Management of Cover Crop Intercropping for Live Mulch on Plant Productivity and Growth Resources: A Review

Authors: Dzvene, Admire R., Tesfuhuney, Weldemichael A., Walker, Sue, and Ceronio, Gert

Source: Air, Soil and Water Research, 16(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221231180079

Management of Cover Crop Intercropping for Live Mulch on Plant Productivity and Growth Resources: A Review

Air, Soil and Water Research
Volume 16: 1–12

DOI: 10.1177/11786221231180079
Sage

Admire R. Dzvene[1], Weldemichael A. Tesfuhuney[1], Sue Walker[1,2] and Gert Ceronio[1]

[1]University of the Free State, Bloemfontein, South Africa, and [2]Agricultural Research Council – Natural Resources & Engineering (ARC-NRE), Pretoria, South Africa.

ABSTRACT: Cover crops are a valuable tool for improving resources use, soil health, and productivity. However, the effects of intercropping cover crops as live mulches with cash crops can vary depending on the species, management practices, and environmental conditions. This study reviewed the literature on cover crop intercropping and identified key factors to consider for improved plant productivity and resources use when managing these cropping systems. Science Direct, Scopus, and Google Scholar were used to search for literature on managing cover crop intercropping as live mulches. Research has shown that annual cover crops are typically used in annual field crop systems, while perennial cover crops are typically used in orchards and vineyards. The effects of intercropping annual or perennial cover crops in vineyards, orchards, and field crop systems can vary from positive to negative, depending on the climate, soil, management, and production system. Therefore, there is no one-size-fits-all management strategy. However, there are some key factors that should be considered when managing cover crops, such as: compatibility, intercropping time, planting density, and termination time. The benefits of appropriate cover crop management include: extended growing season, increased soil fertility, resource use optimization, and increased biomass productivity. Cover crop intercropping can be a successful way to improve resource use, soil health and productivity, but it is important to carefully consider the specific crop and management practices to ensure success. Therefore, future research should optimize cover crop intercropping time and planting density in maize-based rainwater harvesting systems on productivity and resource use.

KEYWORDS: Agroecological services, water and radiation use; biomass production, living mulch, sustainable agriculture

RECEIVED: November 7, 2022. **ACCEPTED:** May 11, 2023

TYPE: Review

CORRESPONDING AUTHOR: Admire R Dzvene, Department of Soil, Crop, and Climate Sciences, University of the Free State, PO BOX 339, Bloemfontein 9301, South Africa. Email: dzvenea@gmail.com

Introduction

Cover crop, "a crop that covers the soil," is any crop introduced into an annual field crop system, vineyard, and orchard to provide agroecological services. The cover crop is not intended for harvest, and ecological services help mitigate the effects of tillage on soil health and plant productivity (Afshar et al., 2018; Boulet et al., 2021; Thapa et al., 2022). Cover crops, on the other hand, provide agroecosystem services that are dependent on both intrinsic (soil and weather) and extrinsic (cover crop management decisions) factors, as well as the quantity and quality of the residues themselves (Thapa et al., 2022). Crop systems that integrate livestock production can supplement cover crop residues for livestock grazing (Blanco-Canqui et al., 2020). Cover crop adoption generally improves biomass production (Antosh et al., 2022) of an agricultural system and, thus, soil organic matter (SOM) buildup resulting in improved soil's physical, biological, and chemical properties (Adetunji et al., 2020; Arruda et al., 2021; Blanco-Canqui et al., 2011; Saleem et al., 2020; Thapa et al., 2022). Although the cover crop concept is simple, successfully implementing it and reaping the associated agroecosystem benefits usually depends on its management, that is, green manure, living mulch, and catch or smother crops.

The intercropping of cover crops with cash crops to provide living mulch ground cover throughout the growing season is also known as live mulching (Dobbratz et al., 2019; Hartwig & Ammon, 2002; Hiltbrunner et al., 2007). Green manures are cover crops mowed and incorporated into the soil to maximize the efficacy of their agroecological benefits (Boulet et al., 2021; Couëdel et al., 2018). For example, biotoxic compounds found in brassica species that act as fumigant chemicals against plant-parasitic nematodes are only effective when plant cells are raptured and incorporated into the soil (Bui & Desaeger, 2021). As a result, the term "cover crop" is literally used in this study, whereas "living mulch" refers to the intercropped cover crop that provides non-harvest benefits. According to Dobbratz et al. (2019) living mulches are perennial cover crops that grow alongside row crops and remain on the landscape during the fallow season. When "intercropping" is used instead of "living mulch," it refers to the general practice in which component crops provide harvestable grain yield benefits but the association of intercrops has a similar agroecological advantage to live mulches.

The agroecological benefits of cover crops in a cropping system are highly dependent on environmental conditions (Unger & Vigil, 1998). Relay intercropping of cover crops into the standing cash crop is a beneficial adaptation strategy for enriching the soil-crop system with nitrogen (Amossé et al., 2013) in environments with narrow planting windows (Alonso-Ayuso et al., 2020; Antosh et al., 2022), short growing seasons after

*Admire R. Dzvene is also affiliated to University of Fort Hare, Alice, South Africa

cash crop harvest, and a lack of crop diversification (Afshar et al., 2018). The short summer growing season in most semi-arid areas and a lack of winter rainfall make it difficult for smallholder crop systems to incorporate cover crops during the fallow period (Brooker et al., 2020). Therefore, intercropping cover crops is a sustainable approach for extending the crop growing season by increasing total annual water use and nutrient uptake while decreasing nutrient and sediment losses into surface waters (Moore et al., 2019; Tribouillois et al., 2016). However, from another perspective, the growing season is extended when the cover crop species is winter tolerant and continues its growth after harvesting the summer cash crop (Dobbratz et al., 2019). Thus, live mulch frequently involves perennial species maintained yearly with growth suppression (Abdin et al., 2000). However, there is a need to evaluate comprehensive annual summer species to manage the intercropping of cover crops as live mulches in cash crop systems.

Perennial cover crop species are widely used in vineyards and orchards, and research on their application in annual cash crop systems is still ongoing. Some studies evaluating the impact of intercropping perennial species for cover crops in annual cropping systems have shown undesirable effects on cash crop yield (Hiltbrunner et al., 2007; Liedgens et al., 2004). Maize (*Zea mays* L.) growth and productivity were reduced in Italian ryegrass (*Lolium multiflorum* Lam.) living mulch due to the formation of a smaller photosynthetic apparatus and the accelerated senescence of maize plants (Liedgens et al., 2004). Hiltbrunner et al. (2007) found low ear density and reduced wheat (*Triticum*) grain yield when seeded at low seeding density in white clover (*Trifolium repens* L.) living mulch. However, increasing the seeding density of wheat was shown to improve grain yield productivity. These accounts signify the importance of cover crop species selection and management to reduce interspecies resource competition in cropping systems.

Intercropping cover crops that produce a lot of biomass in a short period of time is an important decision for dryland farming. However, Fageira et al. (2005) and Baligar and Fageira (2007) argue that biomass productivity should not be the only factor considered when selecting a cover crop. Cover crops with a high growth rate can exert similar interspecies competition to the weeds they replace for resources, such as light, water, and nutrients, which can reduce productivity. Therefore, it is important to consider the interspecific competitive ability of cover crops with cash crop when making a selection. Annual legume species are recommended as a companion crop in tropical dryland environments because they fill the late-season gap in the cropping season when the cereal crop matures, and the soil would otherwise be left fallow. However, intercropping management of the legume depends on the desired outcomes, but the agroecological benefit is related to species biomass productivity. Therefore, management choices on cover crop intercropping seek to address a single underlying issue: how can a farmer reap the benefits of cover crops while maintaining cash crop yields? Weed suppression is one of the essential functions of living mulches, especially when compared to terminated cover crops, because they may control weeds through various mechanisms and throughout their life cycles (Abdin et al., 2000; Kunz et al., 2016). The objectives were to review key factors to consider for managing intercropping of cover crops on plant productivity, water, radiation, and nitrogen resources and recommend strip cover crop adoption with the in-field rainwater harvesting (IRWH) technique.

Methodology

Articles on cover crop intercropping for live mulching were searched on Science Direct, Scopus, and Google Scholar. There was also a search of the library's books, reports, and Congress proceedings. There was no time frame for the articles selected, because research on intercropping cover crops as live mulches as a sustainable climate-smart strategy is still ongoing. The most important information from the reviewed articles was how the intercropping management of cover crop living mulches optimized the agroecological services provided and productivity.

Intercropping Cover Crops for Live Mulching

The most effective management strategy for incorporating cover crops into a cropping system for improved biomass production is intercropping. Cover crops act as live mulches when intercropped with dominant crops, allowing farmers to plant cover crops without losing land for dominant crop production (Afshar et al., 2018; Alonso-Ayuso et al., 2020). Intercropping cultivates two or more crop species in the same field during the growing season (R. W. Brooker et al., 2015). The subordinate crop is typically a short-statured species that take advantage of diffuse radiation intercepted by the dominant species, and a vast body of literature exists on intercropping studies (Amossé et al., 2013; Gaiser et al., 2004). Improvements in resource utilization efficiency were demonstrated with the adoption of intercropping practice (Morris & Garrity, 1993). The basic assumption of all intercropping studies is that resource use is optimized by combining crop species rather than monoculture cultivation. That optimization results from managing variations in how the species exploits growth resources or behaves concerning the ecosystem they are grown.

Intercropping management is therefore pivotal for enhancing the productivity of the cropping system. This is because plant yields and field operations are influenced in all intercropping systems due to (i) interspecific complementarity and competition for nutrients, light, and water, (ii) inability to cultivate or apply herbicides for weed control, and (iii) phytotoxic effects due to allelopathy in the case of cover crops (Gitari et al., 2020; Hu et al., 2016). In addition, farmers may be concerned about intercropping's economic feasibility and profitability. Therefore, it is necessary to pool intercropping knowledge based on theory and practice to develop interactive management practices that optimize resource use in intercropping of cover crops. This information is vital in advancing the adoption of cover crops in dryland cropping systems that prioritize cash crop growth, particularly with subsistence farmers.

Table 1. Cover Crop Species Selection Rationale for Agroecosystem Benefits in Tropical Areas.

JUSTIFICATION	SELECTION BASIS OF COVER CROP	REFERENCES
Criteria for adoption	(a) Robustness [ability to grow under different conditions], (b) Versatility [multi-functional], (c) Accessibility [knowledge, seed availability, cost of seed and other inputs], (d) “Fit” with other components of the farming system [e.g., crop rotations, livestock-keeping system], (e) “Fit” with socioeconomic resources [land, labor, capital], (f) Ability to tolerate difficult conditions and/or improve these for associated cash-crops [e.g., water-logging, compacted soils, high/low pH, Al toxicity, high/low temperatures].	Alonso-Ayuso et al. (2020), Belfry and Van Eerd (2016), Brooker et al. (2020)
Soil improvement	(a) Speed and completeness of cover, (b) Seasonality and longevity, (c) Biomass dry matter (DM) production, (d) C:N ratio for buildup of soil organic matter, (e) Crop habit and architecture to shade and protect soil, (f) Rooting depth, density, and strength, (g) Rhizobial and mycorrhizal associations, N-fixation, P-accumulation, (h) Degradation rate of residue [synchrony of availability and demand for nutrients].	Arruda et al. (2021), Antosh et al. (2022), Blanco-Canqui et al. (2011), Gaimaro et al. (2022).
Livestock feed and forage provision	(a) Fodder production [timing, amount, quality, persistence], (b) Seed production [timing, amount, quality], (c) Anti-nutritive components and processing required	Blanco-Canqui et al. (2020), Dzvene et al. (2022a)
Pest and weed control	(a) Speed and completeness of cover development, (b) Persistence, (c) Competitiveness, (d) Allelopathy.	Pouryousef et al. (2015), Kunz et al. (2016), Abdin et al. (2000).
Generation of income	(a) Market for seed or other component, (b) Ease of harvest, (c) Keeping qualities, (d) Bulk for transportation	Blanco-Canqui et al. (2020)

Intercropping literature for optimizing resource use has emphasized management practices, such as interspecific relationships such as competition and facilitation (Hu et al., 2016). Jalilian et al. (2017) discovered that intercropping safflower (*Carthanmus tinctorius* L.) and bitter vetch (*Vicia ervilia* L.) at a 2:2 ratio yielded the highest biomass yields when compared to other planting patterns and sole crops. The intercropping treatment with the highest land equivalent ratio (LER) best minimized interspecies competition and promoted species complementarity in resource use. In contrast, mustard-pea and lentil-gram intercropping resulted in significantly more significant yield losses of component crops, as indicated by a higher actual yield loss (AYL) (Banik et al., 2000). These findings suggest that cereal legume intercropping systems are more resource complementary, and productivity relies heavily on management practices that adhere to basic ecological principles for resource efficiency.

Intercropping indices are used to measure how well component crops compete for resources. However, biomass yield data from intercropping cover crops is rarely used to assess these indices because most research focuses on grain yield. As a result, there is a lot of knowledge about intercropping indices for intercrop systems that can be used to determine grain yield comparability (Banik et al., 2000; Gitari et al., 2020; Iqbal et al., 2019). This knowledge can be applied to intercropping cover crops by using a variety of management practices to recommend the best practices or interactions for high biomass production. Relay intercropping allows the sowing of cover crops to be delayed to promote crop dominance and avoid resource limitation (Amossé et al., 2013; Brooker et al., 2020; Mhlanga et al., 2016). The benefit of establishing dominant crop growth before sowing the cover crop is that it will have better growth resource access. Cover crop growth and development, on the other hand, is disadvantaged due to the dominant crop's temporal competitive advantage (Belfry & Van Eerd, 2016). Mhlanga et al. (2016) demonstrated that intercropping cover crops into standing maize could restrict their growth and result in negligible overall increase in intercropping plant biomass. Gitari et al. (2020) used a combination of intercropping indices to evaluate the impact of intercropping potato (*Solanum tuberosum* L.) with two legume species, dolichos (*Lablab purpureus* L.) and climbing bean (*Phaseolus vulgareus* L.), including LER, land equivalent coefficient (LEC), area time equivalent ratio (ATER), land use efficiency (LUE), system productive index (SPI), percentage yield difference (PYD), relative crowding coefficient (K).

Management Factors for Intercropping of Cover Crops

Selection of compatible plant species

Agroecosystem benefits vary depending on the botanical family of the cover crop, as does its suitability for cultivation (Table 1). Differences in component species' morphological and physiological factors have been identified as reliable predictors of final intercropping yields (R. W. Brooker et al., 2015; Li et al., 2021). Fast-growing species are desirable for adoption in the intercropping of cover crops (Alonso-Ayuso et al., 2020). The component crops preferred in cover crop intercropping combination should be different in their grand growth period; otherwise, there may be a chance of interspecies competition for necessary growth resources if it coincides (Banik et al., 2000; R. W. Brooker et al., 2015). Therefore, complementarity among the species is desirable to obtain the benefits of cover crop intercropping reflected by biomass productivity. Hence, differences in growth duration and morphology between crop species will result in interspecies complementarity. It may be stated that maize has been considered a suitable cereal species and treated as a dominant crop because of its economic value in smallholder continuous cropping systems. Its association with preferably legume species results in higher plant productivity which is indicated by an overyielding effect.

However, a significant question surrounding intercropping cover crops in annual crop systems revolves around whether their benefits exceed the losses, particularly of scarce resources such as water (Thornton et al., 2018). Intercropped cover crops that provide a dense ground cover early in the growing season are most recommended and prevent weed establishment in annual crop systems (Kunz et al., 2016; Pouryousef et al., 2015). Although yearly and perennial cover crops should be selected according to different criteria for the agroecosystem services provided. Appreciation of perennial species is low in dryland cropping systems because of the fear of competition and limited water resources (Abad et al., 2021). Self-seeding annuals benefit from the rapid and complete establishment, which is particularly suitable in no-till strip crop systems and thus reduces the need for re-planting during the next growing season (Leoni et al., 2020). Termination of annual cover crops before seed set is a management activity vital in preventing volunteer plants from emerging in the next season and reducing competition.

Cover crop species are chosen based on their positive environmental impacts in an agroecosystem. Cover crops can help to reduce water pollution in agroecosystems where nitrogen (N) leaching is a problem by trapping or absorbing excess nitrogen in their biomass and later releasing it when residues decompose to improve soil health (Arruda et al., 2021; Dobbratz et al., 2019; Gaimaro et al., 2022; Saleem et al., 2020). Legumes are often selected for biological N_2 fixation. The legume species is beneficial, especially in cereal grain cropping systems, which may reduce N inputs required for the cash crop (Liang et al., 2014). However, in-season and post-season availability of fixed N to the component crop may vary (Sanders et al., 2017). Some crop species have taproots that can penetrate and loosen the soil profile, thereby improving the soil's physical condition (Zhang & Peng, 2021). For example, brassicas are deep soil tillage crop species capable of producing large taproots that can penetrate up to 1.8 m to alleviate soil compaction (Thorup-Kristensen, 2006). Other research has shown that cover crop mixtures are more effective in maximizing the agroecological benefits than sole species (Couëdel et al., 2018; Gaimaro et al., 2022).

Appropriate planting and termination times

The selection of a suitable intercropping or termination time of cover crops is another vital management practice because they have been shown to interfere with the dominant crop by competing for plant growth resources (Antosh et al., 2022; Mhlanga et al., 2016). Late intercropping time, growth suppression, and earlier termination are all management techniques to control living mulch interference (Abdin et al., 2000; Afshar et al., 2018; Amossé et al., 2013; Wortman et al., 2012). Cover crops are generally recommended to be introduced when the cash crop is nearing maturity or has completed a significant period of growth to reduce the intensity and outcome of mulch-crop competition on yield losses (Amossé et al., 2013; Belfry & Van Eerd, 2016). However, Kunz et al. (2016) recommend that additional weed control measures be implemented before living mulch establishment when planting living mulches late in the cash crop growing season. The disadvantage of late intercropping cover crops is a lack of early weed control, which may result in no benefits during the growing season (Alonso-Ayuso et al., 2020). Earlier intercropping can result in better cover crop establishment and improved ground cover, which is desirable when living mulches are not highly competitive (Abdin et al., 2000; Brooker et al., 2020).

A delay in cover crop intercropping usually decreases weed control and the risk of cash crop yield losses. Complementary management practices such as living mulch suppression can be recommended to prevent yield losses (Abdin et al., 2000). Brooker et al. (2020) mentioned that delayed living mulch planting might minimize maize yield losses. For example, in Pennsylvania State, USA, rye biomass increased by 50% when planted in early September rather than mid-October (Mirsky et al., 2011). Lawson et al. (2015) also observed that delaying rye planting by 2.5 weeks reduced average winter ground cover by 65% and biomass by 50% in Washington State, USA.

Limiting the living mulch interference time by killing the living mulch during the growing season with either chemical or mechanical control techniques may also reduce mulch-crop competition (Brandsaeter et al., 1998). Wortman et al. (2012) studied the effect of cover crop termination methods like disking or undercutting on cash crop yield. Cover crop mixtures increased cash crop yield and profitability when paired with an undercutter for termination compared to a traditional no cover crop organic cropping system. In Montana, USA, Afshar et al. (2018) discovered that terminating living mulches at the sugarbeet V2 stage did not reduce sugarbeet (*Beta vulgaris* L.) yield. Glyphosate-resistant sugarbeet species were also utilized to allow for targeted chemical termination of the living mulch. Therefore, the optimum termination time of a living mulch can significantly improve cash crop yield. Early termination of living mulches, like late planting, is most likely a proper complementary management technique when mulch-crop competition is high. However, complementary approaches are sometimes applicable and limited, depending on the cash crop species, planting patterns and tillage system. Strip planting of living mulch is quickly killed, allows for cash crop planting and establishment, and can decrease interspecific competition. Cash crop herbicide-resistant varieties are ideal for chemical suppression or termination of living mulches. In one of 2 years, terminating 61 cm bands of kura clover with glyphosate and post-emergence dicamba resulted in higher maize yield than treating the entire field with glyphosate and post-emergence bromoxynil (Zemenchik et al., 2000). Strip tilling was used to manage Kentucky bluegrass in the fall, followed by applying paraquat and glyphosate in preparation for the planting of maize as the cash crop prevents maize grain loss (Wiggans et al., 2012).

Optimum planting density and pattern

Planting geometry and spacing of dominant and subordinate species in intercropping systems are modified or altered to achieve the desired plant stand (Campiglia et al., 2014; Maitra et al., 2021; Nurgi et al., 2023). Plant density, that is, the number of plants per unit area, is required to obtain optimal yield outputs from the living mulch and the cash crop. However, if the replacement series is chosen, the plant population of both the cash crop and the cover crop species will be reduced, whereas the cash crop will have a similar plant stand in the additive series (Maitra et al., 2021). A higher planting density of a subordinate crop or living mulch can influence its competition with the cash crop and its ability to provide the desired agroecosystem services (Dzvene et al., 2022a; Mohammadi, 2010; Nurgi et al., 2023). Previous research using different living mulch seeding rates has linked the interaction to excessive mulch-crop competition at high living mulch density where weed pressure is not severe (Kaneko et al., 2011; Mohammadi, 2010; Pouryousef et al., 2015). As a result, mulch-crop competition can result in three possible outcomes for cash crop yield: (i) decline with increasing living mulch density in resource-constrained environments (Pouryousef et al., 2015); (ii) increase with increasing living mulch density where weed pressure is severe (Kaneko et al., 2011); and (iii) no difference at either low and high living mulch densities, indicating that the competitive effects of living mulch on the cash crop are similar to the weeds (Mohammadi, 2010).

Furthermore, the paired-row geometry pattern of planting the cash crop is advantageous because more space is available for planting the living mulch at higher densities (Campiglia et al., 2014). A uniform crop plant arrangement pattern increases the chances of a single plant obtaining an equal share of the available resources (light, water, and nutrients), resulting in less intraspecific competition (Thorsted et al., 2006). A uniform spatial arrangement of crop plants increases weeds' competitive ability because a more significant proportion of the weeds will be affected by crop competition (interspecific competition). Thorsted et al. (2006) found that increasing the width of the rototilled strip reduced early competition for light by leaving a narrower band of clover before sowing the wheat. Again, planting maize in paired rows is meant to facilitate complementary management of living mulch (i.e. mechanical or chemical suppression) and possibly reduce interspecific competition. To increase maize grain yield, Sanders et al. (2017) suggested planting maize in 90 cm rows on top of 20 cm herbicide bands applied to a white clover mulch. The planting pattern and method of living mulch can significantly impact cash crop yield more than the cash crop itself.

Impacts of Intercropping Cover Crops on Plant Growth Resources

Dominant crop yield is the fundamental consideration for assessing the benefits of living mulching. The cash crop is treated as a crop without much plant stand variation. Many studies in the literature have revealed the no effects of living mulch species planting from V1 to V6 stages into a standing maize cash crop on grain yield. Baldé et al. (2011), Mhlanga et al. (2016), Curran et al. (2018), Schmitt et al. (2021), and Antosh et al. (2022) investigated the impact of cover crops on maize grain yield. Baldé et al. (2011) found that planting pigeon pea (*Cajanus cajan*) and Brachiaria (*Brachiaria ruziziensis*) as cover crops in maize at two different sowing dates did not affect maize grain yield. In Zimbabwe, introducing eight cover crop species into standing maize at three planting dates of 8, 11, and 15 weeks after maize planting did not reduce maize grain yield (Mhlanga et al., 2016). Cover crops planted in North Dakota at the V7 and R4 maize growth stages included rye (*Secale cereal* cv ND-Dylan), winter camelina (*Camelina sativa* cv. Joelle), and radish (*Raphanus raphanistrum* subsp. sativus cv. Daikon). They did not reduce maize yield (Schmitt et al., 2021). Cover crop planting of a grass mixture [cereal rye and spring triticale (*Triticale hexaploide*)] and legumes purple top turnip (*Brassica rapa*), and cowpea (*Vigna unguiculata* L.) at V4, V6, and V8 maize growth stages did not affect maize grain yield in a similar environment (Antosh et al., 2022). In Maryland, Pennsylvania, and New York, experiments also demonstrated intercropping annual ryegrass [*Lolium perenne* L.ssp. multiflorum (Lam.) Husnot], red clover (VNS), crimson clover (*Trifolium incarnatum* L.), and hairy vetch (*Vicia villosa* Roth) cover crops between the V4 and V6 maize growth stages did not reduce maize yield (Curran et al., 2018). In cropping systems, living mulches' effects on cash crop yield are related to interspecific facilitation or competition for water, radiation, and nitrogen.

Water

Living mulches can significantly impact the soil-water relationship, with the magnitude varying depending on the species, cropping system, climate, and soil type. The importance of understory vegetation in agricultural systems for controlling soil erosion influenced by runoff water is now widely acknowledged. Intercropping cover crops by planting them between rows of an economic crop allows for a more diverse agroecosystem (Baldé et al., 2011). Conventional tillage practices leave bare soil between crop rows, making it less stable, prone to rainwater and wind erosion, and quickly degrading. The striking actions of raindrops can erode the bare or uncovered soil. Still, the coverage of soil by cover crop canopy and the leaves can intercept most of the rainfall, reducing the effects of rain splash (Blanco-Canqui et al., 2011). Therefore, residues and understory vegetation can increase flow resistance and slow flow velocities in living mulch systems, which is critical in effectively controlling soil erosion.

Furthermore, rainfall penetrating living mulch due to interception can increase precipitation retention and promote infiltration. Cover crops reduce soil compaction, improve soil aggregate stability and enhance water infiltration through the fibrous root with is extended by arbuscular mycorrhizal fungi system (Arruda et al., 2021; Blanco-Canqui et al., 2011). Living mulch soil cover improves soil water retention compared to bare soils, but the result is highly dependable on the water use of the living mulch species (Liedgens et al., 2004).

Intercropping increases yields on a given plot of land by utilizing water that would otherwise be lost as unproductive in monocropping. However, soil type significantly impacts how much water a soil can retain and how much water plant roots can extract at different soil water potentials. There is a death of information balancing the water costs used by intercropping crops and water conserved by the living cover crop mulch, particularly in dryland farming systems. Morris and Garrity (1993) argue that the difference in the water consumption of intercropping system during the growing season is lower than the weighted average value of the corresponding sole-cropping water consumption. Although the consumption of intercropping water is higher than that of monocultures, the water consumption of intercropping systems varies considerably due to environmental conditions and crop types (Morris & Garrity, 1993). Water-sufficient environments have a great potential for developing intercropping systems due to the ability to meet the water requirements of high-yield sole-cropping systems. However, under rainwater harvesting (RWH) systems in dryland areas, the water consumption of intercropping is not apparent. For example, in irrigated areas, intercropping water consumption is not a simple accumulation of the water consumption of component crops. It is lower than the accumulation value due to water competition and complementary utilization effects during the growing season (Yin et al., 2018).

There are conflicting reports on the impact of managing living mulches on soil water. According to some studies, living mulches may compete with plants for water, and thus mulched soils may have lower moisture content than bare soils (Qu et al., 2019). Other research has shown that living mulches can increase soil moisture content (Liedgens et al., 2004; Ni et al., 2016; Thorsted et al., 2006). Ni et al. (2016) observed that live mulching with turf grass increased soil moisture at the 0 to 5 cm depth but had no effect at the 5 to 10 cm depth. A separate study, however, found that living mulches increased plant transpiration, resulting in soil water competition at 10 to 20 and 20 to 40 cm depths (Qu et al., 2019). Living mulches increased soil water use in a wheat cropping system through increased canopy transpiration from cash crop and living mulch (Thorsted et al., 2006). Reduced soil water content (30–90 cm) was reported in maize production with living mulch [Italian ryegrass (*Lolium multiflorum* Lam.)] compared to the control bare treatment (Liedgens et al., 2004).

The fraction of transpirable soil water (FTSW) was higher at the end of the maize cycle when maize was the sole crop than in the living mulch system (Figure 1a and b), indicating that the living mulch systems used soil moisture and rainfall more efficiently (Baldé et al., 2011). However, other studies indicated that cover crops did not affect soil moisture (Nielsen et al., 2015; Payero et al., 2021). Payero et al. (2021) study found no differences in soil moisture due to the humid conditions of South Carolina, where 1400 mm of rainfall was received during the growing season in cotton (*Gossypium hirsutum* L.) with single and mixed cover crop species. Gravimetric soil water content in maize grown with kura clover as a living mulch showed no difference from a pure kura clover stand, which could be attributed to an abundant rainfall water supply (Zemenchik et al., 2000). Through water uptake and transpiration, live cover crops can reduce soil water content (Unger & Vigil, 1998); however, differences in soil moisture can be negligible during growing seasons with average or above-average rainfall (Wortman et al., 2012).

Light

The ability of intercropping to absorb, transmit, and reflect solar energy modifies soil temperature; thus, plant canopy shading affects soil temperature modification. Above-ground interactions in living mulches influence competition for light which is size asymmetric (Thorsted et al., 2006). Living mulch species with high legume biomass productivity have been shown to use solar radiation better while limiting the amount of light that reaches the ground when relay intercropped (Amossé et al., 2013). Living mulches should remain short to prevent excessive competition for light with the cash crop because competition for light is largely asymmetric (Leoni et al., 2020). If living mulches develop sufficiently early in the growing stage of the cash crop and their canopy reaches that of the cash crop leaf, there may be light competition (Carof et al., 2007). As a result, the late planting of living mulches into a cash standing crop implies that the cash crop takes precedence over the living mulch, suggesting that light competition negatively impacts the living mulch rather than the cash crop (Shili-Touzi et al., 2010). The benefit of relay planting living mulch into a standing cash crop is due to the senescence of older leaved cash crops at grain filling, which allows for an increased

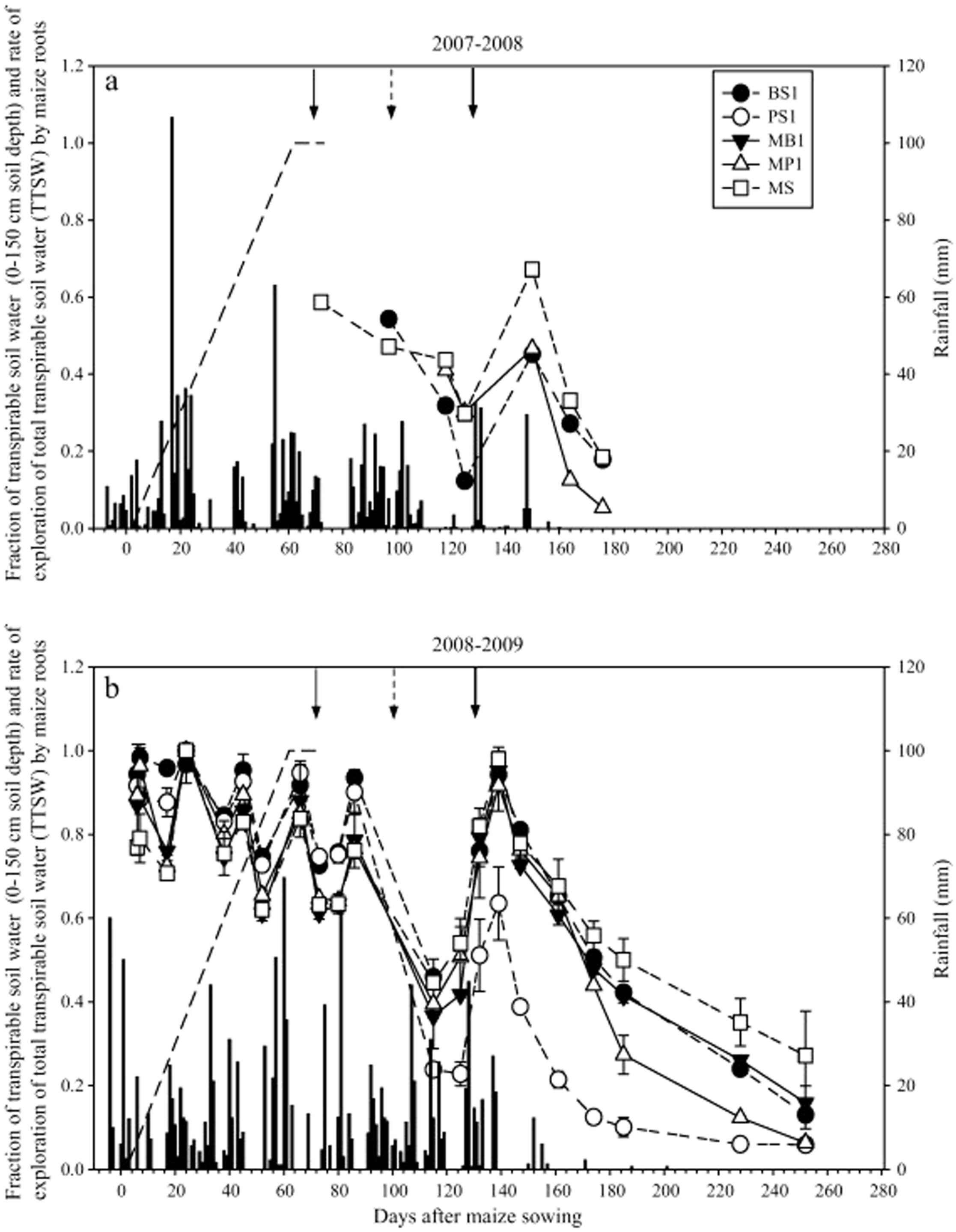

Figure 1. The fraction of transpirable soil water (FTSW) in 0 to 150 cm soil depth during (a) 2007-2008 and (b) 2008-2009 growing seasons as affected by BS1: early sown Brachiaria as sole crop, PS1: early sown pigeon pea as sole crop, MB1: maize intercropped with early sown Brachiaria, MP1: maize intercropped with early sown pigeon pea, MS: maize as sole (Source: Baldé et al., 2011).

light transmittance to the cover crops. The available photosynthetically active radiation (PAR) at the soil surface and for living mulches planted at the R4 maize stage increased as the lower maize leaves began to senesce (Schmitt et al., 2021). They discovered a significant decrease in PAR reaching the living mulches by the third week after living mulch planting in their study (Figure 2a and b). Green cover from living mulches planted at the V7 maize growth stage decreased as PAR levels increased throughout the maize canopy, according to Schmitt et al. (2021). They concluded this was due to the significant stress imposed on plant development by the maize canopy's low light intensity. Gallo et al. (1985) discovered that the

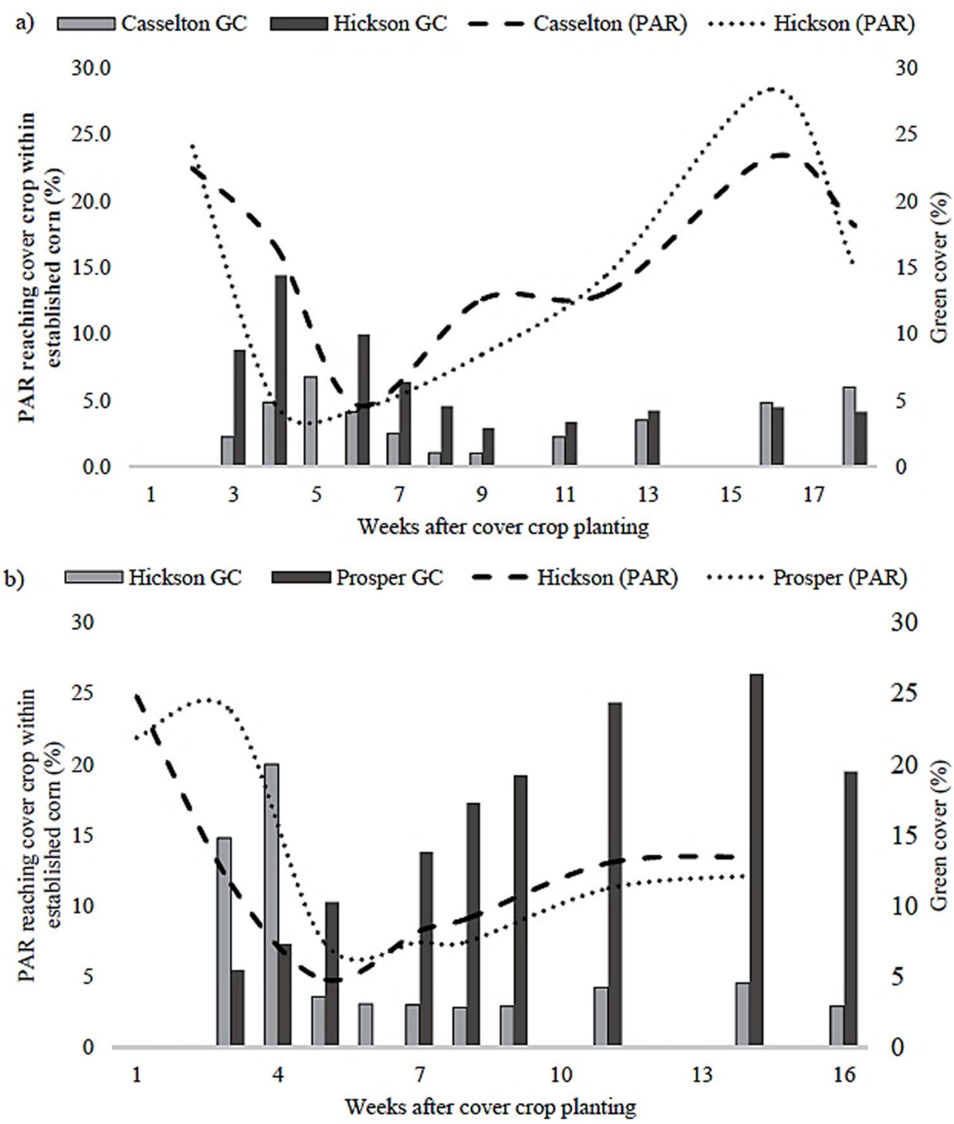

Figure 2. The percentage of living green mulch cover planted at the V7 maize growth stage concerning PAR reaching the living mulch canopy within established maize at (a) Caseelton and Hickson in 2018 and (b) Hickson and Prosper in 2019 (Source; Schmitt et al., 2021).

percentage of incoming PAR absorbed by the maize canopy increases rapidly between the V5 and V12 stages of maize growth, from about 20 to 90%. They added that the canopy absorbs more than 80% of the incoming PAR from the V12 maize growth stage to the dough stage of grain fill (R4).

Nitrogen

Soil nutrient content is not expected to change significantly during 1 year of live mulching, but long-term mulching may affect soil nutrient concentrations and availability. Cover crops impact soil functioning substantially by adding to the stock of SOM through both below-ground and above-ground production (Saleem et al., 2020). Cover crops encourage soil biota activity by providing a readily available food source and creating a more favorable soil habitat (Arruda et al., 2021). Few studies that used living mulches in perennial crops focused on the effects of living mulches on soil nutrient dynamics and availability (Carof et al., 2007). Cover crop species, management, and site-specific factors, the short-term impact on soil fertility is frequently influenced by cover crop species. However, the literature on legume-living mulches and nitrogen availability is contradictory.

Despite their ability to fix nitrogen (N) and ability to scavenge excess N, thereby reducing potential nutrient leaching (Mohammed et al., 2020), legume living mulches can reduce cash crop yields due to nitrogen competition (Mia et al., 2020; Paušič et al., 2021). Cover crop mixtures that included crucifer and legume species produced nitrate catch crop services that were on par with or better than those supplied by cover crops that only contained crucifers (Couëdel et al., 2018). Cover crop mixtures containing a legume and a non-legume can provide

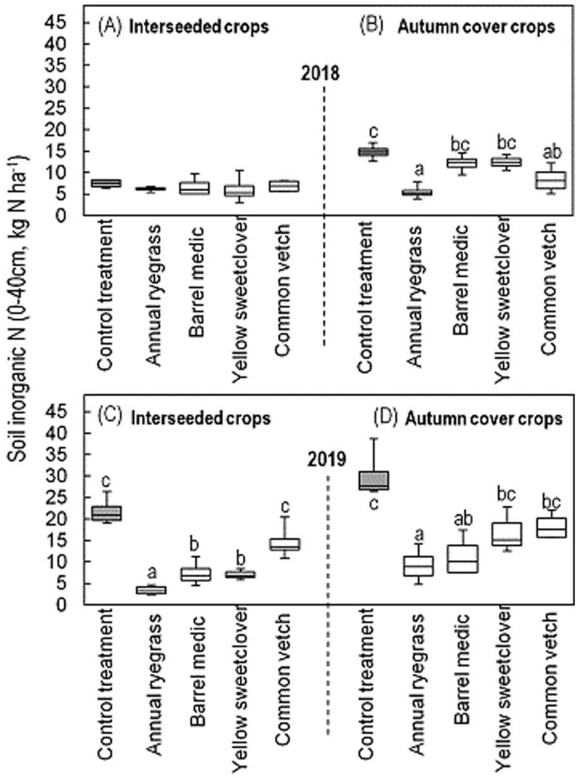

Figure 3. The box and whisker of soil inorganic N content (kg N ha^{-1}) that were present at 0 to 40 cm depth in late March before cover crop termination (Source; Alonso-Ayuso et al., 2020).

more efficient green manure and nitrate catch crop services than non-legume cover crops (Tribouillois et al., 2016). Some research has shown that legume-living mulches can reduce nitrogen fertilizer requirements compared to the standard for a crop in the sole (Jeranyama et al., 1998; Radicetti et al., 2018). They observed that intercropped medic cover crop species have a positive yield response of subsequent maize grain and reduced maize fertilizer needs in the following year. In Spain's semi-arid cold Mediterranean climate, Alonso-Ayuso et al. (2020) found that intercropped cover crop treatments had lower soil inorganic nitrogen in the spring before termination than autumn cover crop treatments (Figure 3). They concluded that intercropping enabled earlier cover crop planting, resulting in more significant biomass accumulation and nitrogen scavenging in autumn.

Intercropping of Cover Crops Under in-field Rainwater Harvesting

The in-field rainwater harvesting (IRWH) technique which consists a 1 m wide basin area and a 2 m wide no-till strip with mulch application is best suited for reducing drought pressure for rural farmers in semi-arid environments of South Africa (SA) (Botha et al., 2003; Dzvene et al., 2022a, 2022b; Hensley et al., 2000). The 2 m no-till strip serves as an in-field runoff water collection zone, channeling it to basins where it can be stored and infiltrated deeper into the soil for plant extraction later. Furthermore, farmers lack crop residues for mulch because it is used for livestock feed or fuel (Vanlauwe et al., 2014). At the same time, applying 50% organic reed mulch in the basin and on the runoff strip accounted for 74% of the annual rainwater harvested lost to evaporation (Botha et al., 2003). Therefore, adopting living mulch cover crops can improve yield per unit land area by maximizing precipitation use efficiency while also accumulating crop residues that can be used as mulch (Baldé et al., 2011).

The structure of IRWH technique comprising of a 1:2 basin tillage (BT) to runoff (no till, NT) ratio illustrates that there is a lot of photosynthetic potential that is untapped in the 2 m no till runoff area (Figure 4). This is because cropping is done in tramlines which are 1 m wide. Land use efficiency (LUE) can be boosted by incorporating living mulch cover crops in the 2 m wide runoff strip, thus increasing the techniques' photosynthetic capacity and biomass productivity. More biomass would be produced than sole cropping because of the more efficient use of available resources (Baldé et al., 2011; Dzvene et al., 2022a). The amount of recommended residue retention as a mulch for effective evaporation control requires at least 30% ground cover, is equivalent to approximately 2.5 t/ha, and, in most cases, the majority of farmers in the sub-Saharan Africa (SSA) produce less than desired yields to generate enough biomass (Vanlauwe et al., 2014).

On the other hand, most parts of the SSA countries have a long dry off-season period, and it is during this dry period. Therefore, livestock face reduced grazing options, making maize residues a good feed option for livestock (Blanco-Canqui et al., 2020; Giller et al., 2009). Therefore, careful management of living mulch cover crops can increase the production of biomass while at the same time maintaining or improving crop productivity.

Summary and Future Directions

While living mulch generally tends to increase crop yield with appropriate management, there is no one-size-fits-all living mulch to improve all aspects of perennial or annual crop production reliably. Choosing a suitable living mulch for a specific agricultural system and production goal is the first and most crucial step when exploring these tools. This decision should be made based on the particular crop, the production system (e.g. cash crop production), climate and soil conditions, agronomic or horticultural goal(s) of living mulch use, and management practices' feasibility. Modified soil and plant canopy microclimates with living mulch use usually improve plant vegetative and reproductive growth and may improve cash crop yield. Additional benefits through live mulching could be attributed to improved resource use and sharing; however, very few studies have been conducted to ascertain these impacts. Living mulch can generally conserve soil moisture, but its effects on soil and plant canopy temperatures vary. Multiple factors influence soil nutrient content, and most studies report increased

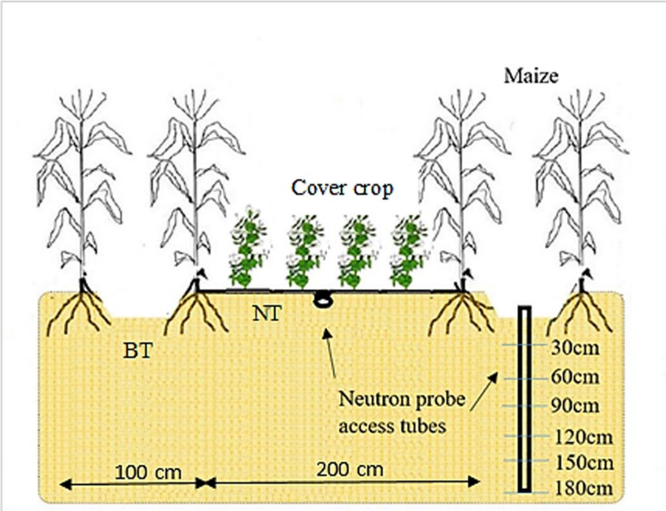

Figure 4. Illustration of the opportunity for living mulch cover crop integration within the IRWH technique to improve resource use.

nutrient concentrations when living mulches are used. Due to the mulch-crop duration, these impacts on plant and soil variables can last for months to years. Cover crop intercropping can be a successful way to improve resource use, soil health and productivity, but it is important to carefully consider the specific crop and management practices to ensure success

As for future directions, it is important to explore different living mulch management practices in various crop production systems across a wide range of climates and soil conditions. Following such studies, it would be helpful to create a predictive model regarding how different living mulch species and management practices can impact a crop production system in a given climate and soil system. Second, with increasing interest and potential use of cover crop in arable crop systems, the economic implication should be studied to assist farmers' decision-making, which is presently lacking. Third, more research is needed to explore how soil health and yield-resource use dynamics are impacted by living mulch. Finally, due to the uncertainty of living mulch use in dryland crop production systems, low water use species adopted on croplands must have vigorous growth, and full canopy cover would be beneficial to reduce mulch-crop competition. Cropping system diversification with the adoption of living mulch cover crops can enhance the over system productivity of the IRWH technique by utilization the underutilized land, water and radiation resources.

Acknowledgements

The authors would also like to thank the editor and anonymous reviewers for their valuable comments and suggestions for improving the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was jointly supported by the Water Research Commission (WRC Project No. K5/2128//4.), National Research Fund (NRF), and Food and Beverages Manufacturing Sector Education and Training Authority (FoodBev SETA).

REFERENCES

Abad, J., Hermoso de Mendoza, I., Marín, D., Orcaray, L., & Santesteban, L. G. (2021). Cover crops in viticulture. A systematic review (2):Implications on vineyard agronomic performance. *OENO One*, 55(2), 1–27. https://doi.org/10.20870/oeno-one.2021.55.2.4481

Abdin, O. A., Zhou, X. M., Cloutier, D., Coulman, D. C., Faris, M. A., & Smith, D. L. (2000). Cover crops and interrow tillage for weed control in short season maize (Zea mays). *European Journal of Agronomy*, 12(2), 93–102. https://doi.org/10.1016/S1161-0301(99)00049-0

Adetunji, A. T., Ncube, B., Mulidzi, R., & Lewu, F. B. (2020). Management impact and benefit of cover crops on soil quality: Areview. *Soil and Tillage Research*, 204, 104717. https://doi.orga/10.1016/j.still.2020.104717

Afshar, R. K., Chen, C., Eckhoff, J., & Flynn, C. (2018). Impact of a living mulch cover crop on sugarbeet establishment, root yield and sucrose purity. *Field Crops Research*, 223, 150–154. https://doi.org/10.1016/j.fcr.2018.04.009

Alonso-Ayuso, M., Gabriel, J. L., Pancorbo, J. L., & Quemada, M. (2020). Interseeding cover crops into maize: Characterization of species performance under Mediterranean conditions. *Field Crops Research*, 249, 107762. https://doi.org/10.1016/j.fcr.2020.107762

Amossé, C., Jeuffroy, M. H., & David, C. (2013). Relay intercropping of legume cover crops in organic winter wheat: Effects on performance and resource availability. *Field Crops Research*, 145, 78–87. https://doi.org/10.1016/j.fcr.2013.02.010

Antosh, E., Liebig, M. A., Archer, D. W., & Luciano, R. (2022). Cover crop interseeding effects on above-ground biomass and corn grain yield in western North Dakota. *Crop, Forage & Turfgrass Management*, 8(1), e20148. https://doi.org/10.1002/cft2.20148

Arruda, B., Herrera, W. F. B., Rojas-García, J. C., Turner, C., & Pavinato, P. S. (2021). Cover crop species and mycorrhizal colonization on soil phosphorus dynamics. *Rhizosphere*, 19, 100396. https://doi.org/10.1016/j.rhisph.2021.100396

Baldé, A. B., Scopel, E., Affholder, F., Corbeels, M., Da Silva, F. A. M., Xavier, J. H. V., & Wery, J. (2011). Agronomic performance of no-tillage relay intercropping with maize under smallholder conditions in central Brazil. *Field Crops Research*, 124(2), 240–251. https://doi.org/10.1016/j.fcr.2011.06.017

Baligar, V.C., & Fageria, N.K. (2007). Agronomy and physiologogy of tropical cover crop. *Journal of Plant Nutrition*, 30(8), 1287–1339. https://doi.org/10.1080/01904160701554997.

Banik, P., Sasmal, T., Ghosal, P. K., & Bagchi, D. K. (2000). Evaluation of mustard (Brassica compestris Varr.Toria) and legume intercroping under 1:1 and 2:1Row-Replacement Seriis Systtmsundefined. *Journal of Agronomy and Crop Science*, 185(1), 9–14. https://doi.org/10.1046/j.1439-037X.2000.00388.x

Belfry, K. D., & Van Eerd, L. L. (2016). Establishment and impact of cover crops intersown into corn. *Crop Science*, 56(3), 1245–1256. https://doi.org/10.2135/cropsci2015.06.0351

Blanco-Canqui, H., Mikha, M. M., Presley, D. R., & Claassen, M. M. (2011). Addition of cover crops enhances No-till potential for improving soil physical properties. *Soil Science Society of America Journal*, 75(4), 1471–1482. https://doi.org/10.2136/sssaj2010.0430

Blanco-Canqui, H., Drewnoski, M. E., MacDonald, J. C., Redfearn, D. D., Parsons, J., Lesoing, G. W., & Williams, T. (2020). Does cover crop grazing damage soils and reduce crop yields? *Agrosystems, Geosciences & Environment*, 3(1), e20102. https://doi.org/10.1002/agg2.20102

Botha, J. J., Van Rensburg, L. D., Anderson, J. J., Hensley, M., Macheli, M. S., Van Staden, P. P., Kundhlande, G., Groenewald, D. G., & Baiphethi, M. N. (2003). Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable crop production. *Water Research Commission Report*, 1176(1), 03.

Boulet, A. K., Alarcão, C., Ferreira, C., Kalantari, Z., Veiga, A., Campos, L., Ferreira, A., & Hessel, R. (2021). Agroecological services delivered by legume cover crops grown in succession with grain corn crops in the Mediterranean region. *Open Agriculture*, 6(1), 609–626. https://doi.org/10.1515/opag-2021-0041

Brandsaeter, L. O., Netland, J., & Meadow, R. (1998). Yields. weeds, pests, and soil nitrogen in a white cabbage-living mulch system. *Biological Agriculture &Horticulture*, 16(3), 291–309. https://doi.org/10.1080/01448765.1998.10823201

Brooker, A. P., Renner, K. A., & Basso, B. (2020). Interseeding cover crops in corn: Establishment, biomass, and competitiveness in on-farm trials. *Agronomy Journal*, 112(5), 3733–3743. https://doi.org/10.1002/agj2.20355

Brooker, R. W., Bennett, A. E., Cong, W. F., Daniell, T. J., George, T. S., Hallett, P. D., Hawes, C., Iannetta, P. P., Jones, H. G., Karley, A. J., Li, L., McKenzie, B. M., Pakeman, R. J., Paterson, E., Schöb, C., Shen, J., Squire, G., Watson, C. A., Zhang, C., . . . White, P. J. (2015). Improving intercropping: A synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, 206(1), 107–117. https://doi.org/10.1111/nph.13132

Bui, H. X., & Desaeger, J. A. (2021). Volatile compounds as potential bio-fumigants against plant-parasitic nematodes - a mini review. *Journal of Nematology*, 53(53), e2021. https://doi.org/10.21307/jofnem-2021-014

Campiglia, E., Mancinelli, R., Radicetti, E., & Baresel, J. P. (2014). Evaluating spatial arrangement for durum wheat (Triticum durum Desf.) and subclover (trifolium subterraneum L.) Intercropping systems. *Field Crops Research*, 169, 49–57. https://doi.org/10.1016/j.fcr.2014.09.003

Carof, M., Tourdonnet, S., Saulas, P., Floch, D., & Roger-Estrade, J. (2007). Undersowing wheat with different living mulches in a no-till system. II. Competition for light and nitrogen. *Agronomy for Sustainable Development*, 27(4), 357–365. https://doi.org/10.1051/agro:2007017

Couëdel, A., Alletto, L., Tribouillois, H., & & Justes, É. (2018). Cover crop crucifer-legume mixtures provide effective nitrate catch crop and nitrogen green manure ecosystem services. *Agriculture Ecosystems & Environment*, 254, 50–59. https://doi.org/10.1016/j.agee.2017.11.017

Curran, W. S., Hoover, R. J., Roth, G. W., Wallace, J. M., Dempsey, M. A., Mirsky, S. B., Ackroyd, V. J., Ryan, M. R., & Pelzer, C. J. (2018). Evaluation of cover crops drill-interseeded into corn across the Mid-Atlantic. *Crops and Soils*, 51(5), 18–60. https://doi.org/10.2134/cs2018.51.0506

Dobbratz, M., Baker, J. M., Grossman, J., Wells, M. S., & Ginakes, P. (2019). Rotary zone tillage improves corn establishment in a kura clover living mulch. *Soil and Tillage Research*, 189, 229–235.

Dzvene, A. R., Tesfuhuney, W., Walker, S., & Ceronio, G. (2022a). Effects of intercropping sunn hemp into maize at different times and densities on productivity under rainwater harvesting technique. *Frontiers in Sustainable Food Systems*, 6, 1009443. https://doi.org/10.3389/fsufs.2022.1009443

Dzvene, A. R., Tesfuhuney, W., Walker, S., Fourie, A., Botha, C., & Ceronio, G. (2022b). Farmers' knowledge, attitudes, and perceptions for the adoption of in-field rainwater harvesting (IRWH) technique in Thaba Nchu, South Africa. *African Journal of Science Technology Innovation and Development*, 14(6), 1458–1475. https://doi.org/10.1080/20421338.2021.1960542

Fageira, N. K., Baligar, V. C., & Baliley, B.A. (2005). Role of cover crops in improving soil and row crop productivity. Communications in soil science and plant analysis, 36(19- 20), 2733–2757. https://doi.org/10.1080/00103620500303939

Gaimaro, J., Timlin, D., & Tully, K. (2022). Comparison of cover crop monocultures and mixtures for suppressing nitrogen leaching losses. *Agricultural Water Management*, 261, 107348. https://doi.org/10.1016/j.agwat.2021.107348

Gaiser, T., de Barros, I., Lange, F. M., & Williams, J. R. (2004). Water use efficiency of a maize/cowpea intercrop on a highly acidic tropical soil as affected by liming and fertilizer application. *Plant and Soil*, 263(1), 165–171. https://doi.org/10.1023/B:PLSO.0000047733.98854.9f

Gallo, K. P., Daughtry, C. S. T., & Bauer, M. E. (1985). Spectral estimation of absorbed photosynthetically active radiation in corn canopies. *Remote Sensing of Environment*, 17(3), 221–232. https://doi.org/10.1016/0034-4257(85)90096-3

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Research*, 114(1), 23–34. https://doi.org/10.1016/j.fcr.2009.06.017

Gitari, H. I., Nyawade, S. O., Kamau, S., Karanja, N. N., Gachene, C. K. K., Raza, M. A., Maitra, S., & Schulte-Geldermann, E. (2020). Revisiting intercropping indices with respect to potato-legume intercropping systems. *Field Crops Research*, 258, 107957. https://doi.org/10.1016/j.fcr.2020.107957

Hartwig, N.L., & Ammon, H. U. (2002). Cover crops and living mulches. *Weed Science*, 50(6), 688–699. https://doi.org/10.1614/0043-1745(2002)050[0688:AIACCA]2.0.CO;2

Hensley, M., Botha, J. J., Anderson, J. J., van Staden, P. P., & du Toit, A. (2000). Optimising rainfall use efficiency for developing farmers with limited access to irrigation water. Water Research Commission Report 878/1/00, Pretoria, South Africa.

Hiltbrunner, J., Streit, B., & Liedgens, M. (2007). Are seeding densities an opportunity to increase grain yield of winter wheat in a living mulch of white clover? *Field Crops Research*, 102(3), 163–171. https://doi.org/10.1016/j.fcr.2007.03.009

Hu, F., Gan, Y., Chai, Q., Feng, F., Zhao, C., Yu, A., Mu, Y., & Zhang, Y. (2016). Boosting system productivity through the improved coordination of interspecific competition in maize/pea strip intercropping. *Field Crops Research*, 198, 50–60. https://doi.org/10.1016/j.fcr.2016.08.022

Iqbal, M. A., Hamid, A., Hussain, I., Siddiqui, M. H., Ahmad, T., Khaliq, A., & Ahmad, Z. (2019). Competitive indices in cereal and legume mixtures in a South Asian environment. *Agronomy Journal*, 111(1), 242–249. https://doi.org/10.2134/agronj2017.11.0658

Jalilian, J., Najafabadi, A., & Zardashti, M. R. (2017). Intercropping patterns and different farming systems affect the yield and yield components of safflower and bitter vetch. *Journal of Plant Interactions*, 12(1), 92–99. https://doi.org/10.1080/17429145.2017.1294712

Jeranyama, P., Hesterman, O. B., & Sheaffer, C. C. (1998). Medic planting date effect on dry matter and nitrogen accumulation when clear-seeded or intercropped with corn. *Agronomy Journal*, 90(5), 616–622. https://doi.org/10.2134/agronj1998.00021962009000050009x

Kaneko, M., Uozumi, S., Touno, E., & Deguchi, S. (2011). No-till, no-herbicide forage soybean (Glycine max (L.) Merrill) cropping system with an Italian ryegrass (Lolium multiflorum lam.) living mulch. *Grassland Science*, 57(1), 28–34. https://doi.org/10.1111/j.1744-697X.2010.00205.x

Kunz, C., Sturm, D. J., Peteinatos, G. G., & Gerhards, R. (2016). Weed suppression of living mulch in sugar beets. *Gesunde Pflanzen*, 68(3), 145–154. https://doi.org/10.1007/s10343-016-0370-8

Lawson, A., Cogger, C., Bary, A., & Fortuna, A. M. (2015). Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. *PLoS One*, 10(6), e0129597. https://doi.org/10.1371/journal.pone.0129597

Leoni, F., Lazzaro, M., Carlesi, S., & Moonen, A. C. (2020). Legume ecotypes and commercial cultivars differ in performance and potential suitability for use as permanent living mulch in Mediterranean vegetable systems. *Agronomy*, 10(11), 1836. https://doi.org/10.3390/agronomy10111836

Liang, S., Grossman, J., & Shi, W. (2014). Soil microbial responses to winter legume cover crop management during organic transition. *European Journal of Soil Biology*, 65, 15–22. https://doi.org/10.1016/j.ejsobi.2014.08.007

Liedgens, M., Frossard, E., & Richner, W. (2004). Interactions of maize and Italian ryegrass in a living mulch system: (2) nitrogen and water dynamics. *Plant and Soil*, 259(1/2), 243–258. https://doi.org/10.1023/B:PLSO.0000020965.94974.21

Li, S., van der Werf, W., Zhu, J., Guo, Y., Li, B., Ma, Y., & Evers, J. B. (2021). Estimating the contribution of plant traits to light partitioning in simultaneous maize/soybean intercropping. *Journal of Experimental Botany*, 72(10), 3630–3646. https://doi.org/10.1093/jxb/erab077

Maitra, S., Hossain, A., Brestic, M., Skalicky, M., Ondrisik, P., Gitari, H., Brahmachari, K., Shankar, T., Bhadra, P., Palai, J. B., Jena, J., Bhattacharya, U., Duvvada, S. K., Lalichetti, S., & Sairam, M. (2021). Intercropping—A low input agricultural strategy for food and environmental security. *Agronomy*, 11(2), 343. https://doi.org/10.3390/agronomy11020343

Mhlanga, B., Cheesman, S., Maasdorp, B., Mupangwa, W., Munyoro, C., Sithole, C., & Thierfelder, C. (2016). Effects of relay cover crop planting date on their biomass and maize productivity in a sub-humid region of Zimbabwe under conservation agriculture. *NJAS-Wageningen Journal of Life Sciences*, 78, 93–101. https://doi.org/10.1016/j.njas.2016.05.001

Mia, M., Monaci, E., Murri, G., Massetani, F., Facchi, J., & Neri, D. (2020). Soil nitrogen and weed biodiversity: An assessment under two orchard floor management practices in a nitrogen vulnerable zone in Italy. *Horticulturae*, 6(4), 96.

Mirsky, S. B., Curran, W. S., Mortenseny, D. M., Ryany, M. R., & Shumway, D. L. (2011). Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. *Weed Science*, 59(3), 380–389. https://doi.org/10.1614/WS-D-10-00101.1

Mohammadi, G. R. (2010). Weed control in irrigated corn by hairy vetch interseeded at different rates and times. *Weed Biology and Management*, 10(1), 25–32. https://doi.org/10.1111/j.1445-6664.2010.00363.x

Mohammed, Y. A., Matthees, H. L., Gesch, R. W., Patel, S., Forcella, F., Aasand, K., Steffl, N., Johnson, B. L., Wells, M. S., & Lenssen, A. W. (2020). Establishing winter annual cover crops by interseeding into maize and soybean. *Agronomy Journal*, 112(2), 719–732. https://doi.org/10.1002/agj2.20062

Moore, K. J., Anex, R. P., Elobeid, A. E., Fei, S., Flora, C. B., Goggi, A. S., Jacobs, K. L., Jha, P., Kaleita, A. L., Karlen, D. L., Laird, D. A., Lenssen, A. W., Lübberstedt, T., McDaniel, M. D., Raman, D. R., & Weyers, S. L. (2019). Regenerating agricultural landscapes with perennial groundcover for intensive crop production. *Agronomy*, 9(8), 458. https://doi.org/10.3390/agronomy9080458

Morris, R. A., & Garrity, D. P. (1993). Resource capture and utilization in intercropping: Water. *Field Crops Research*, 34(3-4), 303–317. https://doi.org/10.1016/0378-4290(93)90119-8

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K., & Holman, J. D. (2015). Cover crop biomass production and water use in the Central Great Plains. *Agronomy Journal*, 107(6), 2047–2058. https://doi.org/10.2134/agronj15.0186

Ni, X., Song, W., Zhang, H., Yang, X., & Wang, L. (2016). Effects of mulching on soil properties and growth of tea olive (Osmanthus fragrans). *PLoS One*, 11(8), e0158228. https://doi.org/10.1371/journal.pone.0158228

Nurgi, N., Tana, T., Dechassa, N., Alemayehu, Y., & Tesso, B. (2023). Effects of planting density and variety on productivity of maize-faba bean intercropping system. *Heliyon*, 9, e12967. https://doi.org/10.1016/j.heliyon.2023.e12967

Paušič, A., Tojnko, S., & Lešnik, M. (2021). Permanent, undisturbed, in-row living mulch: A realistic option to replace glyphosate-dominated chemical weed control in intensive pear orchards. *Agriculture Ecosystems & Environment*, 318, 107502.

Payero, J. O., Marshall, M. W., Davis, R. H., Bible, J., & Nemire, N. (2021). Effect of Rye and mix cover crops on soil water and cotton yield in a humid environment. *Open Journal of Soil Science*, 11(05), 271–284. https://doi.org/10.4236/ojss.2021.115015

Pouryousef, M., Yousefi, A. R., Oveisi, M., & Asadi, F. (2015). Intercropping of fenugreek as living mulch at different densities for weed suppression in coriander. *Crop Protection*, 69, 60–64. https://doi.org/10.1016/j.cropro.2014.12.004

Qu, B., Liu, Y., Sun, X., Li, S., Wang, X., Xiong, K., Yun, B., & Zhang, H. (2019). Effect of various mulches on soil physico-Chemical properties and tree growth (Sophora japonica) in urban tree pits. *PLoS One*, 14(2), e0210777. https://doi.org/10.1371/journal.pone.0210777

Radicetti, E., Baresel, J. P., El-Haddoury, E. J., Finckh, M. R., Mancinelli, R., Schmidt, J. H., Thami Alami, I., Udupa, S. M., van der Heijden, M. G. A., Wittwer, R., & Campiglia, E. (2018). Wheat performance with subclover living mulch in different agro-environmental conditions depends on crop management. *European Journal of Agronomy*, 94, 36–45. https://doi.org/10.1016/j.eja.2018.01.011

Saleem, M., Pervaiz, Z. H., Contreras, J., Lindenberger, J. H., Hupp, B. M., Chen, D., Zhang, Q., Wang, C., Iqbal, J., & Twigg, P. (2020). Cover crop diversity improves multiple soil properties via altering root architectural traits. *Rhizosphere*, 16, 100248. https://doi.org/10.1016/j.rhisph.2020.100248

Sanders, Z. P., Andrews, J. S., Saha, U. K., Vencill, W., Lee, R. D., & Hill, N. S. (2017). Optimizing agronomic practices for clover persistence and corn yield in a white clover–corn living mulch system. *Agronomy Journal*, 109(5), 2025–2032. https://doi.org/10.2134/agronj2017.02.0106

Schmitt, M. B., Berti, M., Samarappuli, D., & Ransom, J. K. (2021). Factors affecting the establishment and growth of cover crops intersown into maize (Zea mays L. *Agronomy*, 11(4), 712. https://doi.org/10.3390/agronomy11040712

Shili-Touzi, I., De Tourdonnet, S., Launay, M., & Dore, T. (2010). Does intercropping winter wheat (Triticum aestivum) with red fescue (Festuca rubra) as a cover crop improve agronomic and environmental performance? A modeling approach. *Field Crops Research*, 116(3), 218–229. https://doi.org/10.1016/j.fcr.2009.11.007

Thapa, R., Tully, K. L., Reberg-Horton, C., Cabrera, M., Davis, B. W., Fleisher, D., Gaskin, J., Hitchcock, R., Poncet, A., Schomberg, H. H., Seehaver, S. A., Timlin, D., & Mirsky, S. B. (2022). Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. *Agriculture Ecosystems & Environment*, 326, 107823. https://doi.org/10.1016/j.agee.2021.107823

Thornton, P. K., Rosenstock, T., Förch, W., Lamanna, C., Bell, P., Henderson, B., & Herrero, M. (2018). A qualitative evaluation of CSA options in mixed crop-livestock systems in developing countries. *Climate smart agriculture: Building resilience to climate change*, 385-423. https://doi.org/10.1007/978-3-319-61194-5_17

Thorsted, M. D., Olesen, J. E., & Weiner, J. (2006). Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Research*, 95(2-3), 280–290. https://doi.org/10.1016/j.fcr.2005.04.001

Thorup-Kristensen, K. (2006). Effect of deep and shallow root systems on the dynamics of soil inorganic N during 3-year crop rotations. *Plant and Soil*, 288, 233–248. https://doi.org/10.1007/s11104-006-9110-7

Tribouillois, H., Cohan, J. P., & Justes, E. (2016). Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: Assessment combining experimentation and modelling. *Plant and Soil*, 401(1-2), 347–364. https://doi.org/10.1007/s11104-015-2734-8

Unger, P. W., & Vigil, M. F. (1998). Cover crop effects on soil water relationships. *Journal of Soil and Water Conservation*, 53(3), 200–207.

Vanlauwe, B., Wendt, J., Giller, K. E., Corbeels, M., Gerard, B., & Nolte, C. (2014). A fourth principle is required to define conservation agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crops Research*, 155, 10–13. https://doi.org/10.1016/j.fcr.2013.10.002

Wiggans, D. R., Singer, J. W., Moore, K. J., & Lamkey, K. R. (2012). Response of continuous maize with stover removal to living mulches. *Agronomy Journal*, 104(4), 917–925. https://doi.org/10.2134/agronj2011.0395

Wortman, S. E., Francis, C. A., Bernards, M. L., Drijber, R. A., & Lindquist, J. L. (2012). Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agronomy Journal*, 104(5), 1425–1435. https://doi.org/10.2134/agronj2012.0185

Yin, W., Yu, A., Guo, Y., Wang, Y., Zhao, C., Fan, Z., Falong, H., & Chai, Q. (2018). Straw retention and plastic mulching enhance water use via synergistic regulation of water competition and compensation in wheat-maize intercropping systems. *Field Crops Research*, 229, 78–94. https://doi.org/10.1016/j.fcr.2018.10.003

Zemenchik, R. A., Albrecht, K. A., Boerboom, C. M., & Lauer, J. G. (2000). Corn production with kura clover as a living mulch. *Agronomy Journal*, 92(4), 698–705. https://doi.org/10.2134/agronj2000.924698x

Zhang, Z., & Peng, X. (2021). Bio-tillage: A new perspective for sustainable agriculture. *Soil and Tillage Research*, 206, 104844. https://doi.org/10.1016/j.still.2020.104844