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Review

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

Sibongiseni Silwana [1,2], Azwimbavhi Reckson Mulidzi [1] and Nebo Jovanovic [2]

[1] *ARC Infruitec-Nietvoorbij, Stellenbosch, South Africa*
[2] *Department of Earth Sciences, University of the Western Cape, Bellville, South Africa*
* *Corresponding author, Email: silwanas@arc.agric.za*

Cover crops are used in sustainable agricultural practices to improve soil quality and minimise the effect of climate change, water restrictions and drought. The South African citrus industry produces and exports a diverse range of citrus fruits; however, knowledge of cover crops in citrus orchards in South Africa is limited. This review focuses mostly on evaluating cover crop selection, effects on the 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. The 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 substantially improved the cost savings of nitrogen fertiliser. 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% Bx. This demonstrates that the benefits of cover crops to South African citrus growers include improved soil quality and fruit yields and decreased costs.

Keywords: fruit yield, legumes, nitrogen fixation, organic carbon, organic matter, soil microbial community, South Africa, tree shading

Introduction

South Africa is the second-largest citrus fruit exporter in the world after Spain, with 54% of the total citrus production exported (Ndou and Obi 2011; Moore and Manrakhan 2022). The world's largest citrus producers, including Brazil, have taken an interest in more sustainable production methods, such as planting cover crops to enhance soil organic matter and reducing the use of harmful agrochemicals (Linares et al. 2008; Azevedo et al. 2020). However, the use of cover crops to improve soil organic matter is infrequently used, even as an increase in the use of chemical inputs has been observed in South Africa (Wright et al. 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 can promote soil biology and soil water retention, resulting in potential reduction in 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 by converting nitrogen gas from the atmosphere into a form suitable for plant use (O'Reilly et al. 2011; Hungria and Mendes 2015). Cover crop species such as vetch can conserve moisture (Villamil et al. 2006; Adetunji et al. 2020). Additionally, cover crops can reduce herbicide use in orchards by controlling weeds that compete for water, nutrients and light (Jannoyer et al. 2011; Blanco-Canqui et al. 2015). Fourie et al. (2017) showed that oats and white mustard cover crops successfully suppressed ryegrass weeds in a vineyard. In citriculture, cover crops are commonly established between the rows of orchards to benefit the soil (Barenbrug 2020), being mown and placed under the tree canopy to create mulching (Martinelli et al. 2017; Schmidt et al. 2018), with the root mass and leaf litter being a soil carbon input year-round (Strauss et al. 2019).

Once a cover crop is planted, the soil microbial community changes owing to the increased amount of soil organic matter, resulting in an abundance of cycling organisms that increase soil carbon and nitrogen (Mbuthia et al. 2015). Proper management of cover crops is essential to minimise competition with the main crop for water and nutrient immobilisation as well as to avoid pest and disease outbreaks (Adetunji et al. 2020). Scrupulous attention to the choice of a suitable cover crop species and determination of the correct planting period, growth period and termination method are therefore required (Chapagain et al. 2020).

In this review, the effects and benefits of cover crops in citrus orchards is discussed, with specific attention to correct cover crop selection, impacts on the soil microbial community, nitrogen fixation, weed control and fruit quality.

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. Knowing the season in which the cover crop will be planted is essential for selecting a cover crop as there are annual and perennial cover crops (Wright et al. 2017). Winter annual cover crops are short-lived and suitable for cool, short days, whereas summer annual cover crops are suitable for hot, long days (Wright et al. 2017). Winter cover crops include hairy vetch, lupine and winter rye; summer cover crops include cowpeas, sunn hemp and velvet beans (Wright et al. 2017). Perennial cover crops, such as bahiagrass and rhizoma peanut, generally grow for many years. 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 (Hartwig and Ammon 2002; Qi and Helmers 2010).

Cover crops can be selected using the three steps, as outlined in Figure 1 (Jannoyer et al. 2011). The first step of selection screens the cover crop based on its vegetative characteristics, such as height (< 500 mm), tree shading tolerance, regrowth ability, covering capacity and perennial versus annual species (Jannoyer et al. 2011). It is necessary to select cover crops that can tolerate shading because citrus orchards create a high degree of shading under the dense tree canopy (Evans et al. 1998). The second step of selection considers practicality, especially the 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 third step of selection screens for ecological factors, such as the cover crop's capacity for weed competition, potential to host pests, biomass production and ability to improve the physical and biological properties of the soil (Jannoyer et al. 2011).

Legume cover crops

Many researchers have reported that legume cover crops are highly beneficial in comparison with grass cover crops as they provide nitrogen for the current and next seasons through nitrogen fixation (Teasdale et al. 2007; Fischer et al. 2010). The symbiotic nitrogen-fixation process associated with legumes (Wright et al. 2017) is executed by diazotrophic bacteria, such as rhizobia, which are found in root nodules in the rhizosphere (Andrews and Andrews 2017). Non-legume cover crops such as grasses and brassicas are not able to fix nitrogen (Pommeresche and Hansen 2017).

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 much attention from citrus growers because of its potential to reduce the need for inorganic N fertilisation (Abobatta and El-Azazy 2020) and thus as an ecofriendly practice. Nitrogen-fixing organisms also improve cell division and cell enlargement through the release of growth hormones, the result being an increase in citrus fruit size and quality (Abobatta and El-Azazy 2020). Selim et al. (2020) stated that citrus tree shading helps cover crops to stimulate the nitrogen-fixing bacteria.

In areas where legume cover crops are planted, the rhizobacteria decompose soil biomass, releasing nitrogen and other beneficial nutrients to improve microbial activities (Mbuthia et al. 2015) and boost plant and fruit growth (Aseri et al. 2008; Mulinge et al. 2018). Table 1 lists studies that have validated the positive effects of legume cover crops on soil nitrogen, demonstrating wide agreement on the use of legume cover crops to increase soil nitrogen. The lowest soil nitrogen increase reported was just above 60 kg N ha^{-1} and the highest was > 200 kg N ha^{-1}. In 2022 this amounted to cost savings of 585 ZAR and 900 ZAR per hectare at the fertiliser replacement value of 65 kg N ha^{-1} and 100 kg N ha^{-1}, respectively. Most of these studies were conducted under no-till soil conditions (e.g., Ebelhar et al. 1984; Hargrove 1986; Blevins et al. 1990; Dou and Fox 1994) to allow crop residue retention and decomposition for organic matter (Li et al. 2019).

Effects of cover crops

Effects of cover crops on soil microbial community composition/diversity

The composition of the soil microbial community, along with nitrogen-cycling microorganisms, changes as soil organic matter increases (Strauss et al. 2019). In addition to increased soil organic matter, several cover crops affect the soil microbial community by enhancing soil enzyme activities, bacteria and soil respiration. Stagno et al. (2008) observed that leguminous cover crops in pots of *Citrus unshiu* Marcovitch increased the substrate-induced respiration and nitrogen-ammonia (N-NH_3) content in the soil, and they concluded that atmospheric nitrogen fixation by rhizobia cause legume cover crops in the long term to increase total nitrogen and total organic carbon.

Oats and cereal rye cover crops enhanced arbuscular mycorrhizal fungi; in contrast, hairy vetch cover crops favoured non-arbuscular mycorrhizal fungi (Sharma et al. 2018). Chavarría et al. (2016) found that in a mixture of oat-with-radish, and oat-with-radish-and-vetch cover crops, the total bacterial population (including Gram-positive bacteria) was significantly higher than in no-cover crop treatments. A significantly more diverse bacterial community composition was also found with a bahiagrass cover crop after just six months when compared with farmer-standard mowed weeds (Strauss et al. 2019). Soil enzyme activity also increases where cover crops are planted (Chavarría et al. 2016). In a long-term study (31 years), hairy vetch significantly increased the microbial community and enzyme activities (β-glucosidase, β-glucosaminidase, phosphodiesterase) compared to wheat

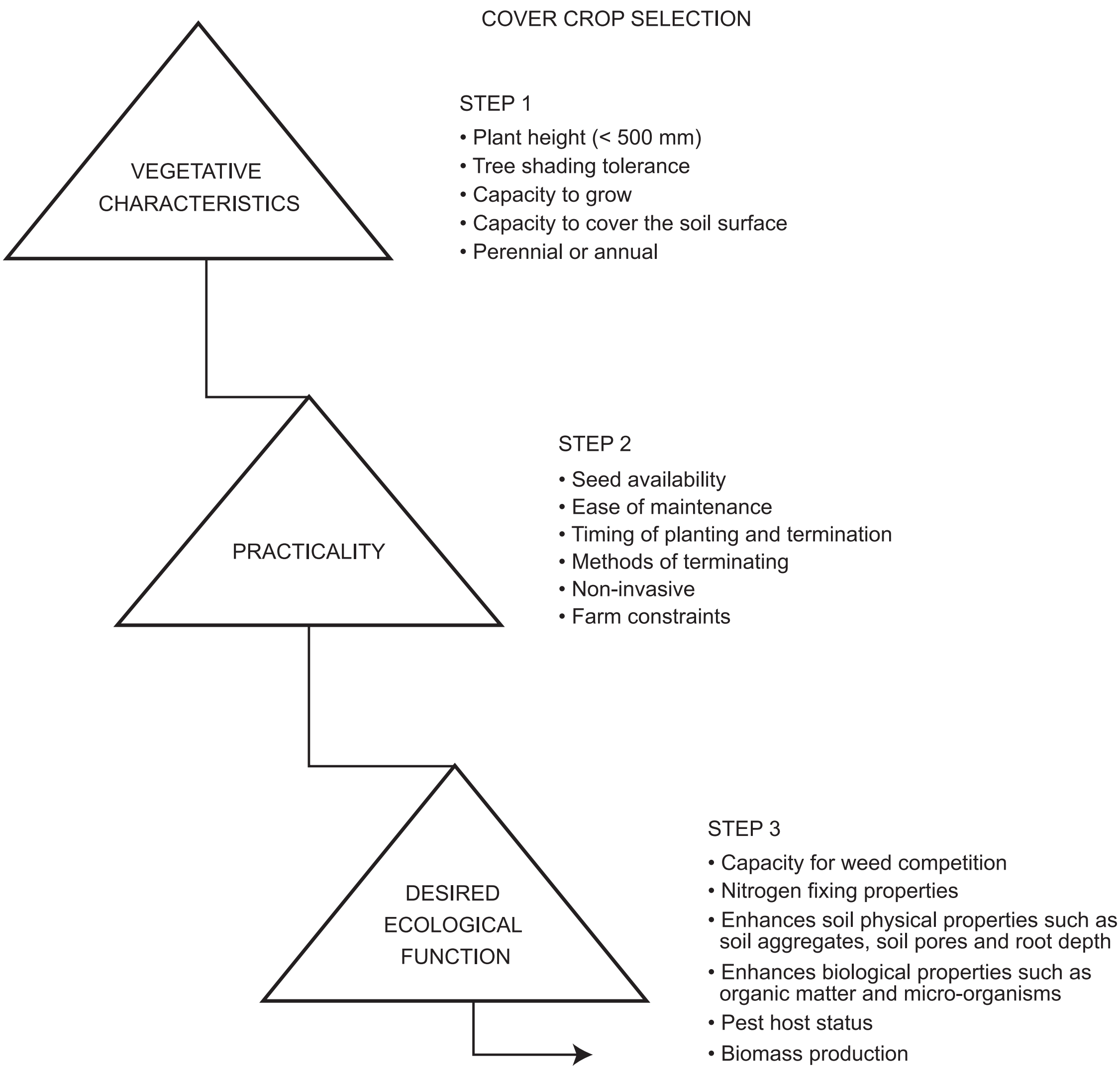

Figure 1: Three steps for screening cover crops for citrus orchards (adapted from Jannoyer et al. 2011)

and control treatments where there was no cover crop (Mbuthia et al. 2015).

Effects of cover crops on soil organic carbon

Soil organic carbon plays a crucial role in soil quality and crop productivity (Liu et al. 2006; Haruna et al. 2020). It enhances soil porosity (Villamil et al. 2006), soil compaction (Demir et al. 2019), bulk density (Nascente and Crusciol, 2015), water availability (Adeli et al. 2020), microbial activity (Strauss et al. 2019), availability of nutrients (Castellano-Hinojosa and Strauss 2020) and crop yield (dos Santos Cordeiro et al. 2021).

Table 2 lists studies that investigated the effects of cover crops on soil organic carbon. The results display positive trends of an increase in soil organic carbon. A similar trend of increased soil organic carbon under cover crop systems was also observed with other fruit trees, such as olive trees (Beniaich et al. 2023), vineyards (Fourie et al. 2007), pears and apples (Sánchez et al. 2007). Notably, some of the studies included in Table 2 used cover crop mixtures to enhance soil organic carbon. The use of a mixture of species rather than a single species provides more biomass, resulting in more organic carbon (Mbuthia et al. 2015; Chavarría et al. 2016; Scavo et al. 2022).

Nonetheless, an increase in soil organic carbon resulting from cover crops depends on many factors, including precipitation, air temperature, soil texture and tillage (Scavo et al. 2022). Generally, cover crop benefits are favoured by weekly precipitation of ~18 mm in the coastal region of South Africa (Fourie et al. 2001), loamy soil (Mazzoncini et al. 2011), a no-till rather than tilled system (Nascente and Crusciol 2015) and a warm environment to accelerate the decomposition of the cover crop residue (Hu et al. 2022).

Effects of cover crops on weeds

Weed growth in young citrus orchards can be excessive since the trees provide little shade to suppress their growth (Singh and Sharma 2008). Weeds interfere with citrus trees as they compete for essential resources, such as water and

Table 1: Studies on the contributions of legume cover crops on 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 equivalencye (kg N ha^{-1})	Cost savings (ZAR ha^{-1}) in 2022	Reference
Coastal Plain site, Georgia, USA	Crimson clover	Corn	108	99	891	McVay et al. (1989)
Department of Agronomy, University, University Park, USA	Hairy vetch	Maize	151	164	1 476	Dou and Fox (1994)
Coastal Plain site, Georgia, USA	Hairy vetch	Grain sorghum	128	123	1 107	McVay et al. (1989)
Department of Agronomy, Pennsylvania State University, USA	Red clover	Maize	134	186	1 674	Dou and Fox (1994)
Kentucky experimental farm, USA	Hairy vetch	Corn	103	75	675	Blevins et al. (1990)
Indian Agricultural Research Institute, New Delhi, India	Sesbania	Maize	131	67	603	Sharma and Behera (2009)
Kentucky experimental farm, USA	Bigflower vetch	Corn	67	65	585	Blevins et al. (1990)
Georgia Agric experimental Station, USA	Hairy vetch	Grain sorghum	153	97	873	Hargrove (1986)
Kentucky experimental farm, USA	Hairy vetch	Corn	209	100	900	Ebelhar et al. (1984)
INIA Cauquenes Experimental, Chile	Clover and burr medic	Vineyard	112	40	360	Ovalle et al. (2010)

Table 2: Studies on the effects of cover crops on soil organic carbon (adapted from Haruna et al. 2020)

Study site	Cover crop	Main crop	Organic carbon increase (%)	Reference
State of Paraná, Brazil	Signal grass	Pera oranges	52	Balota and Auler (2011)
Instituto Nacional de Tecnología Agropecuaria, Argentina	Oats, vetch and radish	Soybean	8.8	Chavarría et al. (2016)
Fort Valley State University, Georgia, USA	Rye, hairy vetch and crimson clover	Wheat and soybean	12	Sainju et al. (2002)
Hesston, Kansas, USA	Sunnhemp	Winter wheat and grain sorghum	30	Blanco-Canqui et al. (2011)
University of Missouri, USA	Cereal rye, hairy vetch and Austrian winter pea	Perennial biofuel crops	26	Haruna et al. (2017)
Interdepartmental Centre for Agro-Environmental Research, Pisa, Italy	Durum and sunflower	Maize	7	Mazzoncini et al. (2011)
Middle Tennessee State University, USA	Winter wheat	Corn	36	Haruna (2019)
Dixon Springs Agricultural Research Center, Illinois, USA	Hairy vetch and cereal rye	Corn and soybean	30	Olson et al. (2014)
Urbana, Illinois, USA	Hairy vetch and cereal rye	Corn and soybean	9	Villamil et al. (2006)
State of Paraná, Brazil	Signal grass	Pera oranges	70	Bould and Jarrett (1962)
Alabama Agricultural Experiment Station, USA	Rye	Cotton and corn	9	Sainju et al. (2008)
Mississippi Agricultural and Forestry Experiment Station, US	Winter wheat	Soybean	15	Adeli et al. (2020)
Washington, USA	Cereal rye, ryegrass, winter pea	Corn	7	Kuo et al. (1997)
West Tennessee AgResearch and Education Center, USA	Hairy vetch and winter wheat	Cotton	19	Mbuthia et al. (2015)

Table 3: Studies on the effects of cover crops on weeds in citrus orchards

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

nutrients (Martinelli et al. 2017), and are hosts for pests and pathogens (Hosseini and Dianat 2014). Herbicides often result in environmental pollution (Olorunmaiye et al. 2011), so more-sustainable options to control weeds are needed. According to the studies listed in Table 3, cover crops provide effective biological control of weeds in citrus orchards and have positive effects on soil fertility (Knezevic et al. 2002).

Previous studies indicated that numerous cover crops, including hairy vetch, sorghum species (Isik et al. 2014), medics and berseem clover (Fisk 1997), perennial peanut (Rouse and Mullahey 1997) and peas have the ability to reduce weed dry weight, weed density and the total number of weed species that emerge (Fisk et al. 2001; Mennan et al. 2006; Isık et al. 2009). It was also observed 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, many factors are responsible for effective weed suppression by cover crops, including allelopathic phytotoxins that prevent weed growth (Isık et al. 2009), as well as reduced light transmittance, daily soil temperature and soil moisture provided by the living cover crop (Teasdale and Mohler 1993).

Linares et al. (2008) evaluated the effectiveness of cover crops in controlling weeds and reported that winter cover crop mixtures allowed higher dry-matter accumulation and suppressed weeds more effectively than single cover crop species. Campiglia et al. (2010) and Hayden et al. (2012) observed that grass and legume cover crop mixtures suppress weeds more effectively and provide the benefit of soil nitrogen enrichment fixed biologically. More weed biomass suppression by using mixed cover crops was likewise evident in other agricultural fields, including apple orchards (Webber et al. 2022), olives (Volakakis et al. 2022), vineyards (Miglécz et al. 2015) and apricot (Karaman et al. 2021).

Effect of cover crops on soil moisture

The Western Cape province of South Africa is expected to experience increasing air temperatures, which will affect irrigated agriculture (Volschenk 2020). Therefore, the utilisation of sustainable management practices that conserve soil moisture, such as cover crop systems, is required. As reported by Sharma et al. (2018), cover crops improve soil moisture by increasing soil organic matter, which improves the infiltration rate due to an increase in soil pores formed by cover crop root growth. Cover crop root growth extends through soil macrospores and decomposes to create an area for water storage (Blanco-Canqui et al. 2011). Additionally, cover crops with long tap roots, such as mustard, create soil pores through loosening up the soil and increasing soil aggregate stability (Hudek et al. 2022).

It was also reported that cover crops increase soil water holding capacity as well as soil evaporation (O'Connell and Synder 2000). An increase in soil water holding capacity reduces runoff and the leaching of nutrients from the root zone (Kaspar et al. 2011; Qi and Helmers 2010). Cover crops reduce soil water evaporation by intercepting incoming solar radiation, and by covering the soil (Abdel-Aziz et al. 2008; Kahimba et al. 2008; Blanco-Canqui et al. 2015).

Previous studies demonstrated an increase in soil moisture retention when annual cover crops are sown, such as the climbing legume *Macuna pruriens* (Mulinge et al. 2018), vetch (Villamil et al. 2006; Bilek 2007; Adetunji et al. 2019), oats (Sharma et al. 2018) and berseem clover (Kahimba et al. 2008). However, soil moisture retention is highly endorsed by a cropping system that lessens surface soil disturbance and maximises plant cover on the soil surface (Rainbow and Derpsch 2011). Several studies have shown the significant effects of cover crops on soil moisture retention under a no-tilled soil system. Acharya et al. (2019) and Blanco-Canqui et al. (2011) reported that soil moisture retention was higher when cover crops were planted under no-tilled soil compared with conventional tillage. Similarly, Nouri et al. (2019) reported an increase in soil moisture retention of 28.6% under vetch cover crops planted under no-tillage compared with conventional tillage.

Citrus yield and fruit quality

The use of legume cover crops has been recommended to complement trees and enhance fruit quality in citrus orchards (Naveen 2020). However, little is known regarding the effect of cover crops on citrus yield and fruit quality in South Africa. Fruit yield was found in various studies to increase significantly when cover crops are used in citrus orchards (Table 4). Significant increases in percentage fruit weight and °Brix were also found when legume cover crops were used in citrus orchards (Table 5).

Economides (1976) observed an increase in citrus tree sizes by 26% and a reduced fruit rind thickness on plots with a cover crop compared with plots without a cover crop. Moreover, an increase in the size of orange fruit under cover crop plots was observed by Parker and Jones (1951). The better citrus tree growth, fruit yield and fruit quality under cover crops may be promoted by an increase of soil organic matter which improved soil quality.

There is wide agreement in the literature on increased fruit yield and fruit quality when cover crops are sown in other fruit

Table 4: Studies on the effects of cover crops 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)
University of California Citrus Experiment Station, California	Unspecified	Washington navel orange	30	Parker and Jones (1951)
El-Kassaseen Agricultural Station, Egypt	Soybean (Giza 22)	Mandarin trees	7.6	Selim et al. (2020)
El-Kassaseen Agricultural Station, Egypt	Lupine	Valencia orange	9.6	Hefny et al. (2020)
Citrus Experiment Station, Cyprus	Common vetch	Valencia orange	27	Economides (1976)

Table 5: Studies on the effects of cover crops 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 Station, Egypt	Soybean (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 Station, Egypt	Soybean (Giza 22)	Mandarin trees	2.4 °Brix	Selim et al. (2020)

orchards, including apples (Bould and Jarrett 1962), peaches (Fang et al. 2022), apricot (Demir et al. 2019), guava (Bhattacharjee et al. 2020), mango (Wei et al. 2021) and vineyards (Muscas et al. 2017). However, the positive influence of cover crops on the yield may take a relatively long time to manifest, since it takes a long time to stabilise the soil carbon from the cover crop residues (Sainju et al. 2006).

Cover crop limitations

Many citrus farmers lack knowledge of certain aspects of the cultivation of cover crops, such as the best time for planting, aspects of their maintenance, and suitable methods for terminating their growth (Sharma et al. 2018). Furthermore, not having the proper machinery for planting cover crop seeds and the intensive labour required for the cultivation thereof can make it more challenging for citrus farmers to plant cover crops. Different types of machinery are necessary for preparation of the soil, sowing of seeds and termination of the cover crops. Therefore, farmers must purchase suitable machinery to sow cover crops effectively and successfully. In this regard, smallholder citrus farmers generally cannot afford machinery purchases, which makes it difficult for them to benefit from cover crop production. The cultivation of cover crops does not give positive results immediately and this may result in an increase in production costs because of labour and machinery costs (Hoorman 2009). A lack of rainfall can also limit the establishment of cover crops (Kaspar 2008). Cover crops should therefore be planted when rainfall is expected or else the cover crop must be irrigated, causing a further expense.

The sowing of cover crops in citrus orchards tends to interfere with harvesting, especially for early-maturing cultivars. As a result, labour is needed for planting cover crops and harvesting the fruit simultaneously. Tractors can damage the cover crop's growth during spraying and harvesting of the main crop. Additionally, cover crops may host insects and pathogens (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, such as by citrus root nematode *Tylenchulus semipenetrans* (Walker 1997). Poor termination of cover crops may result in their regrowth (Cordeau et al. 2015; Singh et al. 2016), which then competes with the citrus trees for water, solar radiation and nutrients, and acts as a shelter for citrus thrips and other pests that can potentially damage the fruit (Ingels et al. 1994).

Conclusions

Cover crops can benefit soil quality and citrus fruit yield and quality if managed correctly. Choosing the correct cover crop is crucial to obtain real benefits. Therefore, it is advisable to use a three-step method (Figure 1) for selecting cover crops to be planted in citrus orchards. Cover crops enhance soil quality by improving soil moisture, soil organic carbon and nitrogen, and the soil microbial population, and can help to suppress weeds. The cultivation of cover crops also helps to enhance fruit quality since fewer chemical inputs are used in the orchards. This is an important consideration for consumers who are becoming increasingly aware of the effects of crop production on the environment. However, studies have shown that the benefits from utilising cover crops often come after long-term use; therefore, a citrus farmer should not expect immediate gains. In addition, more information needs to be gained on the effects of cover crops in citrus farming under South African conditions.

ORCID

Sibongiseni Silwana — http://orcid.org/0000-0003-0082-5611
Azwimbavhi Reckson Mulidzi — http://orcid.org/0000-0002-2059-7532
Nebo Jovanovic — http://orcid.org/0000-0003-2101-8130

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