significantly between the RM and CC treatments with the mean weed count ($weeds.m^{-2}$) being 2.17 (SE = 0.33) for the RM treatment and 11.17 (SE = 1.54) for the CC treatment (Table 6). The variation within the RM treatment was also much lower than that of the CC treatment.

4.4.6 Destructive Root Analysis (RC)

Across all root diameter classes, the total mean root count was 1441 in the RM treatment and 1048 in the CC treatment. Root counts were quantified on a vertical scale, and therefore the mean number of roots per row was determined. The RM treatments showed larger root numbers for roots smaller than 1 mm (Fig. 17), while the CC showed higher numbers for all root categories larger than 1 mm in diameter. The RM treatment had a higher number of roots per row at all depths except for the bottom row (80-90 cm) (Fig. 18). However, in the top 20 cm, it was extremely difficult to distinguish between *Ripgut* roots and plum tree roots, which may have negatively influenced the accuracy of the root counts in the this region.

Tables 3 and 4 provide a visual representation of the root profiles of three trees in each respective treatment. Using a series of symbols and colour codes the roots are displayed on a grid similar to the one used in practice. Results clearly show that the RM treatments had much higher root densities in the top 20 cm, where the *Ripgut* roots were also present.

4.5 Discussion

4.5.1 Water-Holding Capacity (WHC)

The WHC was significantly higher for the RM treatment in both autumn and winter (Fig. 5). However, compared to autumn, the WHC was higher for both treatments in winter. This is probably because the study site received most of its rain in winter and frequent rainfall generally results in higher overall soil moisture contents. Soil samples were also collected two days after substantial rainfall. These two sampling times represented the WHC of the soil in both the drier and wetter seasons. At the time when the autumn samples were collected, the *Ripgut* from the previous growing season had formed a dead mulch layer on the surface of the soil, and the new seeds have not yet germinated. The dead vegetative cover possibly provided protection against both wind and water erosion, and prevented the soil surface from forming a crust layer (Zuazo and Pleguezuelo 2008). This likely improved water infiltration into the soil, as the amount of water penetrating the soil profile at nearly all soil depths were increased, judging from Fig. 11. The SM in the RM treatment was greater at all soil depths except at 10 cm and 60 cm. The vegetative cover may also increase the organic material in the soil, which further improves soil aeration, infiltration rate and storage capacity (Fidalski et al. 2007). Contrarily, in the CC treatment, the exposed soil surface may have been subjected to erosion and the impact of rain drops may have caused compaction of the topsoil – resulting in crusting, which instead increased runoff and subsequently reduced the amount of water able to penetrate the soil profile (Zuazo and Pleguezuelo 2008). This can also be seen in Figs. 12, 13, and 14, which show the changes in SM content throughout the soil profile, over a three-day rain event. The improved infiltration rate in the RM treatment likely allowed deeper and faster penetration of water into the deeper soil levels.

4.5.2 Soil Temperature (ST)

Temperature fluctuations at 10 cm soil depth differed significantly between the RM and CC treatments. The daily maximum temperatures were lower in the RM treatment on most days, but the biggest differences were seen at daily minimum temperatures, which were consistently higher in the RM treatment (Figs. 6, 7, 8). The biggest buffering effects of *Ripgut* were visible in the upper soil profile. Figures 9 and 10 show temperature fluctuation throughout the soil profile for one day, on 4 July 2018 from 08:00 in the morning until 13:00 in the afternoon. In the RM treatment, the temperature fluctuated by less than 3 °C from 08:00 until 13:00 at 10 cm, while in the CC treatment, the temperature fluctuated by nearly 10 °C during this period. However, at soil levels deeper than 20 cm the temperature remained nearly unchanged within a 24 h cycle.

In summer, the maximum daily temperature often exceeds 40 °C and the *Ripgut* mulch may play a significant role in reducing evaporation from the soil surface by lowering the temperature on the soil surface, as well as reducing exposure to direct sunlight (Qian et al. 2015). This study was carried out during the colder months of the year and therefore the potential buffering capacity of the *Ripgut* mulch at extremely high temperatures was not recorded.

4.5.3 Soil Moisture (SM)

A consistent pattern was shown for the mean SM at different soil depths throughout most of the study period (Fig. 11). SM was greater in the RM treatment at all soil depths with the exception of 10 cm and 60 cm. The lower SM at 10 cm is likely due to water consumption of the *Ripgut* during its growth phase and, since most of its roots do not reach up to 20 cm in depth, this effect was only seen at 10 cm. Although the intact *Ripgut* roots may utilize SM in the top 10 cm, they can significantly improve the water infiltration of the upper soil layers, resulting in more water filtering through to deeper soil layers (Zuazo and Pleguezuelo 2008). Thus, the *Ripgut* has a net beneficial effect on SM, especially between 20 cm and 50 cm depths, as it facilitates better penetration throughout most of the soil profile, while only utilizing SM from the top 10 cm. Some moisture within the top 10 cm may also have been lost through evapotranspiration by the *Ripgut.* In Fig. 12, 13 and 14 SM changes over a three-day rain event in both treatments are illustrated. The SM was substantially greater at all depths, except at 10 cm and 60 cm in the RM treatment. Figures 15 and 16 depict how SM increased throughout all depths during a three day rain event for the RM treatment, while in the CC treatment the changes in SM decrease as soil depth increases. Thus, less water reached the deeper soil levels in the CC treatment possibly due to a poorer infiltration rate.

The life cycle and water requirements of *Ripgut* are such that it competes minimally with the trees. In the dry summer months, the dense litter layer may improve soil moisture conditions by improving water infiltration and reducing evaporation (Chen et al. 2018; Fidalski et al. 2007; Zuazo and Pleguezuelo 2008). In winter, when rainwater may be proportionately more, the *Ripgut* improves water infiltration throughout most of the soil profile, while only utilizing water from the top 20 cm for photosynthesis and growth. Thus, it has a net beneficial effect on the SM status of the soil throughout the year.

4.5.4 Microbial Biomass (MB)

There was no significant difference in CO_2 respiration between the two treatments, and thus no difference in estimated PMN and MB either (Table 5). However, because *Ripgut* is a winter annual grass, its effects on the MB in the soil may change throughout the growth cycle. In summer, when it dies off and seeds are dormant, it may have a very different effect in the MB compared to different stages of its growth season. This is supported by the sampling time in early autumn, when the Solvita® CO_2-burst test was performed on one composite sample to gain initial insight before performing the experiment. Results showed that the MB in the RM treatment was nearly half that of the CC treatment. The following Solvita® CO_2-burst test was performed July, during the early growth phase of the *Ripgut*, which showed no difference between the two treatments in terms of CO_2 respiration, estimated PMN and MB. This suggests that the MB in the RM treatment nearly doubled from the time when the *Ripgut* was dormant, to the time when it was in its early growth phase. This could be the result of photosynthesis taking place during its growth phase, and subsequent root exudates stimulating microbial activity in the soil (Jones 2008; McKenzie 2010; Poeplau and Don 2015). Other analyses, in the late growth phase of *Ripgut*, could provide a more complete insight into this phenomenon, which was not afforded by the limited trial period of this study.

4.5.5 Weed Control (WC)

The WC capabilities of *Ripgut* varied depending on the density of the *Ripgut* stands on the side of the ridge. The weed counts were significantly lower in the RM treatment compared to the CC treatment, despite the great variation in the CC treatment (Table 6). *Ripgut* is known for producing a dense litter layer, which may either promote or inhibit the establishment of other species, depending on the context (Chen et al. 2018). In this case, it confirmed the competitive advantage of *Ripgut* in the RM treatment over the other weeds, resulting in some form of weed control compared to the CC treatment and corroborated findings from previous studies (Chen et al., 2018; Kleemann and Gill 2013).

4.5.6 Destructive Root Analysis (RC)

The differences in root distribution between RM and CC treatments were difficult to quantify for various practical reasons. Firstly, in the case of the RM treatments, some roots were very small and difficult to identify as either plum tree roots or *Ripgut* roots, mostly in the top 20 cm. Nonetheless, the destructive root analysis yielded some results that may give an indication of the possible effects of the *Ripgut* mulch.

The RM trees had higher overall root counts at every soil depth besides the bottom row, but in terms of root numbers in different size categories, the CC treatment yielded higher root counts for all sizes. The RM treatment yielded substantially higher root counts for roots smaller than 1 mm. Considering the root maps, this was especially apparent in the top 20 cm (Table 3, 4), which was likely due to the dense root systems of the *Ripgut* at this level. However, the *Ripgut* roots were mostly found in the top 10 cm, and some up to 20 cm, but beyond the reach of these roots, between depths of 20 cm and 80 cm, the RM treatments still yielded higher root counts than the CC treatment. This could be a result of the improved water infiltration into the deeper soil levels (Fig. 15, 16) and higher SM content at these depths (Fig. 11) in the RM treatment. It may have led to improved root development, especially for roots smaller than 1 mm. There is no clear evidence that the prevalence of *Ripgut* roots in the upper soil layers caused the root concentration of the trees to be higher at deeper soil levels, a phenomenon often found in agroforestry systems where living mulches utilize shallow soil moisture and trees develop higher root concentrations at deeper soil levels (Dawson et al. 2001; Fernandez et al. 2008).

4.6 Conclusions

Utilizing *Ripgut* as a living mulch influenced various mechanisms that govern the soil-water status of the soil profile, as both SM and WHC were higher in the RM treatment. The mulch layer formed by the *Ripgut* litter improved water infiltration throughout the soil profile while competing minimally with trees. It may therefore serve as a useful alternative floor management option to improve water-use efficiency and reduce water stress during the dry season.

The *Ripgut* mulch also provided a buffer layer, which significantly reduced soil temperature fluctuations, especially at shallow soil depths. Soil temperature in the RM treatment was lower at high ambient temperatures, which may reduce evaporation from the soil surface in the hot summer months, while ST was higher at extreme low ambient temperatures, which may improve microbial activity and nutrient cycling in the colder months. However, the influence of *Ripgut* on soil water dynamics at high temperatures (during dry hot summer months) may require further investigation, as this trial was conducted during the colder months.

While results showed no significant differences between treatments with regard to soil microbial activity, preliminary results indicate that the effect of *Ripgut* on soil microbial activity may vary throughout its annual life cycle. Thus, the timing of performing these analyses should be taken into consideration.

Ripgut provided effective chemical-free weed control in the areas where it was well established, reducing the need for chemical weed control methods. Furthermore, *Ripgut* required minimal management, as it is quite tolerant to adverse conditions, and did not interfere with production practices. *Ripgut* had no adverse effects on root development of trees as quantified by the destructive root analyses and it is thus likely that it does not compete directly with trees for water and nutrients.

Although *Ripgut* provided a number of ecosystem services that reduce the need for inputs, and also did not interfere with usual management practices, *Ripgut* is an alien grass species that has been associated with invasive behavior in some areas. While its physiological characteristics may give it the competitive advantage over other weed species, *Ripgut* may be problematic if it spreads into the natural vegetation in surrounding areas and should therefore be cautiously managed.

Low input systems have been found to be more resilient and sustainable, and *Ripgut* is a possible tool that may assist in reducing the inputs and building such production systems. Therefore, with full understanding of its invasive nature and the possible ecological dangers associated with it, this study concludes that *Ripgut* is a good potential living mulch species for plum orchards in the Western Cape of South Africa, and may improve the sustainability and resilience of commercial fruit production systems.

4.7 References

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APPENDIX B

Table 1. Key used for classification of roots according to diameter. Roots within each category are represented by the corresponding symbol in the root map, to provide a visual illustration of the root distribution.

Diameter	Symbol
< 1 mm	Colour code
1 mm – 5 mm	·
5 mm – 10 mm	∘
> 1 cm	○

Table 2. Colour scale used to represent the number of roots within each block that are smaller than 1 mm in diameter. Each block was assigned a shade of grey that corresponds with the number of roots (< 1 mm) within it. This method was used instead of symbols due to the large number of roots smaller than 1 mm.

Number of roots	Shade
0	
1-9	
10-19	
20-29	
30-40	
>40	

Table 3. Root maps of three randomly selected trees in the RM treatment (*Ripgut* mulch). The different shades of grey represent the corresponding number of small roots (< 1 mm) (Table 2). The symbols each represent one root within the corresponding size category (Table 1).

Tree 1										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10			∘	▪	▪	▪▪▪			∘	
20	▪		▪▪	▪▪▪▪	▪▪▪	▪▪∘∘○○		▪▪▪∘○	▪▪∘	▪▪
30	▪	▪▪▪	▪	▪▪▪	▪▪	▪▪▪▪	▪▪▪▪	▪	▪∘	▪▪▪▪▪∘
40	▪▪▪▪	▪▪∘	▪▪	▪▪	▪▪▪▪▪∘∘	▪▪▪▪▪▪				▪▪▪▪
50	▪	▪▪	▪▪		▪▪▪▪▪		▪▪▪▪▪∘∘	▪▪▪▪▪		▪▪
60	▪		▪	▪▪	▪▪▪▪		▪▪	▪▪	▪▪	▪▪
70		▪▪▪∘		▪			▪▪▪		▪	▪
80	▪▪					▪▪		▪▪		
90	▪						▪			▪
Tree 2										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10	∘	∘	○	▪▪		∘				
20	▪	▪▪	▪▪▪		▪	▪				
30	▪▪▪∘	▪∘						▪○		
40	▪	▪	▪	▪						
50										
60										
70										
80										
90	▪▪▪▪									
Tree 3										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10										
20		▪○	▪▪▪▪▪	▪○○	▪▪∘∘∘	▪▪▪∘		▪▪▪∘		
30				▪▪∘	▪▪	▪▪▪▪	▪▪▪		▪∘	
40		▪	▪▪		▪▪					
50		▪								▪
60										
70										
80			▪			▪∘				
90	▪▪▪						▪			

Table 4. Root maps of three randomly selected trees in the CC treatment (no mulch). The different shades of grey represent the corresponding number of small roots (< 1 mm) (Table 2). The symbols each represent one root within the corresponding size category (Table 1).

Tree 1										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10										
20		▪○	▪▪▪▪▪	▪○○	▪▪	▪▪▪◦		▪▪▪◦		
30				▪▪◦	▪▪	▪▪▪▪	▪▪▪		▪◦	
40		▪	▪▪		▪▪					
50		▪								▪
60										
70										
80			▪			▪◦				
90	▪▪▪						▪			

Tree 2										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10								▪▪▪	▪▪▪▪▪	▪▪▪
20	▪		▪▪▪	▪▪	▪▪	▪▪	◦◦◦◦○	▪▪○	◦◦◦○	▪
30	◦◦◦	▪▪▪▪▪◦◦◦	○○○	◦	▪▪	▪	◦	▪	▪▪▪▪▪▪	▪▪
40		▪▪◦	▪▪◦			▪◦	▪○	▪	▪▪▪	▪▪◦
50	◦	▪						▪◦	▪▪	▪
60			▪		▪▪▪					▪▪▪
70										
80										
90								▪		▪▪

Tree 3										
Profile width (cm)										
	10	20	30	40	50	60	70	80	90	100
10	▪▪▪	▪	▪	▪	▪◦		▪▪▪▪			▪▪
20	▪▪	▪	▪▪▪▪◦	▪	▪	▪○		▪▪▪	▪◦◦◦○	
30	▪▪▪▪▪◦◦	▪▪◦	▪▪▪○	▪▪▪▪▪	▪▪◦◦	▪	▪▪	▪▪▪▪▪	▪▪▪	▪▪▪
40	▪▪◦	▪▪◦	▪▪◦◦○	▪▪	▪▪			▪▪◦○	▪◦○	▪◦◦○
50	◦		▪			▪◦	▪▪	▪▪◦	▪	▪
60	▪	▪▪		◦		▪◦				▪
70	▪	▪▪◦	◦							◦
80	▪▪◦					◦			▪	▪▪
90								▪	▪	▪▪◦

Table 5. Results of the Solvita CO_2-Burst test for both the RM and CC treatments. The amount of carbon released as CO_2, through microbial respiration, is shown in ppm C. The estimated potential mineralizable nitrogen is shown as Estimated PMN (kg/ha), and the Calculated microbial biomass (MB) in kg/h.

	ppm C	Estimated PMN (Kg/ha)	Calculated microbial biomass (Kg/ha)	Number of weeds per m^2
RM	14.2 ± 2.50	24.29 ± 3.09	731.58 ± 128.80	2.17 ± 0.60
CC	14.83 ± 3.03	24.99 ± 3.81	764.21 ± 156.28	11.17 ± 1.54

Fig. 1. Plum orchard in which the *Ripgut* is well established in the tree row. Here, in late summer, the Ripgut forms a layer of dead litter, covering the dormant seeds.

Fig. 2. *Ripgut* during its growth phase in late winter.

Fig. 3. DFM® probes measuring SM and ST in both the RM and CC treatments.

Fig. 4. Destructive root analysis using a 1m x 1m grid to quantify root distribution.

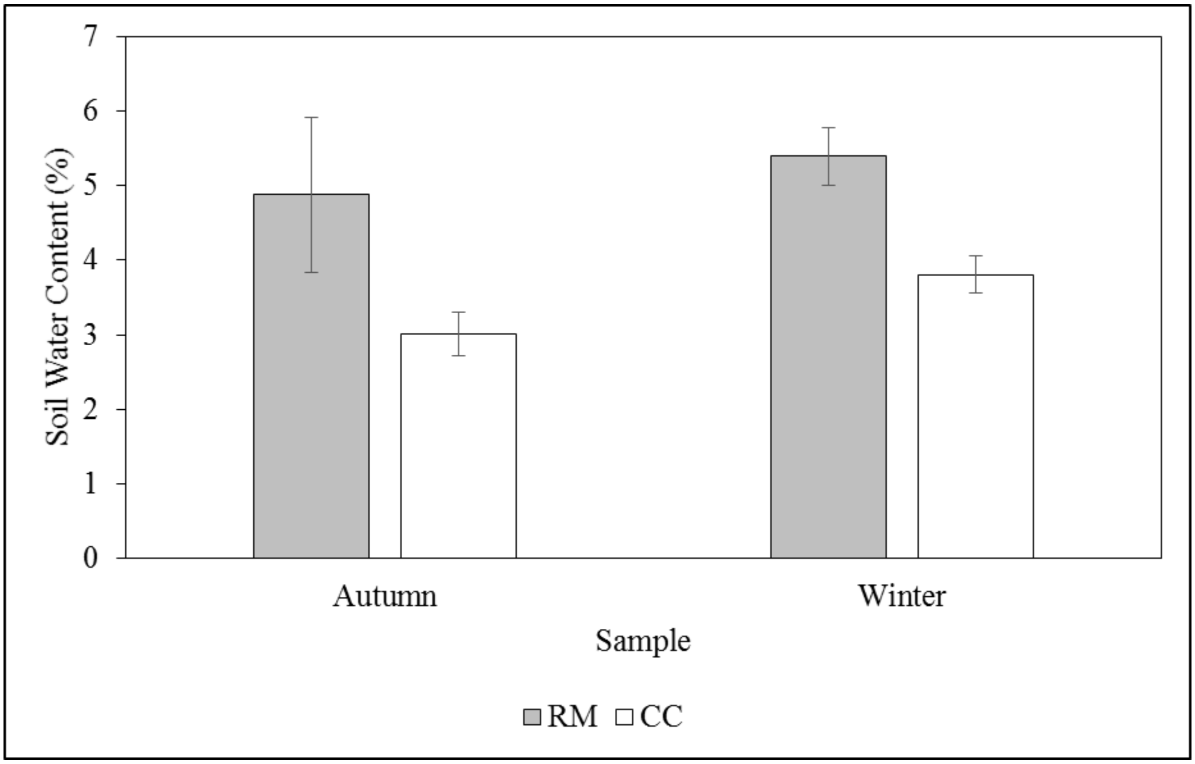

Fig. 5. Mean water-holding capacity (WHC) for both the autumn and winter measurements, for both the RM (Mulch) and CC (No Mulch) treatments.

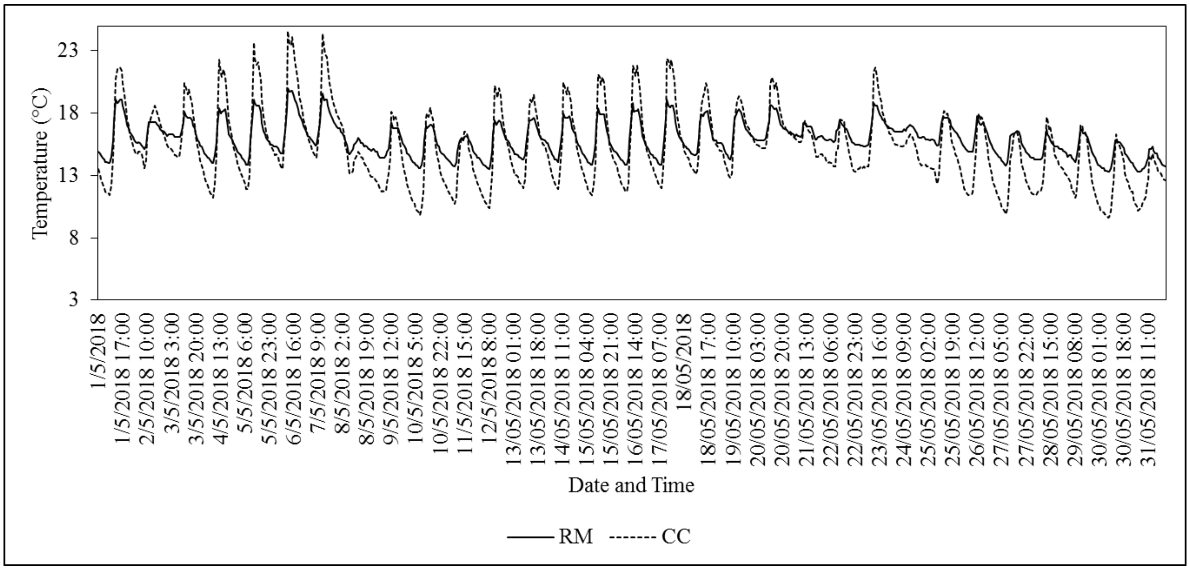

Fig. 6. Soil temperatures (ST) for both the RM treatment (Mulch) and CC treatment (No Mulch), at 10 cm soil depth, throughout May 2018. Soil temperature was measured using DFM continuous logging probes.

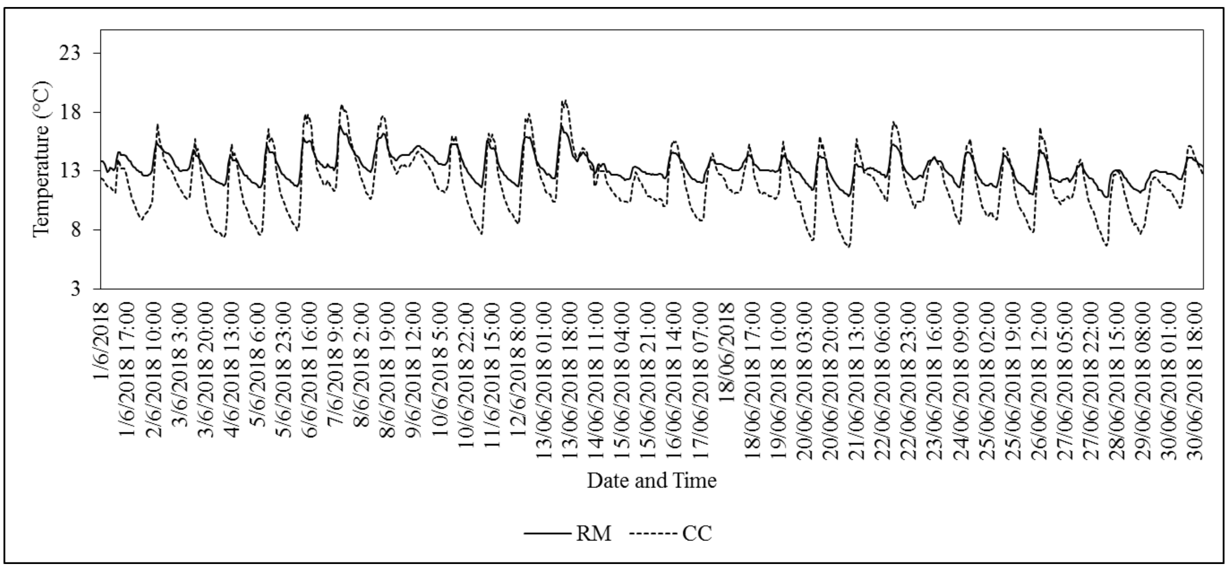

Fig. 7. Soil temperatures (ST) for both the RM treatment (Mulch) and CC treatment (No Mulch), at 10 cm soil depth, throughout June 2018. Soil temperature was measured using DFM continuous logging probes.

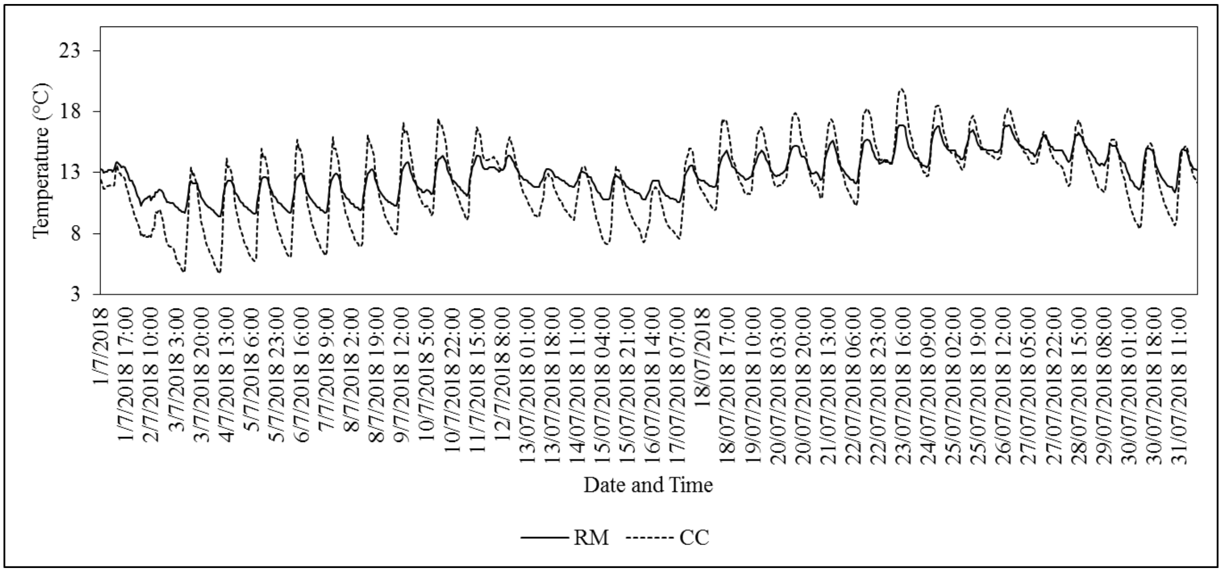

Fig. 8. Soil temperatures (ST) for both the RM treatment (Mulch) and CC treatment (No Mulch), at 10 cm soil depth, throughout July 2018. Soil temperature was measured using DFM continuous logging probes.

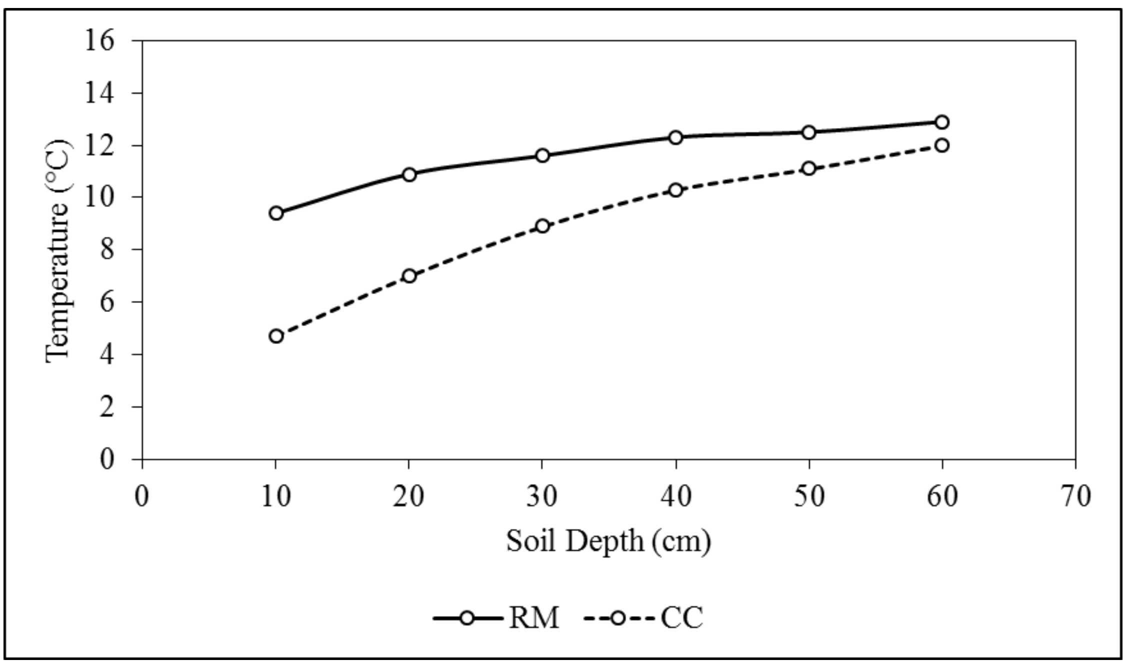

Fig. 9. ST at different soil depths for both RM and CC treatments on recorded at 10 cm depth on 4/7/2018 at 8:00. The minimum daily temperature was recorder at 8:00 on most days.

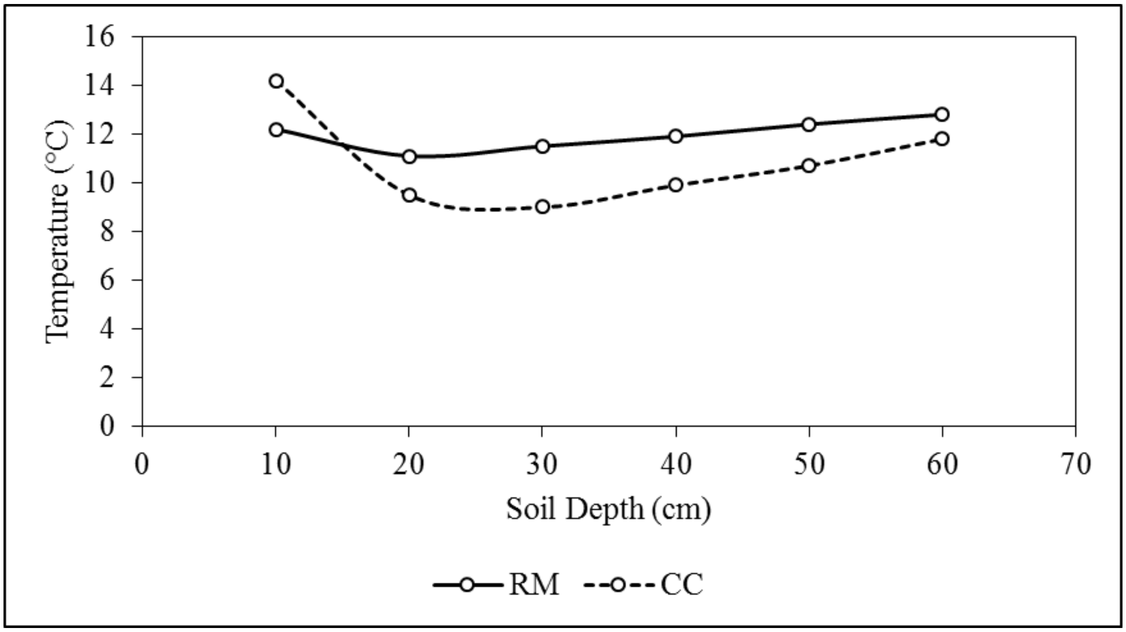

Fig. 10. ST at different soil depths for both RM and CC treatments on recorded at 10 cm depth on 4/7/2018 at 13:00. The minimum daily temperature was recorder at 13:00 on most days.

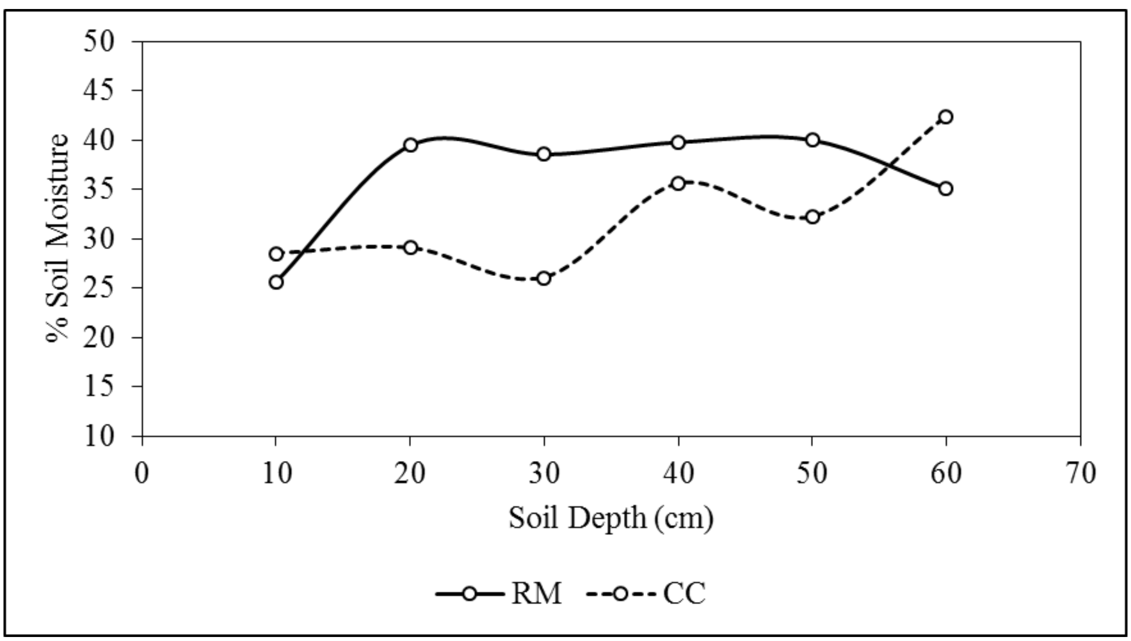

Fig. 11. Average soil moisture (SM) content (%) at different soil depths from the beginning of May to the end of July 2018, for both the RM (Mulch) and CC (No Mulch) treatments. Soil

moisture was measured using DFM continuous logging probes. Soil moisture content was recorded at hourly intervals.

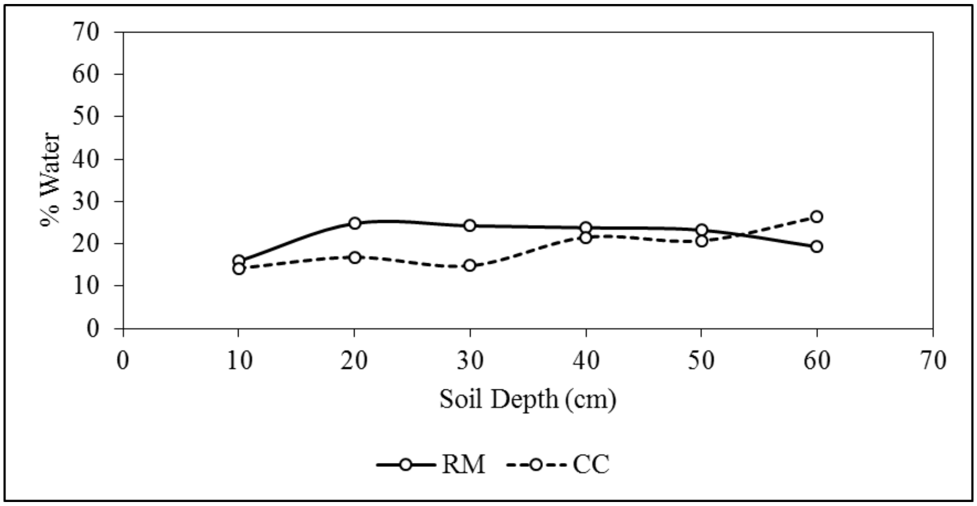

Fig. 12. Soil Moisture content at different soil depths for both RM and CC treatments on the first day of a rain event (7/5/2018, 16:00).

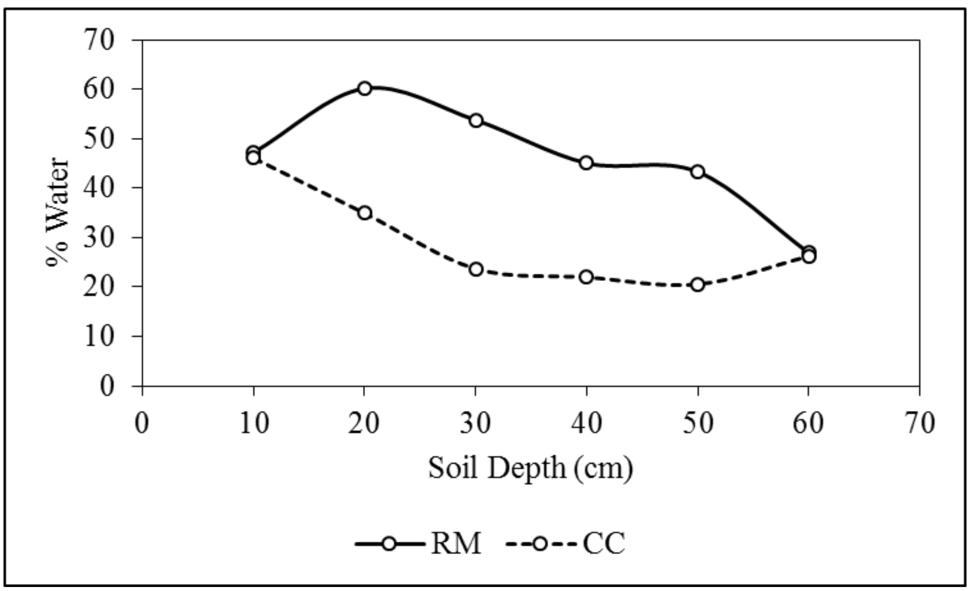

Fig. 13. Soil Moisture content at different soil depths for both RM and CC treatments on the second day of a rain event (8/5/2018, 16:00).

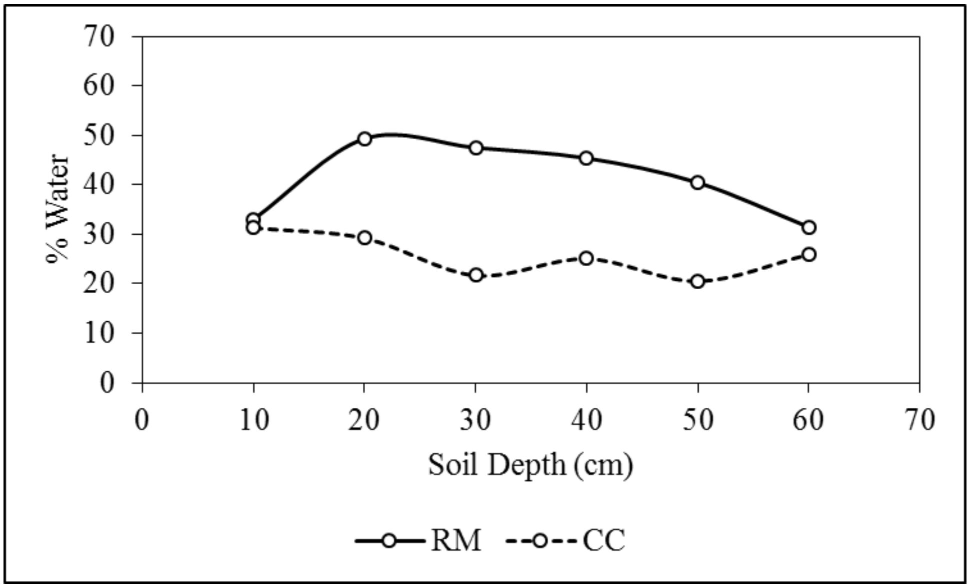

Fig. 14. Soil Moisture content at different soil depths for both RM and CC treatments on the third day of a rain event (8/5/2018, 16:00)

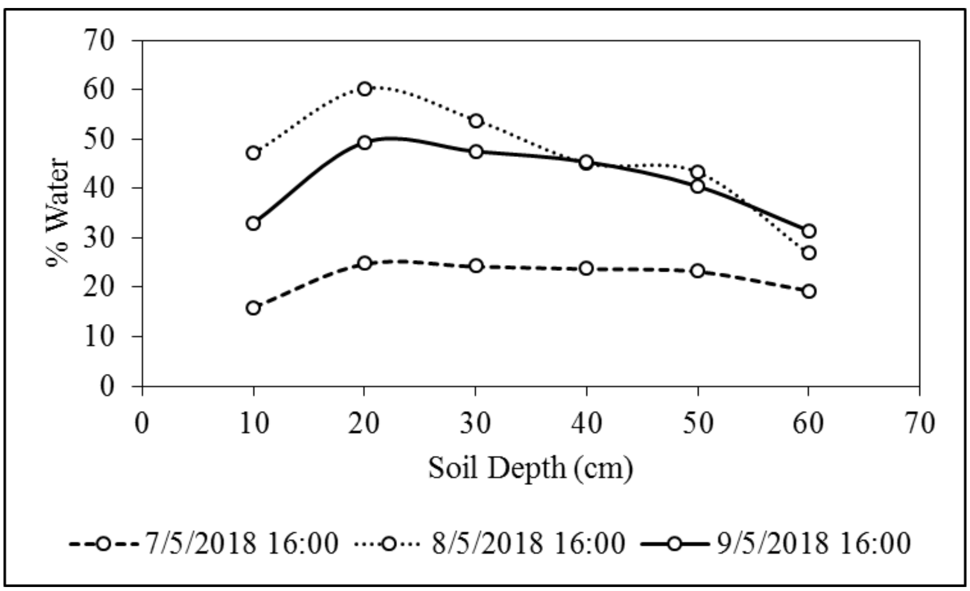

Fig. 15. Soil moisture content at different soil depths for the RM treatment on three consecutive days during a rain event.

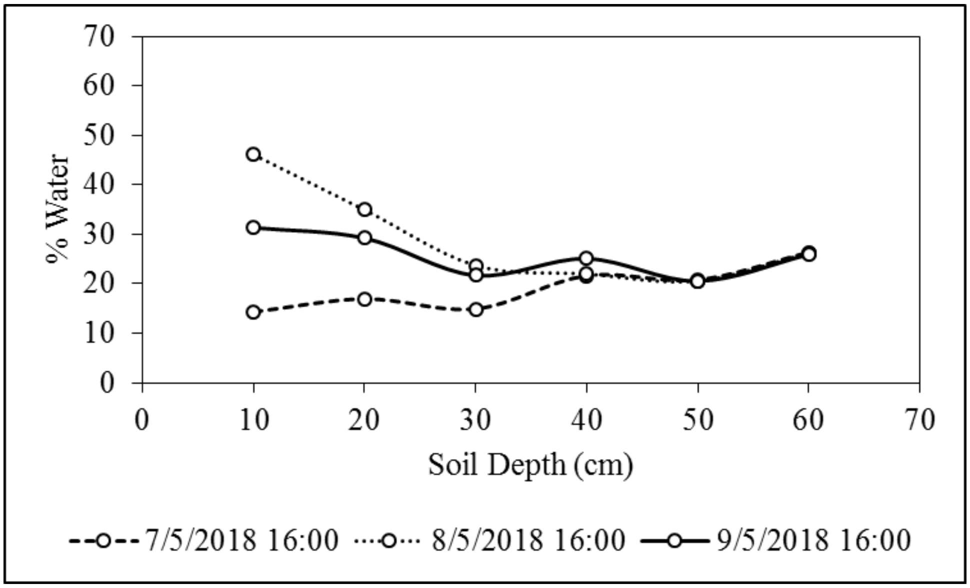

Fig. 16. Soil moisture content at different soil depths for the CC treatment on three consecutive days during a rain event.

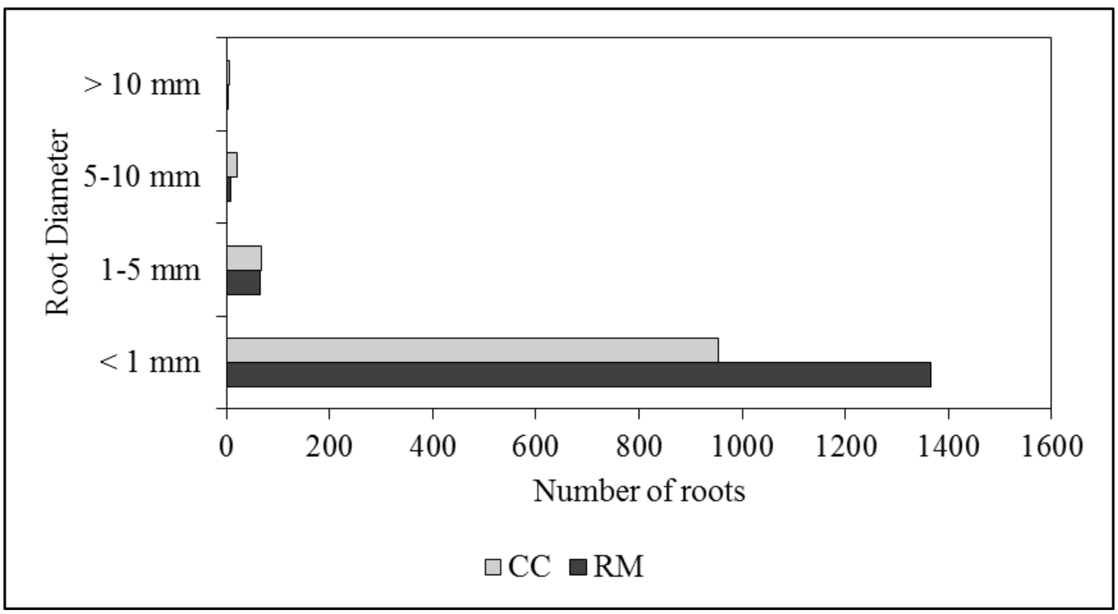

Fig. 17. Mean number of roots within each respective size category for both RM and CC treatments.

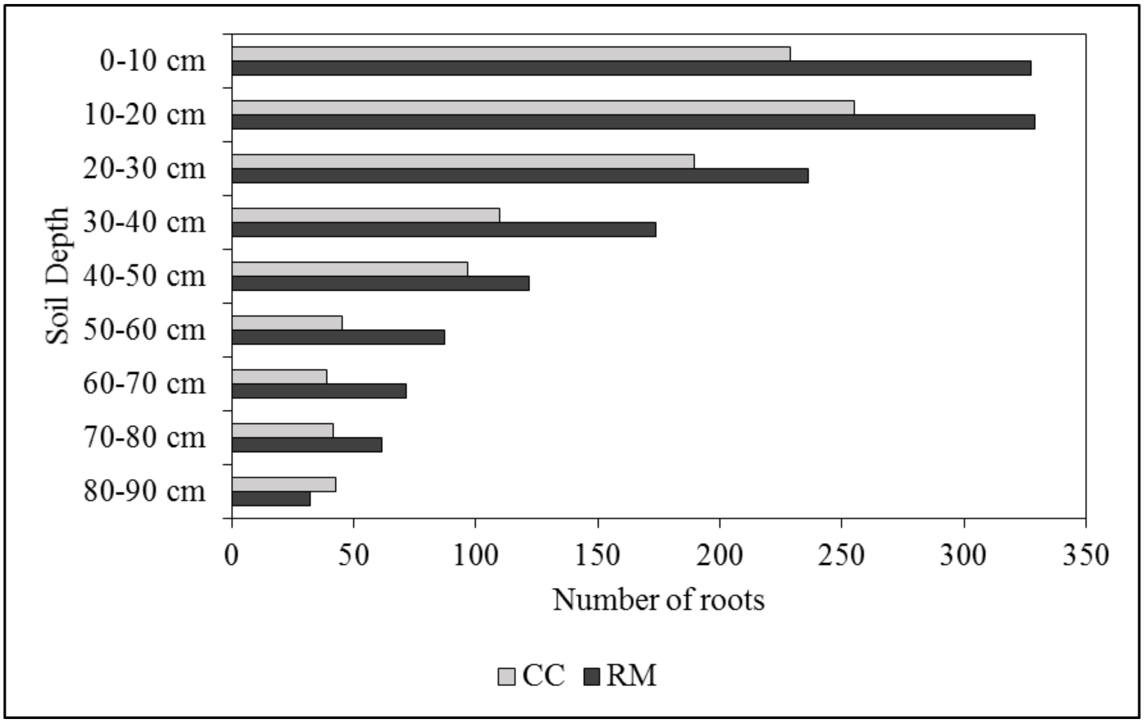

Fig. 18. Mean number of roots at different soil depths for both RM and CC treatments.

CHAPTER 5

General Conclusion

Both plant species investigated in this study displayed desirable characteristics pertaining to living mulches. *Tradescantia* and *Ripgut* significantly improved the water-holding capacity (WHC) in the top 30 cm of the soil profile in the citrus and plum orchards respectively. Both species also improved the soil moisture (SM) content throughout most of the soil profile, while only negatively influencing SM in the top 10 cm of the soil profile through competition and at 40 cm depth for unknown reasons. Both species acted as temperature buffers and significantly reduced soil temperature (ST) fluctuations, especially at shallow soil depths, and this was particularly true for *Ripgut*.

Tradescantia had a significant influence on the microbial biomass (MB) in the citrus orchard, as well as estimated potential mineralisable nitrogen (PMN). The effect of *Ripgut* on MB and estimated PMN was not as clear, as there was no significant difference between the two treatments. However, previous data suggests these results may be differently influenced at different stages of the *Ripgut* life cycle. Further investigation is needed in order to better understand these interactions.

In addition, both *Tradescantia* and *Ripgut* provided sufficient weed control (WC) in the respective orchards, compared to chemical application. The root distribution of the citrus trees differed slightly between the two treatments, as trees in the TO treatment had higher root concentrations at lower soil depths compared to the BO treatment, which is possibly the result of competition provided by the *Tradescantia* in the top soil layers. The influence of *Ripgut* on plum tree root distribution was less clear. However, trees under the *Ripgut* mulch had higher overall average root counts compared to trees in the CC treatment, even when the top 20 cm is disregarded where the *Ripgut* roots are present.

Furthermore, both species seem to be well adapted to their respective climates and anatomical and physiological traits, as well as life cycles present minimal problems in terms of management, maintenance and competition. However, they are known to be invasive in many ecosystems globally, with *Tradescantia* being listed as a class 1b invasive species in South Africa. Therefore, much of the hardiness, adaptability and high success rate of these species stems from their invasive nature, which may be problematic if they are to be implemented on commercial scale, especially if they are not managed very carefully. Thus, from this study alone it is not recommended for commercial implementation, as further investigations may be necessary to analyze the ecological dangers associated with these species.

Nevertheless, when implemented under the correct circumstances, both species may have net beneficial effects in perennial fruit orchards in their respective climatic regions, and may be useful living mulch species. The understanding, harnessing and integration of ecosystem services offered by different plant species may be integral to creating more resilient production systems. Reducing the reliance on external and chemical outputs and conserving natural resources, while simultaneously reducing soil erosion and increasing SOC levels through carbon sequestration, is central in the pursuit of building more sustainable commercial production systems.