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REVIEW ARTICLE

# Living mulch in fruit and olive orchards. A review

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## Abstract

Sustainable weed management is a key challenge in fruit and olive orchards. Conventional practices, such as intensive weed control and monoculture, can degrade soil quality and reduce biodiversity, threatening long-term productivity. Living mulch, defined as an herbaceous soil coverage, grown alongside the main crop, represents a promising agroecological strategy for enhancing ecosystem services. However, current knowledge on living mulch in orchards remains fragmented, with studies often focusing on single ecosystem functions and providing context-dependent and sometimes contrasting results. This limits the ability to identify consistent patterns and to support practical decision-making. To address this gap, this systematic review synthesizes and integrates the available evidence on the effects of living mulch on orchard agroecosystems, focusing on weed suppression, soil fertility, biodiversity, soil physical and chemical properties, pest control, agronomic performance, and tree root system dynamics. Findings indicate that living mulch contributes to undesired species suppression (82 records), increases biodiversity and soil fertility (109 records), enhances soil microbial activity and nutrient cycling (120 records), improves soil structure and water retention (66 records), and supports beneficial insect populations for natural pest control (49 records). However, living mulch may also introduce challenges such as resource competition with fruit trees and potentially provide habitats for rodents. The magnitude of these effects varies depending on species selection, pedoclimatic conditions, and management practices. A satisfactory outcome of introducing living mulch in an orchard depends on selecting the appropriate living mulch species and management practices, as well as on shifting farmers' perspectives to emphasize the long-term ecosystem services of living mulches rather than focusing solely on short-term crop yield. A participatory approach involving farmers is essential for optimizing living mulch integration into orchard systems. Long-term studies are needed to assess the resilience and productivity of living mulch-based management strategies over time.

**Keywords** Cover crop · Orchard sustainability · Agroecology · Weed management · Biodiversity · Soil fertility

**Contents**



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## 1 Introduction

The soil hosts about 25% of described living species (soil biota) (Decaëns et al. 2006) and is the foundation of most ecosystem processes (Barrios 2007) and services, such as nutrient cycling, food and raw material production, the water cycle, climate regulation (emission and sequestration of greenhouse gases), carbon cycle, biodiversity regulation and biocontrol (resulting from the interactions of soil organisms), maintenance of genetic diversity, and recreation (FAO 2020). Intensive weed control, monoculture, use of fertilizers, and high specialization alter biological balances in the agroecosystem and lead to the degradation of natural resources upon which agriculture depends (such as land degradation, soil erosion, greenhouse gas emission, water contamination, loss of genetic diversity, and decrease in soil organic matter), requiring greater external inputs to maintain high yields and thus threatening future productivity (Granatstein and Sánchez 2009; Gliessman and Engles 2014; IPES-Food 2016).

The current and future challenge is to sustain the intensification of fruit orchards and to preserve the integrity of the environment at the same time. To achieve this goal, a new approach is required, based on the redesign of the orchard system and its components (Rosati et al. 2020). In this context, agroecology provides the knowledge and methodology to achieve sustainability while preserving high productivity (to meet the growing demand due to the increasing population) (Gliessman and Engles 2014). Agroecology can be defined as a multidisciplinary approach to food systems, which includes ecological, economic, and social dimensions (Francis et al. 2003). The agroecosystem is redesigned to enhance soil functionality and to prevent system failures (Gliessman 2020), with practices based on various ecological processes and ecosystem services (Wezel et al. 2014). The main aim of agroecological practices is to develop farming systems that mimic natural ecosystems and can self-regulate (Scherr and McNeely 2008; Doré et al. 2011). A general principle is: "the greater the structural and functional similarity of an agroecosystem to the natural ecosystem in its biogeographic region, the greater the likelihood that the agroecosystem will be sustainable" (Gliessman and Engles 2014). A term that can summarize this approach is ecological intensification, that consists of intensifying ecological processes in the cultivated space to enhance overall performance (Caron et al. 2014; Tittonell 2014). What is sought is not simply increasing biodiversity in the orchard agroecosystem, but introducing specific species whose functional traits influence the processes of interest (Bàrberi 2002). In fact, a few dominant species already guarantee ecosystem functioning while other species seem redundant, and gain importance only in the long term. The question is "which are the main services that the agroecosystem should provide?" (Moonen and Bàrberi 2008).

The part of biodiversity that is sought in an agroecosystem is called functional biodiversity. Moonen and Bàrberi (2008) defined functional biodiversity as "that part of the total biodiversity composed of clusters of elements (at the gene, species or habitat level) providing the same (agro)ecosystem service, that is driven by within-cluster diversity."

Therefore, the first step is to identify the type of biodiversity that is desirable to maintain and/or enhance in order to foster the ecosystem services and then to determine the best practices to achieve this goal. In the case of perennial crops, an agroecological approach aiming to avoid monoculture is the introduction of herbaceous ground cover, which increases ecological diversity and stability (Altieri 1999). Soil management in orchards is increasingly considering the growth of spontaneous or planted herbaceous species mainly in the soil between the rows and rarely along the tree row (Neri et al. 2022). The cover can be permanent or limited to a specific season and is referred to in the literature by various terms such as cover crop, grassing, or living mulch (LM). The meaning of each term is not consistent in literature; therefore, in this review the term LM will be used, considered as one or more herbaceous species that are planted or seeded and coexist with the main crop (Paine and Harrison 1993; Hartwig and Ammon 2002).

Farmers regard weed management as their primary concern within soil management strategies. However, they struggle to develop effective and economical weed management practices that can be also sustainable for the agroecosystem. The term "weed" cannot easily be defined, and its perception varies based on location, plant species, population size, and other factors. What a farmer considers a weed, may not be considered one by others. Weeds are defined purely in terms of human criteria based on their negative impact on cultivated plants, competing for resources (light, nutrients, and water) with cultivated plants and potentially reducing yields. Moreover, weeds lead to increased production costs—the costs of controlling them, and the insects and pests they harbor (Finney and Creamer 2008).

Fruit growers strongly believe that all these negative effects can dramatically reduce yields, and therefore they often aim to eliminate all weeds from the orchard, especially along the tree rows in specialized orchards (Lipecki 2006).

Generally, both integrated and organic fruit tree orchards are managed with grassing between the rows (recurrently mowed) and weeding along the row. The weed-free strip near the tree trunks (about 2 m) provides an area where tree roots can grow without competition; the grassed alley represents a zone for equipment transit, prevention of soil erosion, and increase of water infiltration (Roper 2005).

**Fig. 1** Living mulch (LM) with wild strawberry, along the row in Italian vineyard (ColleStefano, Castelraimondo, MC). Photocredit: F. Marchionni.

Cover crops are generally established in the inter-row (with wild species or selected seeded species) and the soil along the row is often managed through tillage or chemical weeding, that can provide effective and affordable weed control. The cover crops can suppress weeds by competing for light, nutrients, and space, and by creating a physical mulch after termination, thus providing effective and affordable weed control. However, this system does not address some of the problems of tilled or bare soil, which persist along the rows. Bare soil is known to negatively impact soil quality, especially regarding organic matter, nutrient availability, and soil structure (Granatstein and Sánchez 2009; Daelemans et al. 2022), and in some studies even tree growth was reduced, in case of coarse soils or shallow tree roots (Granatstein and Mullinix 2008; Bokszczanin et al. 2021).

There is therefore an increasing interest in studying the effects of vegetative soil cover in the orchards along the row, to implement new sustainable soil management strategies that combine environmental conservation and fruit production efficiency (Fig. 1).

The purpose of this review is to explore the use of living mulch (LM) in orchards and its impact on agroecosystem characteristics, highlighting the advantages and disadvantages of vegetative cover both in the inter-row and along the tree rows.

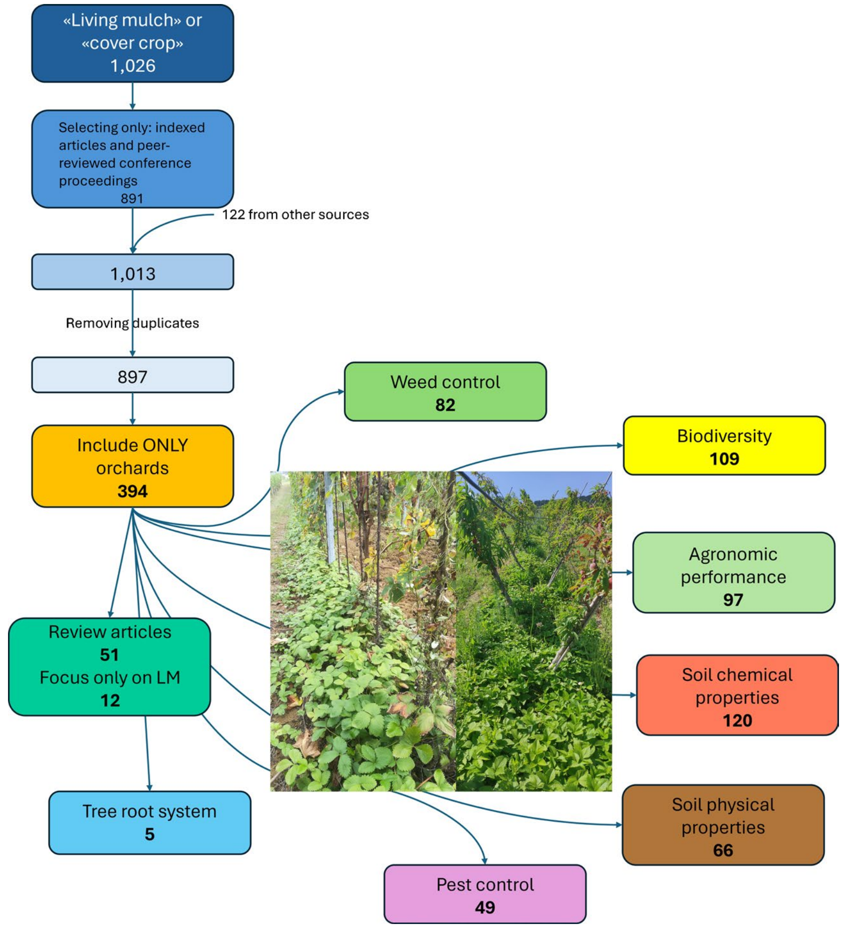
## 2 Methodology

The presence of LM in an orchard affects multiple aspects of the agroecosystem. Therefore, we conducted a systematic-narrative review, following the indication by Turnbull et al. (2023). First a broad literature search was performed, followed by specific sub-searches to explore the various factors influenced by LM. A general search was conducted on the Web of Science platform using the terms "living mulch" or "cover crop," yielding 1,026 articles. After filtering for research articles, review articles, and peer-reviewed conference proceedings, 891 records were retained. These publications were imported into Mendeley, and an additional 122 articles were retrieved from other sources. These sources included searches conducted at different times using similar criteria across PLOS, JSTOR, ScienceDirect, Oxford Journals, SpringerLink, Taylor & Francis Journals, and Wiley Online. After removing duplicates, 897 records were retained.

The initial screening focused on articles specifically related to orchards, reducing the dataset to 394 records. This subset formed the basis for subsequent sub-searches. The first sub-search identified 51 review articles, of which only 12 specifically addressed LM in orchards. Thereafter, six additional sub-searches were performed, each targeting a specific effect of LM: weed control, biodiversity, soil chemical properties, soil physical properties, pest control, and the tree root system (Fig. 2).

The records analyzed in the following chapters were selected from an initial set of 394 articles and classified into seven categories: weed control, biodiversity, agronomic performance, soil chemical properties (organic carbon content and nutrient availability), soil physical properties (porosity, bulk density, water infiltration, soil erosion, and temperature), pest control, and effects on the tree root system. Each record was assigned one or more category tags, and an UpSet analysis was conducted to visualize the

Fig. 2 Flow diagram of the systematic review.




distribution of records across the different categories and their interactions.

A manual screening was conducted within each category, selecting research articles that specifically focused on trials involving soil vegetative cover in orchards, where the primary objective was to assess the effects of LM. These selected articles were used for a narrative review of each category.

## 3 Results

An initial overview of the retrieved publications showed that research on LM in orchards has gained increasing interest within the scientific community, as indicated by a sharp rise in both the number of articles and citations over the past five years (Fig. 3).

Only a limited number of reviews (12) focused exclusively on LM in orchards, and each addressed one or a few specific effects of LM on the agroecosystem (Table 1).

Among the 394 articles, 120 addressed soil chemical properties, 109 focused on biodiversity, 97 on agronomic performance, 82 on weed control, 66 on soil physical properties, 49 on pest control, and 5 on the tree root system. The UpSet analysis (Fig. 4) highlighted soil chemical properties as the most frequently represented standalone category (49 articles addressed this topic exclusively). The most common category interactions were between agronomic performance and soil chemical properties, and between biodiversity and weed control, each represented by 18 articles.

The selected articles were also categorized according to the tree species considered. Most records included different fruit species (112). Among the monospecific studies, apple was the most represented (84), followed by olive (62), citrus *spp.* (46), pear (15), almond (13), peach (11), and grapevine (10). An additional 43 records concerned a total of 18 other species.

From the analysis of the articles selected, the presence of LM in orchards has an influence on the agroecosystem (Fig. 5). Living mulch can be established along the tree rows or in the inter-row areas, leading to various ecological and agronomic impacts. It increases biodiversity, including pollinators, predators, and pest species, potentially improving pest control. It helps control undesirable herbaceous species and may affect tree size and root distribution. Living mulch enhances soil quality by improving physical properties,

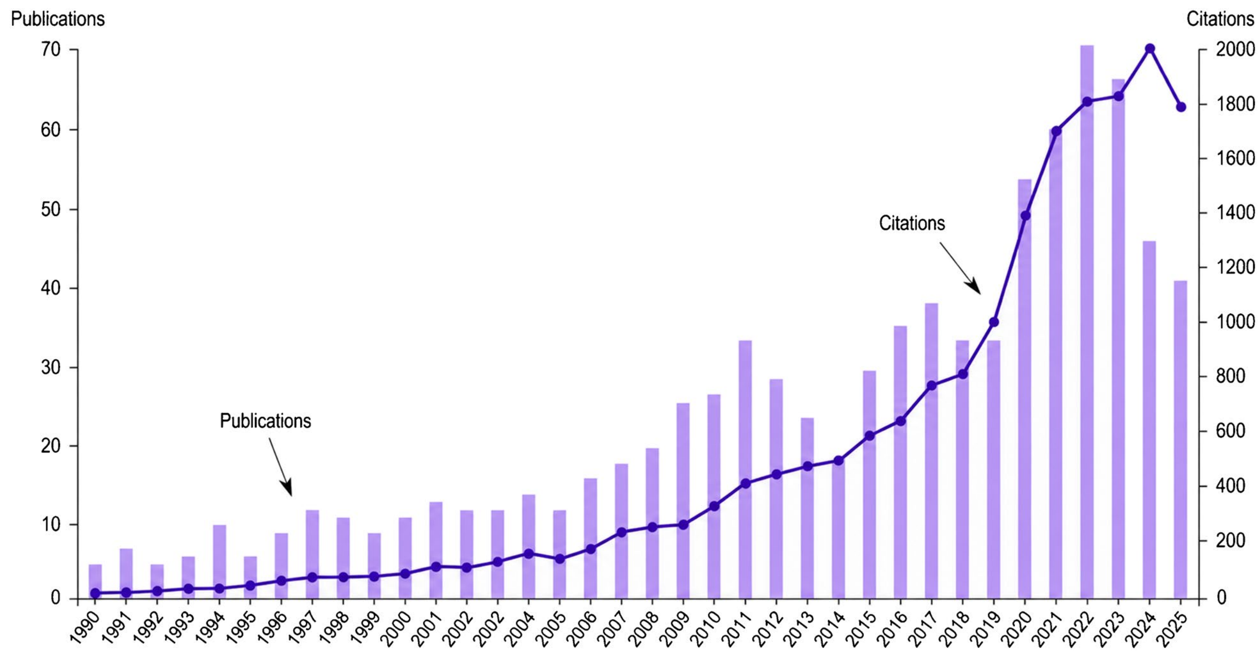



**Fig. 3** Publication and citation number over the years (from the Web of Science platform 15/05/2025).

microbial biodiversity, and nutrient cycling (N, K, P), as well as by increasing soil organic matter (SOM) and carbon sequestration. Additionally, it can lead to greater humus formation, reduction of allelopathic effects, and improved soil structure, which together contribute to better water retention, erosion control, porosity, and soil temperature regulation. In the following chapters, a narrative review of the selected articles will be presented.

### 3.1 Control of undesired weed species

The main reason of the use of living mulches is the control of weeds. Controlled plant diversity, through the introduction of specific functional species as living mulch, allows to better control undesired weed species. In fact, diversified farming systems show a lower weed density and biomass compared to conventional ones (Liebman and Davis 2000; Ngouajio and McGiffen 2002; Fonteyne et al. 2020. This occurs as a result of both direct and indirect effects, such as competition for growth factors (water, light and nutrients), prevention of seeds germination, and release of allelopathic compounds. The release into the soil of molecules with allelopathic effect (positive or negative) is a method for plant community organization and a way for plants to compete for soil niches occupation (Schenk 2006; Bonanomi et al. 2022). High weed biomass is related to a significant negative impact on crop yields. In fact, in simplified agroecosystems weed diversity has declined (due to intensive control), leading to the dominance of a few competitive, highly adapted and widely distributed weed species (Lisek and Sas-Paszt 2015). The presence of few herbaceous species (with similar resource requirement to the main crop) is detrimental to perennial crop productions. On the contrary, crop productions and weed diversity are positively correlated (Cierjacks et al. 2016; Ferrero et al. 2017; Storkey and Neve 2018; Adeux et al. 2019), since the competition is less pronounced where diverse species have different resources acquisition traits (Resource Pool Diversity Hypothesis) (Smith et al. 2010).

Different mulching species have been tested for their ability as LM to control undesired weeds. Plants belonging to the families of *Graminaceae* and *Fabaceae* have been more frequently tested as LM, both individually and in a mix (Steinmaus et al. 2008; Kitis et al. 2011; Isik et al. 2014; Mauro et al. 2015; Tursun et al. 2018; Scavo et al. 2022). In addition to the competition for growth factors, these two families have also shown allelopathic activities. Allelopathic effects of many herbaceous species have been studied as a tool to control undesired weed presence. Most of the studies exploring the allelopathic effect were concentrated on arable crops but the results could be applied also in fruit tree orchards (Putnam 1986; Narwal and Tauro 1994; Abbas et al. 2021; Khamare et al. 2022). Allelopathic effects of *Poaceae* have been studied intensively and their allelochemicals can be divided into four groups, with different mode of action: phenolic acids, hydroxamic acids, alkaloids, and quinones. These compounds can be found in different plant parts (grains, pollen, root exudates, etc.) and affect rate of germination, speed of germination, radicle length, root and shoot growth, emergence, plant density and biochemical and physiological processes (Sanchez-Moreiras et al. 2004).

**Table 1** Review articles identified through the systematic search on "Living Mulch and cover crop in orchards" and main topic treated

| Authors | Year | Title | Weed control | Pest control | Fruit performance | Biodiversity | Soil physical properties | Soil chemical properties |
|---|---|---|---|---|---|---|---|---|
| Mia et al. | 2020 | Sustainable alternatives to chemicals for weed control in the orchard – a Review | x | | | | | |
| Bugg and Waddington | 1994 | Using cover crops to manage arthropod pests of orchards: A review | | x | | | | |
| Silwana et al. | 2023 | Evaluating the effects and benefits of cover crops in citrus orchards: a review | x | | x | x | | |
| Simon et al. | 2010 | Biodiversity and pest management in orchard systems. A review | | x | | | | |
| Dzvene et al. | 2023 | Management of Cover Crop Intercropping for Live Mulch on Plant Productivity and Growth Resources: A Review | x | | | x | x | x |
| Steenwerth and Guerra | 2012 | Influence of floor management technique on grapevine growth, disease pressure, and juice and wine composition: A review | | x | x | | | |
| Giacalone et al. | 2021 | Are cover crops affecting the quality and sustainability of fruit production? | | | x | x | | |
| Fang et al. | 2022 | The effects of ground cover management on fruit yield and quality: a meta-analysis | | | x | | | |
| Gómez et al. | 2003 | Evaluating the impact of soil management on soil loss in olive orchards | | | | | x | |
| Rosati et al. | 2020 | Agroforestry and organic agriculture | | | | x | | |
| Hu et al. | 2022 | Organic carbon and nitrogen accumulation in orchard soil with organic fertilization and cover crop management: A global meta-analysis | | | | | | x |
| Novara et al. | 2021 | Cover crop management and water conservation in vineyard and olive orchards | | | | | x | |

Among *Fabaceae*, the allelopathic activity carried out by *Vicia villosa* has been widely studied. Cynamide was identified as the main allelopathic compound in this species and its action is related mostly to disturbances in cell division (Kamo et al. 2003; Soltys et al. 2011). *Trifolium pratense* also exhibit phytotoxic activities on other plants, mainly through the production and release of isoflavonoids (Liu et al. 2013b). Fine fescue grasses (*Festuca* spp.) produce root leachates containing M-tyrosine, a non-protein amino acid that has a natural herbicide effect on post-germination development and early establishment of neighboring plants (Khamare et al. 2022).

The success in weed control depends primarily on the study of weed population dynamics and crop-weed interference (Liebman and Dyck 1993); therefore, it is important to test different combinations of cover crop species for living mulch systems based on the prevailing local weed populations (Kitis et al. 2011).

### 3.2 Influence on agroecosystem biodiversity

Simplified cropping systems and monoculture lead to the accumulation of single crop residues that disrupts the humification processes and increases the release of toxic

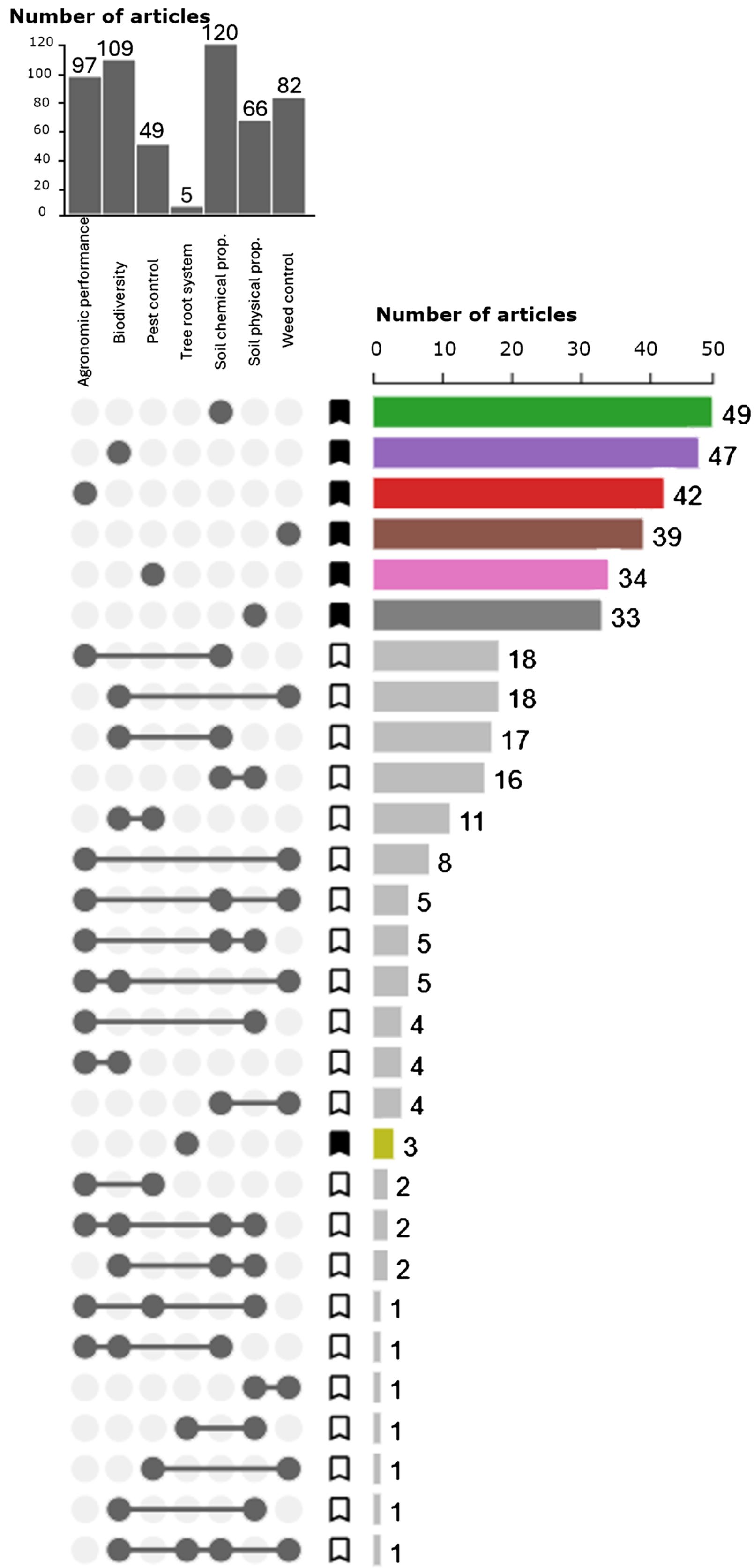



**Fig. 4** UpSet graph describing the distribution of the 394 dataset in 7 categories and relative intersections between categories. The bar chart (top left) shows the number of articles addressing each individual category. The matrix (bottom left) represents the combinations of categories, where each row corresponds to a specific combination and filled dots indicate the categories included. The bar chart on the right shows the number of articles addressing each combination of categories.

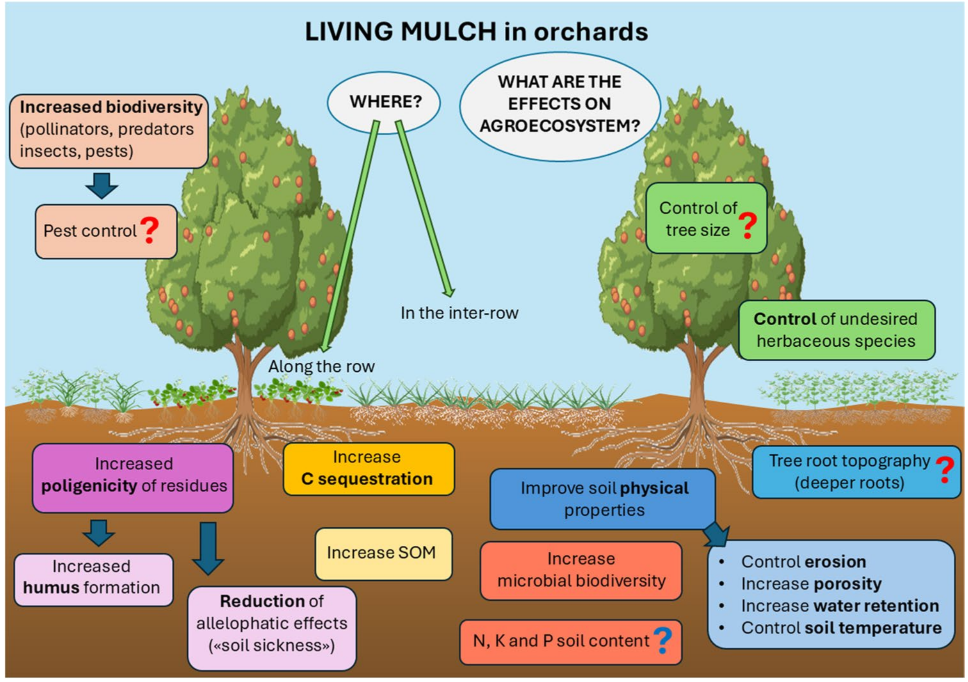



**Fig. 5** Effects of the LM on different agroecological parameters.

metabolites in the soil (Zucconi 1996). In fact, the substrate's monogenicity leads to a less diverse, specialized microbial flora. Under these conditions, the degradation processes are less efficient and humification is delayed, leading to a greater toxins release. This results in "soil sickness" (due to allelopathic effects of toxins) and, thus, precludes the return of the same species in the same field (Polverigiani et al. 2014). Biodiversity plays an important role in enhancing soil fertility. In fact, the presence of other plant species leads to high polygenicity of crop residues, which promotes the presence of a large community of microorganisms. Therefore, the variety of processes occurring simultaneously reduces the substrate's degradation time, keeping toxins release low and speeding up humus formation (Zucconi 1996; Gangatharan and Neri 2012; Neri 2013). Thus, living mulches enhance soil fertility, since they increase the amount of humified organic matter in the soil (Gandomkar 2018; Demir 2020; Scavo et al. 2021; Repullo-Ruibérriz de Torres et al. 2021).

Soil management techniques that enhance soil organic matter also promote root activity, longevity, and plasticity, increasing plant resilience, since allelopathic compounds (accumulated due to the presence of single crop residue) can cause root dystrophy, compromising root activity and plant growth. This is especially important in intensive systems, where techniques that promote root activity allow a more effective and stable water and nutrient uptake (Polverigiani et al. 2018).

Living mulched soils, show greater microbial flora biomass, biodiversity, and activity compared to bare soils (Moreno et al. 2009; Qian et al. 2015; Turrini et al. 2017). In fact, the high polygenicity of residues derived from the presence of a living mulch creates conditions for the establishment of a varied microbial flora. As mentioned before, the higher microbial biodiversity leads to a faster degradation of the organic matter towards the formation of humic compounds, keeping toxic metabolites production low. Organic matter degradation is leading to mineralization and humus formation. Biodiversity of the organic matter and of the microbial population leads towards humus formation and reduced mineralization, therefore enhancing soil long-term fertility. (Zucconi 1996; Gangatharan and Neri 2012; Neri 2013).

A balanced microbial flora supports plant growth, improves plant stress-resistance and can suppress soil pathogens (Shen 1997; Leary and Defrank 2000; Simon et al. 2010; Zepeda-Paulo et al. 2023; Malusà et al. 2023). Moreover, weed communities in terms of abundance, diversity, and functional traits are influenced by management of the vegetative cover. Undisturbed grassing (no-tillage) increases perennial presence in the weed community, while the use of annual cover crops (tillage and seeding) decreases species richness and abundance (Ciaccia et al. 2022; Lodolini and Ciaccia 2022). However, in some conditions, when the vegetal cover is perennial, the presence of a LM (selected species) compared to a spontaneous vegetal cover can bring an increase of biodiversity. In fact, spontaneous grassing, especially along the row, is managed with frequent mowings, that bring to a selection of species and therefore a reduction in biodiversity (Mia et al. 2020a, 2021; Sattler et al. 2024). Conservative management of the inter-row with a vegetative cover, combined with a living mulch along the row increases not only the wild species abundance, but also the presence of beneficial insects (pollinators and predators) (Las Casas et al. 2022).

### 3.3 Influence on soil chemical properties—organic carbon content and nutrients availability

The beneficial effects of living mulch (LM) on many chemical properties of agricultural soils are widely recognized, particularly in tree crops, where LM can be more easily adopted as a conservation practice compared to arable land. Studies conducted under various pedoclimatic conditions have demonstrated that the presence of LM increases the content of nitrogen (N), potassium (K), and organic carbon (C) compared to bare soil (Ordóñez-Fernández et al. 2018; Zhong et al. 2018; Wang et al. 2021). This effect is especially pronounced when leguminous herbaceous species are used (Fageria et al. 2005; Mullinix and Granatstein 2011; Qian et al. 2015; Lv et al. 2022).

Responses vary depending on the species used as LM; for instance, a single-species cover may increase one nutrient more than another (Repullo-Ruibérriz de Torres et al. 2021). Consequently, a more diverse cover, combining multiple species, may be more effective. If the fertilizing ability of LM is compared to that one of an organic amendment, the results show that in some cases, organic fertilization has a higher nutrient content than LM, particularly during the early years of LM establishment (Hu et al. 2022). The presence of LM could therefore be considered as a strategy for reducing fertilization and not an alternative to fertilization.

Furthermore, a permanent grass cover can lead to reduced phosphorus (P) availability, as observed in a meta-analysis by Morugán-Coronado et al. (2020). Nevertheless, this study also found that the presence of vegetative cover in the alleyways did not negatively impact fruit yields. Similar conclusions were reported by Repullo-Ruibérriz de Torres et al. (2021), who suggested that to prevent potential depletion of soil P and N and avoid yield reductions, it may be preferable to grow annual alley crops with minimal tillage rather than permanent crops with no tillage, particularly in dry and warm regions. Importantly, the reduction in P availability might be temporary, as it could be linked to competition for P absorption by herbaceous roots during the initial years (Chen et al. 2020).

Microbial biomass nitrogen, a significant sink for soil nitrogen, plays a key role in enhancing soil N dynamics. Greater microbial activity, stimulated by LM, makes nitrogen more readily available for the primary crop (Steenwerth and Belina 2008). For a more accurate understanding of nutrient availability, the seasonal fluctuations in microbial activity must also be taken into account. The phases of plant nutrient uptake should coincide with the availability of nutrients in forms readily accessible to plants. Furmanczyk et al. (2024) reported seasonal fluctuations in soil nutrient levels, showing differentiated effects among LM species.

Enhanced microbial activity and plant biodiversity lead to higher levels of carbon sequestration, as well as N, playing critical role for mitigating climate change. In fact, increasing root biomass through a groundcover implies larger total C in topsoil (while the amount of C in deeper soil layers depends mostly on-site conditions) (FAO 2020; Hirte et al. 2021).

### 3.4 Influence on soil physical properties—porosity and bulk density, aggregates formation and stability, water infiltration, soil erosion and temperature

The presence of living mulch is often associated with soil physical properties improvement, that is fundamental to increase the capacity of soil to receive water. As soil bulk density decreases along with the increase of soil porosity, higher water infiltration may occur even in the presence of very intense precipitations. The soil also becomes more capable of contrasting erosion, becoming able to preserve its thickness and superficial layers which are the most fertile layers in agricultural soils. At the same time, water storage can increase and form natural reserves particularly important in rainfed orchards to cope with periods of prolonged drought. In a recent study by Daelemans et al. (2022) tilled soil under the crop rows showed a lower bulk density than natural grasslands, while the presence of a permanent cover of vegetation in inter-rows allowed bulk density values comparable to semi-natural systems, which are likely to let water infiltrate and move into soil.

Amelioration of soil physical properties induced by living mulches (*Agrostis vulgaris* With. and *Festuca ovina* L.) was found in a 13-year field experiment, carried out in apple orchards in south-west Poland (Żelazny and Licznar-Małańczuk 2018). Plots with living mulches had higher soil porosity, capillarity, and non-capillarity pores, than soil treated with herbicide or covered with black woven polypropylene. Improvement in aggregates stability was also obtained in *Festuca* treatment and estimated as 1.38-fold increase of stable-to-unstable aggregates ratio. Despite soil porosity increased along with the potential for higher soil water content, fruit yield decreased likely due to living mulch competition for water. Nevertheless, the same authors argued on the possible higher vulnerability induced by living mulch on the young apple trees, since, in this study, living mulch was established contemporary to young trees. This condition could have impaired the ability of young roots to develop more efficiently into the deepest soil layers by exacerbating competition for water uptake.

The presence of a living mulch can also modify water soil balance and total evapotranspiration; the effect, however, depends on pedoclimatic conditions. In arid zones water consumption and evapotranspiration can be higher in soils with LM. However, water depletion of soils with LM can be limited to the more superficial layers as in a trial of intercropping of apple orchard with cocksfoot (*Dactylis glomerata* L.), seeded in the inter-row (Cao et al. 2021). The authors found that water depletion occurred specifically at first 0–100 cm soil layer in the covered inter-row, while it went to 0–200 cm along the tilled tree rows. Interestingly the increasing of the LM mowing frequency could reduce the negative effects on soil water content by not causing any significant impairment of apple yield.

The above-cited studies provide evidence on the amelioration of physical properties and water infiltration and storage but also warned on the importance of carefully choosing the suitable strategy to manage living mulch to avoid yield depletion, especially in rainfed orchards under semi-arid or temperate zones.

The presence of a green cover and the possible competition with the main crop can be counterbalanced by choosing LM species with commercial value. This kind of LM was tested in a rainfed organic almond orchard (*Prunus dulcis* Mill.) situated in Murcia (Spain) comparing common soil management (repeated plowing and tillage) with LM with aromatic caper (*Capparis spinosa* L.) or winter thymus (*Thymus hyemalis*) (Almagro et al. 2023). Three years after their implementation, cover cropped systems showed no overall significant effects on soil bulk density; however, winter thyme increased soil aggregation stability and soil available water content. Crop diversification did not significantly affect the main crop yields over a period of 3 years, nonetheless, it was concluded that, considering the global yield of annual aromatics plus almond, the intercropping with aromatics can improve the productivity of a monocrop orchard.

Besides increasing water infiltration and storage, the presence of living mulch can contribute markedly to reduce soil erosion that continues to be a major threat in many regions of the world since it causes depletion of the first soil layers with higher soil organic matter and nutrients content by also reducing optimum rooting zone (FAO 2019).

This was confirmed in experimental trials in different parts of the world, with different soil and climatic conditions. In 15-years field experiment conducted on a rainfed citrus orchards in south China (Tu et al. 2021), results highlighted that the establishment of grass mulching (with *Paspalum notatum* Flugge or *Cynodon dactylon* L. Pers.) was able to decrease bulk density and to increase soil porosity and field capacity when compared to clean tilled soil. Further, grass mulching limited soil erosion from the first year of experimentation. After 15 years, erosion in covered soil was on average 0.57% of that measured in clean tilled soil and strip or full grass mulching allowed 83.57% (annual average basis) of runoff reduction, being more efficient than tilled soil also under abrupt rainfall events.

The faster water absorption by covered soils can be caused by the improved soil bulk density and porosity, but the presence of the root system of the herbaceous cover plants has also a pivotal role. Roots can in fact promote water infiltration by creating pores during their development and by allowing conditions for soil particles binding. LM in an olive grove (23% slope) in tropical climate conditions showed little effect on soil bulk density and formation of aggregates, only a major tendency to the formation of soil crust and sealing of the soil pores was observed in bare soil. Nevertheless, the highest soil losses were observed in bare soil, especially at the beginning of the rainy season when high rainfall erosivity occurs. Water runoff reached half of the rainfall in bare soil while it was drastically reduced in the presence of cover crops (spontaneous vegetation with *Brachiaria decumbens* Stapf being the dominant species, seeded species like jack beans, millet, and sunn hemp) (Beniaich et al. 2023).

Results obtained in this short-period study suggest that living mulch, either spontaneous or selected, has an immediate effect in reducing runoff and soil erosion even in the absence of an effective improvement of the soil physical properties and farmers should decide to plant species in accordance with economic or technical aspects, which means, for instance, to choose species with conservative water use rates (low daily transpiration) and characterized by isohydric response to drought to preserve leaf water status and to cope with extended periods of water deficit (Ntshidi et al. 2021).

The positive role of LM in decreasing annual runoff to annual rainfall ratio was highlighted as well in olive groves and vineyards in the Mediterranean area (Novara et al. 2021). However, the effectiveness of cover crops to increase soil-water content is significant in regions where rainfall is higher than 700 mm $y^{-1}$, while it is not relevant in the drier areas where cover crops can compete for the available water with main crops. This fact may threaten yield in driest regions but can positively influence the yield quality in the rainiest areas. However, even in dry regions, if the rainfalls are concentrated and there are frequent downpour events, the covered soil proved to reduce water runoff and erosion (Keesstra et al. 2016; Márquez-García et al. 2024).

The presence of a permanent herbaceous cover in the field improves positively soil physical properties, also thanks to the greater soil microbial biodiversity (e.g., fungal hyphae capable of binding soil particles or earthworms that mix together soil and organic compounds in their gut), organic matter content, and root biomass (Russell 1971; Beare et al. 1997; Shepherd et al. 2002; Gucci et al. 2012).

The presence of a ground cover also has a soil temperature buffering effect (Lodolini and Ciaccia 2022): this is especially important in hot-dry seasons, where the plant can reduce the daily mean soil temperature and maintain soil moisture, reducing the risks of water and heat stress. This will influence fruit tree root growth in case of extreme temperatures that are more frequent with the changing climate conditions. For example, high summer temperatures in temperate climates are increasing in frequency and duration, and this impacts root wellbeing because the first 20 to 30 cm of soil are the more exposed to high temperatures and the more occupied by fruit tree roots (Giorgi et al. 2024; Guizzardi et al. 2024). Tree roots have an optimal temperature range (species dependent), and high air temperatures combined with high solar radiation on bare soils might increase temperature over the species limit for root survival (Barney 1951; Barr and Pellett 1972; Gur et al. 1972; Liu et al. 2013a). The presence of a vegetal cover of the soil reduces the temperature fluctuation at the surface and in the first soil layers, reducing the risks of high summer temperatures and low winter temperatures (Chen et al. 2004; Tang et al. 2022).

### 3.5 Pest control

One of the concerns of farmers regarding the presence of spontaneous species in their fields is that some weeds can be host plants for pest and pathogens and can hence cause a higher risk of plant illness development. On the other hand, considering an ecological point of view, it is true that plant biodiversity plays an important role in biological pest control (Gontijo et al. 2013; Galloway et al. 2021; Alvarez-Baca et al. 2023). Diverse plant communities provide multiple ecological benefits, such as floral resources that sustain natural enemies of pests, including parasitoids, predators, and pollinators. Moreover, the microclimatic conditions generated by heterogeneous vegetative covers such as increased soil and air humidity, moderated temperature, and reduced wind speed—can create favorable habitats for a wide range of insects and microorganisms. These conditions foster complex trophic interactions that contribute to the suppression of pest populations (Altieri et al. 2005; Paredes et al. 2013; Herz et al. 2019). It is important to note, however, that an increase in biodiversity does not automatically translate into more effective biological control. The effectiveness of natural enemies in regulating pest populations depends on their specific ecology, abundance, and interactions with other components of the agroecosystem (Eilenberg et al. 2001). Therefore, it is necessary to evaluate which species of natural enemies are present, under what environmental and management conditions they thrive, and how their activity translates into measurable pest suppression.

The results on the effect on development or reduction of pests in presence of LM are influenced deeply by many other factors, other than the presence of soil vegetal coverage. The management and distribution of the LM, for example, can influence the presence of natural enemies and the presence of pests. If the LM is limited to a narrow strip in the middle of the inter-row with a tilled or herbicide-treated row, for example, the effect of a higher microbial biodiversity and potential increase of pest enemies is limited to the inter-row and might not be enough to influence the canopy area (Bone et al. 2009). When the cover crop is monospecific and has a short-life cycle, its presence might not be enough to influence biodiversity changes in the agroecosystem. Rodríguez et al. (2009) compared a tilled soil in olive orchards, with a barely cover crop present over the soil only for a short time and preceded and followed by an herbicide treatment. This management did not affect the presence of main olive pests, probably because the short presence of the cover crop and the herbicide treatments could not increase biodiversity in the field. Different results are found if the vegetal coverage is more diversified and extended in time and space. In olive orchards, a permanent mixed grass cover managed with mowing is effective in modifying the arthropod community with increased number of predators for pests (Gómez et al. 2018). In apple orchards similar results were found with a mixed grass that showed increased biodiversity of beneficial and neutral canopy insects, with a greater effect of a non-mowed cover, where the seeded species were left uncut until flowering (Markó et al. 2013). Different studies on citrus orchards report an increase in biocontrol of pests with the use of LM, either by monitoring a direct reduction of the pest species or an increased presence of natural enemies (Aguilar-Fenollosa et al. 2011; Aguilar-Fenollosa and Jacas 2013; Tsuchida and Masui 2024). This effect can be LM species depended as reported by Aguilar-Fenollosa and Jacas (2013) or LM management dependent, with an increased biocontrol effect by a LM where the plant cycle is not interrupted by mowing and flowering seems to have a great effect on predators and pest population (Tsuchida and Masui 2024).

### 3.6 Agronomic performance of tree crop

The use of a vegetative cover might influence main tree crop growth and production. In fact, one of the main concerns of farmers for the adoption of LM strategies is the possible competition of the trees with the herbaceous plants for nutrients and water.

The literature reviewed provides a comprehensive overview of the effects of living mulch on fruit yield in orchards, revealing a high degree of variability among studies. Yield responses range from positive (27% of references) to neutral (30%) or negative (34%), some (5%) report a variable effect, reflecting the strong influence of crop species, orchard age, climatic conditions, soil characteristics, and living mulch composition and management. In several studies, yield increases were associated with improvements in soil physical and chemical properties and increased soil biological activity. These benefits were more frequently observed when living mulches were properly managed through mowing (Fu et al. 2023), or when the vegetable cover does not cover all the soil surface (Demir and Isik 2019, 2020a, b; Demir et al. 2019), or if it is not a permanent cover (Aengelo Rodrigues et al. 2015), allowing the reduction of competition with fruit trees while maintaining (at least partially) ground cover functions.

Conversely, a number of studies reported yield reductions (Slatnar et al. 2020; Sosna and Fudali 2024), mainly attributed to competition for water and nutrients between living mulches and trees. This effect was especially pronounced in young orchards (Foshee et al. 1995; Licznar-Małańczuk and Kwiecińska 2023), under rainfed or water-limited conditions, or when highly competitive species were used without adequate control (Hornig and Bunemann 1995). In these cases, excessive vegetative growth of the living mulch reduced resource availability for trees, negatively affecting fruit production.

Importantly, many authors found no significant differences in yield between living mulch systems and conventional orchard floor management (Sanchez et al. 2003; Sharifi et al. 2016; Lisek and Buler 2018; Tarantino et al. 2020; Mia et al. 2020a).

Other studies report a variable effect, depending on LM species (Marsh et al. 1996; Andersen et al. 2013; Fang et al. 2022), on tree species or cultivar (Garcia-Tejero et al. 2024), on the age of the trees (Foshee et al. 1995; Reeve et al. 2017) and on water availability (Garcia-Tejero et al. 2024).

These results suggest that, under appropriate management and site-specific conditions, living mulches can be integrated into orchard systems without compromising productivity. Overall, the reviewed studies indicate that living mulch represents a promising agroecological practice for orchard management; however, its impact on yield is strongly context-dependent and must be carefully evaluated in relation to local environmental conditions, orchard developmental stage, and management objectives.

### 3.7 Effect on the tree root system

The presence of a vegetative cover can significantly impact the growth of fruit trees, particularly in the root zone and, consequently, in the canopy. In bare soil, the root systems of fruit trees can utilize the entire soil volume available. However, introducing herbaceous species requires this volume to be shared with the root system of the LM. The natural development of roots depends on the species and is influenced by environmental factors. The presence of roots from another species may have either a repulsive effect or stimulate root growth. It is certain that tree roots will be influenced by the presence of LM roots, potentially leading to morphological changes, such as an increase in root hairs and enhanced mycorrhizal infection. Trinchera et al. (2017) reported these effects in artichokes grown with mixed LM.

In the literature, few studies have focused on the effect of LM on fruit tree roots, and the results are often contradictory. This variability arises because the effects depend on tree species, LM species, and pedoclimatic conditions. For instance, Mulinge et al. (2017) observed that orange tree roots increased fibrous root presence in shallow soil layers (0–40 cm) due to enhanced soil moisture caused by LM in a dry region. Conversely, Klodd et al. (2016) found that the presence of LM shifted vine roots to deeper soil layers, with a significant reduction in root density in the shallow layers. Similarly, Mia et al. (2021) reported that the effect of LM on apple tree roots varied depending on the LM species used, with higher root dry weight density observed in the presence of monospecific LM compared to natural grassing.

Generally, the presence of LM along the row tends to reduce root biomass of the tree crop and shift root density toward deeper soil layers. This adjustment creates a more resilient root system, as deeper soil layers are less susceptible to environmental changes and stresses, such as temperature fluctuations and water shortages. However, this adaptation may also reduce the aerial growth of the plant.

In some cases, this effect can be advantageous, as it may help control tree size. Controlled competition with herbaceous plants and limited soil volume for roots can reduce the vegetative growth of young trees, thereby accelerating the onset of the productive phase (Zucconi 2004). Living mulch has also been effectively used to reduce excessive vegetative growth in grapevines, with positive effects on grape quality, particularly regarding phenolic and anthocyanin content (Lopes et al. 2008; Muscas et al. 2017)

## 4 Critical issues of living mulch

Despite the numerous advantages, the orchard's response to living mulch is highly dependent on the cultivation site and the main crop variety and on the distribution of the cover. Since fruit trees are poor competitors with herbaceous plants, the cover crops can compete for resources and therefore its management is extremely important, as well as the correct choice of the species. The competition is higher with young trees, therefore in fields with limited resources where a competition between tree and living mulch is likely, living mulch along the row should be used only in established fruit orchards (Granatstein and Sánchez 2009, 2010; Muscas et al. 2017; Mia et al. 2020a). Moreover, Hammermeister (2016) suggested the use of living mulches in orchards where there is a great background soil fertility and where the risk of moisture stress is reduced by favorable climatic conditions or irrigation.

However, in a 16 years' trial, Atucha et al. (2011) found that, even though in the first 3 years the living mulch affected negatively tree performances, during the final decade the growth and yields were not statistically different from those in the weed-free plots. This result shows that fruit trees are able to adapt to the presence of a vegetative groundcover. Moreover, the degradation of soil health found in weed-free orchards is more detrimental than a short-term competition in the initial establishment of the living mulch.

The use of LM along the row can also create a suitable habitat for rodents (e.g., *Microtus* spp.) that can be highly destructive for fruit trees especially if the LM is along the row, where the main part of the fruit tree root is. The challenge is to find LM species with a repellency for rodents to prevent damages on trees (Wiman et al. 2009; Granatstein et al. 2010; Sullivan et al. 2018). For example, coumarin contained in the tissues of sweet woodruff (*Galium odoratum*) has shown a reduction in vole activity (Granatstein and Mullinix 2008). Plant secondary metabolites can be used as natural rodent repellents, such as essential oils and terpenoids (Hansen et al. 2016). Another alternative method to reduce vole damages on cultivated trees may be the use of alternative food sources in the field, that fulfill the minimal dietary requirements and that are more palatable than fruit trees (Sullivan and Sullivan 1973). Finally, a mechanical method can also be employed to prevent rodent infestations: the use of a horizontal blade weeder. Blade weeding facilitates the establishment of the selected LM species by cutting the taproots of the most aggressive weeds without disrupting the soil profile or harming shallow-rooted species. Additionally, the soil disturbance created by this method helps deter rodent populations (Neri et al. 2021).

## 5 Selection of suitable species

Living mulch species should be chosen according to the following: ecosystem services sought, main crop variety, agronomic characteristics (limited growth to limit competition with the main crop, quick ground cover to compete with undesired weeds, climate adaptation, and complementarity in the interception of resources), possibility of a second income, and capacity to repel rodents. Local species should be preferred due to their adaptation to the environment conditions and because imported species could become invasive.

Jannoyer et al. (2011) proposed a multicriteria evaluation grid for the choice of an "optimal" mulch species in the orchard, considering ecological, agro-economical, and socio-economical objectives and constraints, defined with the producers. The framework includes 3 steps and each one proceeds in a binary choice: if the species achieves the criteria, it is selected for the next step; if not, the species is rejected. The criteria are chosen according to the sought objectives. The first step consists in the selection of the species based on vegetative characteristics (e.g., height, perenniality, covering capacity). The second step takes into account practicability criteria (e.g., seed availability, farm constraints). The third step considers sought ecological services (e.g., weed competition, N fixing properties, auxiliaries hosting). However, choosing a single crop is generally not enough to cover all functional traits required, so mixing several species may be more efficient in the orchard system. Multi-specific living mulch may be also designed with specific spatial arrangements (e.g., legumes located understory for N fixing properties and grass in the inter-row for runoff control).

The use of a mixture of allelopathic cover crops can result in release of diverse allelochemicals and higher biomass that can synergistically suppress weeds efficiently (Khamare et al. 2022).

Moreover, as for cash crops, living mulch species should be rotated in order to avoid the build-up of plant-specific pests (Ingels et al. 1994).

## 6 Conclusion

This review confirms that effective weed management in orchard systems is increasingly associated with the diversification of cropping systems. However, the results also highlight that the successful implementation of such approaches is strongly constrained by local pedoclimatic conditions and socio-economic factors. In this context, a system-based approach should be preferred over weed control per se.

The findings of this review indicate that the paradigm now is no longer the total absence of weeds in the orchard (especially in the row), but their sustainable management (as living mulch) in order to obtain the desired services. Accordingly, the concept of "weed" changes meaning, from competitor to plant with a specific functional role in the orchard agroecosystem.

Across the reviewed studies, the presence of a permanent herbaceous cover showed multiple positive effects on orchard management. The use of living mulch can control undesired weed species and pests, while also contributing to tree size regulation. In addition, it enhances soil quality by increasing soil organic matter, stimulating microbial activity, and improving nitrogen dynamics. Furthermore, it improves soil physical properties, including erosion control, moisture retention, and temperature regulation, while reducing greenhouse gas emissions and promoting plant resilience (Fig. 5).

The review also highlights that, while vegetative cover in the inter-row (cover crops, CC) is now a well-established practice, the use of living mulch (LM) along the tree row is still less commonly adopted. Extending vegetative cover to the tree row has the potential to extend ecosystem and agronomic services to the entire orchard surface, particularly in zones of high root activity. However, the success of LM for farmers is often linked to its effects on the tree crop, which can range from reduced to increased growth and yield.

These findings underline that living mulch should be considered a context-dependent agroecological strategy rather than a uniform practice. Its successful adoption relies on the careful selection and management of species to balance ecosystem service provision and resource competition with the main crop. In this perspective, increasing farmers' awareness of the long-term benefits of living mulch, beyond short-term yield responses, may support its wider adoption.

Further long-term research is needed to better understand interactions between LM and the main crop and to assess how these systems evolve over time, so that the benefits of LM to the agroecosystem can be more accurately described and quantified.

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