THE USE OF COVER CROPS FOR SUSTAINABLE CITRUS ORCHARD PERFORMANCE

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Environmental and Water Science, University of the Western Cape

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DECLARATION

I declare that *The Use of Cover Crops for Sustainable Citrus Orchard Performance* is my own work, that it has not been submitted before for any degree or examination in any other university and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Sibongiseni Silwana

Signed: Date: 26 March 2025

ABSTRACT

Cover crops play a pivotal role in maintaining and improving agricultural sustainability through enriching organic matter content. They are commonly planted between tree rows to enhance soil quality, suppress weeds and improve production and fruit quality in citrus orchards. However, there is limited information regarding plantation of cover crops in citrus orchards in South Africa. Current conventional agricultural production systems in citrus orchards rely heavily on a high level of agrochemicals. This study is an attempt to alleviate some of the direct input costs and high application of agrochemicals.

A cover crop field study was conducted at Lamara farm at Franschhoek, South Africa to assess the effect of cover crop species on soil quality, weed suppression, soil enzymes, citrus fruit yield and soil water content under two termination methods (slashed and non-slashed). Cover crop species tested were vetch, medics, oats and control (no cover crop). The experiment was set up in a randomised block design with a factorial treatment structure (Factor 1 - cover crop species; Factor 2 – cover crop termination methods) replicated six times.

In the first study, effect of cover crop species on soil organic carbon, weed control and citrus fruit weights using two termination methods (slashed and non-slashed) were assessed. Soil samples were taken before planting cover crops and one year after planting cover crops to determine soil fertility. Dry weight samples of cover crop and weed were collected during the termination stage and fruit weight measurements were taken at harvest. Results showed that vetch and medics cover crops were more effective in enhancing soil organic carbon with 0.14% increase in a period of one season compared to oats and control treatments at 0-30 cm depth but there was no significant difference in deeper soil (30-60 cm). Oats cover crop suppressed weeds more effectively than other cover crops but there was no effect of the termination methods used to terminate cover crops. There was no effect on citrus fruit weight regardless of the cover crop species used and termination methods. In summary, legume cover crops were effective in improving soil organic carbon while oats were more effective in suppressing weeds.

The second study assessed the effect of cover crop species on soil pH, soil enzymes (β-glucosidase, phosphatase and urease) activities with two termination methods (slashed and non-slashed). The same cover crop species and experiment were set up as in the first study. Soil was sampled before planting cover crops and one year after planting cover crops to determine soil enzyme activities. Results showed that introducing cover crops caused soil pH to increase from 5.42 to 6.0 after one year. There was a slight decrease in β-glucosidase whereas

there was an increase in phosphatase and urease activities after one year of introducing cover crops. Under different cover crop species, there was a marginal increase of β-glucosidase, phosphatase and urease activities under legumes (vetch and medics) in the topsoil. In deeper soil, β-glucosidase activity was higher under oats while phosphatase and urease activities were higher under medics and vetch cover crops, respectively. There were no significant differences on β-glucosidase, phosphatase and urease activities regardless of soil depth and termination methods.

The third study examined use of soil water by different cover crop species in a citrus orchard. This included suitable cover crop termination methods capable of conserving soil water. The same cover crop species and experiment were set up as in the first study. In this experiment, soil water content was monitored at 10, 20, 30, 40, 60 and 80 cm soil depth using DFM soil moisture probes, during the winter season in oats, medics, vetch and control plots. The results showed that soil water content was mostly depleted in the oat's treatment at 10 cm depth, however, there was no significant influence in other soil depths. The root water uptake was observed at 30 cm depth regardless of the species of cover crop planted. Furthermore, the termination methods did not influence the soil water content regardless of soil depths. However, slashed treatments gave less depletion of soil water content compared to non-slashed treatments when tested against the same cover crop species.

This study highlights the significant role of cover crops in enhancing soil quality, suppressing weeds and influencing soil enzyme activities in citrus orchards. The findings demonstrate that different cover crop species provide diverse benefits with leguminous cover crops (vetch and medics) improving soil organic carbon, and oats being the most effective in weed suppression. Vetch and medics increased soil organic carbon by 0.14% within one season at 0-30 cm depth, whereas oats and the control showed minimal improvement. There was no significant change in deeper soil (30-60 cm). Cover crop termination methods did not influence the effectiveness of weed suppression. While cover crops contributed to soil pH increase and enzyme activity changes, their effect on citrus fruit weight was not significantly different. Legume cover crops increased phosphatase and urease activities in topsoil, while oats improved β-glucosidase in deeper soil. No significant effects of termination methods were observed on soil enzyme activities. Additionally, soil water depletion varied depending on the cover crop species, with oats depleting more water at shallow depths. Oats led to the highest soil water depletion at 10 cm depth, but there were no significant differences at deeper soil levels. Root water uptake was detected at 30 cm depth across all cover crops. Slashed treatments showed slightly better soil water conservation compared to non-slashed treatments. The termination method (slashed vs. non-slashed) had minimal impact on most measured parameters, except for a slight reduction in soil water depletion under slashed treatments. Lastly, no significant differences in fruit weight across different cover crop species or termination methods were observed.

Recommendations

Leguminous cover crops (vetch and medics) can be used to enhance soil organic carbon in citrus orchards while oats should be considered for effective weed suppression. Regular soil testing should be done to monitor soil organic carbon and enzyme activities over multiple seasons. Further studies should explore long-term effects of cover crops on water retention and their impact under different climatic conditions. Slashed termination methods may be preferable for better soil water conservation. Implementation of cover crops can reduce the use of synthetic fertilisers and herbicides, contributing to more sustainable citrus production. Additional research on multi-season effects of cover crops on yield and fruit quality should be conducted. By adopting these recommendations, South African citrus orchard farmers can optimise soil quality, water use, minimise agrochemical inputs and promote sustainable agricultural practices.

Keywords: Citrus fruit weight, cover cops, *Eureka* lemon, soil enzymes, soil water content, soil quality, suppression, weed.

BIOGRAPHICAL SKETCH

Sibongiseni Silwana was born on 01 January 1991 in Dutywa, Eastern Cape. He started his school career at Mzimkhulu Junior Secondary School and matriculated from J.S Skenjana Senior Secondary School, Dutywa in 2009. In 2010, he enrolled at University of Fort Hare and obtained a B.Sc. Agric. degree in 2013, majoring in Soil Science. He obtained his Hons. B.Sc. Agric. (Soil Science) from University of Fort Hare in 2014. He started working at the University of Stellenbosch as an Assistant Research Technician (2015 to 2017). In 2019, he obtained his M.Sc. Agric. (Agronomy) from the University of Stellenbosch. Thereafter, he joined Bossman Adama (Soil scientist intern), Woodlands dairy farms (Junior Soil Science Researcher), Firstfruit Consulting (Soil Science Consultant), DFM company (Irrigation Specialist), Agricultural Research Council (Soil Science Researcher) and is currently working as Production Scientist for the Eastern Cape Department of Rural Development and Agrarian Reform.

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DEDICATION

I dedicate this dissertation to my late father and mother Sindisile Kolisi and NoSign Silwana, for their love, encouragement and sacrifices over the years.

PREFACE

The research work presented in this thesis was conducted under the Department of Environmental and Water Science, University of the Western Cape, Bellville, South Africa. The experimental work was conducted at the Agricultural Research Council (ARC) Infruitec-Nietvoorbij in Stellenbosch and Lamara Farm in Franschhoek, Western Cape Province, South Africa.

RESEARCH OUTPUTS

1. Journal papers

Published

Silwana, S., Mulidzi, A.R. and Jovanovic, N., 2023. Evaluating the effects and benefits of cover crops in citrus orchards: a review. South African Journal of Plant and Soil, 40(2), pp.117-126. https://doi.org/10.1080/02571862.2023.2236075 (Chapter 2).

Accepted

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Short-Term Effects of Cover Crop Species and Termination Methods on Soil pH and Key Enzymatic Activities (β-Glucosidase, Phosphatase and Urease Activities) in a Citrus Orchard (Eureka Lemons). *MPDI Horticulturae* (Manuscript ID: 3765108) (Chapter 4).

Submitted

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Soil organic carbon, weed suppression and fruit yield in response to cover crop species and termination method in citrus orchard (Eureka lemon). Submitted to *International Journal of Agronomy* (Manuscript ID: 7139963) (Chapter 3).

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Impact of rainfed cover crop species on soil water content in citrus orchard. *Submitted to Water SA* (Chapter 5).

2. Conference and seminar Attended

Local

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Evaluating the effects and benefits of cover crops in citrus orchard (Eureka lemon). Combined congress held in Wilderness Hotel, George (South Africa) on the 22-25 January 2024 (Oral presentation).

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Soil organic carbon, weed suppression and fruit yield in response to cover crop species and termination method in citrus orchard (Eureka lemon). Eastern Cape Department of Agriculture Seminar Series held in Dohne Agricultural Research Institute, Stutterheim (South Africa) on the 24 February 2025 (Oral presentation).

International

Silwana, S., Mulidzi, A.R. and Jovanovic, N. Evaluating the effects and benefits of cover crops in citrus orchards. 10th SANUMARC Annual Research Conference on the 1-4 September 2025 in Walvis Bay, Namibia (Oral presentation).

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AI3	Soil alteration index three
ANOVA	Analysis of variance
ARC	Agricultural Research Council
C	Carbon
C: N	Carbon to nitrogen ratio
CGA	Citrus Grower Association
CRI	Citrus Research Institute
DF	Degree of freedom
DFM	Dirk Friedhelm Mercker
GPRS	General Packet Radio Service
GWC	Gravimetric water content
K	Potassium
$K_2Cr_2O_7$	Potassium dichromat
KCl	Potassium Chloride
LSD	Least significant difference
N	Nitrogen
NH_4^+	Ammonium
NH_4-N	Nitrogen content in Ammonium
N-NH_3	Nitrogen-Ammonia
NO_3-N	Nitrate Nitrogen
P	Phosphorus
PCA	Principal Component Analysis
SAR	Sodium adsorption ratio
SCWG	Soil Classification Systems in South Africa
SOC	Soil organic carbon
SOM	Soil organic matter
SIZA	Sustainability Initiative of South Africa
UWC	University of the Western Cape
ZAR	Zuid-Afrikaanse Rand

Chapter 1
General introduction

1.1 Introduction

One of the serious challenges facing agricultural production in the world is soil degradation (Bhattacharyya et al., 2015). Soil degradation is defined as a decline in soil quality and ecosystem leading to a remarkable long-term deterioration in soil productivity (Bindraban et al., 2012). A major consequence of soil degradation includes the destruction of physical, chemical and biological soil properties, such as soil structure, soil strength, aggregate stability and organic matter depletion (Stagno et al., 2008; Lal, 2015). However, soil degradation can be mitigated by employing sustainable soil management practices that increase soil organic matter. The soil organic matter is considered to be the sole indicator of soil degradation and is highly influential on soil properties (Murphy, 2015; Obalum et al., 2017). The lower the organic matter percentage, the greater the chance of soil degradation. Since the organic matter in soil serves as a cement, it binds the soil particles to create a stable soil environment. Furthermore, soil organic matter functions as a sponge to increase water holding capacity, infiltration rate, nutrient cycling, cation exchange capacity, microbial activity, soil aggregates, and bulk density (Baumhardt et al., 2015).

The sowing of cover crops is an effective and environmentally friendly strategy for improving soil organic matter (Blanchart et al., 2006; López-Vicente et al., 2020). As these cover crops decompose, microbial activity breaks down their residues, contributing to soil organic matter and releasing essential nutrients such as organic carbon and nitrogen. Djigal et al. (2012) state that cover crops also support sustainable and cost-effective citrus production by improving yields and reducing the environmental footprint of farming systems. In South Africa, citrus is a high-value, export-oriented sector, with cultivars like Eureka lemons accounting for a significant share of production (CGA, 2023). However, long-term reliance on intensive management practices particularly the widespread use of synthetic fertilizers has contributed to soil degradation, especially in sandy soils prevalent in citrus growing regions such as the Eastern Cape, Limpopo, and Western Cape (Goble et al., 2010). While chemical fertilizers are easy to apply and provide immediate nutrient availability, but these chemical fertilizers do not contribute to organic matter replenishment and are associated with soil acidification and water pollution (Lal, 2015).

Field observations and local trials have reported declining orchard productivity in some areas despite continued fertilizer use, indicating a need for more regenerative and soil-conscious practices (Srivastava & Singh, 2009). Although the global benefits of cover crops are well documented, their use in South African citrus orchards remains limited. The increased use of chemical fertilizers, combined with the underutilization of organic matter building practices such as cover cropping, highlights the urgent need to explore ecologically sound alternatives. As noted by Mauro et al. (2015), such practices can play a critical role in improving the ecological profile of agroecosystems and ensuring the long-term sustainability of fruit production.

Nonetheless, there is limited scientific information on cover crop water consumption and the partitioning of natural resources between cover crops and citrus trees in South Africa. The findings of this study may provide a basis for growers to expand local experience with cultural practices using cover crops for soil management in orchards. This study measured the moisture and monitored the soil quality improvements made by the use of cover crops in a citrus orchard. The expected outcomes of the use of cover crops in citrus orchards include an increase in soil organic matter, which will improve microbial activity, soil quality and soil moisture.

1.2 Problem statement and rationale

Current conventional agricultural production systems in citrus orchards rely heavily on a high level of inputs of inorganic fertilisers; pesticides and heavy machinery that have negative environmental impacts, pose health risks and loss of biodiversity. Therefore, this study is an attempt to alleviate some of these challenges, so that the input costs, as well as the management requirements can be reduced to a level where production systems are more profitable. In citriculture, these above-mentioned challenges can be solved through planting cover crops between the tree rows for soil quality improvement and sustainability (Strauss et al., 2019).

The cover crop system adaptability and performance can be further enhanced through using different types of cover crop species (Wright et al., 2017). The development of cover crop systems using different species specific for citrus production systems is being done in Florida (USA) with apparent success (Campiglia et al., 2012; Strauss, 2020) while planting cover crop in citrus orchards has not been commonly practiced in South Africa. The same cover crop systems will be of much benefit to South African citrus growers, and especially to small-scale growers. This will also help citrus growers to employ environmentally friendly practices and improve soil health. Though finding the best cover crop system to address specific needs may take some patience, long-term experimentation, and management practices.

Hence, the research is seen as a first step towards a possible long-term objective, i.e., to develop a suitable citrus cover crop system for each growing region through continuous measuring and monitoring of the performance of different types of cover crop species to reduce inputs and improve soil quality and tree performance.

1.3 Hypotheses

- Soil carbon improvements will differ significantly between the cover crops species.
- Weed suppression will differ between the cover crop species.
- Sowing of different types of cover crops will result in a positive increase in soil enzyme activity.
- Biomass production will differ between cover crop species.
- Soil moisture content will differ significantly between cover crop species.
- Citrus fruit yield improvements will differ between cover crop species.

1.4 Significance of the study

Small-scale citrus growers often struggle with sufficient cash flow and resources to successfully employ typical commercial farming style practices (i.e., regular mineral nutrition, chemical weed, pest and disease control, mulching, etc.). However, to successfully produce export quality fruit, their orchards require the same level of nutrition, weed control and soil water availability as that of large commercial orchards. Adoption of cover crop practices in citrus orchards will address these above-mentioned challenges through suppressing weeds and improving soil enzyme activities, soil carbon, soil moisture, and fruit yield. This practice will also help citrus growers to employ environmentally friendly practices and improve soil fertility. Lastly, this study will assist citrus growers in meeting Sustainability Initiative of South Africa (SIZA) Environmental Standards, which is to ensure sustainable farming practices relating to soil, water, energy, and waste (improve farm input efficiencies) and mitigate environmental risks on farm levels.

1.5 Research aim and objectives

1.5.1 Aim of the study

To develop and propose a basic, generic citrus cover crop system applicable to both small-scale and commercial citrus producers in South Africa.

1.5.2 Objectives of the study

- Objective 1: To evaluate the effect of cover crops on soil carbon.
- Objective 2: To determine the effect of cover crops on soil enzyme activity.
- Objective 3: To determine the effect of cover crops on weed suppression.
- Objective 4: To evaluate the use of cover crops residue as mulch for soil moisture conservation.
- Objective 5: To evaluate the effect of planting cover crops on fruit yield.

1.6 Research gaps

Despite the potential benefits of cover crops in enhancing soil organic carbon and moisture retention, their adoption in citrus orchards remains limited in South Africa. Instead, there has been an increasing use of chemical inputs, which contribute to environmental degradation, loss of biodiversity and health risks. However, the potential of cover crops to enhance soil organic carbon, retain soil moisture and reduce the dependency on chemical inputs remains underexplored. Further research is needed to evaluate the effectiveness of cover crop integration in citrus orchards and its impact on soil quality and sustainability.

Small-scale citrus farmers in South Africa continue to face declining productivity due to high input costs associated with inorganic fertilisers and pest control chemicals. The inability to afford these inputs results in low yields and poor fruit quality (Mather & Greenberg, 2003). Therefore, there is a need for research into the development of sustainable citrus farming systems that optimise internal resource use, including soil organic carbon conservation, efficient water management and nutrient cycling. In addition, investigating how cover crops can mitigate environmental and health impacts, improve biodiversity and maintain high productivity in both small-scale and commercial citrus orchards remain a critical research gap.

1.7 Thesis structure

The thesis structure is presented as a collection of articles submitted and published in different peer-reviewed scientific journals. The experimental site was located at Lamara farm in Franschhoek, Western Cape Province, South Africa. The thesis consists of six chapters; Chapter 1 provides a general introduction with problem statement and rationale, hypotheses, the significance of the study, research aim, objectives and research gaps. Chapter 2 presents a detailed review of evaluating the effects and benefits of cover crops in citrus orchards in terms of cover crop selection, soil microbial community diversity, legume cover crops, soil organic matter and carbon, weeds, soil moisture, citrus yield and fruit quality. Chapter 3 examines soil enzyme activities and organic carbon in response to cover crop species in a citrus orchard. It presents the effect of different cover crop species (oats, vetch and medics) and their residues on soil enzyme activities using two termination methods − biological and mechanical methods. Chapter 4 focuses on the impact of planting different cover crop species on weeds, plant population and dry weights (cover crops and weeds) in a citrus orchard. Chapter 5 explores the impact of cover crop species on soil moisture. It presents the determination of soil moisture using DFM probes. Chapter 6 covers a synthesis, general conclusions and recommendations.

1.8 References

Baumhardt, R.L., Stewart, B.A. and Sainju, U.M., 2015. North American soil degradation: Processes, practices, and mitigating strategies. Sustainability, 7(3), pp.2936-2960.

Bhattacharyya, R., Ghosh, B.N., Mishra, P.K., Mandal, B., Rao, C.S., Sarkar, D., Das, K., Anil, K.S., Lalitha, M., Hati, K.M. and Franzluebbers, A.J., 2015. Soil degradation in India: Challenges and potential solutions. Sustainability, 7(4), pp.3528-3570.

Bindraban, P.S., van der Velde, M., Ye, L., Van den Berg, M., Materechera, S., Kiba, D.I., Tamene, L., Ragnarsdóttir, K.V., Jongschaap, R., Hoogmoed, M. and Hoogmoed, W., 2012. Assessing the impact of soil degradation on food production. Current Opinion in Environmental Sustainability, 4(5), pp.478-488.

Blanchart, E., Villenave, C., Viallatoux, A., Barthès, B., Girardin, C., Azontonde, A. and Feller, C., 2006. Long-term effect of a legume cover crop (Mucuna pruriens var. utilis) on the communities of soil macrofauna and nematofauna, under maize cultivation, in southern Benin. European Journal of Soil Biology, 42, pp.S136-S144.

Campiglia, E., Radicetti, E. and Mancinelli, R., 2012. Weed control strategies and yield response in a pepper crop (Capsicum annuum L.) mulched with hairy vetch (Vicia villosa Roth.) and oat (Avena sativa L.) residues. Crop Protection, 33, pp.65-73.

Citrus Grower Association of South Africa (CGA), 2023. Industry Statistics, export seasons.https://c1e39d912d21c91dce811d6da9929ae8.cdn.ilink247.com/ClientFiles/cga/CitrusGowersAssociation/Company/Documents/2024%20Stats%20Book%20(03_06_24%20Final%20digital%20copy)_compressed.pdf. Accessed: 21/10/2024.

Djigal, D., Saj, S., Rabary, B., Blanchart, E. and Villenave, C., 2012. Mulch type affects soil biological functioning and crop yield of conservation agriculture systems in a long-term experiment in Madagascar. Soil and tillage research, 118, pp.11-21.

Goble, T.A., Dames, J.F., P Hill, M. and Moore, S.D., 2010. The effects of farming system, habitat type and bait type on the isolation of entomopathogenic fungi from citrus soils in the Eastern Cape Province, South Africa. BioControl, 55(3), pp.399-412.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability, 7(5), pp.5875-5895.

López-Vicente, M., Calvo-Seas, E., Álvarez, S. and Cerdà, A., 2020. Effectiveness of cover crops to reduce loss of soil organic matter in a rainfed vineyard. Land, 9(7), p.230.

Mather, C. and Greenberg, S., 2003. Market liberalisation in post-apartheid South Africa: The restructuring of citrus exports after deregulation. Journal of Southern African Studies, 29(2), pp.393-412.

Mauro, R.P., Anastasi, U., Lombardo, S., Pandino, G., Pesce, R., Alessia, R. and Mauromicale, G., 2015. Cover crops for managing weeds, soil chemical fertility and nutritional status of organically grown orange orchard in Sicily. Italian Journal of Agronomy, 10(2), pp.101-104.

Murphy, B.W., 2015. Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. Soil Research, 53(6), pp.605-635.

Obalum, S.E., Chibuike, G.U., Peth, S. and Ouyang, Y., 2017. Soil organic matter as sole indicator of soil degradation. Environmental monitoring and assessment, 189, pp.1-19.

Srivastava, A.K. and Singh, S., 2009. Citrus decline: Soil fertility and plant nutrition. Journal of Plant Nutrition, 32(2), pp.197-245.

Stagno, F., Abbate, C., Intrigliolo, F., Abbate, V. and Gennari, M., 2008. Effect of leguminous cover crops on soil biological activity in pots of Citrus unshiu Marcovitch. Italian Journal of Agronomy, 3(3), pp.183-190.

Strauss, S., 2020. Using Cover Crops to Combat Citrus Greening. <https://griffinfertilizer.com/using-cover-crops-to-combat-citrus-greening. (accessed: April, 2023).

Strauss, S., Kadyampakeni, D., Kanissery, R., Wade, T., Diepenbrock, L. and Popenoe, J., 2019. Cover crops for citrus. EDIS, 2019.

Wright, D.L., Mackowiak, C. and Blount, A., 2017. Cover crops. University of Florida, IFAS Extension Service, Gainesville, Florida, USA. Publication# SS-AGR-66.

Chapter 2

Literature review: Evaluating the effects and benefits of cover crops in citrus orchards

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Abstract

Cover crops are used in sustainable agricultural practices to improve soil quality and minimise the effect of climate change, water restrictions and drought. However, knowledge of cover crops in citrus orchards in South Africa is limited. This review focuses mostly on evaluating cover crop selection, effects on soil microbial community, weed control, citrus yield and fruit quality. In terms of cover crop selection, legumes seem to be preferred over non-legume cover crops. Reviewed literature reported that legume cover crops increased nitrogen by 67 to 209 kg N ha^{-1} through the nitrogen fixation process. Additionally, the cultivation of legume cover crops increased the cost savings of nitrogen fertiliser substantially by 585 ZAR to 1 674 ZAR ha^{-1}. The fruit yield improved by 7.6% to 64% while fruit quality improved by 2.3% to 12.4% fruit weight and 2.4% to 5.8% Brix. As a result, citrus growers can reap the benefits of cover crops including improved soil quality, yield and decreased costs.

Keywords: Legumes, nitrogen fixation, organic carbon, organic matter, soil microbial community, tree shading.

2.1 Introduction

South Africa is the second largest citrus fruit exporter in the world after Spain with 54% of the total citrus production exported (Moore & Manrakhan, 2022; Ndou & Obi, 2011). Twenty-five per cent of citrus fruit is processed and 21% is consumed locally as fresh fruit (Ndou & Obi, 2011). South Africa grows and exports a diverse range of citrus fruits including soft citrus, limes, lemons, grapefruits, citrus juice and oranges (Ndou & Obi, 2011). The world's largest citrus producers, like Brazil, have taken an interest in more sustainable production methods such as planting cover crops to enhance soil organic matter and reduce the use of harmful agrochemicals (Azevedo et al., 2020; Linares et al., 2008). However, the use of cover crops in improving soil organic matter has been limited while an increase in the use of chemical inputs has been observed in South Africa (Wright et., 2017). Numerous studies have clearly demonstrated that excessive levels of chemical inputs lead to serious environmental impacts, loss of biodiversity and health risks (Dabney et al., 2010; Jannoyer et al., 2011). The cultivation of cover crops in citrus orchards enhances soil biology and retains soil moisture, reducing the use of chemical inputs such as pesticides and fertilisers (Jannoyer et al., 2011).

The purpose of planting cover crops is to cover the soil surface and improve soil quality (Benedict et al., 2014). Cover crops include non-legumes (such as grasses and brassicas) and legumes (Adetunji, 2019). Legumes are the biggest contributors to biological nitrogen fixation and are able to convert nitrogen gas from the atmosphere into a suitable form for plant use (Hungria & Mendes, 2015). Cover crop species such as vetch can conserve moisture (Adetunji et al., 2020; Villamil et al., 2006). Additionally, cover crops can reduce herbicide use in orchards by controlling weeds. Cover crops control weeds by competing with them for water, nutrients and light (Blanco-Canqui et al., 2015; Jannoyer et al., 2011). Fourie et al. (2017) showed that oats and white mustard cover crops successfully suppressed ryegrass weeds. In citriculture, cover crops are commonly planted between the rows of orchards to benefit the soil (Barenbrug Cover Crop Guide, 2020). Thereafter, cover crops are mowed and placed under the tree canopy to create mulching (Martinelli et al., 2017). The root mass and leaf litter offer soil carbon input year-round (Strauss et al., 2019).

Once a cover crop is planted, the soil microbial community changes due to the increased amount of soil organic matter, resulting in an abundance of cycling organisms that increase carbon and nitrogen (Mbuthia et al., 2015). A cover crop increases soil carbon and nitrogen through root exudates, residue decomposition and symbiotic nitrogen fixation (Schmidt et al., 2018). Cover crops such as legumes harvest nitrogen gas from the atmosphere through the nitrogen fixation process and retain the excess nitrogen in the soil for the next crop (O'Reilly et al., 2011). Proper management of cover crops is essential as improper management will cause competition with the main crop for water, nutrient immobilisation and may result in pests and disease outbreaks (Adetunji et al., 2020). Proper cover crop management includes selecting suitable cover crop species, determining the correct planting period, growth period and termination methods (Chapagain et al., 2020).

In this review, the effects and benefits of cover crops in citrus orchards in terms of cover crop selection, soil microbial community, legumes and nitrogen fixation, weed control and fruit quality will be discussed.

2.2 Cover crop selection

The selection of the correct cover crop is based on a specific goal that needs to be achieved, for example, to enhance the soil carbon. The season in which the cover crop will be planted is a factor for selecting a cover crop as there are annual and perennial cover crops (Wright et al., 2017). Annual cover crops are grown in winter or summer. Winter cover crops are short-lived, suitable for cool short days while summer cover crops are suitable for hot long days (Wright et al., 2017). Winter cover crops include hairy vetch, lupine and winter rye while summer cover crops include cowpeas, sunn hemp and velvet beans (Wright et al., 2017). The perennial cover crops such as Bahiagrass and rhizome peanut generally grow for many years.

Knowledge of how to manage cover crops, such as sowing timing, sowing methods, time and method of killing cover crops, is essential when selecting a cover crop (Sharma et al., 2018). The cover crop is planted between the tree rows or after the main crop and killed before the next crop using chemical or mechanical equipment (Qi & Helmers, 2010; Hartwig & Ammon, 2002). Cover crops can be screened using the three steps, as indicated in the diagram (Fig. 2.1). The first step of selection screens vegetative characteristics which include cover crop height (< 50 cm), tree shading tolerance, re-growth ability, covering capacity and perennial or annual (Jannoyer et al., 2011). It is necessary to select cover crops that can tolerate shading as citrus trees have a high degree of shading under the dense tree canopy (Evans et al., 1998). The second step takes into account the cover crop practicality uses, such as availability of seed, cover crop management (maintenance, time of planting and termination), regulations and farm constraints which may include labour costs and labour demand. The final step screens for the desired ecological services, which include weed competition capacity, potential pest hosting, biomass production and the ability to improve soil physical and biological properties, such as soil aggregates and micro-organisms (Jannoyer et al., 2011). The cover crop is selected if suitable or if it fits all the diagram steps (Jannoyer et al., 2011).

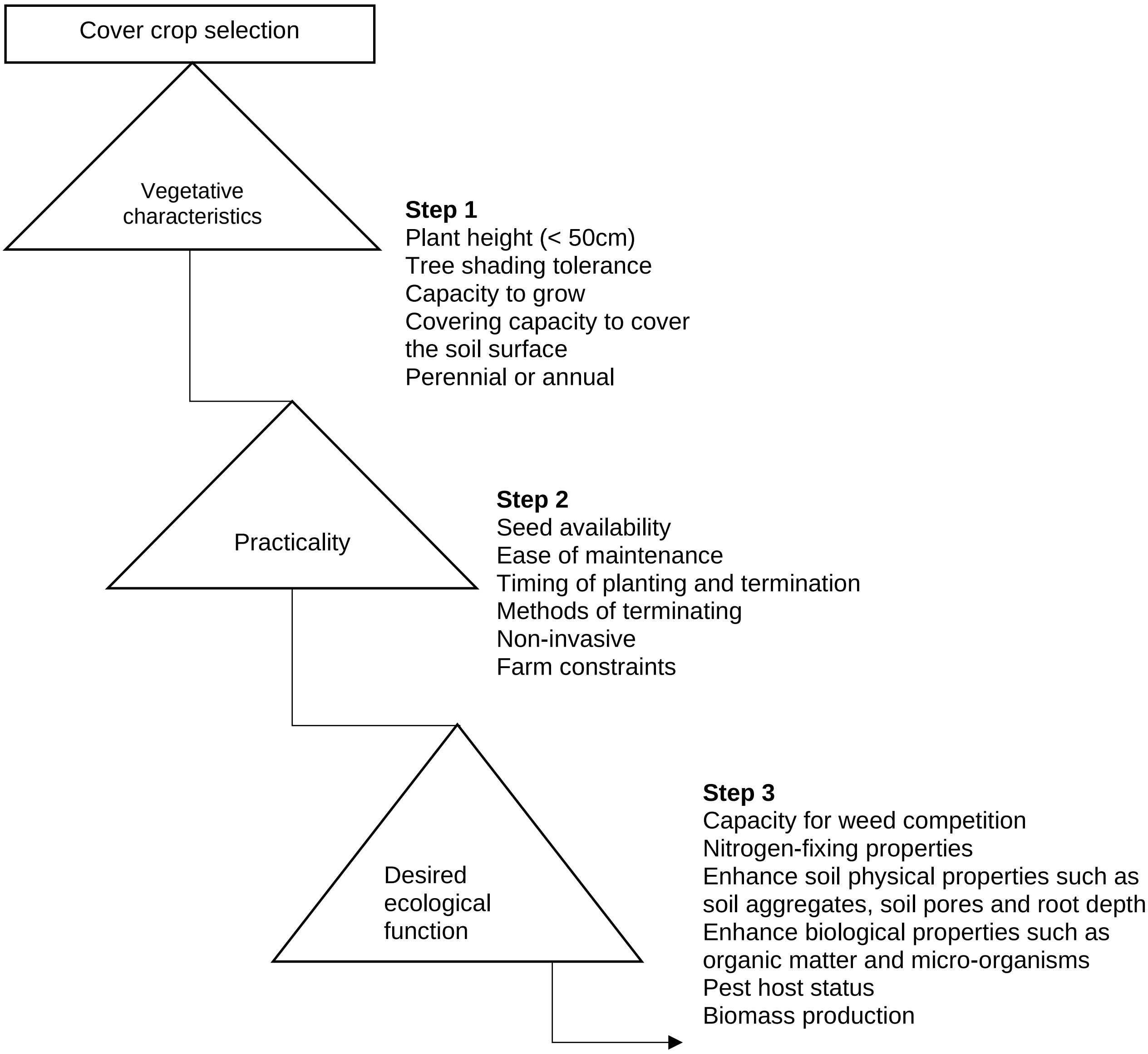

Figure 2.1. Diagram designed for screening cover crop steps for orchards adapted from Jannoyer et al. (2011).

2.3 Soil microbial community composition/diversity

Soil microbial community composition changes through an increase in soil organic matter, which increases nitrogen-cycling microorganisms (Strauss et al., 2019). Several cover crops affect the soil microbial community by enhancing soil enzyme activities, bacteria and soil respiration. Stagno et al. (2008) examined the effect of leguminous cover crops on microbial communities in pots of *Citrus unshiu Marcovitch*. There was an increase in substrate-induced respiration and nitrogen-ammonia (N-NH_3) content in the soil. The increase of N-NH_3 may be the result of the atmospheric nitrogen fixation by rhizobia and, in the long term, the legume cover crops will result in an increase of other parameters such as total nitrogen and total organic carbon (Stagno et al., 2008).

Ryegrass cover crops in conventional tillage and a no-tillage system had a higher microbial population in the upper 2 cm layer compared to no-cover crop plots (Sharma et al., 2018). Oats and cereal rye cover crops enhanced arbuscular mycorrhizal fungi while hairy vetch cover crops favoured non-arbuscular mycorrhizal fungi (Sharma et al., 2018). In a preliminary study conducted by Strauss et al. (2019), a significantly diverse bacterial community composition was found under Bahiagrass cover crop after just six months compared to farmer-standard mowed weeds. Chavarría et al. (2016) tested a mixture of oat with radish and oat with radish and vetch cover crops. Total bacterial and Gram-positive bacteria were significantly higher by 6.8% in cover crop mixtures compared to no-cover crop treatments. The soil enzyme activities, such as acid phosphatase, esterase activity and dehydrogenase activity were higher in cover crop treatments than in the control treatments (Chavarría et al., 2016). Soil enzyme activities were 20% higher under cover crop mixtures than the control treatments (no cover crops). Mbuthia et al. (2015) conducted a long-term study (31 years) to evaluate the effect of tillage, cover crop and fertilisation on microbial community structure. In that particular study, hairy vetch significantly increased microbial community compared to wheat and control treatments where there was no cover crop. The enzyme activities (β-glucosidase and β-glucosaminidase) increased by approximately 14% and phosphodiesterase increased by 10% under no-till conditions (Mbuthia et al., 2015).

Mycorrhiza increased citrus tree growth and nutrient uptake (Abobatta, 2020). The mycorrhiza can be inoculated to enhance citrus tree water uptake, tolerance against stress conditions and reduce iron-chlorosis symptoms (Wang & Xia, 2009; Vives-Peris et al., 2018). Abobatta and El-Azazy (2020) reported that phosphorus-solubilising microbes such as the *Bacillus* species, convert insoluble phosphorus to a form that is suitable for plant use. Inoculation of legume cover crop seeds with phosphorus-solubilising microbes will improve phosphorous uptake by roots, stimulate plant growth hormones, fruit quality and overcome phosphorus deficiency (Saleemi et al., 2017; El-Khawaga & Maklad, 2013).

2.4 Legume cover crops

Legumes form a symbiotic relationship with soil bacteria that fix atmospheric nitrogen (Wright et al., 2017). The nitrogen fixation process is executed by diazotrophic bacteria such as rhizobia which are found in nodules in the rhizosphere (Andrews & Andrews, 2017). At times, legume seeds are inoculated with rhizobium bacteria before planting, to convert nitrogen gas from the atmosphere into a form of nitrogen that is readily available for plant use (Wright et al., 2017). Many researchers have reported that legume cover crops are highly beneficial compared to grass cover crops as they provide nitrogen for the current and next seasons through nitrogen fixation (Fischer et al., 2010; Teasdale et al., 2007).

Nitrogen fixation is a microbiological process that transforms atmospheric nitrogen into a form that is usable by plants (Selim et al., 2020). Nitrogen fixation offers an economically beneficial and ecologically sound means of enhancing internal natural resources and reducing external inputs (Bohlool et al., 1992). Currently, nitrogen fixation receives a great deal of attention from citrus growers abroad due to its potential in reducing the use of inorganic fertilisers (Abobatta & El-Azazy, 2020). Nitrogen-fixing organisms play a vital role in improving cell division and cell enlargement by releasing growth hormones, which increase citrus fruit size and fruit quality (Abobatta & El-Azazy, 2020). Selim et al. (2020) state that citrus tree shading helps cover crops to stimulate the nitrogen-fixing bacteria. In summary, nitrogen fixation is an essential component of nutrient management, as it is eco-friendly, enhances fruit quality and is cost-effective. However, nitrogen-fixing microorganisms are only found in the nodules of legume cover crops, therefore, non-legume cover crops such as grass and brassicas are not able to fix nitrogen (Pommeresche & Hansen, 2017).

In areas where legume cover crops are planted, the rhizobacteria decompose soil biomass, releasing nitrogen and other nutrients to improve plant and fruit growth (Mulinge et al., 2018). Legume cover crops are easily decomposable in the soil and release nutrients beneficial for plant growth (Aseri et al., 2008). Mbuthia et al. (2015) reported that legume cover crops such as vetch improved microbial activities, carbon and nitrogen cycling. Few studies are found regarding the effect of leguminous cover crops on soil nitrogen (Table 2.1). These studies demonstrate that legume cover crops increase soil nitrogen. The lowest soil nitrogen increase was 67 kg N ha^{-1} and the highest was 209 kg N ha^{-1} with the fertiliser replacement value of 65 kg N ha^{-1} and 100 kg N ha^{-1}, respectively (Blevins et al., 1990; Ebelhar et al.,1984). This brings cost savings of 585 ZAR and 900 ZAR ha^{-1} at the fertiliser replacement value of 65 kg N ha^{-1} and 100 kg N ha^{-1}. Most of these studies were conducted under no-till soil conditions in different crop types (Blevins et al., 1990; Ebelhar et al., 1984; Dou and Fox, 1994; Hargrove, 1986). No-till soil is a zero or minimum tillage practice that permits crop residue retention to provide effective mulch (Li et al., 2019). The no-till soil practice allows for the decomposition of crop residue to give organic matter which increases soil nitrogen.

Table 2.1. Contributions of legume cover crops to nitrogen (N) and fertiliser cost savings adapted from Dabney et al. (2010).

Study site	Cover crop (Legumes)	Main crop	Nitrogen increase (kg N ha^{-1})	Fertiliser-Nitrogen equivalency (kg N ha^{-1})	Cost saving (ZAR ha^{-1})	Reference
Coastal Plain site, Georgia, United States	Crimson clover	Corn	108	99	891	McVay et al. (1989)
Department of Agronomy, University Park, United States	Hairy vetch	Maize	151	164	1 476	Dou & Fox (1994)
Coastal Plain site, Georgia, United States	Hairy vetch	Grain Sorghum	128	123	1 107	McVay et al. (1989)
Department of Agronomy, University Park, United States	Red clover	Maize	134	186	1 674	Dou & Fox (1994)
Kentucky experimental farm, United States	Hairy vetch	Corn	103	75	675	Blevins et al. (1990)
Indian Agricultural Research Institute, New Delhi	Sesbania	Maize	131	67	603	Sharma & Behera (2009)
Kentucky experimental farm, United States	Bigflower vetch	Corn	67	65	585	Blevins et al. (1990)
Georgia Agric experimental Station, Unites States	Hairy vetch	Grain Sorghum	153	97	873	Hargrove (1986)

Kentucky experimental farm, United States	Hairy vetch	Corn	209	100	900	Ebelhar et al. (1984)
Experimental Center of Cauquenes, Maule Region in Chile	Clover and burr medic	Vineyard	112	40	360	Ovalle et al. (2010)

2.5 Effects of cover crops on soil organic matter and carbon

Soil organic matter is an important indicator of soil quality and a source of carbon (Liu et al., 2006). Soil quality is defined as the ability of the soil to support plant growth without harming the environment (Acton & Gregorich, 1995). Dabney et al. (2010) state that the cultivation of cover crops is one of the most cost-effective practices to improve soil organic matter. The decomposition of above and below ground cover crop biomass enhances organic matter in the soil (Fourie et al., 2007). An increase in soil organic matter increases soil microbial activity and results in the release of beneficial nutrients such as organic carbon and nitrogen (Strauss et al., 2019). Organic matter contains approximately 58% organic carbon (Khatoon et al., 2017). Soil organic matter also increases soil water holding capacity due to its ability to absorb water. Many studies have shown that cover crops not only enhance soil organic matter and carbon but also suppress weeds, prevent runoff and wind or soil erosion and improve nitrogen mineralisation (Dian-Ming et al., 2011; Wright et al., 2017).

Various studies investigating the effect of cover crops on soil organic carbon are summarised in Table 2.2. Signal grass cover crop increased organic carbon by 52% and 70% in a Pera orange orchard under no-till conditions (Balota & Auler, 2011; Bould & Jarrett,1962). Cover crops also increased organic carbon when planted in grain fields under no-till conditions (Chavarría et al., 2016; Mbuthia et al., 2015). Cover crop mixtures (oats, vetch and radish) resulted in 8.8% increase in organic carbon in soybean trials (main crop), while hairy vetch and winter wheat resulted in a 19% increase (Table 2.2). Cover crops increased organic carbon by 0.61 mg ha^{-1} in a maize field and 9.8 mg ha^{-1} in Pera orange orchards under no-till conditions and mechanically mowed after flowering (Oliveira et al., 2016; Mazzoncini et al., 2011). Some of the results in Table 2.2 indicate that the planting of cover crop mixtures of legume and non-legume cover crops enhanced soil organic carbon since the mixture provided more biomass above and below the ground resulting in more organic matter (Chavarría et al., 2016; Mbuthia et al., 2015).

Table 2.3. Literature summary of cover crop effects on soil organic carbon

Study site	Cover crop	Main crop	Organic carbon increase (%)	Reference
State of Paraná, Brazil	Signal grass	Pera oranges	52%	Balota & Auler (2011)
Instituto Nacional de Tecnología Brazil	Oats, vetch and radish	Soybean	8.8%	Chavarría et al. (2016)
State of Paraná, Brazil	Signal grass	Pera oranges	70%	Bould & Jarrett (1962)
West TN AgResearch and Education Center (US)	Hairy vetch and winter wheat	Cotton	19%	Mbuthia et al. (2015)

2.6 Effects of cover crops on weeds

The presence of weeds is a big problem especially in young citrus orchards since the trees provide little shade to suppress weed growth (Singh & Sharma, 2008). In general, weeds interfere with citrus trees as they compete for essential resources such as water and nutrients (Martinelli et al., 2017). Weeds also act as hosts for pests, diseases and pathogens (Hosseini & Dianat, 2014). It was reported that a 33% loss of yield can be experienced due to weed competition in citrus orchards (Singh & Sharma, 2008). Therefore, farmers primarily depend on chemical control (Hosseini & Dianat, 2014). The herbicides used to control weeds result in environmental pollution (Olorunmaiye et al., 2011). More sustainable options to control the weeds including the use of cover crops are needed since citrus is one of the most valuable crops economically in South Africa. Researchers have described cover crops as one of the important biological ways to control weeds and have positive effects on enhancing soil fertility (Knezevic et al., 2002).

Several studies have demonstrated the effects of different cover crops on suppressing weeds in citrus orchards (Table 2.3). According to these studies, cover crops are an effective method for controlling weeds because weed reduction was consistently above 50%; the lowest was 56% and the highest was 97% (Table 2.3). Common vetch was the most beneficial for weed control with 97% weed reduction, followed by Bahiagrass (95%), cowpea (90%) and signal grass (56%). These cover crops were planted under no-till soil conditions and mowed using different types of mowers (Table 2.3). Linares et al. (2008) evaluated the effectiveness of cover crops to control weeds and reported that winter cover crop mixtures gave higher dry matter accumulation and suppressed weeds effectively compared to single species. Mauro et al. (2015) studied the effects of four cover crops (wild mustard-fenugreek, medics-oats-perennial ryegrass, faba bean-oats-oats and oats-faba bean-perennial ryegrass) in suppressing weeds on the organic orange orchard. The faba bean-oats-oats efficiently controlled weeds compared to other treatments (Mauro et al., 2015). A study conducted by Abdel-Aziz et al. (2013) found that butterfly pea forage legume and mix of stylo, butterfly pea and finger millet gave the best results in suppressing weeds, improving mandarin citrus trees growth and final yield.

Table 2.4. Literature summary of cover crops effects on weeds in citrus orchards

Study site	Cover crop	Main crop	% Weed reduction	Reference
University of Florida, United States	Cowpea	Hamlin and navel orange	90%	Linares et al. (2008)
University of Florida trial, United States	Bahiagrass	Citrus	95%	Strauss et al. (2019)
Mogi Mirim, Brazil	Signal grass	Tahiti acid lime citrus	56%	Martinelli et al. (2017)
Cukurova University, Turkey	Common vetch	Citrus	97%	Kolören & Uygur (2007)
Eastern Sicily, Italy	Faba bean-oats-oats	Tarocco Comune orange	92%	Mauro et al. (2015)

2.7 Effect of cover crops on soil moisture

The Western Cape province in South Africa will have a streamflow reduction with increased temperatures that will impact irrigated agriculture (Volschenk, 2020). Planting cover crops may reduce the amount of irrigation required by increasing soil water holding capacity in citrus orchards. An increase in soil water holding capacity reduces the leaching of nutrients and runoff of water below the root zone as well as soil evaporation (O'Connell & Synder, 2000; Kaspar et al., 2011). Cover crops also improve soil hydraulic properties such as water infiltration by enhancing soil organic carbon and microbial population (Sharma et al., 2018). Rye cover crops significantly reduced monthly subsurface drainage by 21% compared to bare soil (Qi & Helmers, 2010). The bromegrass, resident vegetation and strawberry clover cover crops increased the infiltration rate by 37% to 41% (Folorunso et al.,1992). Water infiltration increases due to an increase of soil pores formed by cover crop root growth (Sharma et al., 2018). Oats and vetch significantly lowered the surface soil strength by 20% to 41% and enhanced cumulative water intake (Folorunso et al.,1992).

Mucuna cover crops increased soil moisture retention compared to cowpea and dolichos cover crops in a citrus orchard (Mulinge et al.,2018). Mucuna is a legume cover crop known for its effectiveness in enhancing soil moisture and promoting carbon sequestration in the soil (Barthès et al., 2004). Cover crops significantly improved soil moisture between 4.2% and 10% (Abdel-Aziz et al., 2013). Interestingly, Ntshidi et al. (2021) evaluated the water use of cover crops commonly grown in South African fruit orchards. The legumes had the highest daily water use ranging from 2 to 2.5 $Lm^{-2}d^{-1}$, followed by exotic grass with 1.5-21 $Lm^{-2}d^{-1}$ and indigenous grasses with 0.8-12 $Lm^{-2}d^{-1}$ (Ntshidi et al., 2021). Winter cover crops such as oats and rye increase soil organic carbon, thereby increasing soil moisture content and water infiltration (Sharma et al., 2018). Furthermore, the use of winter annual cover crops (rye and vetch) increases soil water storage (Bilek, 2007; Villamil et al., 2006). The rye and vetch can conserve moisture in the soil (Adetunji et al., 2019; Villamil et al., 2006). In general, cover crops have a positive effect on soil moisture due to cover crops' ability to decrease soil water evaporation (Abdel-Aziz et al., 2008).

2.8 Citrus yield and fruit quality

Nitrogen and potassium are major factors influencing citrus fruit production (Alva & Paramasivam, 1998). Nitrogen is required for vegetative growth and fruit growth (Fikry et al., 2020), while potassium plays an important role in citrus fruit sizes and vitamin C content (Ashraf et al., 2010). Little is known regarding the effect of cover crops on citrus yield and fruit quality in South Africa. However, the use of legume cover crops has been recommended to complement trees and enhance fruit quality in citrus orchards (Naveen, 2020). Leguminous cover crops discharge substantial nitrogen and other nutrients through the decomposition of soil biomass by rhizobacteria (Gattuso et al., 2007). Fruit yield increased significantly when cover crops were used in citrus orchards (Table 2.4). Signal grass cover crops produced the highest fruit yield increase of 64%, followed by lupine (9.6%) and soybeans (7.6%). The cover crops were planted using a minimum tillage system and interplanting in citrus orchards (Martinelli et al., 2017; Hefny et al., 2020; Selim et al., 2020). After a 22-year long-term study, Parker and Jones (1951) found that the fruit yield of cover crop plots increased gradually to 30% higher than standard plots (clean plots). Cover crops were incorporated with animal manure, which led to bigger fruit. Among the benefits of animal manure is potassium content which positively affects fruit size (Parker & Jones, 1951).

The fruit weight and °Brix increased significantly when legume cover crops were used in citrus orchards (Mulinge et al., 2018; Selim et al., 2020). The highest fruit weight increase of 12.4% was obtained with mucuna cover crop, followed by soybean with 2.3% increase (Table 2.5). Mucuna cover crop increased the °Brix value by 5.8%, while soybean cover crop increased °Brix value by 2.4% (Table 2.5). Fruit weight and °Brix studies were conducted at Vitengeni, Kenya and El-Kassaseen Agricultural Research Center (ARC) in Egypt (Mulinge et al., 2018; Selim et al., 2020). The Vitengeni site gave a higher increase in fruit weight and °Brix than the ARC site. Among other factors, clay content might have contributed to an increase in fruit quality at Vitengeni. The Vitengeni site has a soil clay content of 26%, while ARC has only 12.4%. The clay content allows the soil to hold water longer and become accessible to fruit when needed. The ARC site has higher sand percentages (85.55%), resulting in the soil drying out more quickly. Chakravarty and Wade (2022) concluded that cover crops are an economically feasible practice in citrus production as they have significant potential to enhance fruit quality by 2.7% to 7.1% and 1.1% to 6.1% for Valencia and non-Valencia oranges, respectively.

Table 2.5. Literature summary of cover crops effects on citrus yield

Study site	Cover crops	Main crop	Increase in citrus fruit yield (%)	Reference
Mogi Mirim, Brazil	Signal grass	Tahiti acid lime	64	Martinelli et al. (2017)
Citrus Experiment Station at Riverside, California	Unspecified	Washington navel	30	Parker & Jones (1951)
El-Kassaseen Agricultural Research Center (ARC), Egypt	Lupine	Valencia orange	9.6	Hefny et al. (2020)
El-Kassaseen Agricultural Research Station (ARC), Egypt	Soybean (Cultivar: Giza 22)	Mandarin trees	7.6	Selim et al. (2020)

Table 2.6. Literature summary of cover crop effects on citrus quality

Study site	Cover crops	Main crop	Increase in citrus fruit quality (%)	Reference
Vitengeni, Kenya	Mucuna	Valencia orange	12.4% fruit weight.	Mulinge et al. (2018)
El-Kassaseen Agricultural Research Center (ARC), Egypt	Soybean (Cultivar: Giza 22)	Mandarin trees	2.3% fruit weight	Selim et al. (2020)
Vitengeni, Kenya	Mucuna	Valencia orange	5.8% °Brix	Mulinge et al. (2018)
El-Kassaseen Agricultural Research Center (ARC), Egypt	Soybean (Cultivar: Giza 22)	Mandarin trees	2.4% °Brix	Selim et al. (2020)

2.9 Cover crops limitations

Many farmers lack knowledge of managing cover crops such as best time of planting, maintenance and methods of terminating cover crops (Sharma et al., 2018). Furthermore, machinery limitation for planting cover crops and intensive labour makes it more difficult for farmers to plant cover crops. Different types of machinery are necessary for land preparation, sowing and termination of cover crops. Therefore, farmers are required to purchase suitable machinery in order to sow cover crops effectively and successfully. However, smallholder farmers struggle to afford machinery purchases, which makes it difficult for them to profit from cover crops. Planting cover crops does not give positive results immediately, this may result in an increase in production costs as the farmer needs to spend money on labour and machinery (Hoorman, 2009). Lack of rainfall can also limit the establishment of cover crops (Kaspar, 2008). As a result of the lack of rain, cover crops must be planted late or irrigated with an irrigation system, which is a further expense.

The sowing of cover crops in citrus orchards tends to interfere with harvesting, especially for early maturing cultivars. As a result of interference, labour tends to be stretched as they are needed for planting cover crops and harvesting fruit simultaneously. Sometimes the tractor damages the cover crop's growth during spraying and harvesting of the main crop. Additionally, insects and pathogens may use the cover crops as a host and attack the main crop (Lu et al., 2000). Different types of nematodes use different cover crops as host plants and planting the wrong cover crop can result in severe nematode damage to citrus trees. Poor termination of cover crops may result in regrowth of cover crops which will then compete with the main crop for water, light and nutrients (Cordeau et al., 2015; Singh et al., 2016). There is limited scientific information on cover crop water consumption and the partitioning of natural resources between cover crops and trees.

2.10 Economic Feasibility for Smallholder Farmers

While cover crops offer promising benefits for soil quality, nutrient cycling and citrus yield and quality improvement, their adoption by smallholder farmers in South Africa remains constrained by economic feasibility. Smallholders often operate with limited financial capital and struggle with upfront costs such as seed purchase, equipment rental and labour (Eagle and Saleh, 2020). Although leguminous cover crops can significantly reduce synthetic nitrogen needs over time, the initial investment in high quality seed and specialized sowing tools may not be accessible to resource-constrained farmers. Additionally, labour requirements for sowing, managing and terminating cover crops can be substantial, particularly when mechanization is limited. Therefore, the economic viability of cover crop systems in smallholder contexts is closely tied to context specific support mechanisms, such as group-based machinery sharing, subsidies for seed inputs and technical extension assistance (Shikuku et al., 2024).

2.11 Conclusion

Cover crops have a positive effect on improving soil quality and yield if managed correctly. Choosing the correct cover crop is crucial to obtain real benefits. Therefore, it is advisable that cover crops are planted in citrus orchards following the three-step screen method. Cover crops enhance soil quality by improving soil moisture, soil organic carbon and nitrogen, soil microbial population and control weeds. The cultivation of cover crops also helps to enhance fruit quality as fewer chemical inputs are used in the orchards. This is an important consideration for consumers who are becoming increasingly more aware of the effects of crop production on the environment, which is needed by customers. However, studies have shown that cover crop benefits only come after long-term use, therefore, a farmer should not expect immediate benefits. In addition, there is a lack of information on cover crop effects on citrus under South African conditions.

2.12 References

Abdel-Aziz, R.A., Calegari, A., Vicente, P. and Zaccheo, C., 2013. Impact of cover crops on soil, weeds and citrus trees properties in Brazil. Egyptian Journal of Horticulture, 40(1), pp.47-61.

Abdel-Aziz, R.A., Salem, S.E. and Al-Bitar, L., 2008. Effect of inter-cropping cover crops on citrus orchards growth and fruiting under Toshka conditions. Journal of Agricultural Sciences, 1, pp.101-110.

Abobatta, W.F. and El-Azazy, A.M., 2020. Role of organic and biofertilizers in citrus orchards. Aswan University Journal of Environmental Studies, 1(1), pp.13-27.

Abobatta, W.F., 2020. Biofertilizers and citrus cultivation. MOJ Ecology & Environmental Sciences, 5(4), pp.171-176.

Acton, D.F. and Gregorich, L.J., 1995. The health of our soils—towards sustainable agriculture in Canada. Centre for land and biological resources research, research branch, Agriculture and Agri-Food Canada, Ottawa, 138. https://doi.org/10.5962/bhl.title.58906. Visited 23 July 2022.

Adetunji, A.T., 2019. Impact of cover crop species, termination stage and termination method on soil nitrogen, organic carbon and enzyme activities (Doctoral dissertation, Cape Peninsula University of Technology).

Adetunji, A.T., Ncube, B., Mulidzi, R. and Lewu, F.B., 2020. Management impact and benefit of cover crops on soil quality: A review. Soil and Tillage Research, 204, pp.104717.

Alva, A.K. and Paramasivam, S., 1998. Nitrogen management for high yield and quality of citrus in sandy soils. Soil Science Society of America Journal, 62(5), pp.1335-1342.

Andrews, M. and Andrews, M.E., 2017. Specificity in legume-rhizobia symbioses. International Journal of Molecular Sciences, 18, E705. https://doi.org/10.3390/ijms18040705.

Aseri, G.K., Jain, N., Panwar, J., Rao, A.V. and Meghwal, P.R., 2008. Biofertilizers improve plant growth, fruit yield, nutrition, metabolism and rhizosphere enzyme activities of pomegranate (*Punica granatum L.*) in Indian Thar Desert. Scientia horticulturae, 117(2), pp.130-135.

Ashraf, M.Y., Gul, A., Ashraf, M., Hussain, F. and Ebert, G., 2010. Improvement in yield and quality of Kinnow (*Citrus deliciosa* x *Citrus nobilis*) by potassium fertilization. Journal of Plant Nutrition, 33(11), pp.1625-1637.

Azevedo, F.A.D., Almeida, R.F.D., Martinelli, R., Próspero, A.G., Licerre, R., Conceição, P.M.D., Arantes, A.C.C., Dovis, V.L., Boaretto, R.M. and Mattos Jr, D., 2020. No-tillage and high-density planting for Tahiti acid lime grafted onto Flying Dragon trifoliate orange. Frontiers in Sustainable Food Systems, 4, p.108.

Balota, E.L. and Auler, P.A.M., 2011. Soil carbon and nitrogen mineralization under different tillage systems and permanent groundcover cultivation between orange trees. Revista Brasileira de Fruticultura, 33, pp.637-648.

Barenbrug Cover Crop Guide, 2020. https://www.barenbrug.co.za/downloads. Accessed on 28 February 2022.

Barthès, B., Azontonde, A., Blanchart, E., Girardin, C., Villenave, C., Lesaint, S., Oliver, R. and Feller, C., 2004. Effect of a legume cover crop (*Mucuna pruriens* var*. utilis*) on soil carbon in an ultisol under maize cultivation in southern Benin. Soil Use and Management, 20(2), pp.231-239.

Benedict, C., Cogger, C.G. and Andrews, N.N., 2014. Methods for successful cover crop management in your home garden. Washington State University.

Bilek, M.K., 2007. Winter annual rye cover crops in no-till grain crop rotations: impacts on soil physical properties and organic matter. University of Maryland, College Park.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A. and Hergert, G.W., 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy Journal, 107(6), pp.2449-2474.

Blevins, R.L., Herbek, J.H. and Frye, W.W., 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agronomy Journal, 82(4), pp.769-772.

Bohlool, B.B., Ladha, J.K., Garrity, D.P. and George, T., 1992. Biological nitrogen fixation for sustainable agriculture: A perspective. Plant and soil, 141(1), pp.1-11.

Bould, C. and Jarrett, R.M., 1962. The effect of cover crops and NPK fertilizers on growth, crop yield and leaf nutrient status of young dessert apple trees. Journal of Horticultural Science, 37(1), pp.58-82.

Chapagain, T., Lee, E.A. and Raizada, M.N., 2020. The potential of multi-species mixtures to diversify cover crop benefits. Sustainability, 12(5), p.2058.

Chavarría, D.N., Verdenelli, R.A., Serri, D.L., Restovich, S.B., Andriulo, A.E., Meriles, J.M. and Vargas-Gil, S., 2016. Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. European Journal of Soil Biology, 76, pp.74-82.

Cordeau, S., Guillemin, J.P., Reibel, C. and Chauvel, B., 2015. Weed species differ in their ability to emerge in no-till systems that include cover crops. Annals of Applied Biology, 166(3), pp.444-455.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J. and Reeves, W., 2010. Using cover crops and cropping systems for nitrogen management. Advances in nitrogen management for water quality, pp.231-282.

Dian-Ming, W.U., Yuan-Chun, Y.U., Li-Zhong, X.I.A., Shi-Xue, Y.I.N. and Lin-Zhang, Y.A.N.G., 2011. Soil fertility indices of citrus orchard land along topographic gradients in the three Gorges Area of China. Pedosphere, 21(6), pp.782-792.

Dou, Z. and Fox, R.H., 1994. The contribution of nitrogen from legume cover crops double-cropped with winter wheat to tilled and non-tilled maize. European Journal of Agronomy, 3(2), pp.93-100.

Eagle, D. and Saleh, N., 2020. The economics of smallholder farming. In The sustainable intensification of smallholder farming systems (pp. 33-64). Burleigh Dodds Science Publishing.

Ebelhar, S.A., Frye, W.W. and Blevins, R.L., 1984. Nitrogen from legume cover crops for no-tillage corn. Agronomy Journal, 76(1), pp.51-55.

El-Khawaga, A.S. and Maklad, M.F., 2013. Effect of combination between bio and chemical fertilization on vegetative growth, yield and quality of Valencia orange fruits. Hortscience Journal of Suez Canal University, 1, pp.269-279.

Evans, D.O., Joy, R.J. and Chia, C.L., 1998. Cover crops for orchards in Hawaii.

Fikry, A.M., Abou Sayed-Ahmed, T.A.M., Mohsen, F.S. and Ibrahim, M.M., 2020. Effect of Nitrogen fertilization through inorganic, organic and biofertilizers sources on vegetative growth, yield and nutritional status in Murcott Tangerine trees. Plant Archives, 20(1), pp.1859-1868.

Fischer, G., Winiwarter, W., Ermolieva, T., Cao, G.Y., Qui, H., Klimont, Z., Wiberg, D. and Wagner, F., 2010. Integrated modeling framework for assessment and mitigation of nitrogen pollution from agriculture: Concept and case study for China. Agriculture, Ecosystems & Environment, 136(1-2), pp.116-124.

Folorunso, O.A., Rolston, D.E., Prichard, T. and Loui, D.T., 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technology, 5(3), pp.189-197.

Fourie, J.C., Agenbag, G.A. and Louw, P.J.E., 2007. Cover crop management in a Sauvignon Blanc/Ramsey vineyard in the semi-arid Olifants River Valley, South Africa. 3. Effect of different cover crops and cover crop management practices on the organic matter and macro-nutrient contents of a sandy soil. South African Journal of Enology and Viticulture, 28(2), pp.92-100.

Fourie, J.C., Kunjeku, E.C., Booyse, M., Kutama, T.G., Freitag, K. and Ochse, C.H., 2017. Effect of cover crops and the management thereof, on the weed spectrum in a drip-irrigated vineyard: 2. Weeds growing from grapevine berry set to post-harvest. South African Journal of Enology and Viticulture, 38(2), pp.182-191.

Gattuso, G., Barreca, D., Gargiulli, C., Leuzzi, U. and Caristi, C., 2007. Flavonoid composition of citrus juices. Molecules, 12(8), pp.1641-1673.

Hargrove, W.L., 1986. Winter legumes as a nitrogen source for no-till grain sorghum. Agronomy Journal, 78(1), pp.70-74.

Hartwig, N.L. and Ammon, H.U., 2002. Cover crops and living mulches. Weed Science, 50(6), pp.688-699.

Hefny, Y., Kassem, E. and Ismail, E.S., 2020. Effect of irrigation with fish farm effluent on two legume crops interplanted with orange trees in a sandy soil. Moroccan Journal of Agricultural Sciences, 1(6), pp. 291-300.

Hoorman, J.J., 2009. Using cover crops to improve soil and water quality. Lima, Ohio: Agriculture and Natural Resources, The Ohio State University Extension.

Hosseini, S.M. and Dianat, M., 2014. Weed management in citrus orchards in khuzestan using summer cover crop mulch. International Journal of Advanced Biological and Biomedical Research, 2(10), pp.2696-2703.

Hungria, M. and Mendes, I.C., 2015. Nitrogen fixation with soybean: The perfect symbiosis? In: de Bruijn, F., Ed., Biological nitrogen fixation, John Wiley & Sons, Inc., Hoboken, (99) 2, pp. 1005-1019.

Jannoyer, M.L., Le Bellec, F., Lavigne, C., Achard, R. and Malézieux, E., 2011. Choosing cover crops to enhance ecological services in orchards: A multiple criteria and systemic approach applied to tropical areas. Procedia Environmental Sciences, 9, pp.104-112.

Kaspar, T.C., 2008. Potential and limitations of cover crops, living mulches and perennials to reduce nutrient losses to water sources from agricultural fields in the Upper Mississippi River Basin. Upper Mississippi River Sub-basin Hypoxia Nutrient Committee (UMRSHNC), 10, pp 127-148.

Kaspar, T.C., Singer, J.W., Hatfield, J.L. and Sauer, T.J., 2011. The use of cover crops to manage soil. Madison, WI: American Society of Agronomy and Soil Science Society of America, 409, pp 321-337.

Khatoon, H., Solanki, P., Narayan, M., Tewari, L., Rai, J.P.N. and Hina Khatoon, C., 2017. Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. International Journal of Chemical Studies, 5(6), pp.1648-1656.

Knezevic, S.Z., Evans, S.P., Blankenship, E.E., Van Acker, R.C. and Lindquist, J.L., 2002. Critical period for weed control: the concept and data analysis. Weed science, 50(6), pp.773-786.

Kolören, O. and Uygur, F.N., 2007. Investigation on weed control methods in citrus orchard in Çukurova region-Turkey. Asian Journal of Plant Sciences, 6(4), pp.708-711.

Li, H., Mollier, A., Ziadi, N., Messiga, A.J., Shi, Y., Pellerin, S., Parent, L.É. and Morel, C., 2019. Long-term modelling of phosphorus spatial distribution in the no-tilled soil profile. Soil and Tillage Research, 187, pp.119-134.

Linares, J., Scholberg, J., Boote, K., Chase, C.A., Ferguson, J.J. and McSorley, R., 2008. Use of the cover crop weed index to evaluate weed suppression by cover crops in organic citrus orchards. HortScience, 43(1), pp.27-34.

Liu, X., Herbert, S. J., Hashemi, A. M., Zhang, X. F. and Ding, G. (2006). Effects of agricultural management on soil organic matter and carbon transformation-a review. Plant Soil and Environment, 52(12), 531.

Lu, Y.C., Watkins, K.B., Teasdale, J.R. and Abdul-Baki, A.A., 2000. Cover crops in sustainable agriculture. Food Reviews International, 16 (2), pp.121-157.

Martinelli, R., Monquero, P.A., Fontanetti, A., Conceição, P.M. and Azevedo, F.A., 2017. Ecological mowing: an option for sustainable weed management in young citrus orchards. Weed Technology, 31(2), pp.260-268.

Mauro, R.P., Anastasi, U., Lombardo, S., Pandino, G., Pesce, R., Alessia, R. and Mauromicale, G., 2015. Cover crops for managing weeds, soil chemical fertility and nutritional status of organically grown orange orchard in Sicily. Italian Journal of Agronomy, 10(2), pp.101-104.

Mazzoncini, M., Sapkota, T.B., Barberi, P., Antichi, D. and Risaliti, R., 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil and tillage research, 114(2), pp.165-174.

Mbuthia, L.W., Acosta-Martínez, V., DeBruyn, J., Schaeffer, S., Tyler, D., Odoi, E., Mpheshea, M., Walker, F. and Eash, N., 2015. Long-term tillage, cover crop and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Biology and Biochemistry, 89, pp.24-34.

McVay, K.A., Radcliffe, D.E. and Hargrove, W.L., 1989. Winter legume effects on soil properties and nitrogen fertilizer requirements. Soil Science Society of America Journal, 53(6), pp.1856-1862.

Moore, S. and Manrakhan, A., 2022. Postharvest disinfestation treatments for false codling moth and fruit flies in citrus from South Africa. Horticulturae, 8(3), p.221.

Mulinge, J.M., Saha, H.M., Mounde, L. and Wasilwa, L.A., 2018. Effects of legume cover crops on orange (*Citrus sinensis*) fruit weight and brix. International Journal of Plant and Soil Science, 21(4), pp.1-9.

Naveen Kumar, P. 2020. Effect of intercropping on fruit crops. International Journal of Current Microbiology and Applied Sciences, 9(12), pp 745-755.

Ndou, P. and Obi, A., 2011. The business environment and international competitiveness of the South African citrus industry. In International Food and Agribusiness Association (IFAMA) Ls 21st World Annual Forum and Symposium. June pp. 20-23.

Ntshidi, Z., Dzikiti, S., Mazvimavi, D., Mobe, N.T. and Mkunyana, Y.P., 2021. Water use of selected cover crop species commonly grown in South African fruit orchards and their response to drought stress. Physics and Chemistry of the Earth, Parts A/B/C, 124, p.103070. https://doi.org/10.1016/j.pce.2021.103070.

O'Connell, N.V. and Snyder, R.L., 2000. Cover crops, mulch lower night temperatures in citrus. Plant Health Progress, 1(1), p.6.

Oliveira, F.É.R.D., Oliveira, J.D.M. and Xavier, F.A.D.S., 2016. Changes in soil organic carbon fractions in response to cover crops in an orange orchard. Revista Brasileira de Ciência do Solo, p.40.

Olorunmaiye, P.M., Egberongbe, K.R., Adeoye, P.O., Alamu, O.O. and Taiwo, S.T., 2011. Weed species composition of citrus-based cropping systems at National Horticultural Research Institute Ibadan, Nigeria. Agriculture and Biology Journal of North America, 2(3), pp.529-537.

O'Reilly, K.A., Robinson, D.E., Vyn, R.J. and Van Eerd, L.L., 2011. Weed populations, sweet corn yield and economics following fall cover crops. Weed Technology, 25(3), pp.374-384.

Ovalle, C., Del Pozo, A., Peoples, M.B. and Lavín, A., 2010. Estimating the contribution of nitrogen from legume cover crops to the nitrogen nutrition of grapevines using a 15N dilution technique. Plant and Soil, 334(1), pp.247-259.

Parker, E. and Jones, W., 1951. Orange yield and fruit size: Long-term experiments test the effects of organic matter in cover crops and manure on trees in southern California. California Agriculture, 5(11), pp.4-14.

Pommeresche, R. and Hansen, S., 2017. Examining root nodule activity on legumes. FertilCrop technical note. https://www.fertilcrop.net/fc-publications/technical-notes.html#c16124. Visited 08 July 2022.

Qi, Z. and Helmers, M.J., 2010. Soil water dynamics under winter rye cover crop in central Iowa. Vadose Zone Journal, 9(1), pp.53-60.

Saleemi, M., Kiani, M.Z., Sultan, T., Khalid, A. and Mahmood, S., 2017. Integrated effect of plant growth-promoting rhizobacteria and phosphate-solubilizing microorganisms on growth of wheat (*Triticum aestivum L.*) under rainfed condition. Agriculture & Food Security, 6(1), pp.1-8.

Schmidt, R., Gravuer, K., Bossange, A.V., Mitchell, J. and Scow, K., 2018. Long-term use of cover crops and no-till shift soil microbial community life strategies in agricultural soil. PloS one, 13(2), p.e0192953.

Selim, M.A.F., Hefny, Y.A.A., Abdel-Wahab, E.I. and Mohamed, M.K.A., 2020. Interplanting some soybean cultivars with mandarin trees in sandy soil. Agricultural Sciences, 11(1), pp.88-110.

Sharma, A.R. and Behera, U.K., 2009. Nitrogen contribution through Sesbania green manure and dual-purpose legumes in maize–wheat cropping system: agronomic and economic considerations. Plant and soil, 325(1), pp.289-304.

Sharma, P., Singh, A., Kahlon, C.S., Brar, A.S., Grover, K.K., Dia, M. and Steiner, R.L., 2018. The role of cover crops towards sustainable soil health and agriculture—A review paper. American Journal of Plant Sciences, 9(9), pp.1935-1951.

Shikuku, K., Ochenje, I., Baraza, M. and Schiller, K., 2024. Scaling Strategy for scaling improved feeds and breeds in Kapsabet and Nairobi, Kenya.

Singh, A., Kang, J.S. and Singh, H., 2016. Growth and development of baby corn (*Zea mays* L.) as influenced by non-leguminous forage cover crops and their spell of chopping under conservation agriculture. Research on Crops, 17(4).

Singh, M. and Sharma, S.D., 2008. Benefits of triazine herbicides and other weed control technology in citrus management. The triazine herbicides: 50 years of revolutionizing agriculture, pp.199-210.

Stagno, F., Abbate, C., Intrigliolo, F., Abbate, V. and Gennari, M., 2008. Effect of leguminous cover crops on soil biological activity in pots of *Citrus unshiu* Marcovitch. Italian Journal of Agronomy, 3(3), pp.183-190.

Strauss, S., Kadyampakeni, D., Kanissery, R., Wade, T., Diepenbrock, L. and Popenoe, J., 2019. Cover crops for citrus. EDIS, 2019.

Teasdale, J.R., Brandsaeter, L.O., Calegari, A.D.E.M.I.R., Neto, F.S., Upadhyaya, M.K. and Blackshaw, R.E., 2007. Cover crops and weed management. Non-chemical weed management principles. Concepts and Technology, CABI, Wallingford, UK, pp.49-64.

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W. and Bullock, D.G., 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Science Society of America Journal, 70(6), pp.1936-1944.

Vives-Peris, V., Molina, L., Segura, A., Gómez-Cadenas, A. and Pérez-Clemente, R.M., 2018. Root exudates from citrus plants subjected to abiotic stress conditions have a positive effect on rhizobacteria. Journal of Plant Physiology, 228, pp.208-217.

Volschenk, T., 2020. Water use and irrigation management of pomegranate trees-A review. Agricultural Water Management, 241, pp.106-375.

Wang, M. and Xia, R., 2009. Effects of arbuscular mycorrhizal fungi on growth and iron uptake of Poncirus trifoliata under different pH. Wei Sheng wu xue bao-Acta Microbiologica Sinica, 49(10), pp.1374-1379.

Wright, D.L., Mackowiak, C. and Blount, A., 2017. Cover crops. University of Florida, IFAS Extension Service, Gainesville, Florida, USA. Publication# SS-AGR-66.

Chapter 3

Soil organic carbon, weed suppression and fruit yield in response to cover crop species and termination method in citrus orchard (Eureka lemon)

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Abstract

Cover crops are commonly planted between tree rows to enhance soil quality, suppress weeds and improve production and fruit quality in citrus orchards. This practice of planting cover crops in citrus orchards is currently done abroad with success. However, there is limited information regarding plantation of cover crops in citrus orchards in South Africa. The study was conducted in South Africa to assess the following: (i) the effect of cover crop species on soil organic carbon, (ii) the impact of cover crop species on weed dry weights and (iii) citrus fruit weight using two termination methods (slashed and non-slashed). Cover crop species tested were vetch, medics, oats and control (no cover crop). The experiment was set up in a randomised block design with a factorial treatment structure (Factor 1 - cover crop species; Factor 2 – cover crop termination methods) replicated six times. Soil was sampled before planting cover crops and one year after planting cover crops. Cover crops and weed dry weight samples were collected during the termination stage and fruit weight measurements were taken at harvest. Results showed that vetch and medics cover crops were more effective in enhancing soil organic carbon with 0.14% increase over a period of one cropping season compared to oats and control treatments at 0-30 cm depth but there was no significant difference in deeper depth (30-60 cm). Oats cover crop suppressed weeds more effectively than other cover crops but there was no effect on the termination methods used to terminate cover crops. There was no effect on citrus fruit weight regardless of the cover crop species used and termination methods. In summary, legume cover crops were effective in improving soil organic carbon while oats were more effective in suppressing weeds.

Keywords: Citrus orchard, cover crop, fruit weight, organic carbon, weed suppression

3.1 Introduction

Citrus growers in countries such as the United States (Florida) are advocating for soil quality enhancement, in response to soil degradation (Castellano-Hinojosa et al., 2023). Soil degradation is one of the major challenges facing agricultural production, globally (Bhattacharyya et al., 2015). It triggers the decline in physical, chemical and biological soil properties. Soil degradation may be caused by numerous agricultural activities which include conventional farming practices, such as long-term intensive cultivation, monoculture, inadequate organic biomass input and excessive inorganic fertiliser use. Researchers observed that intensive cultivation reduced the organic matter content of the topsoil over the long term (Fourie et al. 2001; Jakab et al., 2023; Yao et al., 2023) and about 5.7% decrease in soil organic matter over six years was observed (Merwin & Stiles, 1994). This results in significant decreases in agricultural production, biodiversity (Blanco-Canqui et al. 2015) and soil organic carbon (Fourie et al. 2001).

In addition, the use of inorganic fertiliser gradually increased as it is the most widely used agricultural practice to provide nutrients to the plants (Castellano-Hinojosa et al., 2023). However, the application of chemical fertilisers is not sustainable or eco-friendly and tends to lead to environmental pollution. Sustainable soil management practices that increase soil organic matter can be used to manage soil degradation, improve soil nutrient cycling and crop production in fruit orchards. The soil organic matter acts as a binding agent to create soil aggregate stability (Bronick & Lal, 2005) which enhances soil structure and increases soil porosity. Hence, soil organic matter is known as one of the indicators of soil degradation (Obalum et al., 2017). The lower the organic matter percentage, the greater the chance of soil degradation. Also, hyphae from the roots, fungi, and bacteria improve soil aggregation by gluing soil particles and providing extracellular compounds that bind soil particles (Bronick & Lal, 2005). Mulches also improve soil structure by protecting soil against soil erosion, soil runoff and reduce soil evaporation (Layton et al., 1993). The addition of mulches increases the amount of soil organic carbon, adjusts soil temperatures and conserves soil moisture (Bronick & Lal, 2005). The disturbance of soil structure through soil compaction or intensified tillage that changes soil organic matter can result in rapid reduction of nutrients, availability of water and oxygen to the roots (Bronick & Lal, 2005).

One way of reducing soil degradation and chemical fertiliser application in citrus orchards can be achieved through the adoption of cover crops (Morugán-Coronado et al., 2020). This is an effective, cheap and environmentally friendly method of improving soil quality, which maintains and recovers soil organic carbon (Olson et al., 2014) and provides energy to sustain the activities of soil microorganisms (Blanco-Canqui et al., 2015). Numerous studies used cover crops for the maintenance and recovery of soil organic carbon (Bruce et al., 1991; Olson et al., 2014; García-González et al., 2018; Martínez-García et al., 2018) and for promoting soil productivity (Fageria et al., 2005).

Oats, vetch and radish cover crops increased organic carbon by 8.8% (Chavarría et al., 2016), signal grass by 52% (Balota and Auler, 2011) and hairy vetch and winter wheat by 19% (Mbuthia et al., 2015). Nevertheless, cover crops not only improve soil quality but also play a crucial role in suppressing weed growth especially in young citrus orchards since they don’t have enough shade (Singh & Sharma, 2008). They also play a huge role in controlling weeds in older citrus orchards. Weeds in orchards compete for essential resources, such as nutrients and water and act as hosts for pests and pathogens (Linares et al., 2008). Currently, weeds are being suppressed using herbicides. However, herbicides often result in environmental pollution and encourage soil degradation, particularly through herbicide drift and unintended contact with non-target plants and soil organisms (Atucha et al., 2011). Previous studies have shown that citrus yields can be reduced by up to 80% under uncontrolled weeds (Cousens & Mortimer, 1995) and there is an increasing number of weed species becoming resistant to herbicides (Henkes, 1997; Vila-Aiub et al., 2012).

Due to challenges associated with synthetic inorganic herbicides, there has been an increased interest in reducing agrochemical applications and conserving soil resources. Some scholars have also encouraged cover crop mulch killed with mechanical mowers as opposed to herbicides (Merwin et al.,1995; Atucha et al., 2011). Cover crop mulch terminated with a mower encourages increased soil organic matter and capacity to control weeds which results in better fruit yields. However, cover crop species selection is an essential component in cover crop management as they play different roles in the soil (Silwana et al., 2023). *Brassicas* enhance root depth and organic matter while grasses are known for their ability to suppress weeds and increase soil aggregate (Rillig et al., 2002; Fourie et al., 2021). Legume cover crops are known to fix soil nitrogen through the nitrogen fixation process (Schulz et al., 1999) and have a narrow C: N ratio which speeds up the decomposition rate, releasing beneficial nutrients (Amato et al., 1992). The C:N ratio of the legumes being less than 13 as opposed to 73 of the grass cover crops (Fourie et al., 2021).

Several studies have examined the effect of cover crops on grain crops (Belfry & Van Eerd, 2016; Nielsen et al., 2016; Osipitan et al., 2018), vineyards (Van Huyssteen et al., 1984; Monteiro & Lopes, 2007; Fourie et al., 2017) and in deciduous fruit orchards (Birkhofer et al., 2019; Theron, 2023) and obtained positive results. Yet, there is limited knowledge of planting cover crops in citrus orchards throughout the world. Therefore, this study will aid in a better understanding of the choice of appropriate cover crop species and termination methods for citrus orchards to improve productivity and sustainability. The objectives of this study were to determine the effect of cover crop species and termination method on: (1) improving soil quality; (2) weed suppression; and (3) fruit yield in citrus orchards.

3.2 Materials and methods

3.2.1 Site description

A cover crop study on a Eureka lemon cultivar orchard was carried out from May to August of 2021/22 and 2022/23 at Lamara farm (33°51′50.51″ S, 19°07′.66″ E) 86’62 in Franschhoek, district of Cape Winelands, Western Cape Province, South Africa (Fig. 3.1). The soil of the area is characterised as Tsitsikamma soil form (SCWG, 1991) with a rainfall ranging between 280-785 mm (Table 3.1) during cover crop growing season. An orchard with five (5)-year-old Eureka lemon trees grafted on X639 rootstock planted at 3 m x 6 m (square system) apart was selected for the study.

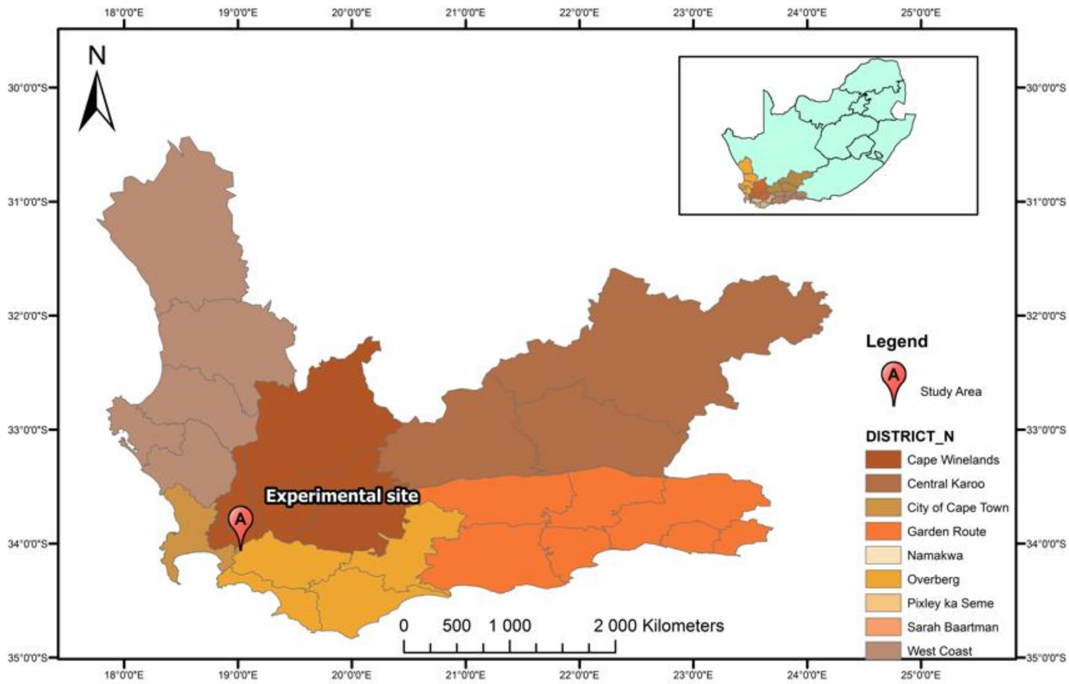

Figure 3.1. Map showing study area

Table 3.1. Rainfall (mm) received monthly from April to August measured over a period of three years

Year	Apr	May	Jun	Jul	Aug	Total (mm)
2021	3.7	72.9	13.6	40.3	161	291.5
2022	21.3	79.8	169.2	101.3	111.3	482.9
2023	107	160	390.1	123.9	2.1	783.1

3.2.2 Experimental design

Three cover crop species (oats, medics and vetch) and standard farmer's practice (control) were used as treatments. The experiment was conducted using a factorial design, with Factor 1 being the cover crop species and Factor 2 being the method of cover crop termination. A randomised complete block design was employed, with six replications of each treatment combination (Fig. 3.2). Each treatment covered approximately 54 m^2 (8 trees per plot). The row was made up of 4 trees in the middle plus 1 buffer tree between cover crop termination plots (slashed /non-slashed), 2 buffer trees between cover crop type plots and 1 buffer row. A mechanical mower (tractor mounted) was used to terminate cover crops in slashed plots while herbicide was used to terminate in non-slashed plots. Cover crops were planted between tree rows at the beginning of the rainy season (May). They were terminated 90 days after sowing, just before flowering and placed as mulch under the tree canopy for slashed plots (Oliveira et al., 2016). The non-slashed cover crop species were controlled using roundup herbicide (glyphosate as active ingredient) during the termination stage (Snapp et al., 2005).

All cover crops were evenly sown by hand using the following seeding rates: Pallinup oats, 90 kg ha^{-1}; grazing vetch, 50 kg ha^{-1}; Parabinga medic, 25 kg ha^{-1}. The gramoxone herbicide (paraquat dichloride) was sprayed at 5 L ha^{-1} to kill weeds before planting. Cover crops received 100 kg ha^{-1} nitrogen after 30 days of planting (Fourie et al., 2001).

Figure 3.2. Experimental design - Treatments replicated randomly in six blocks in a Eureka lemon orchard in Franschhoek (South Africa).

3.2.3 Establishment of a selection of three cover crop species

Potential cover crops were screened for suitability for use as cover crops in citrus orchards following a multi-criteria grid construction as described by Jannoyer et al. (2011) and Silwana et al. (2023). The selection was done in three successive steps based on previously published research, expert assessments from scientists, technical staff and growers, agronomy experiments and eco-physiological measurements (Jannoyer et al., 2011). The following traits were assessed in each step:

- Step 1 (Vegetative characteristics): Plant height (<30 cm); capacity for regrowth, covering capacity, perenniality.
- Step 2 (Practicability): seed availability, regulations (non-invasive) and specific farm constraints (labour demand, labour cost).
- Step 3 (Desired ecological function): capacity for weed competition (% cover/covering rater after sowing), N fixing properties (nodules presence and activity), potential pest hosting capacity, biomass productions (fresh biomass/ha).

3.3 Data collection

Composite soil samples were taken from each experimental sub-plot (0-30 and 30-60 cm depth) using 3.5 cm diameter soil auger before cover crop sowing in April 2022. Other soil samples, to test treatment effects were collected a year after cover crop termination following mulch decomposition (Adetunji, 2019). Soil samples were sent to the laboratory to determine the soil carbon.

3.3.1 Soil organic carbon analyses

The determination of soil organic carbon was based on the Walkley and Black chromic acid wet oxidation method. Oxidisable organic carbon in the soil was oxidised by potassium dichromate ($K_2Cr_2O_7$) solution in concentrated sulphuric acid. The reduced $Cr_2O_7^{2-}$ during the reaction with soil is proportional to the oxidisable organic carbon present in the sample. The organic carbon was then estimated by measuring the remaining unreduced dichromate by back-titration with ferrous ammonium sulphate using an indicator.

3.3.2 Measurements

Dry weight production for both cover crops and associated weeds was determined at the end of August of 2021/22 and 2022/23 seasons. The cover crop and weed samples were randomly collected from each sub-plot using a 0.5 m^2 frame, stored in brown paper bags and oven-dried for 48 hours at 90 °C (Fourie et al., 2021). Thereafter, dried samples were weighed using an electronic balance to determine dry weights. The remaining above ground vegetative growth was terminated using a mower and placed under the tree canopy to create mulching in slashed plots, while above ground vegetative growth was terminated using herbicide in non-slashed plots. Fruit weight (kg) was also determined by harvesting all ripe fruit from different branches of each sub-plot, loaded to plastic crates and weighed using an electronic balance (Mulinge et al., 2018).

3.4 Statistical analysis

ANOVA of the 4x2 factorial experiment in a randomized complete block design was was performed using the General Linear Model procedure (PROC GLM) of SAS statistical software. The data were tested for normality using the Shapiro-Wilk test, histograms and normal probability plots of the Univariate procedure (PROC UNIVARIATE) of SAS statistical software (Mishra et al., 2019). Fisher's least significant difference was calculated at the 5% level of significance to compare treatment means (Ott & Longnecker, 2016). A probability level of 5% was considered significant for all significance tests.

3.5 Results and discussion

3.5.1 Impact of cover crops on soil organic carbon in shallow and deeper soil depths

The soil organic carbon percentage (C%) significantly increased in 2022/23 compared to the 2021/22 season at a depth of 0-30 cm after planting cover crop species (Fig. 3.3). The organic carbon percentage increased by 0.25% from 2021/22 to 2022/23 season. This increase in soil organic carbon is attributed to the increase in organic material on the topsoil from cover crop residues (Nascente et al., 2013). Similar results were also found by Fourie et al. (2007), but the increase was more than 20% over the period of 10 years in medium textured vineyard soil. However, there was no significant increase in soil organic carbon at a deeper depth of 30-60 cm after planting cover crop species between the 2021/2022 and 2022/23 seasons (Fig. 3.4). Nascente et al. (2013) reported that concentrations of organic carbon in surface soils were much higher than deeper soil depth. Diekow et al. (2005) and Zotarelli et al. (2007) also obtained similar results where soil organic carbon accumulated on the soil surface and attributed these results to accumulation of plant material that decomposes in the soil surface. Shallower cover crop roots systems that were planted are also another factor that contributed to more organic carbon accumulated on topsoil compared to deeper depths. Planting cover crops with deeper roots such as *Brassicas* may be the solution in adding soil organic carbon in deeper depths.

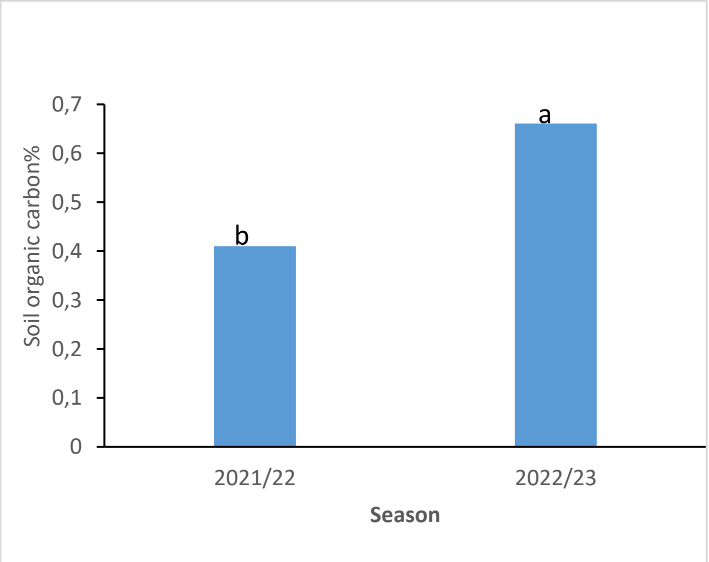

Figure 4.6. Comparison of soil organic carbon between two seasons at a depth of 0-30 cm. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

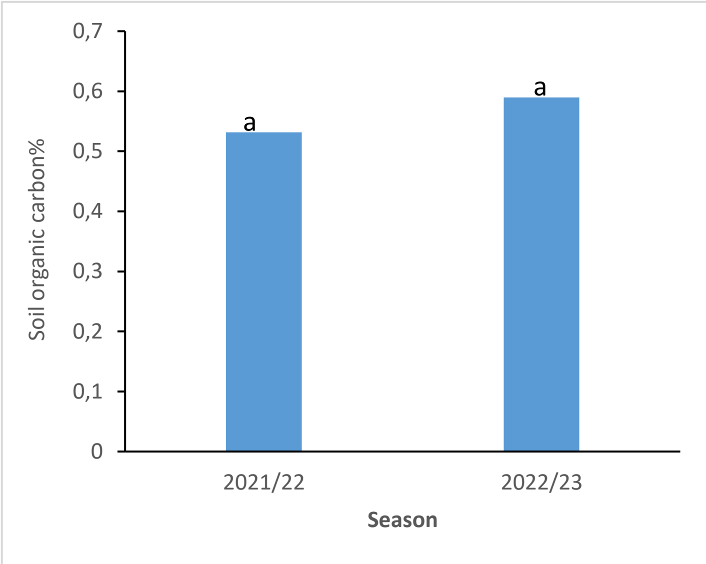

Figure 3.4. Comparison of soil organic carbon between two seasons at a depth of 30-60 cm. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.5.2 Influence of different cover crop species on soil organic carbon

Soil organic carbon percentage did not differ between legume (medics and vetch) cover crop species and likewise in the grass cover crops (oats and control) treatments (Fig. 3.5). However, legume cover crops differed significantly from grass cover crops. They gave the highest soil organic carbon percentage ranging between 0.6% and 0.8% while grass cover crops were below 0.6%. The soil organic carbon percentage increased by about 0.14% units in vetch (highest) compared to oats (lowest) just in a period of one season. Similar findings were observed with soil organic carbon increasing by 19% in hairy vetch with winter wheat (Mbuthia et al., 2015), 9% in hairy vetch with rye (Vilamil et al., 2006), 30% in hairy vetch with cereal rye (Olson et al., 2014), 8.8% in hairy vetch with radish and 12% in hairy vetch and crimson clover (Sainju et al., 2002).

Vetch residue decomposes faster than grass-cover crops such as cereal rye and releases a greater amount of nitrogen (N) in the soil, which results in greater nitrogen concentration and a narrow C:N ratio compared to grass-cover crops (Singh et al., 2020). As a result of the above findings, it is evident that the soil organic carbon increase is explained by the decomposition rate of cover crop species. Legume cover crops decompose very quickly as compared to grass cover crop species due to C:N ratio (Soon & Arshad, 2002). Legume cover crop species such as vetch and medics have a narrow C:N ratio which ranges below 12:1 while grass cover crops such as oats cover crops have higher C: N ranging above 35:1 (Sievers & Cook, 2018). A higher C:N ratio results in a lower decomposition rate and immobilisation process which binds up N in the soil and leads to low release of N (Clark, 2007; Jahanzad et al., 2016). The low N available results in low crop residue decomposition by microorganisms since there is less nitrogen for their energy and diet. While, legume-cover crops such as hairy vetch enhance soil N with symbiotically fixed atmospheric N (Dabney, 2001), which is used up by soil microorganisms for energy for decomposition residue to release C. The decomposition cover crop residues enhance organic matter in the soil (Fourie et al., 2007).

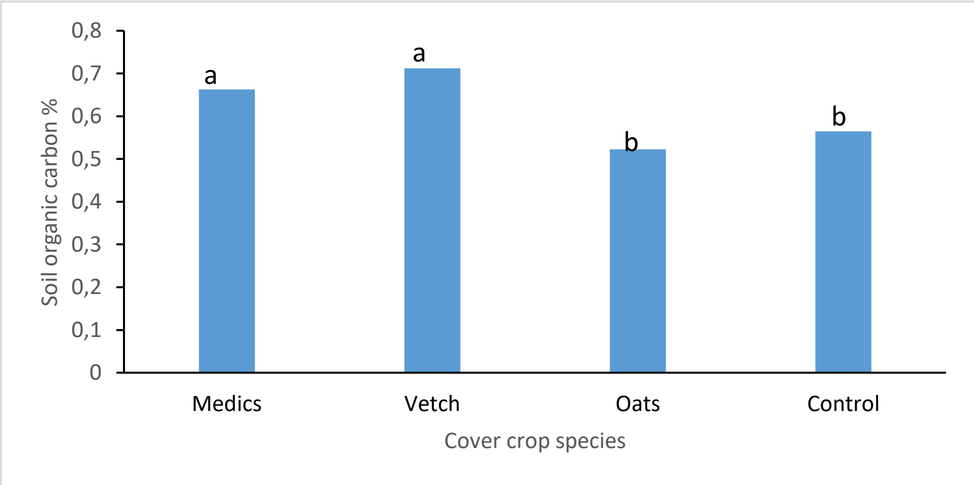

Figure 6.5. Soil organic carbon responses to cover crop species at 0-30 cm depth. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.5.3 Impact of cover crops on weed dry weight

Weed dry weight significantly reduced from above 140 g m^{-2} in 2021/22 to below 60 g m^{-2} in the 2022/23 season after planting cover crop (Fig. 3.6). The reduction in weed dry weight in 2022/23 was influenced by planting cover crop species and termination methods used (slashed and non-slashed methods). Oats was the most effective cover crop species to suppress weeds compared to vetch and medics in 2021/22 (Fig.3.7). The results obtained in this study are in line with results observed by Fourie et al. (2017) where oats cover crop effectively suppressed ryegrass weeds in a vineyard, which is one of the most prevalent and aggressive grass weeds in Western Cape, South Africa. Previous studies also reported that grass cover crops, such as rye and oats, are more effective in suppressing weeds than legume cover crops such as vetch (Campiglia et al., 2010; Hayden et al., 2012). However, there was no significant difference between weed dry weights of oats, vetch and medics in the 2022/23 seasons, but the weed dry weights were effectively reduced compared to the control treatments. The control treatments (farmer's standard of practice) gave the highest weed dry weight in both seasons (2021/22 and 2022/23) since there were no cover crops planted to compete.

Notably, weed dry weights were significantly reduced in 2022/23 compared to the 2021/22 season for all cover crop species except the control treatment (Fig. 3.7). The cover crop weed dry weights ranged between 90-180 g m^{-2} in 2022/23 season and successfully reduced to below 40 g m^{-2}. This shows effectiveness of cover crops in controlling weeds. This reduction in weeds in orchards assists growers in reducing the use of herbicides (Jannoyer et al., 2011). This further reduces weed-to-crop competition of water, pest infestation and nutrients (Blanco-Canquiet et al., 2015)

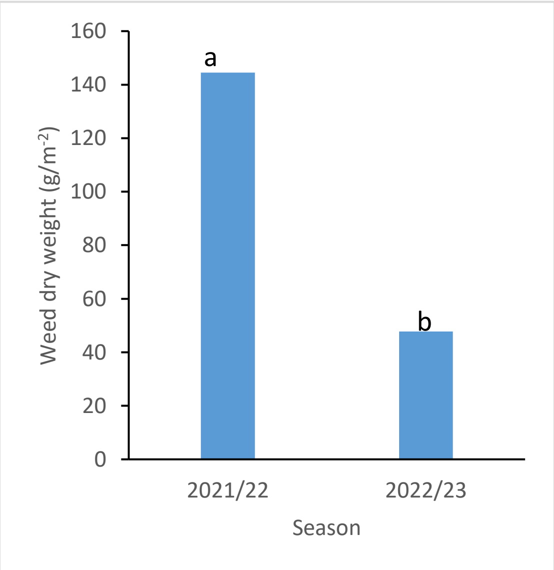

Figure 3.8. Weed dry weight after planting cover crops between 2021/22 and 2022/23 seasons. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

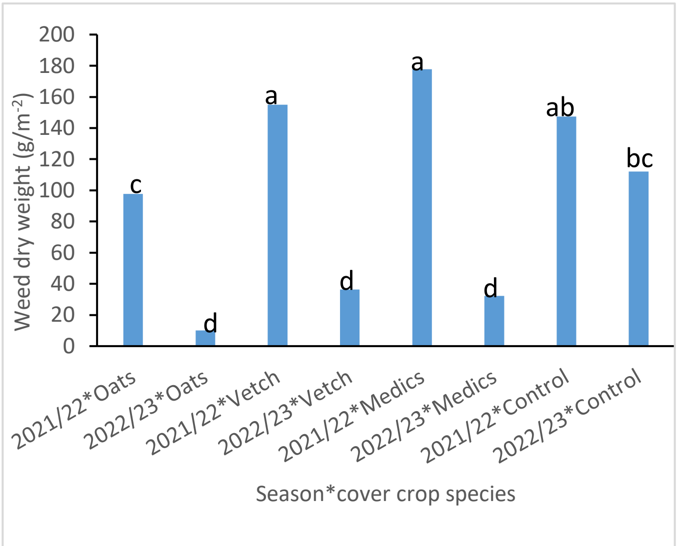

Figure 3.7. Weed dry weight against planting seasons and cover crop species. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.5.4 Cover crop performances over two seasons

Cover crop dry weights were significantly higher in the 2021/22 season ranging between 100 g m^{-2} – 120 g m^{-2} as compared to the 2022/23 season which were lower than 80 g m^{-2} (Fig. 3.8). Oats cover crop gave the highest dry weights ranging above 140 g m^{-2} in 2021/22 compared to other treatments (Fig. 3.9). However, there was no significant difference between all treatments in 2022/23 seasons ranging below 100 g m^{-2}. There was too much rainfall during cover crop establishment in the 2022/23 season (Table 3.1) which affected the cover crop growth negatively and limited the dry weights. Similar findings were observed in the cooler climate of Stellenbosch where Medicago species, subterranean clovers, pink seradella and three Vicia species did not compete effectively with the winter weeds resulting in lower dry weights when weekly precipitation from mid-March to mid-May exceeded 18 mm (Fourie, 2021).

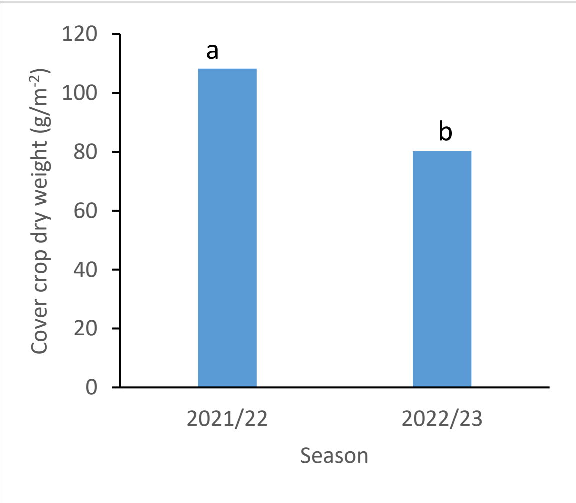

Figure 3.9. Comparison of cover crop dry weight between the two seasons. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

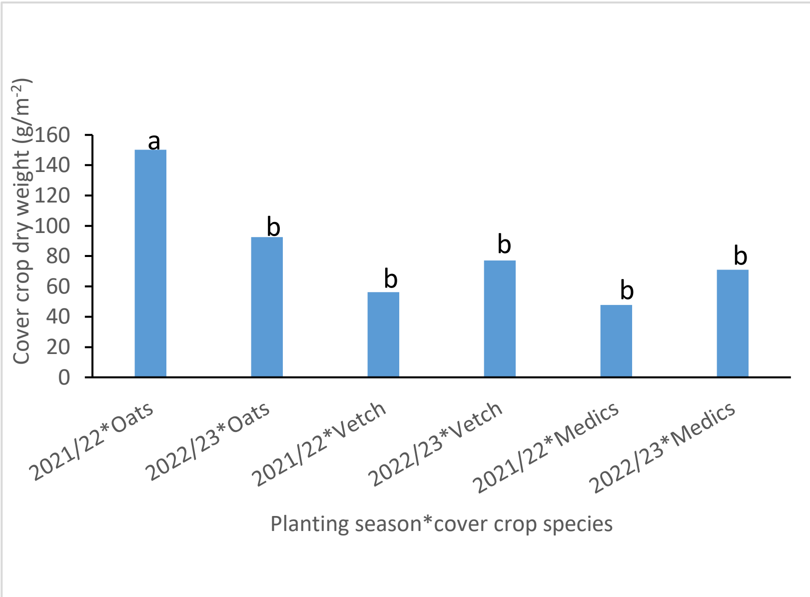

Figure 3.10. Comparison of cover crop dry weight between the cover crop species planted in two seasons. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.5.5 Interaction effects on weed dry weight

The interaction between planting season, termination method, and cover crop species had a statistically significant effect on weed dry weight (g/m²) in a citrus orchard (Table 3.2). Overall, cover crops terminated by slashing were more effective at suppressing weed biomass compared to those left uncut, particularly during the 2022/23 season.

In the 2021/22 season, vetch not slashed resulted in the highest weed dry weight (185.7 g/m²), followed closely by vetch not slashed in 2022/23 (180.4 g/m²), indicating significantly greater weed growth compared to other treatments. In contrast, the lowest weed dry weights were recorded in oats plots during the 2022/23 season under slashed termination, with values ranging between 15.0g/m², supporting their potential for integrated weed management. The control plots generally exhibited moderate to high weed dry weights across all treatments, with the highest (153.6 g/m²) in 2021/22 under slashed conditions. This suggests that slashing alone, in the absence of cover crops, does not provide effective weed control. These findings are consistent with earlier studies indicating that cover crop biomass and termination methods significantly influence weed suppression through physical mulching and competitive exclusion (Teasdale and Mohler, 2000). The results demonstrate the importance of integrating appropriate cover crop species and effective termination strategies to optimize weed suppression in citrus orchards. Notably, slashed oats during the 2022/23 season provided the greatest weed suppression benefits.

Table 3.2. Interaction Effects of Planting Season, Termination Method, and Cover Crop Species on Weed Dry Weight (g/m²). Mean values within a column followed by the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

Planting Season	Termination Method	Cover Crop Species	Weed Dry Weight (g/m²)
2021/22	Not Slashed	Oats	112.5 cde
2021/22	Slashed	Oats	85.6 efg
2022/23	Not Slashed	Oats	18.2 h
2022/23	Slashed	Oats	15.0 h
2021/22	Not Slashed	Vetch	185.7 a
2021/22	Slashed	Vetch	128.9 bdce
2022/23	Not Slashed	Vetch	180.4 a
2022/23	Slashed	Vetch	169.3 ab
2021/22	Not Slashed	Medics	51.0 fgh
2021/22	Slashed	Medics	17.3 h
2022/23	Not Slashed	Medics	37.8 gh
2022/23	Slashed	Medics	19.0 h
2021/22	Not Slashed	Control	144.5 abcd
2021/22	Slashed	Control	153.6 abc
2022/23	Not Slashed	Control	124.7 bcde
2022/23	Slashed	Control	98.4 def

3.5.6 Effect of termination methods on weed dry weights

The type of termination methods (slashed and non-slashed) used did not significantly influence weed dry weights in the 2021/22 season (Fig 3.10). The same results were also observed in 2022/23, when there was no significant difference in weed dry weights between slashed and non-slashed treatments. Similar results were observed when the cover crop was terminated using post-emergent herbicides and a flail mower (Rosario-Lebron et al., 2019). However, when comparing the two seasons, there was a significant difference in weed dry weights between the 2021/22 and 2022/23 seasons. The 2021/22 seasons gave the highest weed dry weight ranging between 140 and 160 g m^{-2} while 2022/23 gave the least weed dry weight ranging below 60 g m^{-2} regardless of slashed or not slashed methods.

3.5.7 Effect of termination methods on cover crops dry weight

There was no significant difference in cover crop dry weight between non-slashed and slashed treatments within the 2021/22 season (Fig. 3.11). The same was observed in the 2022/23 season, where termination method had no significant effect. However, the non-slashed treatment in 2021/22 produced significantly higher dry weight (120 g m^{-2}) compared to all treatments in 2022/23 (both non-slashed and slashed), which yielded less than 100 g m^{-2}. In contrast, the slashed treatment in 2021/22 was not significantly different from either of the 2022/23 treatments . After cover crop termination, all cover crop residue was removed from the work row and placed under the tree row which left the soil exposed under slashed treatments. Dabney et al. (2001) stated that cover crops are one of the cheapest practices to improve soil organic matter. The decomposition of above and below ground cover crop biomass enhances organic matter in the soil (Fourie et al., 2007). An increase in soil organic matter increases soil microbial activity and results in the release of beneficial nutrients such as organic carbon and nitrogen (Strauss et al., 2019).

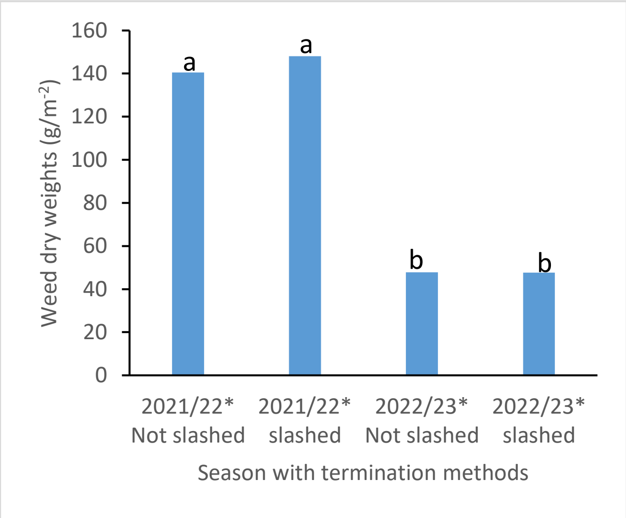

Figure 3.12. Weed dry weights again termination methods (slashed and non-slashed treatments) between 2021/22 and 2022/23 Season. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

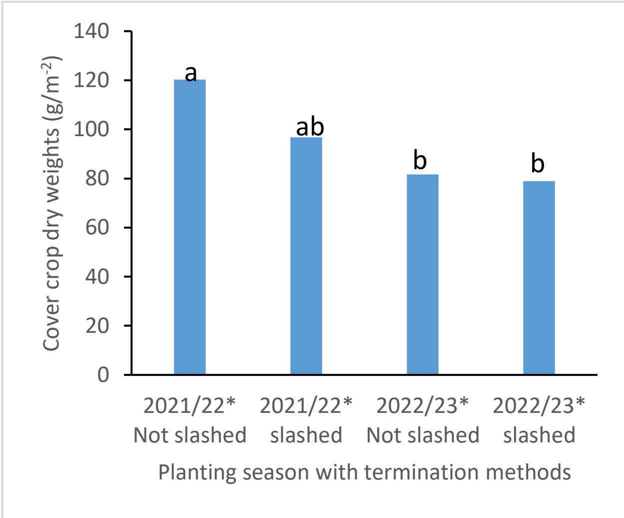

Figure 12. Cover crop dry weights against termination methods (slashed and non-slashed treatments) between 2021/22 and 2022/23 Season. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.5.8 Effect of cover crops against fruit weight

The use of cover crops has been recommended to enhance fruit yield in citrus orchards (Naveen, 2020). However, there was no significant difference between fruit weights regardless of cover crop species and termination methods in this study (Fig. 3.12 and 3.13). Hoorman (2009) reported that the cultivation of cover crops does not give positive results immediately and this may be the case in this study. These results are in accordance with those observed by Martinelli et al. (2017) where fruit increase was only observed in the third growing season using ruzi grass as a cover crop. Cover crop did not affect succeeding crop yield, but decreased evapotranspiration by 6.2% and increased yield by 5.0% compared to no cover crop (Wang et al., 2021). Some studies reported some positive impacts when cover crops were used such as an increase in fruit sizes (Parker & Jones,1951), highest fruit weight and volume, total soluble solids, and fruit yields (Selim et al., 2019). Nitrogen is widely recognized as a key nutrient and common limiting factor in citrus production, particularly due to its role in vegetative growth and fruit development (Selim et al., 2019). However, other macronutrients such as potassium and phosphorus also play important roles, and their relative significance may vary depending on soil conditions, crop stag, and management practices. Therefore, the use of legume cover crops may play a huge role and be beneficial since legumes have been rated as the highest contributor of nitrogen as they are easily decomposed and able to convert atmospheric nitrogen into a suitable form of N for plant use which improves fruit yield (Srivastava et al., 2022).

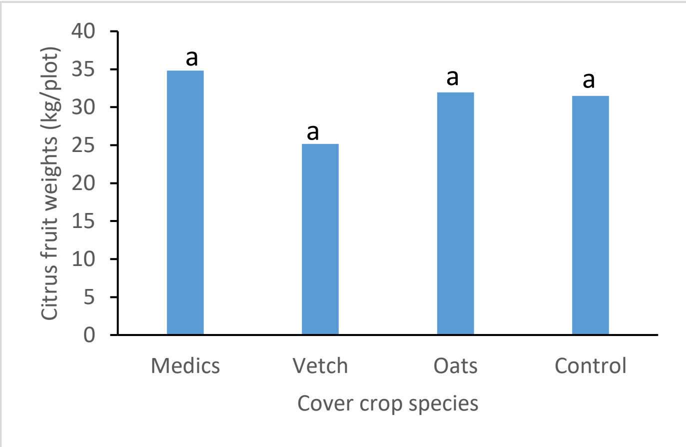

Figure 3.14. Citrus fruit weight against cover crop species. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

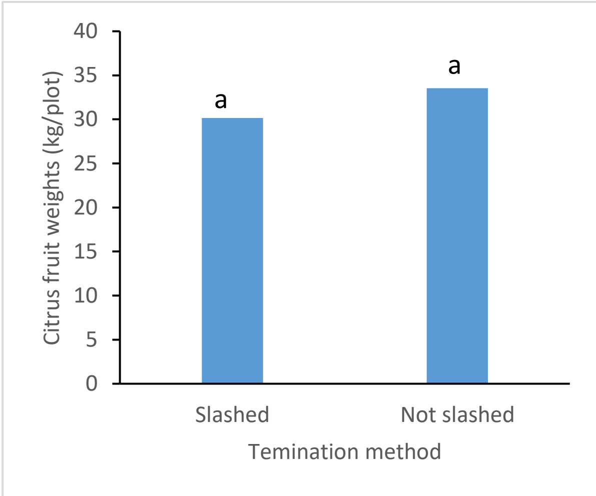

Figure 3.14. Citrus fruit weight against termination method (slashed and not-slashed treatments). Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

3.6 Conclusion

From this experiment, it is concluded that cover crops have a positive effect on improving soil quality and control weeds. Soil organic carbon was effectively increased just in one season of planting cover crops. Legume cover crops were the most effective in increasing soil organic carbon compared to grass cover crops including control treatments. However, it was the other way round when it came to controlling weeds; oats were the most effective cover crop in controlling weeds compared to legume cover crops (vetch and medics). In addition, termination methods also played a significant role in reducing weed dry matter, however, it did not matter what type of termination method (mower or herbicide) were used. Citrus fruit Yield was not significantly influenced by cover crop species and termination methods, but literature displayed that cover crops do not increase fruit quality immediately, it takes some time. Longer term experiments are therefore recommended to determine the full benefits of cover crops in citrus orchards.

Declarations

Author contribution statement

Sibongiseni Silwana: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
Nebo Jovanovic and Reckson Mulidzi: Conceived and designed the experiments; Contributed to writing the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

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3.7 References

Adetunji, A.T., 2019. Impact of cover crop species, termination stage and termination method on soil nitrogen, organic carbon and enzyme activities (Doctoral dissertation, Cape Peninsula University of Technology).

Amato, M. and Ladd, J.N., 1992. Decomposition of 14C-labelled glucose and legume material in soils: properties influencing the accumulation of organic residue C and microbial biomass C. *Soil Biology and Biochemistry*, *24*(5), pp.455-464.

Atucha, A., Merwin, I.A. and Brown, M.G., 2011. Long-term effects of four groundcover management systems in an apple orchard. HortScience, 46(8), pp.1176-1183.

Balota, E.L. and Auler, P.A.M., 2011. Soil carbon and nitrogen mineralization under different tillage systems and permanent groundcover cultivation between orange trees. Revista Brasileira de Fruticultura, 33, pp.637-648.

Belfry, K.D. and Van Eerd, L.L., 2016. Establishment and impact of cover crops intersown into corn. Crop Science, 56(3), pp.1245-1256.

Bhattacharyya, R., Ghosh, B.N., Mishra, P.K., Mandal, B., Rao, C.S., Sarkar, D., Das, K., Anil, K.S., Lalitha, M., Hati, K.M. and Franzluebbers, A.J., 2015. Soil degradation in India: Challenges and potential solutions. Sustainability, 7(4), pp.3528-3570.

Birkhofer, K., Addison, M.F., Arvidsson, F., Bazelet, C., Bengtsson, J., Booysen, R., Conlong, D., Haddad, C., Janion-Scheepers, C., Kapp, C. and Lindborg, R., 2019. Effects of ground cover management on biotic communities, ecosystem services and disservices in organic deciduous fruit orchards in South Africa. Frontiers in Sustainable Food Systems, 3, p.107.

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW,Francis CA, Hergert GW.2015. Cover crops and ecosystem services: insights from studies in temperate soils. AgronomyJournal 107: 2449–2474.https://doi.org/10.2134/agronj15.0086.

Bronick, C.J. and Lal, R., 2005. Soil structure and management: a review. Geoderma, 124(1-2), pp.3-22.

Bruce, R.R., Hendrix, P.F. and Langdale, G.W., 1991. Role of cover crops in recovery and maintenance of soil productivity. Cover crops for clean water, pp.109-115.

Campiglia E, Mancinelli R, Radicetti E, Caporali F. 2010. Effect of cover crops and — Castellano-Hinojosa, A., Kanissery, R. and Strauss, S.L., 2023. Cover crops in citrus orchards impact soil nutrient cycling and the soil microbiome after three years but effects are site-specific. Biology and Fertility of Soils, 59(6), pp.659-678.

Chan, K.Y., Heenan, D.P. and So, H.B., 2003. Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review. Australian Journal of Experimental Agriculture, 43(4), pp.325-334.

Chavarría, D.N., Verdenelli, R.A., Serri, D.L., Restovich, S.B., Andriulo, A.E., Meriles, J.M. and Vargas-Gil, S., 2016. Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. European Journal of Soil Biology, 76, pp.74-82.

Clark, A. 2007. Managing cover crops profitably. 3rd ed. Sustainable Agriculture Network, Beltsville, MD.

Cousens R, Mortimer M. 1995. Dynamics of weed populations (1st ed). Cambridge: Cambridge University Press.

Dabney, S., Delgado, J., & Reeves, D. 2001. Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis, 32, 1221–1250. https://doi.org/10.1081/ CSS-100104110

Diekow, J., Mielniczuk, J., Knicker, H., Bayer, C., Dick, D.P. and Kögel-Knabner, I., 2005. Soil C and N stocks as affected by cropping systems and nitrogen fertilisation in a southern Brazil Acrisol managed under no-tillage for 17 years. Soil and Tillage Research, 81(1), pp.87-95.

Fageria, N.K., Baligar, V.C. and Bailey, B.A., 2005. Role of cover crops in improving soil and row crop productivity. Communications in soil science and plant analysis, 36(19-20), pp.2733-2757.

Fourie JC, Agenbag GA, Louw, PJE. 2007. Cover crop management in a Chardonnay/99 Richter vineyard in the Coastal Region, South Africa. 3. Effect of different cover crops and cover crop management practices on organic matter and macro-nutrient content of a medium-textured soil. South African Journal of Enology and Viticulture 28: 61–68.

Fourie JC, Kunjeku EC, Booyse M, Kutama TG, Freitag K, Ochse CH. 2017. Effect of cover crops and the management thereof,on the weed spectrum in a drip-irrigated vineyard: 2. Weedsgrowing from grapevine berry set to post-harvest.South AfricanJournal of Enology and Viticulture 38: 182–191.https://doi.org/10.21548/38-2-1354.

Fourie, J.C., Howell, C.L., Booyse, M. and Adams, K.M., 2021. Cover crop performance in an apple orchard and its effect on the macro-elements and carbon levels in a loamy sand. South African Journal of Plant and Soil, 38(5), pp.398-406.

Fourie, JC, Louw, PJE and Agenbag, G., 2001. Effect of seeding date on the performance of grasses and broadleaf species evaluated for cover crop management in two wine grape regions of South Africa. South African Journal of Plant and Soil, 18(3), pp.118-127.

García-González, I., Hontoria, C., Gabriel, J.L., Alonso-Ayuso, M. and Quemada, M., 2018. Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. Geoderma, 322, pp.81-88.

Hayden ZD, Brainard DC, Henshaw B, Ngouajio M. 2012. Winter annual weed suppression in rye–vetch cover crop mixtures. Weed Technology 26: 818–825. https://doi.org/10.1614/WT-D12-00084.1.

Henkes, R., 1997. Handling herbicide resistance. The furrow 102, 8-11.

Hoorman JJ. 2009. Using cover crops to improve soil and water quality. Lima, Ohio: Agriculture and Natural Resources, The Ohio State University Extension.

Jahanzad, E., Barker, A.V., Hashemi, M., Eaton, T., Sadeghpour, A. and Weis, S.A., 2016. Nitrogen release dynamics and decomposition of buried and surface cover crop residues. Agronomy Journal, 108(4), pp.1735-1741.

Jakab, G., Madarász, B., Masoudi, M., Karlik, M., Király, C., Zacháry, D., Filep, T., Dekemati, I., Centeri, C., Al-Graiti, T. and Szalai, Z., 2023. Soil organic matter gain by reduced tillage intensity: Storage, pools, and chemical composition. Soil and Tillage Research, 226, p.105584.

Jannoyer ML, Le Bellec F, Lavigne C, Achard R, Malézieux E. 2011.Choosing cover crops to enhance ecological services in orchards:a multiple criteria and systemic approach applied to tropical areas.Procedia Environmental Sciences9: 104–112.https://doi.org/10.1016/j.proenv.2011.11.017.

Layton, J.B., Skidmore, E.L. and Thompson, C.A., 1993. Winter-associated changes in dry-soil aggregation as influenced by management. Soil Science Society of America Journal, 57(6), pp.1568-1572.

Linares, J., Scholberg, J., Boote, K., Chase, C.A., Ferguson, J.J. and McSorley, R., 2008. Use of the cover crop weed index to evaluate weed suppression by cover crops in organic citrus orchards. HortScience, 43(1), pp.27-34.

Martinelli, R., Monquero, P.A., Fontanetti, A., Conceição, P.M. and Azevedo, F.A., 2017. Ecological mowing: An option for sustainable weed management in young citrus orchards. Weed Technology, 31(2), pp.260-268.

Martínez-García, L.B., Korthals, G., Brussaard, L., Jørgensen, H.B. and De Deyn, G.B., 2018. Organic management and cover crop species steer soil microbial community structure and functionality along with soil organic matter properties. Agriculture, Ecosystems & Environment, 263, pp.7-17.

Mbuthia, L.W., Acosta-Martínez, V., DeBruyn, J., Schaeffer, S., Tyler, D., Odoi, E., Mpheshea, M., Walker, F. and Eash, N., 2015. Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Biology and Biochemistry, 89, pp.24-34.

Merwin, I.A. and Stiles, W.C., 1994. Orchard groundcover management impacts on apple tree growth and yield, and nutrient availability and uptake. Journal of the American Society for Horticultural Science, 119(2), pp.209-215.

Merwin, I.A., Rosenberger, D.A., Engle, C.A., Rist, D.L. and Fargione, M., 1995. Comparing mulches, herbicides, and cultivation as orchard groundcover management systems. HortTechnology, 5(2), pp.151-158.

Merwin, I.A., Stiles, W.C. and van Es, H.M., 1994. Orchard groundcover management impacts on soil physical properties. Journal of the American Society for Horticultural Science, 119(2), pp.216-222.

Mishra P, Pandey CM, Singh U, Gupta A, Sahu C, Keshri A. 2019. Descriptive statistics and normality tests for statistical data. Ann Card Anaesth. 22(1):67-72. doi: 10.4103/aca.ACA_157_18. PMID: 30648682; PMCID: PMC6350423

Monteiro, A. and Lopes, C.M., 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agriculture, ecosystems & environment, 121(4), pp.336-342.

Morugán-Coronado, A., Linares, C., Gómez-López, M.D., Faz, Á. and Zornoza, R., 2020. The impact of intercropping, tillage and fertilizer type on soil and crop yield in fruit orchards under Mediterranean conditions: A meta-analysis of field studies. Agricultural Systems, 178, p.102736.

Mulinge, J., Saha, H., Mounde, L. and Wasilwa, L., 2018. Effects of legume cover crops on orange (*Citrus sinensis*) fruit weight and brix. International Journal of Plant & Soil Science, 21(4), pp.1-9.

Nascente, A.S., Li, Y.C. and Crusciol, C.A.C., 2013. Cover crops and no-till effects on physical fractions of soil organic matter. Soil and Tillage Research, 130, pp.52-57.

Naveen Kumar P. 2020. Effect of intercropping on fruit crops: a review. International Journal of Current Microbiology and Applied Sciences 9: 745–755. https://doi.org/10.20546/ijcmas.2020.912. 090.

Nielsen, D.C., Lyon, D.J., Higgins, R.K., Hergert, G.W., Holman, J.D. and Vigil, M.F., 2016. Cover crop effect on subsequent wheat yield in the central Great Plains. Agronomy Journal, 108(1), pp.243-256.

Obalum, S.E., Chibuike, G.U., Peth, S. and Ouyang, Y., 2017. Soil organic matter as sole indicator of soil degradation. Environmental monitoring and assessment, 189, pp.1-19.

Oliveira, F.É.R.D., Oliveira, J.D.M. and Xavier, F.A.D.S., 2016. Changes in soil organic carbon fractions in response to cover crops in an orange orchard. Revista Brasileira de Ciência do Solo, p.40.

Olson, K., Ebelhar, S.A. and Lang, J.M., 2014. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open Journal of Soil Science, 2014.

Osipitan, O.A., Dille, J.A., Assefa, Y. and Knezevic, S.Z., 2018. Cover crop for early season weed suppression in crops: Systematic review and meta-analysis. Agronomy Journal, 110(6), pp.2211-2221.

Ott, R.L. and Longnecker, M., 2016. An introduction to statistical methods and data analysis. Cengage Learning.

Parker, J.C. and Jones, G.R., 1951. Rupture of the gravid uterus. Obstetrical & Gynecological Survey, 6(6), pp.816-818.

Rillig, M.C., Wright, S.F. and Eviner, V.T., 2002. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: comparing effects of five plant species. Plant and soil, 238, pp.325-333.

Rosario-Lebron, A., Leslie, A.W., Yurchak, V.L., Chen, G. and Hooks, C.R., 2019. Can winter cover crop termination practices impact weed suppression, soil moisture, and yield in no-till soybean [*Glycine max (L.) Merr*.]. Crop Protection, 116, pp.132-141.

Sainju, U.M., Singh, B.P. and Whitehead, W.F., 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil and Tillage Research, 63(3-4), pp.167-179.

SAS Institute, Inc. (1999), SAS/STAT User's Guide, Version 9, 1st printing, Volume 2. SAS Institute Inc, SAS Campus Drive, Cary, North Carolina 27513.

Schulz, S., Keatinge, J.D.H. and Wells, G.J., 1999. Productivity and residual effects of legumes in rice-based cropping systems in a warm-temperate environment: I.

Legume biomass production and N fixation. Field Crops Research, 61(1), pp.23-35.

Selim, M.A.F., Hefny, Y.A.A., Abdel-Wahab, E.I. and Mohamed, M.K.A., 2019. Interplanting some soybean cultivars with mandarin trees in sandy soil. Agricultural Sciences, 11(1), pp.88-110.

Sievers, T. and Cook, R.L., 2018. Aboveground and root decomposition of cereal rye and hairy vetch cover crops. Soil Science Society of America Journal, 82(1), pp.147-155.

Silwana, S., Mulidzi, A.R. and Jovanovic, N., 2023. Evaluating the effects and benefits of cover crops in citrus orchards: a review. South African Journal of Plant and Soil, 40(2), pp.117-126.

Singh M, Sharma S.D. 2008. Benefits of triazine herbicides and other weed control technology in citrus management. In: LeBaron HM, McFarland JE, Burnside OC (eds), the triazine herbicides: 50 years revolutionizing agriculture. New York: Elsevier Science. pp 199–210. https://doi.org/10.1016/B978-044451167-6.50019-2.

Singh, G., Dhakal, M., Yang, L., Kaur, G., Williard, K.W., Schoonover, J.E. and Sadeghpour, A., 2020. Decomposition and nitrogen release of cover crops in reduced-and no-tillage systems. Agronomy Journal, 112(5), pp.3605-3618.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J. and O'neil, K., 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agronomy journal, 97(1), pp.322-332.

Soil Classification Working Group (SCWG), 1991. Soil classification: a taxonomic system for South Africa (Vol. 15). Department of Agricultural Development.

Soon, Y.K., and M.A. Arshad. 2002. Comparison of the decomposition and N and P mineralization of canola, pea and wheat residues. Biol. Fertil. Soils 36:10–17. doi:10.1007/s00374-002-0518-9.

Srivastava, A.K., 2022. Soil fertility management in fruit crops amidst climate change: A review. International Journal of Innovative Horticulture, 11(2), pp.259-273.

Strauss S, Kadyampakeni D, Kanissery R, Wade T, Diepenbrock L, Popenoe J. 2019. Cover crops for citrus. Citrus Industry (April): p.16–19. Available at https://citrusindustry.net/2019/04/09/ cover crops-for-citrus.

Teasdale, J.R. and Mohler, C.L., 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Science, 48(3), pp.385-392.

Theron, A., 2023. Orchard Floor Management and Soil Health in Deciduous Fruit Orchards (Doctoral dissertation, Stellenbosch University).

Van Huyssteen, L., Van Zyl, J.L. and Koen, A.P., 1984. The Effect of Cover Crop Management on Soil Conditions and Weed 6ontrol in a Colombar Vineyard in Oudtshoorn. South African Journal of Enology and Viticulture, 5(1), pp.7-17.

Vila-Aiub MM, Balbi MC, Distéfano AJ, Fernándes L, Hopp E, Yu Q, Powles SB. 2012. Glyphosate resistance in perennial *Sorgum halepense* (Johnsongrass), endowed by reduced glyphosate translocation and leaf uptake. Pest Management Science 68: 430–436.

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W. and Bullock, D.G., 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Science Society of America Journal, 70(6), pp.1936-1944.

Wang, J., Zhang, S., Sainju, U.M., Ghimire, R. and Zhao, F., 2021. A meta-analysis on cover crop impact on soil water storage, succeeding crop yield, and water-use efficiency. Agricultural Water Management, 256, p.107085.

Yao, W., Liu, Q., Zhou, J., Wen, Y., Tian, B., Qi, Z., Yang, Y., Zeng, Z., Peixoto, L. and Zang, H., 2023. Short-term reduction in cropping intensity improves soil quality of topsoil rather than subsoil. Land Degradation & Development, 34(8), pp.2393-2402.

Zotarelli, L., Alves, B.J.R., Urquiaga, S., Boddey, R.M. and Six, J., 2007. Impact of tillage and crop rotation on light fraction and intra-aggregate soil organic matter in two Oxisols. Soil and Tillage Research, 95(1-2), pp.196-206.

Chapter 4

Short-Term Effects of Cover Crop Species and Termination Methods on Soil pH and Key Enzymatic Activities (β-Glucosidase, Phosphatase and Urease Activities) in in a citrus orchard (Eureka lemons)

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Abstract

The best management practices for cover cropping in citrus orchards are largely unknown, including suitable cover crop species and termination methods. The study was conducted in South Africa to assess the following: (i) the effect of cover crop species on soil pH, (ii) the reaction of β-glucosidase, phosphatase and urease activities against different cover crop species, and (iii) the response of β-glucosidase, phosphatase and urease activities in two termination methods (slashed and non-slashed). Cover crop species tested were vetch, medics, oats and control (no cover crop). The experiment was set up in a randomised block design with a factorial treatment structure (Factor 1 – cover crop species; Factor 2 – cover crop termination methods) replicated six times. The soil was sampled before planting cover crops and one year after planting cover crops. Results showed that introducing cover crops caused soil pH to increase from 5.42 to 6.0 after one year. There was a slight decrease in β-glucosidase whereas there was an increase in phosphatase and urease activities after one year of introducing cover crops. Under different cover crop species, there was a marginal increase of β-glucosidase, phosphatase and urease activities under legumes (vetch and medics) in the topsoil. In deeper soil, β-glucosidase activity was higher under oats while phosphatase and urease activities were higher under medics and vetch cover crops, respectively. Termination methods had no influence on β-glucosidase, phosphatase and urease activities regardless of soil depth.

Keywords: Cover crop, citrus, soil enzyme activities, soil pH, termination methods

Highlights

- Soil pH was influenced by introduction of cover crops after one season of planting.
- Soil enzyme activities were slightly higher under cover crops compared to control treatment.
- Termination methods used had no significant influence soil on enzyme activities.

4.1 Introduction

South Africa (SA) is one of the major citrus exporting countries globally, it exports more than 60% of its produce to global markets (De Bruin, 2023; Mukhametzyanov et al., 2024). In 2023, SA exported over 35 million cartons (15kg weight) of lemons globally, with over 33 million cartons being Eureka lemon cultivars (Citrus Grower Association (CGA), 2023). These exports are set to increase as the CGA set a goal to increase citrus production from 165 million cartons, in 2022, to 260 million cartons in 2032. These large amounts of citrus fruit are produced mostly through plant manipulation and by applying large quantities of agrochemicals e.g. inorganic fertilisers, plant growth hormones and pesticides (El-Otmani et al., 2011). Fertilisers generally encourage plant growth which encourages an increase in fruit yield and quality (Li et al., 2019). To meet the ever-increasing export and local demands more and more agrochemicals will be utilised in the production of citrus. However, with increasing consciousness of the harmful effects of agrochemicals on human health and the environment, there has been a growing concern about their usage (Nicolopoulou-Stamati et al., 2016). Agrochemicals in the environment negatively affect soil quality and irrigation water quality with wider environmental implications on the biodiversity and activities of soil microorganisms (Meyer, 2016). It has also been noted that soil quality in citrus orchards has been declining over the decades with the main causes being conventional farming practices (Mulinge et al., 2018). Some of the leading causes of soil quality declines include nutrient depletion due to soil organic matter declination and leaching, soil compaction, erosion, contamination, acidification and salinisation (Bindraban et al., 2012). Depleted soil nutrients in citrus orchards have been improved with the use of inorganic fertilisers, especially nitrogen-based fertilisers (Srivastava & Singh, 2009). Nitrogen-based fertilisers tend to encourage the acidification of agricultural soils and in turn soil quality declines (Singh, 2018). This has prompted researchers to explore alternative production methods that promote sustainable practices to enhance soil quality (Karaca et al., 2011; Adetunji et al., 2017).

The use of cover crops is gaining popularity as an alternative approach to maintain and improve soil quality (Knowler & Bradshaw, 2007; Weber et al., 2017; Storr, 2019). The main purpose of cover crops is to conserve soil and water (Meyer, 2016). Cover crop practices form part of the primary conservation agriculture principles which include minimum soil disturbance and crop rotation (Francaviglia et al., 2023). Cover crops aim to improve nutrient availability, yield and long-term orchard sustainability relative to conventional practices (Meyer, 2016). They are grown because of the numerous benefits they provide, including covering and protecting the soil from erosion, reducing runoff and evaporation, conserving soil moisture, increasing infiltration rate, soil porosity, soil organic matter, microbial activities, fixing atmospheric nitrogen, sequestering carbon into the soil and suppressing weeds (Möller et al., 2008; Haruna et al., 2020).

There are two broad types of cover crops, legume and non-legume cover crops. Legume cover crops are responsible for fixing atmospheric nitrogen (N_2) and converting it into a form usable by plants (Thilakarathna et al., 2015). Legumes are easily decomposable due to their narrow C:N ratio (Sievers & Cook, 2018). While non-legume cover crops are known for suppressing weeds, creating a strong soil structure and adding organic material. The increase in organic material can result in a diverse soil microbial community which may change soil parameters, especially soil microbes and enzymes (Karaca et al., 2011). Enzymes are produced by soil microbes and catalyse numerous biochemical reactions involved in the decomposition and recycling of nutrients from organic matter (Das & Varma, 2011; Adetunji et al., 2017).

There is growing interest in the use of soil enzymes as early indicators of soil quality changes under different agricultural practices (Das & Varma, 2011; Karaca et al., 2011; Adetunji et al., 2021). The most studied soil enzymes are urease, β-glucosidase and acid phosphatase activities (Adetunji et al. 2017). These soil enzymes are sensitive to soil organic matter changes and soil management and are easy to analyse (Balota & Chaves, 2010). Urease plays a crucial role in nitrogen cycling (Gao et al., 2019) and is mainly derived from plants; it is also secreted by soil microbes (Li et al., 2014). β-glycosidases are a group of enzymes involved in catalysing the hydrolysis (Gil-Sotres et al., 2005; Adetunji et al., 2017) and biodegrading of various glucosides that are present in plant debris (Martinez & Tabatabai, 1997; Ghosh et al., 2022). These reactions provide glucose as a final end product (Merino et al., 2016), an important carbon energy source for the growth and activity of microbes in the soil (Makoi & Ndakidemi, 2008). Acid phosphatase enzyme play critical roles in the phosphorus cycle (Gabasawa, 2022), by catalysing hydrolysis of esters and anhydrides of phosphoric acid (Condron et al., 2005). Plants and soil microbes are the fundamental sources of acid phosphatase enzymes (Makoi et al., 2010).

As shown by above studies, there has been extensive work done on soil enzymes under different crop fields, however, very little has been reported on their impact in citrus orchards. Hence, research was conducted to determine the effect of cover crops on soil enzyme activities in citrus orchards. This paper determines the reaction of urease, β-glucosidase and acid phosphatase activities under different cover crops and termination methods in citrus orchards. This study was conducted using vetch, medics and oats cover crops that were grown in sandy soil.

4.2 Materials and methods

4.2.1 Study Location

A cover crop study was conducted at Lamara farm (33°51′50.51″ S, 19°07′.66″ E) in Franschhoek, in the district of Cape Winelands in Western Cape Province, South Africa (Fig. 4.1). The study was conducted in a Eureka lemon (*Citrus limon*) cultivar orchard 2021/22 and 2022/23 seasons, May to August in each year. The soil of the area is characterised as Tsitsikamma soil form (SCWG, 1991) with a rainfall ranging between 280-785 mm (Table 4.1) during cover crop growing season. An orchard with five (5)-year-old Eureka lemon trees grafted on X639 rootstock planted at 3 m x 6 m (square system) apart was used for the study.

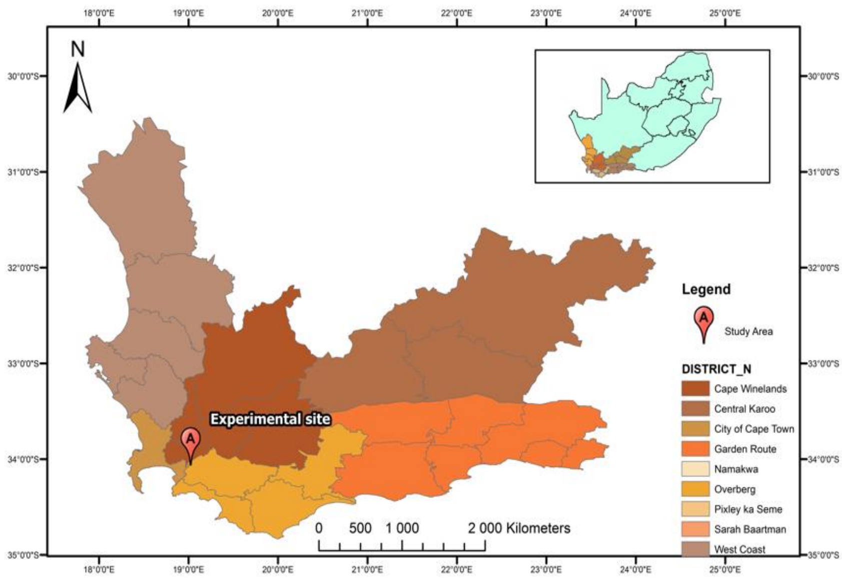

Figure 4.1. Map showing the study area

Table 4.1. Rainfall (mm) received monthly from April to August measured over a period of three years

Year	Apr	May	Jun	Jul	Aug	Total (mm)
2021	3.7	72.9	13.6	40.3	161	291.5
2022	21.3	79.8	169.2	101.3	111.3	482.9
2023	107	160	390.1	123.9	2.1	783.1

4.2.2 Experimental design

Three cover crop species, namely oats (*Avena sativa*), medics (*Medicago truncatula*), and vetch (*Vicia villosa*) were used; the control (standard farmer's practice) were used as treatments. The experiment was conducted using a factorial design, with the first factor being the cover crop species and the second factor being the method of cover crop termination A randomised complete block design was employed, with six replications of each treatment combination (Fig. 4.2). Each treatment covered 54 m^2 (8 trees per plot). The row was made up of 4 trees in the middle plus 1 buffer tree between the termination method plots (slash /non-slash), 2 buffer trees between cover crop type plots and 1 buffer row.

4.2.3 Establishment of a selection of three cover crop species

Potential cover crops were screened for suitability for use as cover crops in citrus orchards following a multi-criteria grid construction as described by Jannoyer et al. (2011). The selection was done in three successive steps based on previously published research, expert assessments from scientists, technical staff and growers, agronomy experiments and eco-physiological measurements (Jannoyer et al., 2011). The following traits were assessed in each step; vegetative characteristics which should not be more than 30 cm plant height; practicality, which include seed availability; and non-invasive and desired ecological function, such as weed competition and N fixing properties (Silwana et al., 2023).

4.2.4 Seed sowing

A glyphosate herbicide was sprayed at 5 L ha^{-1} to kill weeds before sowing cover crops. Cover crops were sown between the tree rows at the beginning of the rainy season (May 2021/22). All cover crops were evenly sown by hand using the following seeding rates: Pallinup oats, 90 kg ha^{-1}; grazing vetch, 50 kg ha^{-1}; Parabinga medic, 25 kg ha^{-1}. All cover crops received 100 kg ha^{-1} nitrogen after 30 days of planting (Fourie et al., 2001).

4.2.5 Termination

Cover crops were terminated 90 days after sowing, just before flowering and placed as mulch under the tree canopy for slashed plots following the methods used in the work by Oliveira et al. (2016). A tractor-mounted brush cutter was used to terminate cover crops in slashed plots while herbicide (roundup: *Glyphosate* as active ingredient) was used to terminate in non-slashed plots.

Figure 4.2. Experiment Design Layout. Treatments (T1 to T8) were replicated randomly in six blocks. Vetch not slashed is T1, vetch slashed is T2, medics not slashed is T3, medics slashed is T4, oats not slashed is T5, oats slashed is T6, control not slashed is T7 and control slashed is T8.

4.3 Data collection

4.3.1 Soil chemical analysis

Soil samples were taken from each experimental plot at soil depths of 0-30 and 30-60 cm depth, using a 3.5 cm diameter soil auger before cover crop sowing and one year after cover crop termination following mulch decomposition (Adetunji, 2021). The soil samples were sent to the laboratory to determine the chemical status (Table 4.2) of the soil. Soil $pH_{(KCl)}$ was determined in a 1:2.5 Soil: KCl mixture (1M KCl solution) using a glass electrode pH meter.

Table 4.2. Soil characteristic from Lamara farm, Franschhoek, Western Cape, South Africa

Soil characteristics	2021/22	2022/23
Soil texture	Sand	Sand
Carbon% (Walkley back)	0.46%	0.59%
$PH_{(KCl)}$	5.42	6.02

P (Ambic 1)	24.5 mg kg^{-1}	28.4 mg kg^{-1}
K (ammonium acetate extraction)	64 mg kg^{-1}	54 mg kg^{-1}'
NO_3 -N (KCl)	-	3.95 mg kg^{-1}
NH_4 -N (KCl)	-	11.88 mg kg^{-1}
Average soil water content (during cover crop growing season)	-	14.04 %

4.3.2 Soil enzyme activity assay

Initial soil enzyme activities of urease, β-glucosidase and acid phosphatase were analysed before the application of treatments and later analysed to see treatment effects. Urease activity (EC 3.5.1.5) associated with nitrogen cycling was determined by mixing 5.0 g of soil with 2.5 mL of 80 Mm solution and incubating for two (2) hours at 37°C (Kandeler & Gerber, 1998). For controls, deionised water was used. The ammonium was extracted with 50 mL KCl solution and measured using a digital UV–Vis spectrophotometer against the reagent blank at 690 nm. Urease activity was expressed as µg ammonium g^{-1} soil 2 h^{-1}.

The β-glucosidase activity (EC 3.2.1.21) which plays a crucial role in C cycling was determined by incubating 1.0 g of moist soil with *p*-nitrophenyl-β-D-glucopyranoside solution (pH 6.0) at 37 °C for 60 min (Eivazi & Tabatabai, 1990). The *p*-nitrophenyl amount during enzymatic hydrolysis was determined using a digital UV–Vis spectrophotometer at 410 nm. The β-glucosidase activity expressed as µg *p*-nitrophenol g^{-1} soil h^{-1}.

Acid phosphatase (EC 3.1.3.2) associated to phosphorous cycling was determined as described for β-glucosidase activity with the exception of reaction mixture consisting of 1.0 mL of 25 mM p-nitrophenol phosphate (substrate), 4.0 mL modified universal buffer (MUB), 0.25 mL toluene and the released *p*-nitrophenol was extracted with 4 mL of 0.5 M NaOH at pH 6.5 (Tabatabai & Bremner, 1969). The acid phosphate activity was expressed as µg *p*-nitrophenol g^{-1} soil h^{-1}.

4.4 Statistical analyses

ANOVA of the 4x2 factorial experiment in a randomized complete block design was performed using the General Linear Model procedure (PROC GLM) of SAS statistical software. The data were tested for normality using the Shapiro-Wilk test, histograms and normal probability plots of the Univariate procedure (PROC UNIVARIATE) of SAS statistical software (Mishra et al., 2019). Fisher's least significant difference was calculated at the 5% level of significance to compare treatment means (Ott & Longnecker, 2016). A probability level of 5% was considered significant for all significance tests.

4.5 Results and Discussion

4.5.1 Influence of cover crops on soil pH after one year

Soil pH has a major influence on soil nutrient availability, soil microbial diversity and soil enzyme activities (Stark et al., 2014). The initial measured soil pH before planting cover crops was just below 5.5. This was below the recommended 5.5 to 6.5 soil pH range suggested for citrus trees (Srivastava & Singh, 2009). In this study, soil pH improved ($p \leq 0.05$) due to the application of cover crops (Fig. 4.3). Similar results were observed where the addition of cover crops increased soil pH values (Silva et al., 2007; Kaspar et al., 2011; Vanzolini et al., 2017).

The increase in soil pH can be attributed to increased soil organic matter from cover crop residue decomposition. It was reported that cover crops have the potential to increase soil organic matter, which positively influences soil microbial activity and stabilises soil pH (Celik et al., 2011). This is because organic matter influences the soil's chemical composition by supplying nutrients to the soil, contains alkaline substances, and acts as a buffer, helping to stabilise soil pH by absorbing and releasing hydrogen (H^+) ions (Dick et al., 2000). The release of H^+ in soils has the potential to decrease soil pH, this is particularly common with legume cover crops and observed in short-term soil changes. Maltais-Landry (2015) experimented with three legume species, fava bean (*Vicia faba* L.), pea (*Pisum sativum* L. cv. Magnus) and purple vetch (*Vicia benghalensis* L.) and found lower pH in legume-planted soil. This may be linked to the legume's release of root exudates into the soil, which can contain organic acids which contribute to lowering the soil pH over time.

Other researchers have found that soil pH was not modified by introducing cover crops (Ensinas et al., 2016; Sharma et al., 2018; Adetunji et al., 2021). However, even though there was no significant influence on soil pH, cover crop treatments were always higher than that of no cover crop treatments by a few units, demonstrating that cover crops and residue increase the pH in topsoil compared to bare soil (Sharma et al., 2018). Cover crops and residue decrease aluminium ion concentrations and neutralise hydrogen ions by adding dissolved soil organic carbon, which lead to an increase in soil pH (Bressan et al., 2013**;** Spera et al., 2014). These soil pH values observed in this study after planting cover crops are appropriate for good citrus fruit growth and development. Citrus (lemon) flourishes best in soil with a pH slightly below the neutral point (Khan et al., 2006). Soil pH below 5.5 reduces yield, fruit and tree sizes and yield due to the toxic effect of aluminium and hydrogen ions (Obreza, 1993; Srivastava & Singh, 2009).

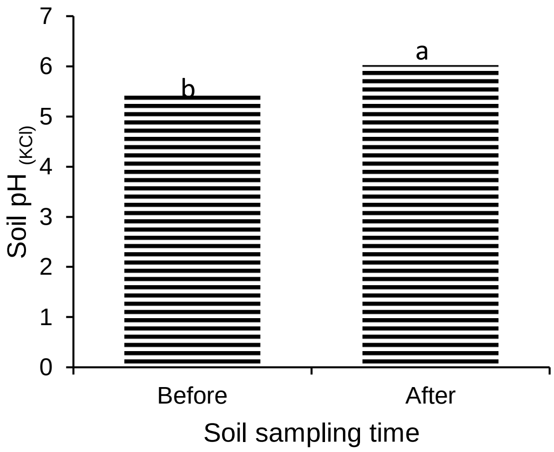

Figure 4.3. Effect of initiation of cover crops on soil pH after a year. Before stands for soil samples taken before planting cover crops while after stands soil samples taken a year from planting cove crops. Bars with different letters indicate significant differences ($p < 0.05$).

4.5.2 Response of soil pH after planting different cover crop species

Choosing the right cover crop species is essential for maintaining or improving soil microbial diversity, soil chemical composition, soil enzyme activities and soil pH (Chavarría et al., 2016). Different plants have varying effects on soil acidity or alkalinity, and selecting species that align with the soil's pH can significantly benefit agricultural practices (Hontoria et al., 2019). In this study, legume cover crops and non-legume cover crops were studied. The results show that there was no significant difference between the cover crop species used and the control treatment after a year (Fig. 4.4). Even though there were no significant differences, however, legume cover crops (vetch and medics) gave a slight increase in soil pH ranging above 6 while grass cover crop (oats) gave the least soil pH ranging below 6.

Probably, the slight pH rise in legume cover crops may be attributed to the strong activity of decomposing microorganisms and it managed to stabilise the pH faster (Vanzolini et al., 2017). Medeiros et al. (2017) also observed similar results, where there was no significant change in soil pH among cover crop treatments. Soil pH is one of the main factors in determining soil quality but there were contradictory results regarding the direction of the soil pH changes after the addition of cover crops. Some authors believe that cover crop residue may cause soil acidification because of an imbalance between carbon and nitrogen during mineralisation, particularly in legume cover crops (Burle et al., 1997; Murungu et al., 2011; Maltais-Landry, 2015). Some authors believe that cover crop residue accumulates organic anions which increase soil pH when they are decomposed by soil microorganisms (Sharma et al., 2018; Ouédraogo et al., 2024).

Vanzolini et al. (2017) conducted a laboratory incubation study and found that organic material releases organic anions which result in a rapid soil pH increase. Similar results were obtained by Tang and Yu (2000) when they incubated legume cover crop residues. The increase in soil pH is also influenced mainly by reactions between hydrogen ions and added organic matter during decomposition (Xu et al., 2003). In addition, two main processes, namely ammonification and nitrification determine the change in the direction of soil pH (Tang & Yu, 2000). The ammonification process converts organic nitrogen into ammonia ions and consumes protons which results in a soil pH increase while the nitrification process oxidises ammonia ions to nitrate and releases protons which leads to the soil pH decline (Xu & Coventry, 2003; Zhou et al., 2014). During nitrogen fixation by legume cover crops, atmospheric nitrogen is converted into ammonia (usable form) which increases soil pH values (Kakraliya et al., 2018; Nitu et al., 2021). This is one of the reasons that several studies have shown that cover crop residues from legume have a greater increase in soil pH than grass crops (Sparling et al., 2000; Xu & Coventry 2003; Vanzolini et al., 2017).

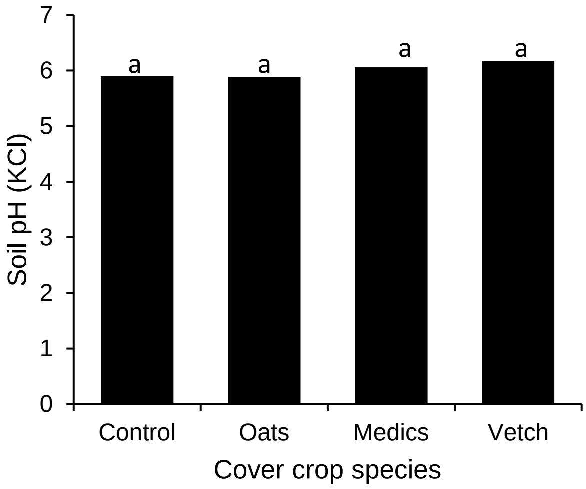

Figure 4.4. Influence of different cover crops on soil pH after a year. Significance between cover crop species is indicated using alphabetic letters, where different letters denote a difference ($p < 0.05$).

4.5.3 Soil β-glucosidase, phosphatase and urease activities after one year of planting cover crops

The presence of cover crops had no significant effect on β-glucosidase, phosphatase and urease activities after one year of planting regardless of soil depth (Table 4.3). However, there was a slight decrease in β-glucosidase activity while there was a marginal increase in activities of phosphatase and urease after planting cover crops as compared to their activities before planting cover crops at both soil depths. The slight decrease in β-glucosidase activity might have resulted from an increase in soil pH. An increase in enzyme activity with increased soil pH was reported by Ghosh et al. (2022). β-glucosidase is very sensitive to changes in soil pH and its activity decreases as soil pH increases (Adetunji et al., 2017).

The observed slight increase in soil acid phosphatase and urease activities after planting cover crops may be due to the enhancement of labile carbon pools which is a major energy source for soil microbes (Singh & Kumar, 2021). An increase in the activities of soil acid phosphatase and urease was also observed by Singh and Kumar (2021). Some studies reasoned that an increase in enzymatic activity after initiation of cover crop treatments is attributed to an increase in soil organic matter inputs from cover crops (Roldán et al., 2003; Mukumbareza et al., 2016; Adetunji et al., 2021).

In the work of Turner et al. (2014), the increase in soil organic matter caused by the incorporation of cover crops led to higher activities of phosphatase and urease. These are important in the mineralisation of phosphorous and nitrogen compounds (Turner et al., 2014). Notably, the increase of soil organic matter is relatively higher in the shallow soil depths as compared to deeper depths. Since the shallow depth receives both above-ground biomass and roots, only roots contribute to the inputs in deeper soil depths (Deng et al., 2021). Nitrogen and phosphorous are very important for citrus fruit production. Nitrogen is the mineral element most used for citrus tree growth including leaves, flowers, fruit and quality more than any other element (Agustí et al., 2014). Whereas, phosphorus is important for citrus fruit cell division and enlargement, photosynthesis and breakdown of carbohydrates (Zekri & Obreza, 2003).

Table 4.3. Soil enzyme activities before and after planting cover crops at different soil depths. Mean values within a column followed by the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

Soil depth	**Sampling time**	**Season**	**β-glucosidase (μg PNP g^{-1} soil h^{-1})**	**Phosphatase (μg PNP g^{-1} soil h^{-1})**	**Urease (μg NH_4^+ g^{-1} soil 2 h^{-1})**
0-30 cm	Before planting a cover crop.	2021/22	59.66 a	98.57 a	16.53 a
	A year from planting cover crops.	2022/2023	41.12 a	154.52 a	21.71 a
30-60cm	Before planting a cover crop.	2021/22	35.67 a	82.28 a	8.22a
	A year from planting cover crops.	2022/2023	24.12 a	131.01a	11.72 a

4.5.4 Soil urease, β-glucosidase and phosphatase activities as affected by cover crop species

At one year, cover crop species did not significantly influence the activities of β-glucosidase, phosphatase and urease at 0-30 cm (Table 4.4). However, the vetch cover crop gave a slight percentage increase in β-glucosidase and urease activities of 22.45% and 36.82%, respectively, compared to the control. While medics cover crop gave the highest percentage increase in phosphatase of 28.93% compared to the control. At deeper depth, medics cover crops gave the least urease activity and differed significantly to vetch, oats and control, whereas there was no significant difference in the activities of β-glucosidase and phosphatase at 30-60 cm soil depth. Oats gave 21.99% and 12.03% increases from the control of β-glucosidase and urease activities, respectively. It is notable in this study that vetch cover crops gave the highest enzyme activities in the topsoil compared to oats.

Murungu et al. (2011) also found that vetch cover crops gave higher soil enzyme activities compared to oats in a maize production field. The marginally increased soil enzyme activities observed under legume cover crops in contrast to the other treatments could be due to the biological nitrogen fixation and lower C:N ratios associated with the legume crops (Mukumbareza et al., 2015). Phosphatase activity was also high under legume cover crops which is consistent with several studies (Maseko & Dakora, 2013; Qian et al., 2015). It was reported that legume cover crops use more phosphorous in the symbiotic nitrogen fixation process compared to grass (Makoi & Ndakidemi 2008) and legume roots release greater amounts of phosphatase (Li et al., 2014).

When it comes to urease activity, the vetch cover crop gave the highest activities regardless of soil depths. This is due to the low C:N ratio and nitrogen fixation ability of legumes as compared to grass cover crops (Qian et al., 2015). Cover crop residues with low C:N ratios less than 30 are generally of better quality as they are known for rapid decomposition which enhances soil microbial and enzymatic activities more than residues with high C:N ratios greater than 30 (Schroth et al., 2007). Legume (vetch) cover crops further gave higher β-glucosidase activity in the topsoil whereas it was higher under oats in deeper depth in this study. This could be attributed to rapid legume residue biomass decomposition in the topsoil while oats have higher root biomass in deeper depth. Similar results were observed by Deng et al. (2021) whereby higher activities of β-glucosidase were obtained under legume cover crops. Some studies also noticed β-glucosidase activity increased on cover crop treated soil compared to bare soil (Adetunji et al., 2017; Nevins et al., 2021) and a decrease in β-glucosidase activity in soil depth due to the organic material available in the topsoil (Xiao-Chang & Qin, 2006; Liang et al., 2019 Długosz & Piotrowska-Długosz, 2022).

Table 4.5. Cover crops effect on soil enzyme activities after a year (2022/23) of planting cover crops. Mean values within a column followed by the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

Soil depth	**Sampling time**	**Cover crops**	**β-glucosidase (µg PNP g^{-1} soil h^{-1})**	**Acid phosphatase (µg PNP g^{-1} soil h^{-1})**	**Urease (µg NH_4^+ g^{-1} soil 2 h^{-1})**
0-30 cm	After one year	Medics	41.60 a	173.29 a	20.29 a
		Vetch	47.78 a	156.24 a	25.77 a
		Oats	36.06 a	154.14 a	21.97 a
		Control	39.02 a	134.40 a	18.83 a
30-60 cm	After one year	Medics	19.75 a	132.76 a	7.30 b
		Vetch	24.62 a	132.36 a	13.96 a
		Oats	28.67 a	127.45 a	13.17 a
		Control	23.50 a	131.46 a	12.46 a

4.5.5 Soil enzyme activity and termination methods

At one year, termination methods did not influence β-glucosidase, phosphatase and urease activities regardless of soil depth (Fig. 4.5 and 4.6). Adetunji et al. (2021) observed similar findings where there was no significant difference in termination methods after one year of introducing cover crops. Termination methods have the same goal, which is to kill cover crops, but the main difference is the place of cover crop residue (Liang et al., 2014). Cover crops under the slashed method are mowed and placed next to citrus tree rows while under non-slashed method, cover crops are killed using herbicide and remain between the citrus tree rows. Previous research reported that mowing of cover crops led to rapid decomposition and enhanced nitrogen mineralisation in contrast to herbicide use (Parr et al., 2011; Jani et al., 2016). Moreover, García-Orenes et al. (2010) found a decrease in phosphatase and urease activities when cover crops were terminated with glyphosate herbicide. It has been reported that herbicides such as glyphosate build up in the soil and become toxic to soil microorganisms, consequently affecting soil enzyme activities and nutrient mineralisation (Abbas et al., 2015). Barriuso and Mellado (2012) also proved that the application of herbicide affected soil rhizobacterial and bacterial diversity under maize production.

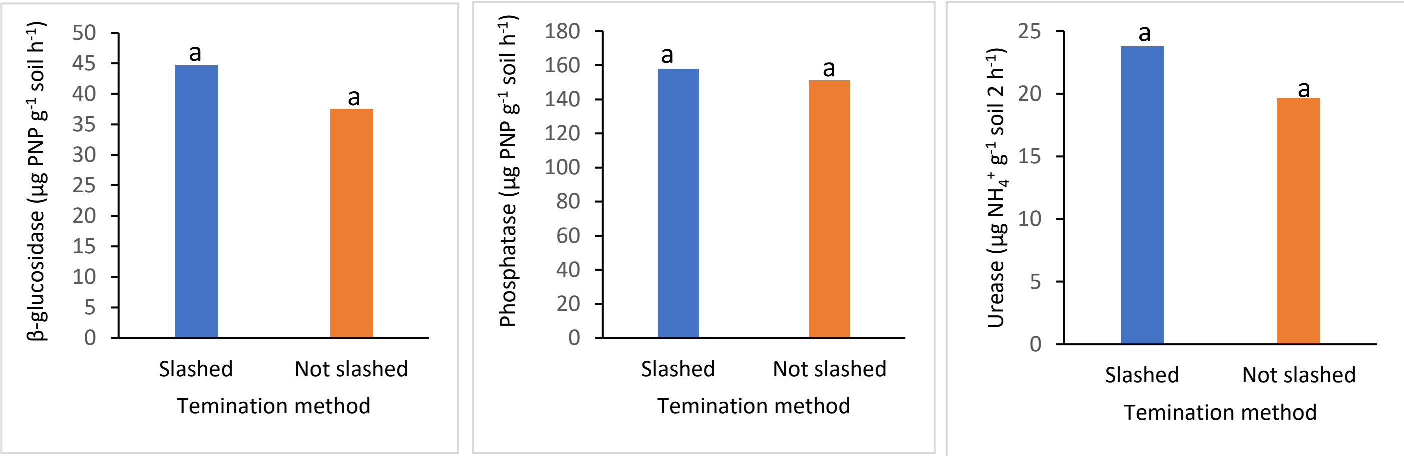

Figure 4.5. Effect of termination method on β-glucosidase, phosphatase and urease activities after one year (2022/23) at 0-30cm. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

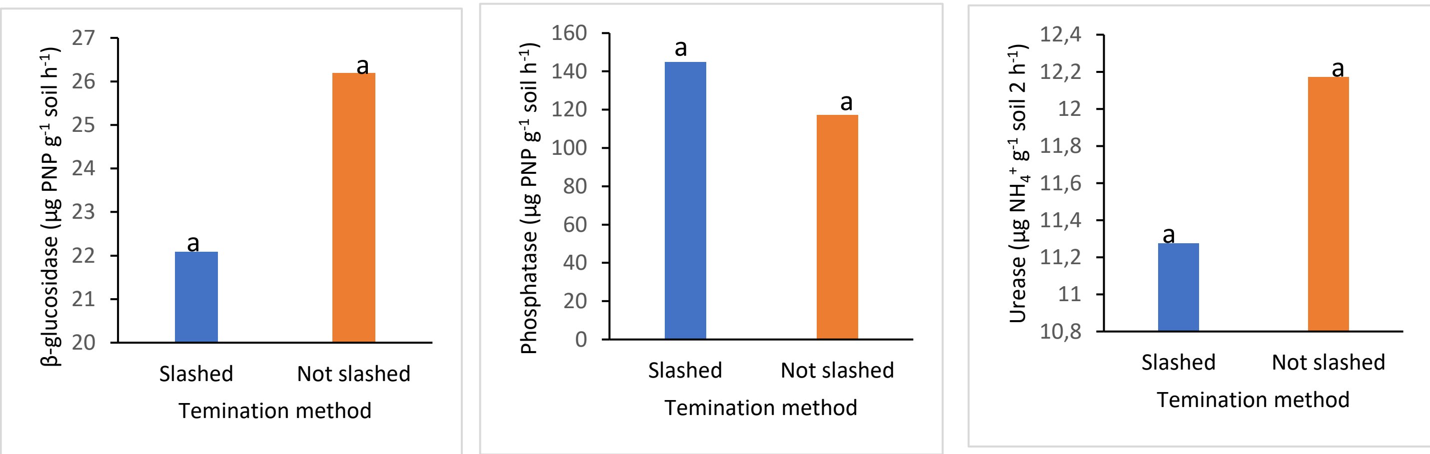

Figure 4.6. The effect of termination method on β-glucosidase, phosphatase and urease activities after one year (2022/23) at 30-60cm. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

4.5.6 Interaction Effects of Cover Crop and Termination Method on Soil Enzyme Activities

At the 0–30 cm soil depth, highest β-glucosidase activity was recorded in the vetch slashed treatment, followed closely by oats slashed and vetch not slashed (Table 4.5). Control plots showed the lowest β-glucosidase activity, with 37.9 µg PNP g^{-1} soil h^{-1} in the not slashed treatment. Despite the variation, all treatments were statistically similar ($p > 0.05$). Acid phosphatase activity at this depth was relatively high across all treatments, ranging from 125.09 to 174.54 µg PNP g^{-1} soil h^{-1}, with medic not slashed exhibiting the highest value. However, no statistically significant differences were detected among treatments ($p > 0.05$). Urease activity showed greater variability, with values ranging from 15.18 to 31.49 µg NH_4^+ g^{-1} soil 2 h^{-1}. The highest urease activity was observed in the vetch slashed treatment, while the control not slashed treatment exhibited the lowest activity. Though vetch slashed differed numerically from other treatments, but it was not significantly different to other treatments excluding control not slashed.

At the 30–60 cm depth, β-glucosidase activity was notably lower across all treatments. Oats not slashed produced the highest activity and significantly greater than medic not slashed, which had the lowest value. Vetch slashed, vetch not slashed and oats slashed were not significantly different. Acid phosphatase activity remained not significant different across treatments ($p > 0.05$), although vetch slashed again displayed the highest numerical value, while vetch not slashed had the lowest. Urease activity at this depth ranged from 5.62 to 15.55 µg NH_4^+ g^{-1} soil 2 h^{-1}. Medic not slashed recorded the lowest activity and was significantly different from oats not slashed, which was among the highest.

These results suggest that while enzyme activities were not strongly influenced by the cover crop × termination method interaction, certain combinations may contribute to improved biological activity under specific conditions. The findings are similar to previous studies were indicated that short-term changes in soil enzyme activity may not be immediately following cover crop implementation, especially in sandy soils (Lupwayi et al., 2004).

Table 6.5. Interaction effects of cover crops and termination method on soil enzyme activities. Mean values within a column followed by the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

Soil depth	Year	Cover crops* termination methods	β-glucosidase (µg PNP g^{-1} soil h^{-1})	Acid phosphatase (µg PNP g^{-1} soil h^{-1})	Urease (µg NH_4^+ g^{-1} soil 2 h^{-1})
0-30 cm	2023	Vetch*slashed	51.13 a	145.8 a	31.486 a
		Vetch*Not Slashed	44.43 a	166.67 a	20.044 ab
		Oats*Slashed	45.46 a	161.82 a	19.49 ab
		Oats*Not Slashed	31.66 a	146.45 a	24.442 ab
		Medics*Slashed	41.97 a	172.04 a	21.636 ab
		Medics*Not Slashed	41.23 a	174.54 a	18.949 ab
		Control*Slashed	40.14 a	125.09 a	22.485 ab
		Control*Not Slashed	37. 9 a	143.72 a	15.175 b
30-60 cm	2023	Vetch*slashed	28,56 ab	172,05 a	12,904 a
		Vetch*Not Slashed	20,69 ab	92,67 a	13,427 a
		Oats*Slashed	20,15 ab	114,76 a	12,381 ab
		Oats*Not Slashed	40,18 a	140,14 a	15,546 a
		Medics*Slashed	22,16 ab	148,69 a	8,989 ab
		Medics*Not Slashed	17,34 b	116,83 a	5,618 b
		Control*Slashed	20,46 ab	143,86 a	10,832 ab
		Control*Not Slashed	26,54 ab	119,06 a	14,096 a

4.6 Conclusion

There was a positive influence on soil pH after planting cover crops as compared before planting after one year. However, planting different cover crop species had no significant difference on soil pH. There was also no significant difference in soil enzyme activities after one year of introducing cover crops. However, there was slight decrease on β-glucosidase activity which might have resulted from increase in soil pH while there was an increase in phosphatase and urease activities at both soil depths. Similarly, there was no significant reaction in soil enzymes when compared against different cover crop species, but slight increases were observed. Vetch gave higher β-glucosidase and urease while medics gave higher phosphates activities in the topsoil. In deeper depths, oats gave higher β-glucosidase, whereas medics gave higher phosphates, and vetch gave higher urease activities. Termination methods had no significant effect on the β-glucosidase, phosphatase and urease activities, after one year. This study, therefore, shows that legume cover crop contributed more effect to the stimulation of biological activity in the topsoil while oats only stimulated more β-glucosidase in deeper depth. Further research with a longer-term study on soil enzymes should be done using different cover crop to develop suitable cover crop system for citrus orchards.

Declarations

Author contribution statement

Sibongiseni Silwana: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Nebo Jovanovic and Reckson Mulidzi: Conceived and designed the experiments; Contributed to writing the paper.

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Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

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4.7 References

Abbas, Z., Akmal, M., Khan, K.S. and Hassan, F.U., 2015. Impacts of long-term application of buctril super (bromoxynil) herbicide on microbial population, enzymes activity, nitrate nitrogen, Olsen-P and total organic carbon in soil. Archives of Agronomy and Soil Science, 61(5), pp.627-644.

Adetunji, A.T., Lewu, F.B., Mulidzi, R. and Ncube, B., 2017. The biological activities of β-glucosidase, phosphatase and urease as soil quality indicators: a review. Journal of soil science and plant nutrition, 17(3), pp.794-807.

Adetunji, A.T., Ncube, B., Meyer, A.H., Olatunji, O.S., Mulidzi, R. and Lewu, F.B., 2021. Soil pH, nitrogen, phosphatase and urease activities in response to cover crop species, termination stage and termination method. Heliyon, 7(1).

Agustí, M., Mesejo, C., Reig, C. and Martínez-Fuentes, A., 2014. Citrus production. Horticulture: plants for people and places, volume 1: production horticulture, pp.159-195.

Ajwa, H.A. and Tabatabai, M.A., 1994. Decomposition of different organic materials in soils. Biology and Fertility of Soils, 18, pp.175-182.

Balota, E.L. and Chaves, J.C.D., 2010. Enzymatic activity and mineralization of carbon and nitrogen in soil cultivated with coffee and green manures. Revista Brasileira de Ciência do Solo, 34, pp.1573-1583.

Barriuso, J. and Mellado, R.P., 2012. Relative effect of glyphosate on glyphosate-tolerant maize rhizobacterial communities is not altered by soil properties. Journal of microbiology and biotechnology, 22(2), pp.159-165.

Bindraban, P.S., van der Velde, M., Ye, L., Van den Berg, M., Materechera, S., Kiba, D.I., Tamene, L., Ragnarsdóttir, K.V., Jongschaap, R., Hoogmoed, M. and Hoogmoed, W., 2012. Assessing the impact of soil degradation on food production. Current Opinion in Environmental Sustainability, 4(5), pp.478-488.

Bressan, S.B., Nóbrega, J.C., Nóbrega, R.S., Barbosa, R.S. and Sousa, L.B., 2013. Cover crops and chemical quality of Yellow Latosol under no-tillage in the cerrado of Maranhão. Brazilian Journal of Agricultural and Environmental Engineering, 17, pp.371-378.

Burle, M.L., Mielniczuk, J. and Focchi, S., 1997. Effect of cropping systems on soil chemical characteristics, with emphasis on soil acidification. Plant and Soil, 190, pp.309-316.

Celik, I., Barut, Z.B., Ortas, I., Gok, M., Demirbas, A.H.M.E.T., Tulun, Y. and Akpinar, C., 2011. Impacts of different tillage practices on some soil microbiological properties and crop yield under semi-arid Mediterranean conditions.

Chavarría, D.N., Verdenelli, R.A., Serri, D.L., Restovich, S.B., Andriulo, A.E., Meriles, J.M. and Vargas-Gil, S., 2016. Effect of cover crops on microbial community structure and related enzyme activities and macronutrient availability. European journal of soil biology, 76, pp.74-82.

Citrus Grower Association of South Africa (CGA), 2023. Industry Statistics, export seasons.https://c1e39d912d21c91dce811d6da9929ae8.cdn.ilink247.com/ClientFiles/cga/CitrusGowersAssociation/Company/Documents/2024%20Stats%2

0Book%20(03_06_24%20Final%20digital%20copy)_compressed.pdf. Accessed: 21/10/2024.

Condron, L.M., Turner, B.L. and Cade-Menun, B.J., 2005. Chemistry and dynamics of soil organic phosphorus. Phosphorus: agriculture and the environment, 46, pp.87-121.

Das, S.K. and Varma, A., 2011. Role of enzymes in maintaining soil health. Soil enzymology, pp.25-42.

De Bruin, A.M., 2023. An evaluation of the risks in South African citrus farming (Doctoral dissertation, North-West University (South Africa).

Deng, J., Ni, H., Zhang, Z., Usman, S., Yang, X., Shen, Y. and Li, Y., 2021. Designing productive, energy-efficient, and environmentally friendly production systems by replacing fallow period with annual forage cultivation on the Loess Plateau of China. Journal of Cleaner Production, 320, p.128-660.

Dick, W.A., Cheng, L. and Wang, P.J.S.B., 2000. Soil acid and alkaline phosphatase activity as pH adjustment indicators. Soil Biology and Biochemistry, 32(13), pp.1915-1919.

Długosz, J. and Piotrowska-Długosz, A., 2022. Changes in carbon-degrading enzyme activities and microbial biomass content–The effect of soil depth and soil-forming processes. Applied Soil Ecology, 180, p.104-629.

Eivazi, F. and Tabatabai, M.A., 1990. Factors affecting glucosidase and galactosidase activities in soils. Soil Biology and Biochemistry, 22(7), pp.891-897.

El-Otmani, M., Ait-Oubahou, A. and Zacarías, L., 2011. Citrus spp.: Orange, mandarin, tangerine, clementine, grapefruit, pomelo, lemon and lime. In Postharvest biology and technology of tropical and subtropical fruits (pp. 437-516e). Woodhead Publishing.

Ensinas, S.C., Serra, A.P., Marchetti, M.E., da Silva, E.F., Lourente, E.R.P., do Prado, E.A.F., Matos, F.A., Altomar, P.H., Martinez, M.A., Potrich, D.C. and do Amaral Conrad, V., 2016. Cover crops affect the soil chemical properties under no-till system. Australian Journal of Crop Science, 10(8), pp.1104-1111.

Fourie, J.C., Louw, P.J.E. and Agenbag, G., 2001. Effect of seeding date on the performance of grasses and broadleaf species evaluated for cover crop management in two wine grape regions of South Africa. South African Journal of Plant and Soil, 18(3), pp.118-127.

Francaviglia, R., Almagro, M. and Vicente-Vicente, J.L., 2023. Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. Soil Systems, 7(1), p.17.

Gabasawa, A.I., 2022. Phosphorus cycle enzymes to remedy soil phosphorus deficiency. Sustainable Agriculture Reviews 58: Phosphorus Use Efficiency for Sustainable Agriculture, pp.177-205.

Gao, Y., Huang, H., Zhao, H., Xia, H., Sun, M., Li, Z., Li, P., Zheng, C., Dong, H. and Liu, J., 2019. Phosphorus affects enzymatic activity and chemical properties of cotton soil. Plant, Soil & Environment, 65(7).

García-Orenes, F., Guerrero, C., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Zornoza, R., Bárcenas, G. and Caravaca, F., 2010. Soil microbial biomass and activity under different agricultural management systems in a semiarid Mediterranean agroecosystem. Soil and Tillage Research, 109(2), pp.110-115.

Ghosh, A., Paul, R., Sarkar, A., Manna, M.C., Bhattacharjya, S., Alam, K., Choudhury, S. and Mondal, P., 2022. Carbon-, Nitrogen-, Phosphorus-, and Sulfur-Cycling Enzymes and Functional Diversity in Agricultural Systems. In Agricultural Biocatalysis (pp. 335-363). Jenny Stanford Publishing.

Gil-Sotres, F., Trasar-Cepeda, C., Leirós, M.C. and Seoane, S., 2005. Different approaches to evaluating soil quality using biochemical properties. Soil biology and biochemistry, 37(5), pp.877-887.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S. and Gao, Y., 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment, 3(1), p.e20105.

Hontoria, C., García-González, I., Quemada, M., Roldán, A. and Alguacil, M.M., 2019. The cover crop determines the AMF community composition in soil and in roots of maize after a ten-year continuous crop rotation. Science of the Total Environment, 660, pp.913-922.

Jani, A.D., Grossman, J., Smyth, T.J. and Hu, S., 2016. Winter legume cover-crop root decomposition and N release dynamics under disking and roller-crimping termination approaches. Renewable Agriculture and Food Systems, 31(3), pp.214-229.

Jannoyer ML, Le Bellec F, Lavigne C, Achard R, Malézieux E. 2011.Choosing cover crops to enhance ecological services in orchards:a multiple criteria and systemic approach applied to tropical areas. Procedia Environmental Sciences9: 104–112.https://doi.org/10.1016/j.proenv.2011.11.017.

Kakraliya, S.K., Singh, U., Bohra, A., Choudhary, K.K., Kumar, S., Meena, R.S. and Jat, M.L., 2018. Nitrogen and legumes: a meta-analysis. Legumes for soil health and sustainable management, pp.277-314.

Kandeler, E. and Gerber, H., 1988. Short-term assay of soil urease activity using colorimetric determination of ammonium. Biology and fertility of soils, 6, pp.68-72.

Karaca, A., Cetin, S.C., Turgay, O.C. and Kizilkaya, R., 2011. Soil enzymes as indication of soil quality. Soil enzymology, pp.119-148.

Kaspar, T.C. and Singer, J.W., 2011. The use of cover crops to manage soil. Soil management: Building a stable base for agriculture, pp.321-337.

Khan, M.M., Khan, M.A., Abbas, M., Jaskani, M.J., Ali, M.A. and Abbas, H., 2006. Evaluation of potting media for the production of rough lemon nursery stock. Pakistan Journal of Botany, 38(3), p.623.

Knowler, D. and Bradshaw, B., 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. Food policy, 32(1), pp.25-48.

Li, H., Song, Y., Li, Q., He, J. and Song, Y., 2014. Effective microbial calcite precipitation by a new mutant and precipitating regulation of extracellular urease. Bioresource technology, 167, pp.269-275.

Li, Z., Zhang, R., Xia, S., Wang, L., Liu, C., Zhang, R., Fan, Z., Chen, F. and Liu, Y., 2019. Interactions between N, P and K fertilizers affect the environment and the yield and quality of satsumas. Global Ecology and Conservation, 19, p.e00663.

Liang, S., Grossman, J. and Shi, W., 2014. Soil microbial responses to winter legume cover crop management during organic transition. European Journal of Soil Biology, 65, pp.15-22.

Liang, Z., Olesen, J.E., Jensen, J.L. and Elsgaard, L., 2019. Nutrient availability affects carbon turnover and microbial physiology differently in topsoil and subsoil under a temperate grassland. Geoderma, 336, pp.22-30.

Lupwayi, N.Z., Harker, K.N., Clayton, G.W., Turkington, T.K., Rice, W.A. and O’donovan, J.T., 2004. Soil microbial biomass and diversity after herbicide application. Canadian journal of plant science, 84(2), pp.677-685.

Makoi, J. H., and P. A. Ndakidemi. 2008. Selected soil enzymes: Examples of their potential roles in the ecosystem. African Journal of Biotechnology 7 (3).

Makoi, J.H., Bambara, S. and Ndakidemi, P.A., 2010. Rhizosphere phosphatase enzyme activities and secondary metabolites in plants as affected by the supply of -'Rhizobium', lime and molybdenum in *'Phaseolus vulgaris' L*. Australian Journal of Crop Science, 4(8), pp.590-597.

Maltais-Landry, G., 2015. Legumes have a greater effect on rhizosphere properties (pH, organic acids and enzyme activity) but a smaller impact on soil P compared to other cover crops. Plant and soil, 394, pp.139-154.

Martinez, C.E. and Tabatabai, M.A., 1997. Decomposition of biotechnology by-products in soils (Vol. 26, No. 3, pp. 625-632). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Maseko, S.T. and Dakora, F.D., 2013. Rhizosphere acid and alkaline phosphatase activity as a marker of P nutrition in nodulated Cyclopia and Aspalathus species in the Cape fynbos of South Africa. South African journal of botany, 89, pp.289-295.

Medeiros, J.C., Dalla Rosa, J., Mafra, A.L. and de Sousa Mendes, W., 2017. Chemical attributes of agricultural soil after the cultivation of cover crops. Australian Journal of Crop Science, 11(11), pp.1497-1503.

Merino, C., Godoy, R. and Matus, F., 2016. Soil enzymes and biological activity at different levels of organic matter stability. Journal of soil science and plant nutrition, 16(1), pp.14-30.

Meyer, A.H., 2016. Soil microbial properties and apple tree performance under conventional and organic management (Doctoral dissertation, Rhodes University).

Mishra P, Pandey CM, Singh U, Gupta A, Sahu C, Keshri A. 2019. Descriptive statistics and normality tests for statistical data. Ann Card Anaesth. 22(1):67-72. doi: 10.4103/aca.ACA_157_18. PMID: 30648682; PMCID: PMC6350423.

Möller, K., Stinner, W. and Leithold, G., 2008. Growth, composition, biological N 2 fixation and nutrient uptake of a leguminous cover crop mixture and the effect of their removal on field nitrogen balances and nitrate leaching risk. Nutrient Cycling in Agroecosystems, 82, pp.233-249.

Mukhametzyanov, R.R., Brusenko, S.V., Khezhev, A.M., Kelemetov, E.M. and Kirillova, S.S., 2024. Changing the Global Production and Trade of Citrus Fruits. In Sustainable Development of the Agrarian Economy Based on Digital Technologies and Smart Innovations (pp. 19-24). Cham: Springer Nature Switzerland.

Mukumbareza, C., Muchaonyerwa, P. and Chiduza, C., 2015. Effects of oats and grazing vetch cover crops and fertilisation on microbial biomass and activity after five years of rotation with maize. South African Journal of Plant and Soil, 32(4), pp.189-197.

Mukumbareza, C., Muchaonyerwa, P. and Chiduza, C., 2016. Bicultures of oat (*Avena sativa* L.) and grazing vetch (*Vicia dasycarpa* L.) cover crops increase contents of carbon pools and activities of selected enzymes in a loam soil under warm temperate conditions. Soil Science and Plant Nutrition, 62(5-6), pp.447-455.

Mulinge, J., Saha, H., Mounde, L. and Wasilwa, L., 2018. Effects of legume cover crops on orange (*Citrus sinensis*) fruit weight and brix. International Journal of Plant & Soil Science, 21(4), pp.1-9.

Murungu, F.S., Chiduza, C., Muchaonyerwa, P. and Mnkeni, P.N.S., 2011. Decomposition, nitrogen and phosphorus mineralization from winter-grown cover crop residues and suitability for a smallholder farming system in South Africa. Nutrient Cycling in Agroecosystems, 89, pp.115-123.

Nevins, C.J., Lacey, C. and Armstrong, S., 2021. Cover crop enzyme activities and resultant soil ammonium concentrations under different tillage systems. European Journal of Agronomy, 126, p.126277.

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P. and Hens, L., 2016. Chemical pesticides and human health: the urgent need for a new concept in agriculture. Frontiers in public health, 4, p.148.

Nitu, T.T., Milu, U.M. and Jahangir, M.M.R., 2021. Cover crops and soil nitrogen cycling. In Cover Crops and Sustainable Agriculture (pp. 209-226). CRC Press.

Obreza, T.A., 1993. Program fertilization for establishment of orange trees. Journal of production agriculture, 6(4), pp.546-552.

Ouédraogo, F., Cornu, J.Y., Fanin, N., Janot, N., Sourzac, M., Parlanti, E. and Denaix, L., 2024. Changes over time in organic matter dynamics and copper solubility in a vineyard soil after incorporation of cover crop residues: Insights from a batch experiment. Chemosphere, 350, p.141137.

Parr, M., Grossman, J.M., Reberg-Horton, S.C., Brinton, C. and Crozier, C., 2011. Nitrogen delivery from legume cover crops in no-till organic corn production. Agronomy Journal, 103(6), pp.1578-1590.

Qian, X., Gu, J., Pan, H.J., Zhang, K.Y., Sun, W., Wang, X.J. and Gao, H., 2015. Effects of living mulches on the soil nutrient contents, enzyme activities, and bacterial community diversities of apple orchard soils. European Journal of Soil Biology, 70, pp.23-30.

Roldán, A., Caravaca, F., Hernández, M.T., Garcıa, C., Sánchez-Brito, C., Velásquez, M. and Tiscareno, M., 2003. No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico). Soil and Tillage Research, 72(1), pp.65-73.

Schroth, A.W., Bostick, B.C., Graham, M., Kaste, J.M., Mitchell, M.J. and Friedland, A.J., 2007. Sulfur species behavior in soil organic matter during decomposition. Journal of Geophysical Research: Biogeosciences, 112(G4).

Sharma, V., Irmak, S. and Padhi, J., 2018. Effects of cover crops on soil quality: Part I. Soil chemical properties—organic carbon, total nitrogen, pH, electrical conductivity, organic matter content, nitrate-nitrogen, and phosphorus. Journal of Soil and Water Conservation, 73(6), pp.637-651.

Sievers, T. and Cook, R.L., 2018. Aboveground and root decomposition of cereal rye and hairy vetch cover crops. Soil Science Society of America Journal, 82(1), pp.147-155.

Silva, M.B.D., Kliemann, H.J., Silveira, P.M.D. and Lanna, A.C., 2007. Biological attributes of the soil under the influence of vegetation cover and management system. Pesquisa Agropecuária Brasileira, 42, pp.1755-1761.

Silwana, S., Mulidzi, A.R. and Jovanovic, N., 2023. Evaluating the effects and benefits of cover crops in citrus orchards: a review. South African Journal of Plant and Soil, 40(2), pp.117-126.

Singh, B., 2018. Are nitrogen fertilizers deleterious to soil health. Agronomy, 8(4), p.48.

Singh, J. and Kumar, S., 2021. Seasonal changes of soil carbon fractions and enzyme activities in response to winter cover crops under long-term rotation and tillage systems. European Journal of Soil Science, 72(2), pp.886-899.

Soil Classification Working Group (SCWG), 1991. Soil classification: a taxonomic system for South Africa (Vol. 15). Department of Agricultural Development.

Sparling, G.P., McLay, C.D.A., Tang, C. and Raphael, C., 2000. Effect of short-term legume residue decomposition on soil acidity. Soil Research, 37(3), pp.561-574.

Spera, S.T., Escosteguy, P.A.V., dos SANTOS, H.P. and Klein, V.A., 2014. The soil solution of a dystrophic red latosol subjected to three types of soil and crop management.

Srivastava, A.K. and Singh, S., 2009. Citrus decline: Soil fertility and plant nutrition. Journal of Plant Nutrition, 32(2), pp.197-245.

Stark, S., Männistö, M.K. and Eskelinen, A., 2014. Nutrient availability and pH jointly constrain microbial extracellular enzyme activities in nutrient-poor tundra soils. Plant and Soil, 383, pp.373-385.

Storr, T., 2019. The effect of cover crops on soil quality indicators in a cereal and salad rotation (Doctoral dissertation).

Tabatabai, M.A. and Bremner, J.M., 1969. Use of p-nitrophenyl phosphate for assay of soil phosphatase activity. Soil biology and biochemistry, 1(4), pp.301-307.

Tang, C. and Yu, Q., 2000. Impact of chemical composition of legume residues and initial soil pH on pH change of a soil after residue incorporation. Plant and Soil, 215, pp.29-38.

Thilakarathna, M.S., Serran, S., Lauzon, J., Janovicek, K. and Deen, B., 2015. Management of manure nitrogen using cover crops. Agronomy Journal, 107(4), pp.1595-1607.

Turner, S., Schippers, A., Meyer-Stüve, S., Guggenberger, G., Gentsch, N., Dohrmann, R., Condron, L.M., Eger, A., Almond, P.C., Peltzer, D.A. and Richardson, S.J., 2014. Mineralogical impact on long-term patterns of soil nitrogen and phosphorus enzyme activities. Soil Biology and Biochemistry, 68, pp.31-43.

Vanzolini, J.I., Galantini, J.A., Martínez, J.M. and Suñer, L., 2017. Changes in soil pH and phosphorus availability during decomposition of cover crop residues. Archives of Agronomy and Soil Science, 63(13), pp.1864-1874.

Weber, J.F., Kunz, C., Peteinatos, G.G., Zikeli, S. and Gerhards, R., 2017. Weed control using conventional tillage, reduced tillage, no-tillage, and cover crops in organic soybean. Agriculture, 7(5), p.43.

Xiao-Chang, W.A.N.G. and Qin, L.U., 2006. Beta-glucosidase activity in paddy soils of the Taihu Lake region, China. Pedosphere, 16(1), pp.118-124.

Xu, R.K. and Coventry, D.R., 2003. Soil pH changes associated with lupin and wheat plant materials incorporated in a red–brown earth soil. Plant and soil, 250, pp.113-119.

Zekri, M. and Obreza, T.A., 2003. Plant nutrients for citrus trees (pp. 1-2). Gainesville, FL, USA: University of Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, EDIS.

Zhou, J., Xia, F., Liu, X., He, Y., Xu, J. and Brookes, P.C., 2014. Effects of nitrogen fertilizer on the acidification of two typical acid soils in South China. Journal of soils and sediments, 14, pp.415-422.

Chapter 5

Significance of rainfed cover crop species on soil water content in citrus orchard (Eureka lemons)

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Abstract

Use of soil water content by different cover crop species in citrus orchards are unknown, including suitable termination methods to conserve water. The study was conducted in South Africa to assess the following: (i) the effect of cover crop species on soil water content, (ii) cover crop termination methods (slashed and non-slashed) on soil water content, and (iii) performance of cover crop species on soil water content when examined against termination methods**.** Cover crop species tested were vetch, medics, oats and control (no cover crop). The experiment was set up in a randomised block design with a factorial treatment structure (Factor 1 - cover crop species; Factor 2 – cover crop termination methods) replicated six times. In this experiment, soil water content was monitored at 10, 20, 30, 40, 60 and 80 cm soil depth using DFM soil moisture probes, during the winter season in oats, medics, vetch and control plots. The results showed that soil water content was mostly depleted in the oat's treatment at 10 cm depth, however, there was no significant influence in other soil depths. The root water uptake was observed at 30 cm depth regardless of the species of cover crop planted. The termination methods did not influence the soil water content regardless of soil depths. However, slashed treatments gave less depletion of soil water content compared to non-slashed treatments when tested against the same cover crop species. These results suggest oats depleted more soil water at root zone (10 cm) while there was no significant difference in soil water content in deeper depths.

Slashed treatments retained more water compared to non-slashed regardless of cover crop species.

Keywords: Citrus, cover crop, DFM probes, soil water content, termination methods

5.1 Introduction

Climate change projection of various model experiments on future climate change scenarios strongly agree on a rise in temperatures and severity of droughts in most of the Mediterranean regions (Iglesias et al., 2016; Tramblay et al., 2020). A consequence of which variable rainfall will be experienced which poses a great threat to both agricultural and environmental sectors (Li et al., 2021). In citriculture context, these changes cause a reduction in the availability of the water and lead to citrus water stress with negative influences on the yield and quality of the citrus fruit. The human population is also rapidly growing and estimated to reach 9.7 billion by 2050 globally (De Bruin, 2023). Therefore, water demand for human consumption and industrial activities are expected to increase due to an increase of human growth (Haruna et al., 2020). It is predicted that water resources will decrease globally by 40% by 2030 (Goedde et al., 2020). While agricultural production is expected to increase by 49% by the year 2030 in rain-fed and by 81% in irrigated crops in most of the developing countries (Shirgure, 2013).

The agricultural sector is identified as the largest water consumer which accounts for nearly half of the water required in South Africa. Citrus fruit are among the agricultural crops that use large amounts of water due to intensive irrigation (Monteiro et al., 2010). Moreover, the citrus tree is an evergreen fruit crop (Hamid et al., 2024), therefore, the amount of moisture in the soil and its availability to a crop throughout the year are essential factors for citrus fruit growth and development (Martinelli et al., 2017; Mulinge et al., 2018). Most water is needed during critical periods of production for growth, vigour and productivity. The shortage of water during these stages affects the fruit yield and quality (Shirgure, 2013). Therefore, assurance of water sources is mandatory for successful commercial citrus fruit production, particularly during critical stages of productivity. Nonetheless, citrus fruit is produced in more than 135 countries (Shirgure, 2013) and South Africa is among these countries with its high-quality citrus fruit, which is in demand worldwide (Tridge, 2023). The country exports citrus to over 100 countries worldwide and the country's largest export market goes to the European Union, accounting for about 40% of total international sales (Tridge, 2023).

However, farmers produce required fruit in the expanses of soil and water resources leading to significant damage to agricultural land and biodiversity conservation (Delgado & Gantzer, 2015). One of the approaches to manage this situation is to invest in soil management practices that enhance soil water storage such as cover crops (Basche et al., 2016). Cover crop is a practice that enhances soil quality and sustain soil nutrients and water for the next crop. Other cover crop benefits include weed pressure reduction; improving organic carbon content; long-term reduction in overall production input costs (Strauss, 2019). However, there are questions and contradictions regarding water use of different cover crop species. Some researchers argue that cover crop reduces water availability for a following crop (Kahimba et al., 2008; Carlson & Stockwell, 2013), while others argue that cover crops increase soil water storage (Villamil et al., 2006; Qi et al., 2011). Blanco-Canqui et al. (2015) contend that cover crops reduce soil water content as they transpire water during establishment and growth. Furthermore, cover crop treatments gave 34% lower soil water content at root zone depth of 0-7 cm compared to non-cover crop treatment (Kahimba et al., 2008). Oats and berseem clover biomass yields were also significantly lower due to reduction of soil moisture by cover crop (Kahimba et al., 2008).

In contrast, it was reported that cover crops improve soil moisture conservation (Adetunji et al., 2019) through reducing water evaporation from the soil surface (Abdel-Aziz et al., 2008; Kaspar et al., 2011). In a study conducted by Abdel-Aziz et al. (2013), cover crops significantly improved soil moisture from 4.2% to 10%. The introduction of cover crop also enhances soil water holding capacity due to an increase of soil organic carbon, which reduces runoff, and improves nutrients and infiltration rates due to an increase of soil pores formed by cover crop root growth (Fleming et al., 2006; Mulinge et al., 2017). In addition, Wang et al. (2021) reported that cover crops did not affect succeeding crop yield but increased soil water storage for the whole soil profile by 13.2% and by 6.0% at 30 cm depth compared to no cover crop treatments.

Soil water storage often varies with cover crop species and management practices (Wang et al., 2021). Legume cover crops such as vetch known for conserving water (Adetunji et al., 2019) and use less water than non-legume cover crops due to lower biomass production (Barker et al., 2018; Zhang et al., 2023). Mulinge et al. (2017) examined effect of three legume cover crops on soil moisture content in citrus orchards. Mucuna cover crop significantly increased soil moisture by 39% and 33%, followed by dolichos with 34.4% and 28.9% and cowpea with 33.6% and 27.3% at 0-20 and 20-40cm, respectively, compared to controls (Mulinge et al., 2017). Ntshidi et al. (2021) conducted a pot experiment to evaluate the water use of cover crops commonly grown in South African fruit orchards. The legumes had the highest daily water use ranging from 2 to 2.5 $Lm^{-2}d^{-1}$, followed by exotic grass with 1.5-21 $Lm^{-2}d^{-1}$ and indigenous grasses with 0.8-12 $Lm^{-2}d^{-1}$ (Ntshidi et al., 2021). Wang et al. (2021) reported that leaving cover crop residue as mulch at the soil surface reduced evapotranspiration by 6.2% and increased water use efficiency by 5.0% compared to cover crop residue removal. While Holman et al. (2021) discovered that cover crop left standing gave 4-27% more available soil water content compared mulch.

Aforementioned studies clearly show that cover crops improve soil quality which enhances soil water dynamics. However, little has been reported on the influence of cover crop species on soil moisture within the soil profile in citrus orchards. Additionally, to increase adoption of cover crops in citrus orchards, it is important to increase our understanding of how different cover crop species deplete or retain soil water. Therefore, our research questions were: (i) How is soil water content affected by oat, medics and vetch cover crops? and (ii) How do termination methods affect soil water content? To answer these questions, DFM (Dirk Friedhelm Mercker) capacitance probes were used to continuously measure soil water content in citrus orchard. The objective of the study was to evaluate how cover crop species and termination methods influence soil water content in citrus orchards.

5.2 Materials and methods

5.2.1 Study Location

A cover crop study was conducted at Lamara farm (33°51′50.51″ S, 19°07′.66″ E) in Franschhoek, in the district of Cape Winelands in the Western Cape Province, South Africa. The study was conducted in a Eureka lemon (*Citrus limon*) cultivar orchard during the 2021/23 to 2023/24 seasons, May to August in each year. The soil of the area is characterised as Tsitsikamma soil form (SCWG, 1991) with a rainfall ranging between 280-785 mm (Table 5.1) during cover crop growing season. An orchard with five (5)-year-old Eureka lemon trees grafted on X639 rootstock planted at 3 m x 6 m (square system) apart was used for the study.

Table 5.1. Rainfall (mm) received monthly from April to August measured over a period of three years

Year	Apr	May	Jun	Jul	Aug	Total (mm)
2021	3.7	72.9	13.6	40.3	161	291.5
2022	21.3	79.8	169.2	101.3	111.3	482.9
2023	107	160	390.1	123.9	2.1	783.1

5.2.2 Experimental design

Three cover crop species (oats, medics and vetch) and control (standard farmer's practice) were used as treatments. The experiment was conducted using a factorial design, with the first factor being the cover crop species and the second factor being the method of cover crop termination. A randomised complete block design was employed, with six replications of each treatment combination. Each treatment covered 54 m^2 (8 trees per plot). The row was made up of 4 trees in the middle plus 1 buffer tree between cover crop slash or non-slash plots, 2 buffer trees between cover crop type plots and 1 buffer row.

5.2.3 Establishment of a selection of three cover crop species

Potential cover crops were screened for suitability for use as cover crops in citrus orchards following a multi-criteria grid construction as described by Jannoyer et al. (2011). The selection was done in three successive steps based on previously published research, expert assessments from scientists, technical staff and growers, agronomy experiments and eco-physiological measurements (Jannoyer et al., 2011). The following traits were assessed in each step; vegetative characteristics which should not be more than 30 cm plant height, practicality which include seed availability and non-invasive and desired ecological function, such as weed competition and N fixing properties (Silwana et al., 2023).

5.2.4 Seed sowing

A glyphosate herbicide was sprayed at 5 L ha^{-1} to kill weeds before planting. Cover crops were between the tree rows at the beginning of the rainy season (May). All cover crops were evenly sown by hand using the following seeding rates: Pallinup oats, 90 kg ha^{-1}; grazing vetch, 50 kg ha^{-1}; Parabinga medic, 25 kg ha^{-1}. All cover crops received 100 kg ha^{-1} nitrogen after 30 days of (Fourie et al., 2007).

5.2.5 Termination

Cover crops were terminated 90 days after sowing, just before flowering and placed as mulch under the tree canopy for slashed plots following the methods used in the work by Oliveira et al. (2016). A tractor-mounted brush cutter was used to terminate cover crops in slashed plots while herbicide (roundup: *Glyphosate* as active ingredient) was used to terminate in non-slashed plots.

5.3 Data collection

Eight (8) GPRS capacitance probes (DFM) were installed in the centre of each plot to measure soil water content over the cover crop growing season (May- August 2023). The DFM capacitance probe sensors arranged to measure soil moisture at 10, 20, 30, 40, 60 and 80 cm depths (DFM software solutions, 2015). The probes were programmed to record measurements at hourly intervals for the duration of the cover crop growing season. The gravimetric soil samples were collected using 2.2 cm diameter core samples in each depth and the wet soil was weighed, oven dried at 105 ^{o}C and weighed again. The values were used to calibrate the DFM probes measurements into soil water contents throughout the cover crop growing season. Gravimetric water content (GWC) was determined as follows: GWC = ½ {(wet soil weight- dry soil weight)/ dry soil weight}*100.

5.4 Statistical analyses

ANOVA of the 4x2 factorial experiment in a randomized complete block design was performed using the General Linear Model procedure (PROC GLM) of SAS statistical software. The data were tested for normality using the Shapiro-Wilk test, histograms and normal probability plots of the Univariate procedure (PROC UNIVARIATE) of SAS statistical software (Mishra et al., 2019). Fisher's least significant difference was calculated at the 5% level of significance to compare treatment means (Ott & Longnecker, 2010). A probability level of 5% was considered significant for all significance tests.

5.5 Results and discussion

5.5.1 Calibration of probe soil water content

The mean soil water content determined through gravimetric method and probe output was scatter plotted to obtain a regression curve (Fig. 5.1). There was a positive linear relationship between gravimetric method and probe output signal. The regression coefficient (R^2) for the soil water content was significant (0.734). This linear relationship is comparable to the calibration equations attained by Huang et al. (2004) and Qi and Helmers (2010).

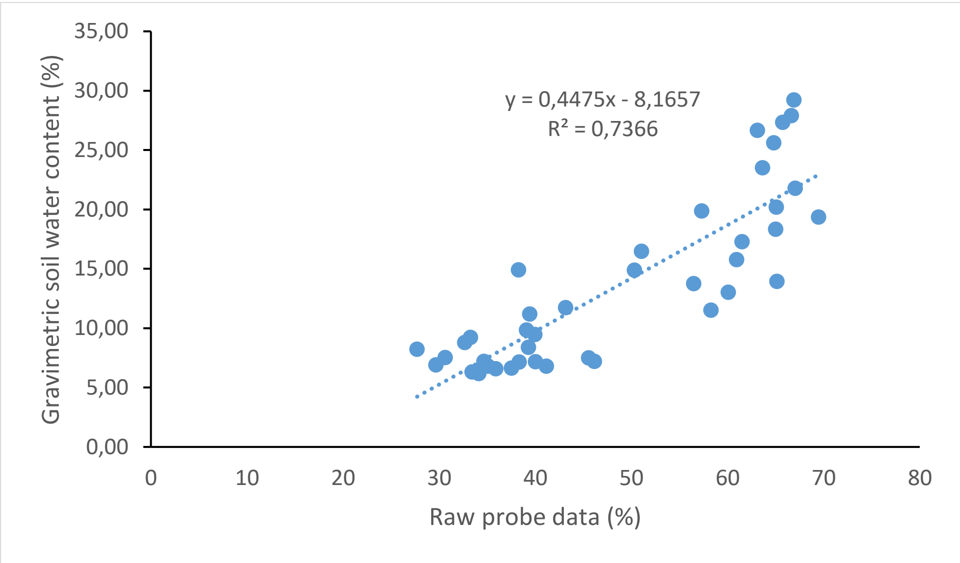

Figure 5.1. Scatter plot on probes data against gravimetric soil water content (%)

5.5.2 Soil water content conserved by different cover crop species

Soil water content status is very important for citrus root system growth, tree growth as well as fruit yield and quality (Rewald et al., 2011). The results of this study showed a significant difference ($P < 0.05$) in soil water content at 10 cm depth, with the oats treatment recording the lowest moisture content among the cover crops (Fig. 5.2). Oats cover crop treated plots recorded the highest decrease in soil water content by 29.07%, medics by 26.34% and vetch by 18.76% at 10 cm soil depth compared to their control. However, there was no significant differences in soil water content at 20 cm, 30 cm, 40 cm, 60 cm and 80 cm soil depths. Interestingly, a graph trends decline was observed at 30 cm depth in all treatments and increased at 40 cm, 60 cm and 80 cm soil depths. The citrus root systems contain dense fibrous roots within the topsoil which is responsible for water and nutrient absorption (Mulinge et al., 2017). Therefore, decline of soil water content at 30 cm depths, may have resulted from citrus fibrous roots within the topsoil which increased the rate of water and nutrient uptake (Mulinge et al., 2017). The vetch biomass accumulation and its growth distribution which mostly grows horizontal to cover the citrus orchard soil surface increased soil water content and storage capacity (Mulinge et al., 2018). Similar results were observed where soil water content of hairy vetch was greater compared to winter triticale (Holman et al., 2021). The grass cover crops such as rye and oats grow densely which takes up more water in the soil (Sanders et al., 2018). However, these grasses and legumes accumulate biomass and may have high mulch in the long run which conserves more water (Qi et al., 2011).

In this study, the control treatment had higher soil water content than cover crops throughout the soil depths. A similar trend was reported where soil water content was significantly lower in cover crop plots compared to non-cover crop treatment possible due of higher evapotranspiration in cover crops (Qi & Helmers, 2010). Even Kahimba et al. (2008) found that cover crop treatments (oats and berseem clover) gave 34% lower soil water content at root zone depth of 0-7 cm than non-cover crop treatment. However, in a three-year study, cover crop treatments had significantly higher soil water content at the 0-30 cm depth compared to the non-cover crop treatment under maize-soybean crop rotation (Basche et al., 2016). A similar trend was observed where rye cover crop planted in a longer study increased soil water content compared to the control no-cover crop plots due to reduced evaporation (Odhiambo & Bomke, 2007; Qi et al., 2011).

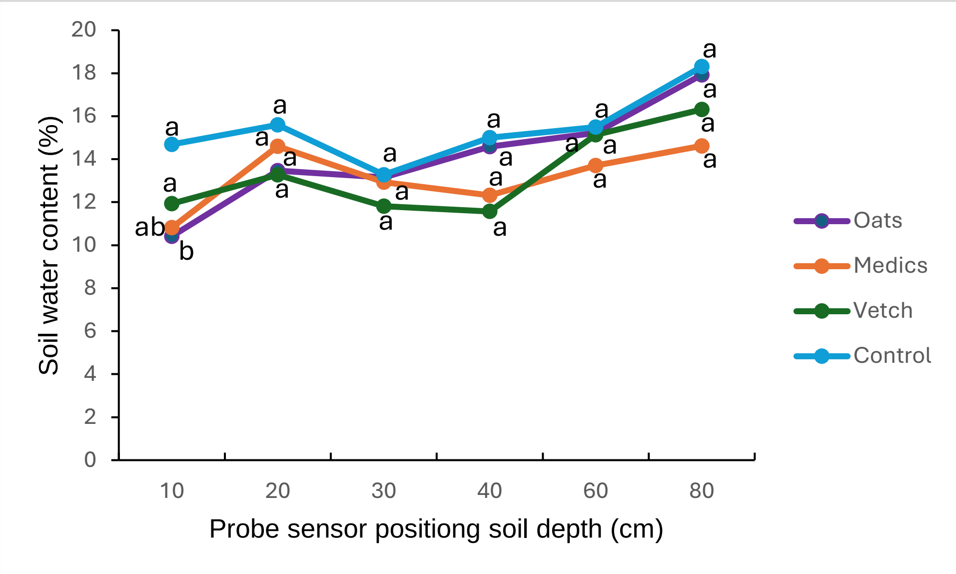

Figure 5.2. Depleted soil water content by different cover crop species at different soil depths in 2022/23 season. Same letters indicate that there is no significance differences based on Fisher's LSD ($p < 0.05$).

5.5.3 Influence of termination methods on soil water content

Methods used to kill or terminate planted cover crops differ among farmers and can affect cover crops benefits that are meant to be received by the following crop (Rosario-Lebron et al., 2019). There was no significant difference between termination methods on soil water content regardless of the soil planting depth (Fig. 5.3). Similar results were also observed in other studies, where methods of termination had no significant effect on soil moisture (Rosario-Lebron et al., 2019). In contrast, it was found that different termination methods for cover crops significantly influenced soil moisture conditions and yield (Price et al., 2009; Li et al., 2021). Mechanical mower was used to terminate winter cover crops and conserve more soil moisture compared to glyphosate (Price et al., 2009). However, soil water content was as 4–27% more for cover crop left standing than hayed cover crops (Holman et al., 2021). Even in this study, there was slightly higher soil water content under non-slashed as compared to slashed treatments at 0-30 cm depth. This may be caused by the removal of cover crop residue by mower and placing it under the tree canopy under slashed treatments. Retention of soil moisture depends on the amount of biomass produced by the cover crop and the management of its residue on the soil surface (Holman et al., 2021). This is in agreement with Frasier et al. (2016), who reported that when the biomass produced by cover crops increases, the greater soil moisture is retained throughout the soil profile. It was noted that mechanical mowed cover crops affect the amount of cover crop residue that accumulates on the soil surface since they are removed and cut into small pieces, and these shredded fragments will presumably break down faster than whole plant residue (Wortman et al., 2012).

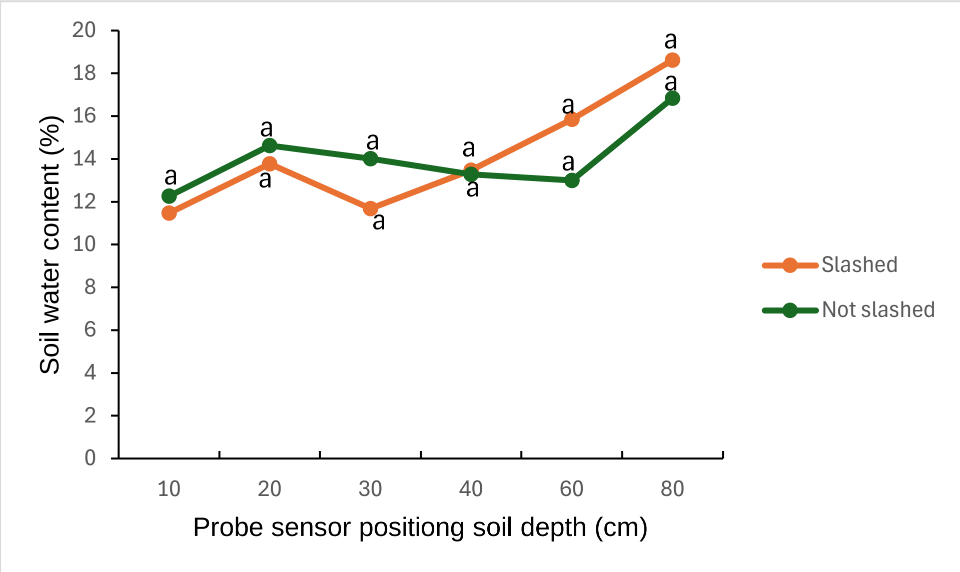

Figure 5.3. Effect of termination methods (slashed and non-slashed) on soil water content at different soil depths in 2023. Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

5.5.4 Impact of cover crop species on soil water content when tested against termination methods during growing season

Characterisation of soil moisture changes is important for understanding the impact of cover crop species and termination methods, which may affect or influence crop growth and yields (Haramoto & Brainard, 2012). The results showed that there is a significant ($P>0.05$) effect on soil water content when cover crop species were examined against termination methods during growing season (Fig. 5.4). Once again, the decline in soil water content at 30 cm was also noted regardless of termination methods and cover crop species. This decline is associated with cover crop and citrus roots water uptake and percolation. This might be where majority of citrus roots are located which led to more water depleted in this soil depth. Nevertheless, all the slashed treatments gave higher soil water content when compared to non-slashed treatments under the same cover crop type in this study. It was mentioned that cover crop mulch tends to hold more soil moisture and further decreases soil temperature as soil organic matter and soil water holding capacity increases (Jun et al., 2014). This was also reported by Abdel-Aziz et al. (2008) and Adetunji et al. (2019) that cover crops mulch improve soil moisture conservation through reducing water evaporation from the soil surface. In a study conducted by Abdel-Aziz et al. (2013), cover crops significantly improved soil moisture from 4.2% to 10%. The soil water content differed through the soil depths because cover crop species have different biomass amounts, and termination methods used also affect soil water content, hence the decrease in soil water content and water storage differed with treatments (Ntshidi et al., 2021). With oats, non-slashed treatment gave least soil water content followed by vetch non-slashed, medics non- slashed and control non-slashed treatments. The control treatments had higher soil water content since the soil was undisturbed, therefore, less growth activity occurred as compared to cover crops treatments.

Notably, oats treatment exhibited the highest soil water content, followed by control. These outcomes underscore the importance of selecting cover crop and termination strategies not only for soil health benefits but also for aligning with the orchard's irrigation plan. Strategic integration of cover crops with appropriate termination method can help improve soil water retention and guide irrigation intervals to match water demand, particularly in citrus production systems.

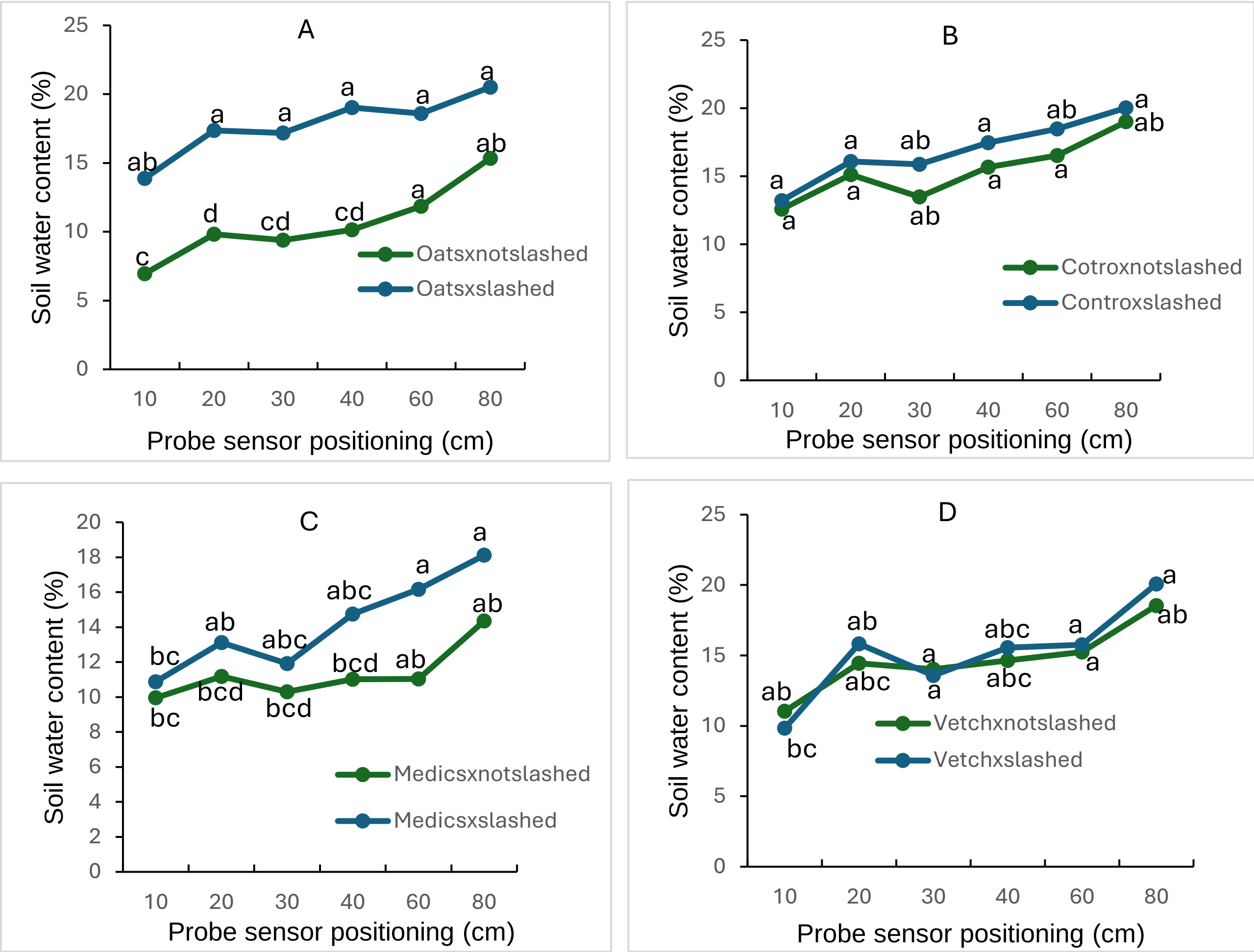

Figure 5.4. Soil content under cover crop species (oats; A, control; B, medics; C and vetch; D) with termination methods (slashed and non-slashed) in different soil depths (probe sensor positioning). Bars with the same letter are not significantly different based on Fisher's LSD ($p < 0.05$).

5.6 Conclusion

The results of this study showed that the oats depleted more soil water content at 10 cm depth while there were no significance influences in other soil depths. Soil water content was also not significantly affected by the termination method used. However, significant difference was observed when soil water content was tested against termination methods under the same cover crop type with slashed treatments giving less soil water content depletion compared to non-slashed treatments. The root water uptake was observed at 30 cm depth regardless of the species of cover crop planted. It was also noted that depletion of soil water content is directly influenced by the amount of biomass accumulated by the cover crop. As in this study, oats cover crop had higher crop biomass compared to other cover crop treatments which lead to more depletion of soil water content. It can be partially concluded that slashed cover crops stored more soil water than non-slashed cover crops; however, further studies are, therefore, recommended to evaluate the long-term effects (>4 years) of the cover crops on soil water content.

5.7 References

Abdel-Aziz, R.A., Calegari, A., Vicente, P. and Zaccheo, C., 2013. Impact of cover crops on soil, weeds and citrus trees properties in Brazil. Egyptian Journal of Horticulture, 40(1), pp.47-61.

Abdel-Aziz, R.A., Salem, S.E. and Al-Bitar, L., 2008. Effect of inter-cropping cover crops on citrus orchards growth and fruiting under Toshka conditions. Journal of Agriculture and Veterinary Science, 1, pp.101-110.

Adetunji, A.T., 2019. Impact of cover crop species, termination stage and termination method on soil nitrogen, organic carbon and enzyme activities (Doctoral dissertation, Cape Peninsula University of Technology).

Barker, J.B., Heeren, D.M., Koehler-Cole, K., Shapiro, C.A., Blanco-Canqui, H., Elmore, R.W., Proctor, C.A., Irmak, S., Francis, C.A., Shaver, T.M. and Mohammed, A.T., 2018. Cover crops have negligible impact on soil water in Nebraska maize–soybean rotation. Agronomy Journal, 110(5), pp.1718-1730.

Basche, A.D., Kaspar, T.C., Archontoulis, S.V., Jaynes, D.B., Sauer, T.J., Parkin, T.B. and Miguez, F.E., 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agricultural Water Management, 172, pp.40-50.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C.A. and Hergert, G.W., 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy journal, 107(6), pp.2449-2474.

Carlson, S. and Stockwell, R., 2013. Research priorities for advancing adoption of cover crops in agriculture-intensive regions. Journal of Agriculture, Food Systems, and Community Development, 3(4), pp.125-129.

De Bruin, A.M., 2023. An evaluation of the risks in South African citrus farming (Doctoral dissertation, North-West University (South Africa).

Delgado, J.A. and Gantzer, C.J., 2015. The 4Rs for cover crops and other advances in cover crop management for environmental quality. Journal of Soil and Water Conservation, 70(6), pp.142A-145A.

Fleming RL, Powers RF, Foster NW, Kranabetter JM, Scott DA, Ponder Jr F, 2006. Effects of organic matter removal, soil compaction, and vegetation control on 5- year seedling performance: A regional comparison of long-term soil productivity sites. Canadian Journal of Forest Research. 36(3):529–550.

Fourie, J.C., Agenbag, G.A. and Louw, P.J.E., 2007. Cover crop management in a Sauvignon Blanc/Ramsey vineyard in the semi-arid Olifants River Valley, South Africa. 3. South African Journal of Enology and Viticulture, 28(2), pp.92-100.

Frasier, I., Quiroga, A. and Noellemeyer, E., 2016. Effect of different cover crops on C and N cycling in sorghum NT systems. Science of the Total Environment, 562, pp.628-639.

Goedde, L., Menard, A. & Revellat, J. 2020. One of the oldest industries must embrace a digital, connectivity-fueled transformation in order to overcome increasing. https://www.mckinsey.com/industries/agriculture/ourinsights/agricultures-connected-future-how-technology-can-yield-new-growth Date of access 20/09/2024.

Hamid, S., Sharma, K., Kumar, K. and Thakur, A., 2024. Types and Cultivation of Citrus Fruits. In Citrus Fruits and Juice: Processing and Quality Profiling (pp. 17-43). Singapore: Springer Nature Singapore.

Haramoto, E.R. and Brainard, D.C., 2012. Strip tillage and oat cover crops increase soil moisture and influence N mineralization patterns in cabbage. HortScience, 47(11), pp.1596-1602.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S. and Gao, Y., 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment, 3(1), p.e20105.

Holman, J.D., Assefa, Y. and Obour, A.K., 2021. Cover-crop water use and productivity in the high plains wheat–fallow crop rotation. Crop Science, 61(2), pp.1374-1385.

Huang, Q., Akinremi, O.O., Sri Rajan, R. and Bullock, P., 2004. Laboratory and field evaluation of five soil water sensors. Canadian Journal of Soil Science, 84(4), pp.431-438.

Iglesias, E., Báez, K. and Diaz-Ambrona, C.H., 2016. Assessing drought risk in Mediterranean Dehesa grazing lands. Agricultural Systems, 149, pp.65-74.

Jannoyer, M.L., Le Bellec, F., Lavigne, C., Achard, R. and Malézieux, E., 2011. Choosing cover crops to enhance ecological services in orchards: A multiple criteria and systemic approach applied to tropical areas. Procedia Environmental Sciences, 9, pp.104-112.

Jun, F., Yu, G., Quanjiu, W., Malhi, S.S. and Yangyang, L., 2014. Mulching effects on water storage in soil and its depletion by alfalfa in the Loess Plateau of northwestern China. Agricultural Water Management, 138, pp.10-16.

Kahimba, F.C., Ranjan, R.S., Froese, J., Entz, M. and Nason, R., 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution in the Canadian Prairies. Applied Engineering in Agriculture, 24(3), pp.321-333.

Li, Y., Tian, D., Feng, G., Yang, W. and Feng, L., 2021. Climate change and cover crop effects on water use efficiency of a corn-soybean rotation system. Agricultural Water Management, 255, p.107042.

Martinelli, R., Monquero, P.A., Fontanetti, A., Conceição, P.M. and Azevedo, F.A., 2017. Ecological mowing: an option for sustainable weed management in young citrus orchards. Weed Technology, 31(2), pp.260-268.

Mishra P, Pandey CM, Singh U, Gupta A, Sahu C, Keshri A. 2019. Descriptive statistics and normality tests for statistical data. Ann Card Anaesth. 22(1):67-72. doi: 10.4103/aca.ACA_157_18. PMID: 30648682; PMCID: PMC6350423.

Monteiro, R.O.C., Kalungu, J.W. and Coelho, R.D., 2010. Irrigation technology in South Africa and Kenya. Ciência Rural, 40, pp.2218-2225.

Mulinge, J., Saha, H., Mounde, L. and Wasilwa, L., 2017. Effect of legume cover crops on soil moisture and orange root distribution. International Journal of Plant & Soil Science, 16(4), pp.1-11.

Mulinge, J., Saha, H., Mounde, L. and Wasilwa, L., 2018. Effects of legume cover crops on orange (*Citrus sinensis*) fruit weight and brix. International Journal of Plant & Soil Science, 21(4), pp.1-9.

Ntshidi, Z., Dzikiti, S., Mazvimavi, D., Mobe, N.T. and Mkunyana, Y.P., 2021. Water use of selected cover crop species commonly grown in South African fruit orchards and their response to drought stress. Physics and Chemistry of the Earth, Parts A/B/C, 124, p.103070. https://doi.org/10.1016/j.pce.2021.103070.

Odhiambo, J.J.O. and Bomke, A.A., 2007. Cover crop effects on spring soil water content and the implications for cover crop management in south coastal British Columbia. Agricultural Water Management, 88(1-3), pp.92-98.

Oliveira, R.A.D., Brunetto, G., Loss, A., Gatiboni, L.C., Kürtz, C., Müller Júnior, V., Lovato, P.E., Oliveira, B.S., Souza, M. and Comin, J.J., 2016. Cover crops effects on soil chemical properties and onion yield. Revista Brasileira de Ciência do Solo, 40, p.e0150099.

Ott, R.L. and Longnecker, M., 2010. An introduction to statistical methods and data analysis. Cengage Learning Inc.

Price, A.J., Arriaga, F.J., Raper, R.L., Balkcom, K.S., Komecki, T.S. and Reeves, D.W., 2009. Comparison of mechanical and chemical winter cereal cover crop termination systems and cotton yield in conservation agriculture.

Qi, Z. and Helmers, M.J., 2010. Soil water dynamics under winter rye cover crop in central Iowa. Vadose Zone Journal, 9(1), pp.53-60.

Qi, Z., Helmers, M.J. and Kaleita, A.L., 2011. Soil water dynamics under various agricultural land covers on a subsurface drained field in north-central Iowa, USA. Agricultural Water Management, 98(4), pp.665-674.

Rewald, B., Ephrath, J.E. and Rachmilevitch, S., 2011. A root is a root is a root? Water uptake rates of Citrus root orders. Plant, cell & environment, 34(1), pp.33-42.

Rosario-Lebron, A., Leslie, A.W., Yurchak, V.L., Chen, G. and Hooks, C.R., 2019. Can winter cover crop termination practices impact weed suppression, soil moisture, and yield in no-till soybean [*Glycine max* (L.) *Merr.*]? Crop Protection, 116, pp.132-141.

Sanders, Z.P., Andrews, J.S. and Hill, N.S., 2018. Water use efficiency in living mulch and annual cover crop corn production systems. Agronomy Journal, 110(3), pp.1128-1135.

Shirgure, P.S., 2013. Research review on irrigation scheduling and water requirement in citrus. Scientific journal of review, 2(4), pp.113-121.

Silwana, S., Mulidzi, A.R. and Jovanovic, N., 2023. Evaluating the effects and benefits of cover crops in citrus orchards: a review. South African Journal of Plant and Soil, 40(2), pp.117-126.

Soil Classification Working Group (SCWG), 1991. Soil classification: a taxonomic system for South Africa (Vol. 15). Department of Agricultural Development.

Strauss, S., Kadyampakeni, D., Kanissery, R., Wade, T., Diepenbrock, L. and Popenoe, J., 2019. Cover crops for citrus. EDIS, 2019.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S.M., Volaire, F., Boone, A., Le Page, M., Llasat, M.C., Albergel, C., Burak, S. and Cailleret, M., 2020. Challenges for drought assessment in the Mediterranean region under future climate scenarios. Earth-Science Reviews, 210, p.103-348. (Accessed 08/08/2024).

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W. and Bullock, D.G., 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Science Society of America Journal, 70(6), pp.1936-1944.

Wang, J., Zhang, S., Sainju, U.M., Ghimire, R. and Zhao, F., 2021. A meta-analysis on cover crop impact on soil water storage, succeeding crop yield, and water-use efficiency. Agricultural Water Management, 256, p.107085.

Wortman, S.E., Francis, C.A., Bernards, M.L., Drijber, R.A. and Lindquist, J.L., 2012. Optimizing cover crop benefits with diverse mixtures and an alternative termination method. Agronomy journal, 104(5), pp.1425-1435.

Zhang, H., Ghahramani, A., Ali, A. and Erbacher, A., 2023. Cover cropping impacts on soil water and carbon in dryland cropping system. PLoS One, 18(6), p.e0286748.

Chapter 6

General conclusions and recommendations

6.1 Synthesis

In this chapter, the relationships between soil carbon, moisture, enzyme activities (β-glucosidase, acid phosphatase, and urease), weeds and cover crops were analysed to determine potential correlations. The primary objective was to assess how these soil properties, weeds and cover crops interact and whether they significantly influence one another. The Pearson correlation method was used to examine these relationships, as it is a widely used statistical method for measuring the strength and direction of linear relationships between two continuous variables (Schober et al., 2018). Pearson correlation was selected because it provides a straightforward approach to assess whether an increase or decrease in one variable corresponds to changes in another (Mukaka, 2012). Additionally, Principal Component Analysis (PCA) was applied to the dataset containing soil properties, weeds and cover crops to identify patterns, groupings and major contributing variables. PCA is a dimensionality reduction method that simplifies complex datasets while retaining significant information, making it useful for detecting trends and relationships among multiple variables (Jolliffe & Cadima, 2016). By using both Pearson correlation and PCA, the study ensured a comprehensive analysis of interactions between soil properties, weeds and cover crops, providing insights into their potential environmental and biochemical relationships.

6.2 Correlation between soil carbon, soil moisture and soil enzyme activities using Pearson method

The correlation between soil carbon, soil moisture, and enzyme activities plays a crucial role in understanding soil nutrient cycling. A negative correlation between soil carbon and soil moisture was observed, indicating that as soil carbon content increases, soil moisture decreases (Table 6.1). This inverse relationship suggests that higher organic carbon levels may modify soil structure, leading to changes in water retention capacity (Lal, 2004; Yadav et al., 2020). A weak correlation was observed between soil carbon and β-glucosidase, acid phosphatase, and urease activities. A negative correlation was also observed between soil moisture and β-glucosidase and urease activities, while acid phosphatase presented a weak relationship with soil moisture. This finding implies that soil moisture may have differential effects on enzyme activities, possibly due to the sensitivity of microbial communities (Adetunjie et al., 2019; Mencel et al., 2022).

Additionally, β-glucosidase exhibited a negative relationship with soil moisture and weak correlation with soil carbon but a strong positive relationship with acid phosphatase and urease activities. This strong relationship suggests that these enzymes may be influenced by similar soil or environmental conditions (Acosta-Martínez & Tabatabai, 2000). Acid phosphatase displayed a weak correlation with soil carbon, moisture and urease, while it presented a strong positive correlation with β-glucosidase, indicating that phosphatase activity may be more closely linked to carbohydrate metabolism processes (Margesin & Schinner, 1997; Adetunji et al., 2017). Urease activity demonstrated varied relationships, showing a negative correlation with soil moisture, a weak relationship with soil carbon and acid phosphatase and a strong positive correlation β-glucosidase activity. These findings highlight the complexity of enzymatic interactions in soil and the potential regulatory role of carbon and moisture levels (Nannipieri et al., 2011).

Overall, the results indicate that soil moisture is negatively affected by increases in soil carbon, β-glucosidase, and urease activities. However, strong positive relationships were observed among β-glucosidase, acid phosphates and urease activities, highlighting the interconnected nature of soil biochemical properties and nutrient cycling.

Table 6.1. Pearson correlation method: soil carbon%, soil moisture and enzyme activities

Variables	**Soil carbon %**	**Soil moisture %**	**β-glucosidase (μg PNP g^{-1} soil h^{-1})**	**Acid phosphatase (μg PNP g^{-1} soil h^{-1})**	**Urease (μg NH_4^+ g^{-1} soil 2 h^{-1})**
Soil carbon	**1**	-0,176	0,348	0,258	0,296
Soil moisture	-0,176	**1**	-0,175	0,114	-0,439
β-glucosidase	0,348	-0,175	**1**	**0,578**	**0,777**
Acid Phosphatase	0,258	0,114	**0,578**	**1**	0,341
Urease	0,296	-0,439	**0,777**	0,341	**1**

Values in bold are different from 0 with a significance level alpha=0.05

6.3 Contribution of the variables and factors using Principal Component Analysis

Soil moisture demonstrated a negative correlation with soil carbon, β-glucosidase, acid phosphatase, and urease activities (Fig. 6.1). Notably, soil moisture was strongly correlated with deeper soil depths (60 cm), while soil carbon, β-glucosidase, acid phosphatase, and urease activities were higher correlated with shallower depths (30 cm), irrespective of cover crop type and termination method. This pattern shows that soil moisture had a weaker relationship with shallow depths, while soil carbon and enzymatic activities were lower correlated with deeper soil depths. Additionally, the correlation between deeper and shallower soil depths remained weak across different cover cropping and termination methods. These findings align with previous research indicating that microbial activity and organic matter content are typically higher in surface soils due to greater organic inputs and root activity, whereas deeper soils retain more moisture due to lower evaporation rates and limited organic matter inputs (Lajtha et al., 2014; Zhang et al., 2020).

Principal Component Analysis (PCA) was conducted to explore the multivariate relationships among soil biological parameters, soil depth, cover crop species and termination methods. The first two principal components (PC1 and PC2) had eigenvalues of 3.17 and 2.11, respectively, and together accounted for 65.9% of the total variation in the dataset (PC1 explained 45.3% and PC2 explained 20.6%). PC1 was primarily associated with positive loadings from β-glucosidase, acid phosphatase, urease and soil carbon, suggesting this axis represents a gradient of microbial activity and organic matter content in the upper soil profile. PC2 was driven more by soil moisture and depth, separating deeper soil layers from surface dynamics. These results reinforce the interpretation that soil biochemical activity is concentrated in the upper 30 cm, while soil moisture is more prominent in deeper layers. Furthermore, clustering patterns in the biplot (Fig. 6.1) show that slashed treatments tended to align with higher enzymatic activity, whereas non-slashed and control treatments showed weaker associations with these indicators.

These findings provide clear multivariate evidence of how soil depth, termination method and cover crop species interact to influence key indicators of soil health in citrus orchards under sandy soil conditions.

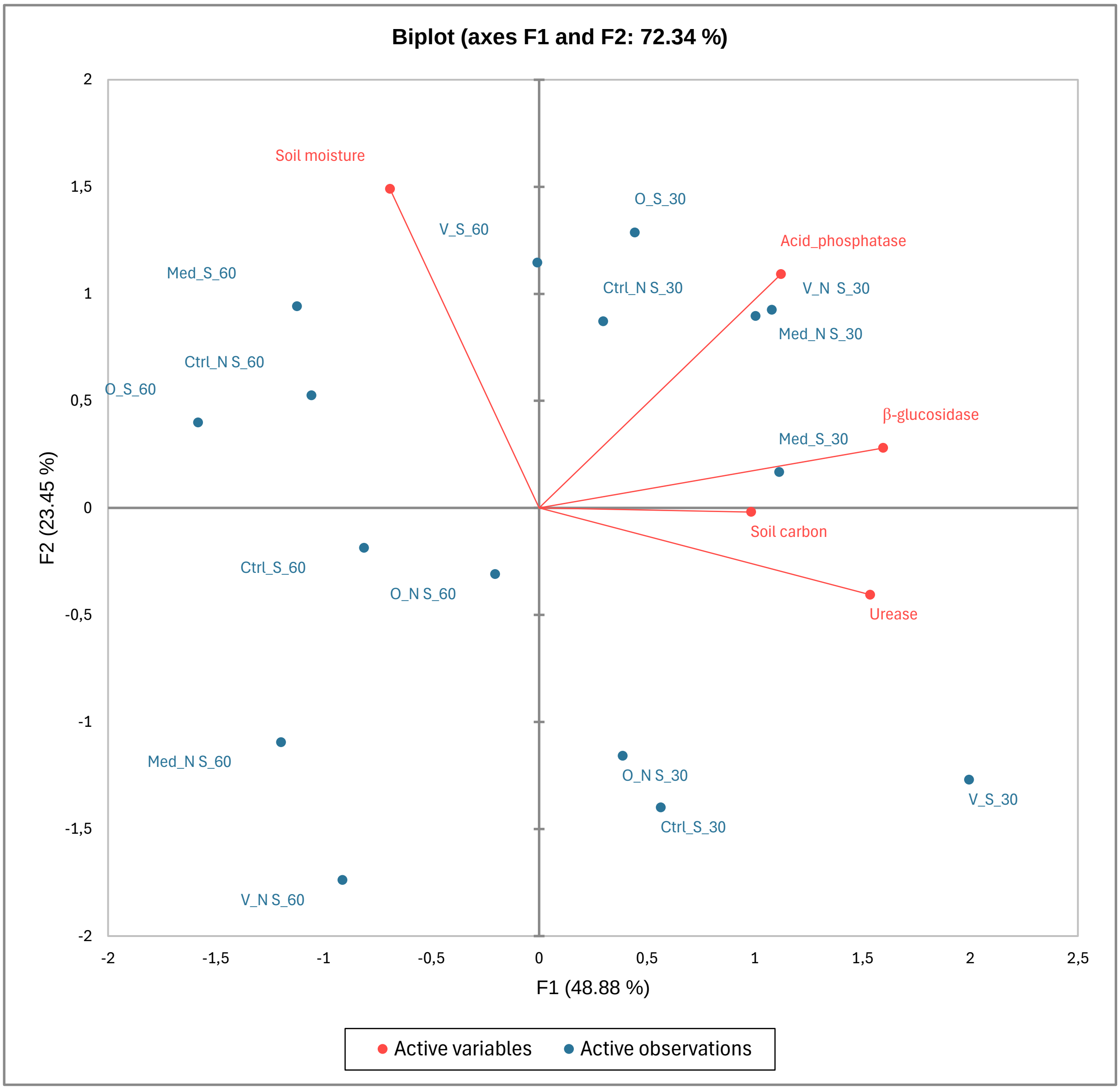

Figure 6.1. Principal Component Analysis (PCA): Correlation of soil moisture, soil carbon and soil enzyme activities (urease, acid phosphatase, β-glucosidase) and type of cover crops (medics-Med, vetch- V, oats-O and control -Ctrl), soil depth (30 and 60 cm) and termination methods (slashed-S and non-slashed- N S).

6.4 Correlation between soil carbon, moisture, soil enzymes and weed dry weight using Pearson method

Soil carbon gave a negative correlation with soil moisture, acid phosphatase and urease activities, while it showed a weak positive relationship with β-glucosidase activity and weed dry weight (Table 6.2). These findings suggest that an increase in soil carbon content is linked to a decline in soil moisture and specific enzymatic activities (Kotroczo et al., 2014). Soil moisture showed a negative correlation with soil carbon, β-glucosidase, acid phosphatase, and urease activities, while exhibited a weak positive relationship with weed dry weight. This indicates that increased soil moisture may reduce enzymatic activities involved in nutrient mineralisation, potentially due to change of microbial activity (Tiemann et al., 2011).

The activity of β-glucosidase was negatively correlated with soil moisture and weed dry weight. However, β-glucosidase activity showed a weak and strong positive relationship with acid phosphatase and urease activities, respectively. This relationship may indicate synergistic interactions among these enzymes in soil organic matter decomposition and nutrient cycling (Gianfreda & Rao, 2008). Acid phosphatase activity had a negative relationship with soil carbon, moisture, and weed dry weight, while it showed a weak positive association with β-glucosidase and urease activities. This enzyme is primarily involved in phosphorus mineralisation, and its activity may be influenced by soil organic matter content and microbial community dynamics (Azene et al., 2023). Similarly, urease activity was negatively correlated with soil carbon, moisture, and weed dry weight, while it had a weak positive relationship with acid phosphatase and a strong positive association with β-glucosidase. Urease plays a key role in nitrogen cycling by hydrolysing urea into ammonium and its interactions with other soil enzymes could be indicative of co-regulation within the soil microbial community (Adetunji et al., 2017; Ma et al., 2024).

Finally, weed dry weight was negatively correlated with all enzyme activities and had a weak relationship with soil carbon and moisture. This suggests that the presence of weeds may influence soil microbial processes, potentially by changing nutrient availability, which may lead to competition with soil microbial communities for resources (Massenssini et al., 2014; Kaur et al., 2018).

Table 6.2. Pearson correlation method: soil carbon%, soil moisture, enzyme activities and weed dry weight

Variables	Soil carbon %	Soil moisture%	β-glucosidase (μg PNP g^{-1} soil h^{-1})	Acid phosphatase (μg PNP g^{-1} soil h^{-1})	Urease (μg NH_4^+ g^{-1} soil 2 h^{-1})	Weed dry weight (g m^{-2})
Soil carbon	**1**	-0,053	0,226	-0,009	-0,139	0,237
Soil moisture	-0,053	**1**	-0,177	-0,255	-0,422	0,203
β-glucosidase	0,226	-0,177	**1**	0,487	**0,861**	-0,043
Acid phosphatase	-0,009	-0,255	0,487	**1**	0,313	-0,307
Urease	-0,139	-0,422	**0,861**	0,313	**1**	-0,156
Weed dry weight	0,237	0,203	-0,043	-0,307	-0,156	**1**

Values in bold are different from 0 with a significance level alpha=0.05

6.5 Contribution of the variables and factors using Principal Component Analysis

Soil moisture and weed dry weight were low correlated with soil carbon, β-glucosidase, acid phosphatase, and urease activities (Fig. 6.2). All non-slashed cover crops and the control treatments (both slashed and non-slashed) had a lower correlation with slashed cover crops. Moreover, soil moisture and weed dry weight showed higher correlation with non-slashed cover crops and control treatments (slashed and non-slashed), whereas soil carbon, β-glucosidase, acid phosphatase, and urease activities were strong correlated with slashed cover crops. Conversely, soil carbon, β-glucosidase, acid phosphatase, and urease activities displayed a weak correlation with non-slashed cover crops and control treatments (slashed and non-slashed), while soil moisture and weed dry weight were weakly correlated with slashed cover crops. These findings suggest that slashing cover crops may enhance soil carbon and enzymatic activity, potentially influencing soil microbial processes and nutrient cycling (Adetunji et al., 2020).

Principal Component Analysis (PCA) was employed to assess the multivariate relationships among soil biological properties (soil carbon, β-glucosidase, acid phosphatase, and urease), soil moisture, weed dry weight and treatment combinations (cover crop species × termination methods). The PCA results revealed that the first two principal components (PC1 and PC2) accounted for 67.4% of the total variability in the dataset (PC1 explaining 43.8% and PC2 explaining 23.6% of the variation). This indicates that a substantial portion of the variability among the treatments and soil parameters could be captured within the two-dimensional PCA space (Fig. 6.2).

PC1 was primarily driven by high positive loadings of soil carbon, β-glucosidase, acid phosphatase and urease activities, suggesting this axis represents a gradient of soil biological activity and organic matter enrichment. Conversely, PC2 was influenced more strongly by soil moisture and weed dry weight, indicating a distinct response axis associated with soil water dynamics and weed pressure.

Slashed cover crop treatments clustered with high scores along PC1, reflecting their strong association with increased soil enzyme activities and soil carbon levels. In contrast, non-slashed cover crops and control treatments (both slashed and non-slashed) aligned more closely with higher weed dry weight and soil moisture on PC2 but showed weak correlations with enzymatic and carbon variables. These findings are consistent with previous reports that mechanical termination (slashing) enhances residue decomposition, microbial activity, and nutrient cycling (Adetunji et al., 2020), whereas non-slashed systems retain more surface moisture but may limit microbial stimulation.

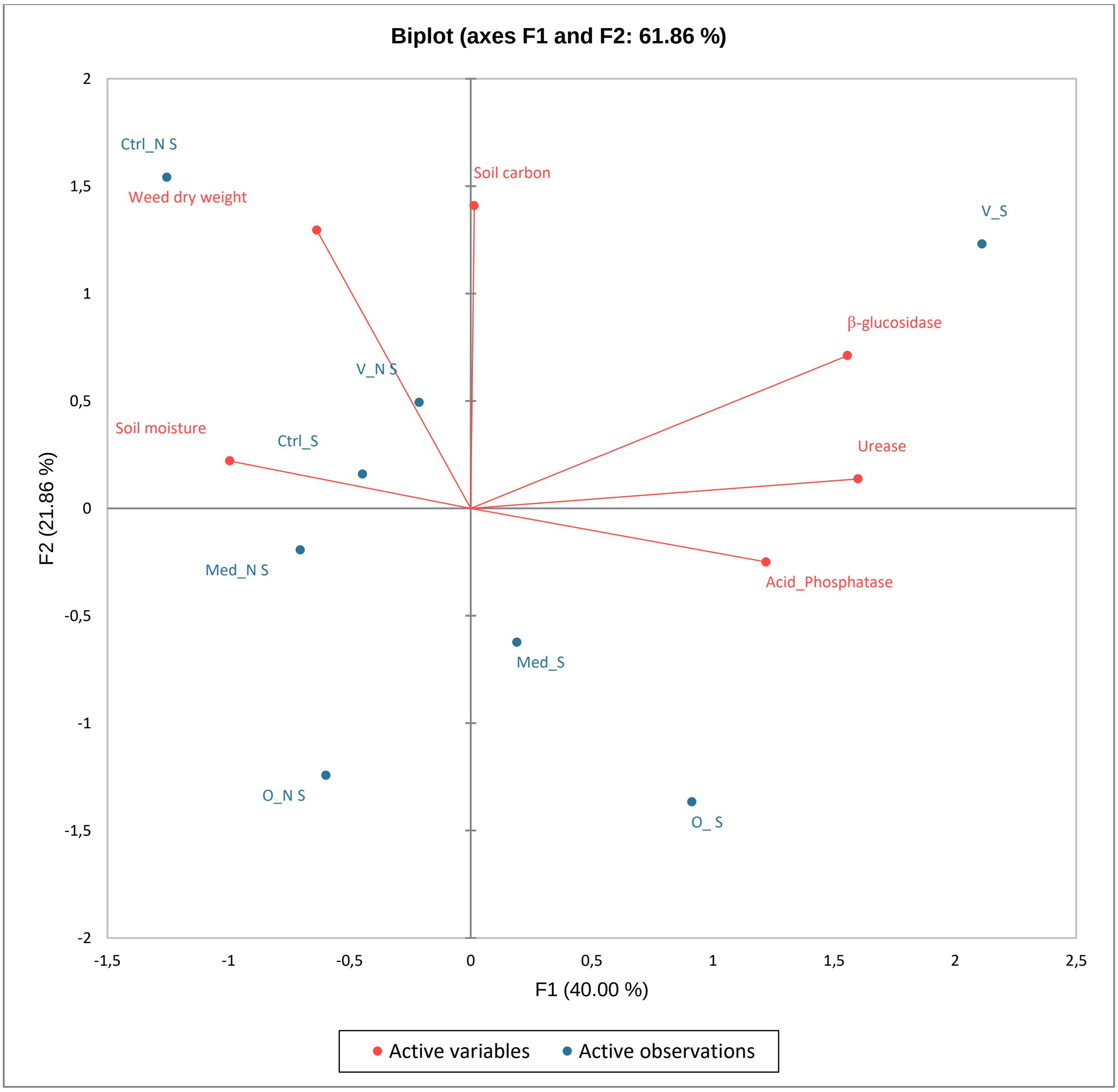

Figure 2. Principal Component Analysis (PCA): Correlation of soil moisture, weed and cover dry weight, soil carbon and soil enzyme activities (urease, acid phosphatase, β-glucosidase) and type of cover crops (medics-Med, vetch- V, oats-O and control -Ctrl) and termination methods (slashed-S and non-slashed- N S.

6.6 Correlation between soil carbon, soil moisture, soil activities, cover crop and weed dry weights using Pearson method

Soil carbon displayed a negative relationship with soil moisture, acid phosphatase, urease activity, and cover crop dry weight, while showing a weak positive correlation with β-glucosidase activity and weed dry weight (Table 6.3). Soil moisture showed a weak positive relationship with both cover crop and weed dry weights, but a negative relationship with soil carbon and enzyme activities. β-glucosidase activity was negatively correlated with soil moisture, cover crop and weed dry weight, but showed a weak positive relationship with acid phosphatase and a strong positive correlation with urease activity. Acid phosphatase activity exhibited a weak positive correlation with both β-glucosidase and urease activities, while negatively correlating with soil carbon, moisture, and both cover crop and weed dry weights. Urease activity was negatively correlated with soil carbon, moisture, and weed dry weight, however, showed weak to strong positive correlations with acid phosphatase and β-glucosidase activities, respectively. Cover crop dry weight was negatively related to soil carbon, weed dry weight and both acid phosphatase and β-glucosidase activities, while showing a weak positive relationship with soil moisture and urease activity. Weed dry weight had negative correlations with soil enzyme activities and cover crop dry weight while displaying a weak positive correlation with soil carbon and moisture.

Table 6.3. Pearson correlation method: soil carbon%, soil moisture, enzyme activities, cover crop and weed dry weight

Variables	**soil carbon %**	**Soil moisture %**	**β-glucosidase (µg PNP g^{-1} soil h^{-1})**	**Acid phosphatase (µg PNP g^{-1} soil h^{-1})**	**Urease (µg NH_4^+ g^{-1} soil 2 h^{-1})**	**Cover crop dry weight (g m^{-2})**	**Weed dry weight (g m^{-2})**
Soil carbon	**1**	-0,053	0,226	-0,009	-0,139	-0,538	0,237
Soil moisture	-0,053	**1**	-0,177	-0,255	-0,422	0,172	0,203
β-glucosidase	0,226	-0,177	**1**	0,487	**0,861**	-0,068	-0,043
Acid phosphatase	-0,009	-0,255	0,487	**1**	0,313	-0,452	-0,307
Urease	-0,139	-0,422	**0,861**	0,313	**1**	0,202	-0,156
Cover crop dry weight	-0,538	0,172	-0,068	-0,452	0,202	**1**	-0,253
Weed dry weight	0,237	0,203	-0,043	-0,307	-0,156	-0,253	**1**

Values in bold are different from 0 with a significance level alpha=0.05

6.7 Contribution of the variables and factors using Principal Component Analysis

Soil moisture, cover crop, and weed dry weight displayed a low correlation with soil carbon and enzyme activities (Fig. 6.3). Specifically, non-slashed treatments of cover crops and the control (both slashed and non-slashed) showed weak correlations with soil enzyme activities and soil carbon content. However, these treatments demonstrated strong positive correlations with soil moisture, cover crop dry weight, and weed dry weight. In contrast, slashed cover crops displayed higher correlations with both soil carbon content and enzyme activities, suggesting a more pronounced influence of cover crop management practices on soil properties (Pervaiz et al., 2020). These findings highlight the role of cover crop management, particularly slashing, in influencing soil quality indicators, including microbial activity and carbon sequestration (Adetunji, 2019).

The multivariate relationships among soil properties (soil carbon and enzyme activities), soil moisture, cover crop dry weight, and weed dry weight under different cover crop and termination treatments was assed using PCA. The first two principal components (PC1 and PC2) accounted for 71.2% of the total variation in the dataset (PC1 explaining 45.3% and PC2 explaining 25.9%). This indicates that these two axes capture most of the variability in soil biological and physical responses to treatment interactions (Fig. 6.3). PC1 was strongly influenced by positive loadings of soil carbon and enzymatic activities (β-glucosidase, acid phosphatase, and urease), suggesting this component primarily represents a gradient in soil biological functioning. In contrast, PC2 was more associated with soil moisture, cover crop dry weight, and weed dry weight, indicating a physical biomass and moisture gradient.

Slashed cover crop treatments were clustered along the positive side of PC1, reflecting strong associations with enhanced soil carbon and enzyme activities. This is consistent with prior research indicating that mechanically terminated cover crops promote microbial activity and organic matter decomposition (Pervaiz et al., 2020). Conversely, non-slashed treatments and controls grouped along PC2, aligning more closely with elevated weed biomass and soil moisture, but showing minimal contribution to biological activity. Overall, the PCA underscores that termination method plays a critical role in shaping soil quality outcomes, with slashed treatments enhancing biochemical indicators, while non-slashed and control plots support more physical biomass and moisture retention.

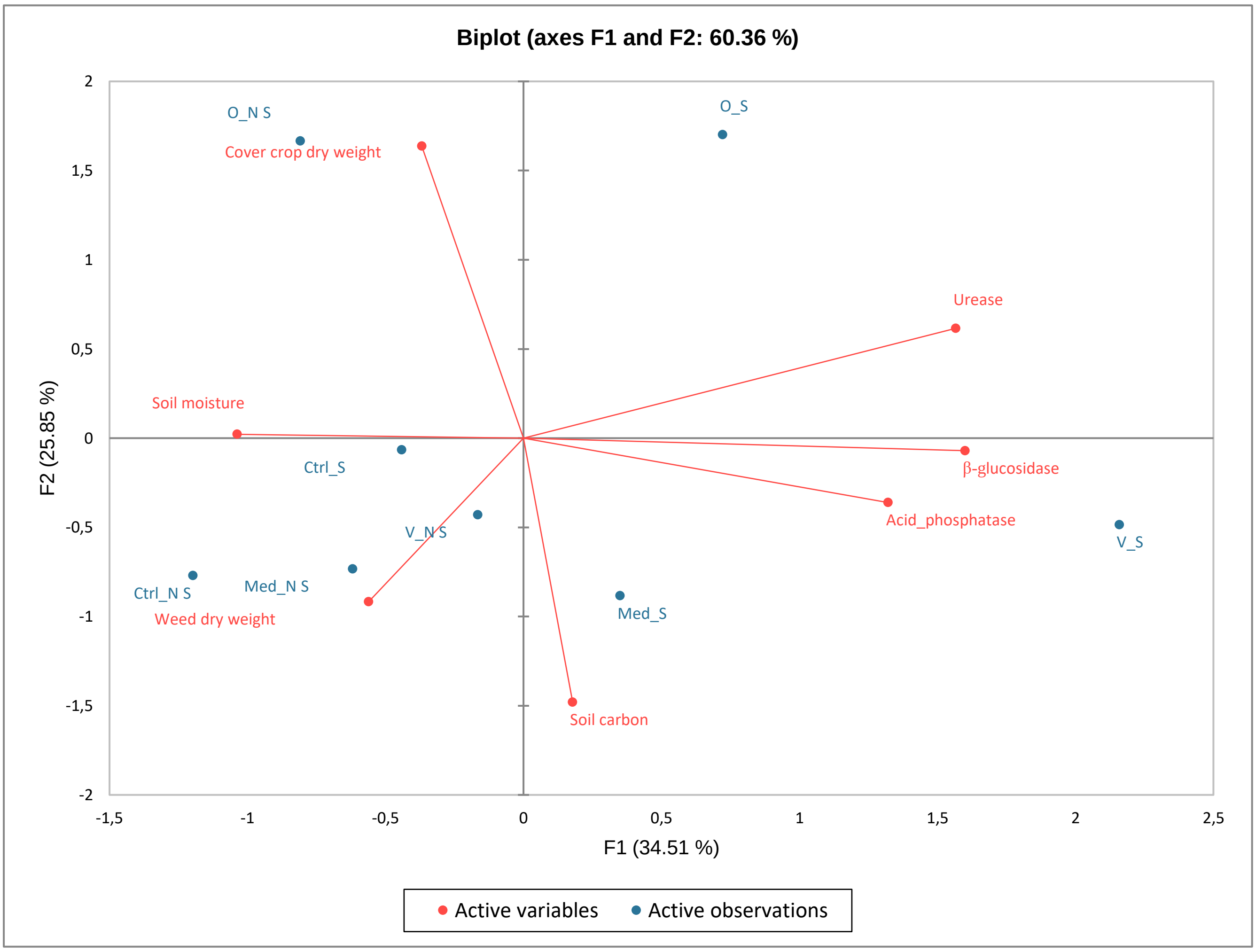

Figure 6.3. Principal Component Analysis (PCA): Correlation of soil moisture, weed and cover dry weight, soil carbon and soil enzyme activities (urease, acid phosphatase, β-glucosidase) and type of cover crops (medics-Med, vetch- V, oats-O and control -Ctrl) and termination methods (slashed-S and non-slashed- N S).

6.8 Summary

South Africa is one of the major citrus producing and exporting countries globally, however, these fruits are produced by applying large quantities of agrochemicals such as inorganic fertilisers, herbicides and pesticides (El-Otmani et al., 2011). Consequently, soil quality in citrus orchard have been declining due to depletion of soil organic matter because of huge application of agrochemicals and conventional farming (Bindraban et al., 2012; Mulinge et al., 2018). However, there is a realisation of the harmfulness of agrochemicals on human health and the environment which influences the need to find sustainable practices that do not pose a threat to humans and environment (Nicolopoulou-Stamati et al., 2016). Cover cropping has been identified as one of the sustainable management practices that enhances soil organic matter; improves soil nutrient cycling; and sustains soil nutrients and water for the next crop (Strauss et al., 2019). They are grown because of the numerous benefits they provide, including weed pressure suppression; enhanced organic carbon content; microbial activities; soil water content; and long-term reduction in overall production input costs (Strauss et al., 2019; Haruna et al., 2020). The use of cover crops is gaining popularity abroad as an alternative sustainable approach to conserve soil and water due to aforementioned cover crop benefits (Strauss, 2019; Storr, 2019).

There are two types of cover crops, namely legume and non-legume cover crops. Legume cover crops are known for fixing atmospheric nitrogen and converting it into a form usable by plants such as vetch and medics (Thilakarathna et al., 2015). Whilst non-legume cover crops are classified as grasses and brassicas and they are known for suppressing weeds and adding organic material (Adetunji, 2019). However, the impact of cover crop management on citrus orchards in South Africa particularly on soil quality, soil enzymes, soil water content and termination methods are still not fully understood. Therefore, field experiments were conducted in citrus orchard (Eureka lemon) due to little information regarding sowing of cover crops.

The first part of the thesis reports the experimental results of soil organic carbon, weed suppression and fruit yield in response to cover crop species and termination method in citrus orchard. The second part of the thesis reports the results of soil pH, β-glucosidase, phosphatase and urease activities in response to cover crop species in citrus orchards. The third part of the thesis reports the impact of cover crop species on soil water content in citrus orchard. This study contains a new report and enhances limited information on sowing cover crops in citrus orchards nationally and globally and the study may find relevance internationally if applied in similar conditions.

In the first experimental study, it was observed that cover crops play a positive role in enhancing soil quality and suppressing weeds. There was increase in soil organic carbon just in one season of planting cover crops. Interestingly, soil organic carbon increased more under vetch and medics cover crops as compared to oats and control treatments. However, oats cover crops suppressed weeds more effectively compared to vetch and medics. There were no significant differences in termination methods used but significant reduction in weed dry matter after one season was observed regardless of the termination method (mower or herbicide) used. Citrus fruit quality was not significantly influenced by cover crop species and termination methods. Longer-term experiments are recommended to determine the full benefits of cover crops in citrus orchards as the literature indicated that cover crops do not increase fruit quality and yield immediately; it takes some time.

The second study observed an increase in soil pH after planting cover crops compared to before planting just after one season. However, there was no significant difference in soil pH between planting oats, vetch and medics cover crop species. There was also no significant difference in soil enzyme activities after one season of introducing cover crops. However, there was slight decrease on β-glucosidase activity which might have resulted from increase in soil pH while there was an increase in phosphatase and urease activities at both soil depths. Similarly, there was no significant reaction in soil enzymes when compared against oats, vetch and medics cover crop species. However, vetch gave higher β-glucosidase and urease while medics gave higher phosphates activities in the topsoil. In deeper depths, oats gave higher β-glucosidase, whereas medics gave higher phosphates, and vetch gave higher urease activities. Lastly, soil enzyme activities were not significantly influenced by cover crop termination methods used. Further research with longer-term study on soil enzymes should be done using different cover crop species to develop suitable cover crop system for citrus orchards.

The third study observed that the oats cover crop depleted more soil water content at 10 cm depth while there were no significance influences in other soil depths. Cover crop termination methods used did not significantly affect soil water content. However, there was significant influence when soil water content was tested against termination methods under same cover crop species, with slashed terminated cover crops giving less soil water content depletion compared to non-slashed terminated plots. Oats cover crop had higher crop biomass compared to other cover crop treatments which lead to more depletion of soil water content. It can be partially concluded that slashed cover crop treatment stored more soil water than non-slashed cover crops.

6.9 Conclusion

Cover crops play a crucial role in enhancing soil quality, suppressing weeds and influencing soil enzyme activities in citrus orchards. This study confirms that different cover crop species offer distinct benefits with leguminous cover crops such as vetch and medics enhancing soil organic carbon while oats were the most effective for weed suppression. The vetch and medics cover crops increased soil organic carbon by 0.14% at a depth of 0-30 cm, while oats and the control presented minimal improvement. No significant effects were observed at deeper soil depth (30–60 cm). Oats gave the highest weed suppression efficiency compared to vetch, medics and the control. The type of the termination method used to terminate cover crop had no significant impact on weed suppression effectiveness. Cover crops contributed to increased soil pH and altered enzyme activity, however, their effect on citrus fruit weights were not significant. Leguminous cover crops enhanced phosphatase and urease activities in the topsoil, while oats improved β-glucosidase activity in deeper soil layers. Termination methods did not significantly influence soil enzyme activities. Soil water depletion differed based on the cover crop species, with oats depleting more water at shallow soil depths. The highest water depletion occurred at 10 cm depth under oats but no significant differences were noted at greater depths. Root water uptake was observed at 30 cm depth across all cover crops. Slashed treatments demonstrated slightly better soil water conservation than non-slashed treatments with a minor reduction in soil water depletion under slashed conditions. Neither cover crop species or termination methods significantly affected citrus fruit weight.

The complex relationships between soil carbon, soil moisture and enzyme activities, providing insights into soil nutrient cycling and microbial activity were observed. Soil enzyme activities, particularly β-glucosidase, acid phosphatase, and urease, showed different relationships with soil carbon and moisture, indicating the complexity of soil biochemical interactions. Strong positive correlations among β-glucosidase, acid phosphatase and urease suggest interconnected roles in nutrient cycling. Additionally, soil depth influenced soil properties with soil moisture levels being higher in deeper soil while enzyme activities and soil carbon were higher in shallower soil depth. Cover crop termination method, specifically slashing, was found to enhance soil carbon and enzyme activities, further influencing microbial activity and nutrient availability.

6.10 Findings

Vetch and medics cover crops increased soil organic carbon by 0.14% at 0-30 cm depth within a season, while oats and the control showed minimal improvement. There was no significant change in deeper soil (30-60 cm). Oats were the most effective in suppressing weeds compared to vetch, medics and the control. However, cover crop termination methods did not influence weed suppression effectiveness. Soil pH increased from 5.42 to 6.0 after one year of cover crop planting. Legume cover crops increased phosphatase and urease activities in topsoil, while oats improved β-glucosidase in deeper soil. Oats gave the highest soil water depletion at 10 cm depth while there were no significant differences at deeper soil levels. Root water uptake was observed at 30 cm depth across all cover crops. Slashed treatments showed slightly better soil water conservation compared to non-slashed treatments. There were no significant differences in fruit weight across different cover crop species or termination methods.

The β-glucosidase, acid phosphatase and urease activities displayed a strong positive correlation, highlighting their interconnected roles in nutrient cycling. Soil moisture negatively correlated with soil carbon content and enzymatic activities, suggesting potential inhibitory effects on microbial processes. Soil enzyme activities and carbon were more prominent in shallower soil depths, whereas soil moisture was higher at deeper depths. Weed dry weight negatively correlated with soil enzyme activities, indicating possible competition between plant and microbial communities for nutrients. Slashed cover crops enhanced soil carbon content and enzymatic activities while non-slashed treatments showed a stronger correlation with soil moisture and weed dry weight.

6.11 Recommendations

This thesis successfully reported the influence of cover crop species on citrus orchards and is a first step towards a possible long-term objective which is to develop a suitable citrus cover crop systems for each growing region applicable to both small scale and commercial citrus producers in South Africa.

By implementing the following recommendations, citrus orchard farmers in South Africa may optimise soil quality, minimise agrochemical inputs and promote sustainable agricultural practices:

- Use leguminous cover crops (vetch and medics) to improve soil organic carbon in citrus orchards while considering oats for effective weed suppression.
- Further studies should be done to explore long-term effects of cover crops on water retention, termination methods on soil microbial dynamics and their impact under different climatic conditions.
- Slashed cover crops should be promoted to enhance soil carbon content, soil water conservation and enzymatic activities which contribute to improved soil quality and nutrient availability.
- Integrating cover crops with weed suppression practices can help mitigate competition for nutrients between weeds and soil microbes, thus promoting healthier soil biological functions.
- Adoption of cover crops can reduce use on synthetic fertilisers and herbicides, contributing to more sustainable citrus production.
- Additional research on multi-season effects of cover crops on yield and fruit quality should be conducted.

6.12 Barriers to Adoption and Support Strategies

Despite the demonstrated benefits of cover cropping and termination methods, several barriers may hinder the adoption among citrus farmers in South Africa. These include:

- Limited awareness and technical knowledge, especially concerning cover crop species selection, timing of sowing and termination and soil monitoring
- High initial costs of seed purchase, sowing and management, particularly for small-scale or resource limited farmers.
- Perceived risks of competition between cover crops and citrus trees for water and nutrients.
- Lack of immediate economic return, which may discourage farmers from investing in long-term soil health strategies.

To overcome these barriers, policy and extension interventions should include:

- Subsidy or incentive schemes to reduce the initial financial burden of cover crop establishment.
- Training programs and field demonstrations delivered through agricultural extension services to increase technical capacity and confidence among farmers.
- Decision-support tools tailored to citrus orchards, such as locally adapted cover crop calendars and moisture management guides.
- Integration into sustainable agriculture policies, encouraging cover crops as part of climate-smart and regenerative agriculture frameworks.

6.13 References

Acosta-Martínez, V. and Tabatabai, M. A. 2000. Enzyme activities in a limed agricultural soil. Biology and Fertility of Soils, 31(1), 85-91.

Adetunji, A.T., 2019. Impact of cover crop species, termination stage and termination method on soil nitrogen, organic carbon and enzyme activities (Doctoral dissertation, Cape Peninsula University of Technology).

Adetunji, A.T., Ncube, B., Meyer, A.H., Mulidzi, R. and Lewu, F.B., 2020. Soil β-glucosidase activity, organic carbon and nutrients in plant tissue in response to cover crop species and management practices. South African Journal of Plant and Soil, 37(3), pp.202-210.

Azene, B., Zhu, R., Pan, K., Sun, X., Nigussie, Y., Gruba, P., Raza, A., Guadie, A., Wu, X. and Zhang, L., 2023. Land use change alters phosphatase enzyme activity and phosphatase-harboring microbial abundance in the subalpine ecosystem of southeastern Qinghai-Tibet Plateau, China. Ecological Indicators, 153, p.110-416.

Bindraban, P.S., van der Velde, M., Ye, L., Van den Berg, M., Materechera, S., Kiba, D.I., Tamene, L., Ragnarsdóttir, K.V., Jongschaap, R., Hoogmoed, M. and Hoogmoed, W., 2012. Assessing the impact of soil degradation on food production. Current Opinion in Environmental Sustainability, 4(5), pp.478-488.

El-Otmani, M., Ait-Oubahou, A. and Zacarías, L., 2011. Citrus spp.: Orange, mandarin, tangerine, clementine, grapefruit, pomelo, lemon and lime. In Postharvest biology and technology of tropical and subtropical fruits (pp. 437-516e). Woodhead Publishing.

Gianfreda, L. and Rao, M.A., 2008. Interactions between xenobiotics and microbial and enzymatic soil activity. Critical Reviews in Environmental Science and Technology, 38(4), pp.269-310.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S. and Gao, Y., 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment, 3(1), p.e20105.

Jolliffe, I.T. and Cadima, J., 2016. Principal component analysis: a review and recent developments. Philosophical transactions of the royal society A: Mathematical, Physical and Engineering Sciences, 374(2065), p.201-208.

Kaur, S., Kaur, R. and Chauhan, B.S., 2018. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. Crop Protection, 103, pp.65-72.

Kotroczo, Z., Veres, Z., Fekete, I., Krakomperger, Z., Tóth, J.A., Lajtha, K. and Tóthmérész, B., 2014. Soil enzyme activity in response to long-term organic matter manipulation. Soil Biology and Biochemistry, 70, pp.237-243.

Lajtha, K., Bowden, R.D. and Nadelhoffer, K., 2014. Litter and root manipulations provide insights into soil organic matter dynamics and stability. Soil Science Society of America Journal, 78(S1), pp.S261-S269.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. science, 304(5677), pp.1623-1627.

Ma, Y., Lv, H., Wang, Y., Wang, Y., Yin, M., Kang, Y., Qi, G., Zhang, R., Wang, J. and Chen, J., 2024. Study on the Synergistic Regulation Model for Lycium barbarum Berries Under Integrated Irrigation and Fertigation in Northwest Arid Regions. Agronomy, 15(1), p.73.

Margesin, R. and Schinner, F., 1997. Laboratory exercises on soil microbiology. Springer Science & Business Media.

Massenssini, A.M., Bonduki, V.H.A., Melo, C.A.D., Tótola, M.R., Ferreira, F.A. and Costa, M.D., 2014. Soil microorganisms and their role in the interactions between weeds and crops. Planta Daninha, 32, pp.873-884.

Mencel, J., Mocek-Płóciniak, A. and Kryszak, A., 2022. Soil microbial community and enzymatic activity of grasslands under different use practices: a review. Agronomy, 12(5), p.1136.

Mukaka, M.M., 2012. A guide to appropriate use of correlation coefficient in medical research. Malawi medical journal, 24(3), pp.69-71.

Mulinge, J., Saha, H., Mounde, L. and Wasilwa, L., 2018. Effects of legume cover crops on orange (*Citrus sinensis*) fruit weight and brix. International Journal of Plant & Soil Science, 21(4), pp.1-9.

Nannipieri, P., Giagnoni, L., Landi, L. and Renella, G., 2011. Role of phosphatase enzymes in soil. Phosphorus in action: biological processes in soil phosphorus cycling, pp.215-243.

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P. and Hens, L., 2016. Chemical pesticides and human health: the urgent need for a new concept in agriculture. Frontiers in public health, 4, p.148.

Pervaiz, Z.H., Iqbal, J., Zhang, Q., Chen, D., Wei, H. and Saleem, M., 2020. Continuous cropping alters multiple biotic and abiotic indicators of soil health. Soil Systems, 4(4), p.59.

Schober, P., Boer, C. and Schwarte, L.A., 2018. Correlation coefficients: appropriate use and interpretation. Anesthesia & analgesia, 126(5), pp.1763-176.

Storr, T., 2019. The effect of cover crops on soil quality indicators in a cereal and salad rotation (Doctoral dissertation).

Strauss, S., Kadyampakeni, D., Kanissery, R., Wade, T., Diepenbrock, L. and Popenoe, J., 2019. Cover crops for citrus. EDIS, 2019.

Thilakarathna, M.S., Serran, S., Lauzon, J., Janovicek, K. and Deen, B., 2015. Management of manure nitrogen using cover crops. Agronomy Journal, 107(4), pp.1595-1607.

Tiemann, L.K. and Billings, S.A., 2011. Changes in variability of soil moisture alter microbial community C and N resource use. Soil Biology and Biochemistry, 43(9), pp.1837-1847.

Yadav, S.S., Guzman, J.G., Meena, R.S., Lal, R. and Yadav, G.S., 2020. Long term crop management effects on soil organic carbon, structure, and water retention in a cropland soil in central Ohio, USA. Journal of Plant Nutrition and Soil Science, 183(2), pp.200-207.

Zhang, Y., Ding, S., Fan, J. and Wang, L. 2020. Depth-dependent soil microbial and enzymatic responses to land use changes in agroecosystems. Applied Soil Ecology, 155, 103648.