Università Politecnica delle Marche
Scuola di Dottorato di Ricerca in Agraria
Curriculum in Dipartimento di Scienze Agrarie, Alimentari ed Ambientali
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Alternative orchard floor management practices in the tree row

Ph.D. Dissertation of:

Md Jebu Mia

Advisor:

Prof. Davide Neri

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Abstract

Orchard floor management in the tree row largely depends on chemical herbicides and soil tillage, and resulted in declining orchard biodiversity, soil quality, and proved to be detrimental to orchard sustainability. However, it can be restored by practicing more sustainable alternatives strategy either single or integrated. The practice should support covered soil with either spontaneous or selected living species in the tree row, as they can play a vital role in agroecosystem services and biodiversity improvement in the fruit orchard.

In the first study, two integrated mechanical approaches; integrated mowing (mower and brush or disc) and integrated tillage (blade weeder and integrated mowing), were compared with the standard herbicide system in two commercial apple and peach orchards in Marche region (Italy). Orchard biodiversity (soil coverage, species number and biomass production), soil quality (organic matter and nitrogen content), tree growth, fruit yield and quality were measured. Overall, both integrated practices demonstrated approximately 82%, 91% and 113% more species diversity, soil coverage, and weed biomass production, respectively, than the herbicide systems. Integrated mowing had a non-significant effect on soil organic matter and N availability; however, an improvement was noticed while maintained a balance in soil N status by reducing nitrate leaching. No negative effect was found on tree growth, tree physiological constituents, fruit yield, and quality. The average costs associated with chemical weed control were 66.5% and 72% lower, respectively, compared to integrated tillage and integrated mowing. However, the government subsidies provided to the orchardists to encourage sustainable management practices were able to offset such additional costs.

In the final study of the thesis, two selected living mulching species: *Alchemilla vulgaris* and *Mentha piperita* were compared with a mixture of natural vegetations with mowing (control) in an experimental organic apple orchard in Skierniewice, Poland. Both selected living mulches suppress weeds and enhance orchard biodiversity by producing 42.5% more dry biomass, 29% more species number, and 33% more soil coverage, compared to mowed plots. Apple leaf chlorophyll index and nutrient content were higher in selected living mulches plots than in control. In addition, they produced 30–46% higher apple root dry weight density (RDWD), while other root morphological traits such as root length (RL), root surface area (RSA), root diameter (RD), and root volume (RV) did not differ. These results suggest that the selected living mulching species can improve orchard biodiversity remarkably without impairing tree physiological constituents and root activity.

(Italian)

La gestione del suolo nel sottofila del frutteto dipende in gran parte dall'uso di erbicidi chimici e dalle lavorazioni e questo concorre al declino della biodiversità e della qualità del suolo, e infine risulta dannosa per la sostenibilità della coltivazione. Tuttavia, il declino del suolo può essere contrastato praticando strategie alternative più sostenibili, singole o integrate. La gestione dovrebbe mantenere il suolo coperto nel filare degli alberi con specie viventi spontanee o selezionate per il loro ruolo vitale nei servizi dell'agroecosistema e nel miglioramento della biodiversità nel frutteto.

Nel primo studio, due approcci meccanici integrati, la falciatura integrata (falciatrice e spazzola o disco) e la lavorazione integrata (sarchiatrice a lame e falciatura integrata), sono stati confrontati con il sistema gestito con erbicida standard in due frutteti commerciali di melo e pesco nelle Marche (Italia). Sono state misurate biodiversità del frutteto (copertura del suolo, numero di specie e produzione di biomassa), qualità del suolo (materia organica e contenuto di azoto), crescita degli alberi, resa e qualità dei frutti. Nel complesso, entrambe le pratiche integrate hanno dimostrato rispettivamente circa l'82%, il 91% e il 113% in più di diversità di specie, copertura del suolo e produzione di biomassa infestante rispetto al sistema gestito con erbicida. La falciatura integrata ha avuto effetti non significativi sulla sostanza organica del suolo e sulla disponibilità di azoto; tuttavia, è stato notato un miglioramento dell'equilibrio nel contenuto di azoto del suolo con riduzione del rischio della lisciviazione dei nitrati. Non è stato riscontrato alcun effetto negativo sulla crescita e sulla fisiologia degli alberi né sulla resa e sulla qualità dei frutti. I costi medi associati al controllo chimico delle infestanti sono stati rispettivamente del 66,5% e del 72% inferiori rispetto alla lavorazione integrata e alla falciatura integrata. Tuttavia, i sussidi forniti ai frutticoltori per incoraggiare pratiche di gestione sostenibile sono stati in grado di compensare tali costi aggiuntivi.

Nello studio finale della tesi, sono state realizzate pacciamature viventi con due specie selezionate: *Alchemilla vulgaris* e *Mentha piperita* a confronto con la vegetaziona naturale sfalciata regolarmente (controllo) in un meleto biologico sperimentale a Skierniewice, in Polonia. Entrambi le pacciamature viventi selezionate hanno soppresso le erbe infestanti e migliorato la biodiversità del frutteto producendo il 42,5% in più di biomassa secca con il 29% in più di specie (numero) e il 33% in più di copertura del suolo, rispetto agli appezzamenti falciati. La clorofilla e il contenuto di nutrienti nelle foglie di melo sono risultati più elevati negli appezzamenti con pacciamatura viva selezionata rispetto al controllo. Inoltre, hanno prodotto una densità del peso secco delle radici di melo (RDWD) superiore del 30-46%, mentre altri tratti morfologici delle radici come la lunghezza della radice (RL), l'area della superficie della radice (RSA), il diametro della radice (RD) e il volume della radice (RV) non sono stati modificati in modo significativo. Questi risultati suggeriscono che le specie utilizzate per la pacciamatura vivente possono migliorare notevolmente la biodiversità del frutteto senza compromettere la produttività degli alberi e l'attività delle radici.

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Chapter 1

Introduction

The orchard floor represents a substantial portion of orchard ecosystem which determines the tree growth, quality fruit yield, and orchard biodiversity. Literally, orchard floor management means managements of weeds, as they can highly compete with fruit trees for the available nutrients and water resources that are essential for plant growth. In a fruit orchard, the trees are grown in rows where the soil can be categorised into four distinct zones: (i) the planting row; (ii) the zone immediately adjacent to the planting row; (iii) the area between the planting rows, known as the alleyway, where there is a clear area compacted by the tractor wheels; and (iv) the free intermediate zone (i.e., the area between the two-wheel tracks of the tractor). Usually, cover crops are maintained in the alleyway, with frequent mowing to provide physical protection to the soil through stabilising and reducing soil erosion, as well as to support the wheel traffic, minimise compaction, increase the habitat available for beneficial insects, and suppress weed growth. However, it is a serious challenge for fruit growers to manage weeds in the tree row area, where the weeds can strongly compete with the fruit trees for water and nutrients, because of the low root density of the trees compared to the weeds (Merwin 2003). Therefore, it is crucial to manage weeds in the tree row to avoid adverse effects on tree performance.

In tree row management, chemical herbicides and soil tillage have dominated traditional weed management approaches in most perennial fruit orchards. The use of various chemicals such as herbicides and pesticides in fruit orchards might improve fruit yield, but this has been achieved at enormous costs to orchard biodiversity including human and environmental health. Some herbicides have been shown to be detrimental to ecosystem health and sustainability (Shorette 2012; Meng et al. 2016). The consequences generated by herbicide applications include declines in plant biomass, biodiversity, and soil quality (Jiang et al., 2016; Robinson and Sutherland, 2002; Yu et al., 2015), as well as contamination of underground water (Meng et al. 2016). Some studies have reported that chemical herbicides can substantially decrease the number of microbial communities and the earthworm population (Gaupp-Berghausen et al. 2015), while the persistent effects of weed suppression can lead to the reduction of nutrient availability and soil biodiversity (Gangatharan, Neri 2012). Eventually, this practice fosters the development and evolution of herbicides resistant weed species (Pieterse, 2010) and favors an insurgence of soil sickness (Polverigiani et al., 2018, 2014). In addition, tillage is proved to be effective in weed control as well, but has been associated with decreased tree growth, lower fruit yield, and fruit quality (Granatstein et al., 2010; Granatstein and Sanchez, 2009). Extensive uses of soil tillage can decline soil quality and plant biodiversity (Jiang et al., 2016; Mia et al., 2020a; Yu et al., 2015), as well as destroys the tree roots that are responsible for the absorption of moisture and nutrients (Hammermeister, 2016). These aforementioned issues are directly linked with orchard profitability and sustainability (Granatstein et al., 2014). Thus, the persistent use of chemical herbicides and soil tillage are of responsible for declining orchard sustainability (Yu et al. 2015; Robinson, Sutherland 2002; Meng et al. 2016).

Nowadays, the concept of weed management has achieved a broader meaning than in past decades, as it regulates the coenoses of orchard agroecosystems and turns into a consistent part of the agroecological approach in fruit orchards. Ground cover with living vegetation can deliver several agroecosystem services (Canali et al., 2015; Demestihas et al., 2017), by promoting functional agrobiodiversity in the orchard (Bianchi et al., 2013). Hence, adopting a sustainable orchard management strategy is vital for enhancing weed biodiversity, which can provide ecological protection (Granatstein et al., 2010) by offering feed and shelter to beneficial organisms (Bàrberi et al., 2018; Muscas et al., 2017), and improving soil fertility by hosting mycorrhizae, and thereby promoting nutrient availability (Kubota and Quideau, 2015) and resilience in the soil (Gangatharan and Neri, 2012). It can also play a crucial role in overall soil quality improvement by reducing soil erosion and increasing humification with improved organic matter in the soil (Rodrigues and Arrobas, 2020). In this regard, maintaining soil vegetation, while augmenting biomass production and species diversity can be considered as fundamental goals in sustainable orchard management systems. Despite the above ground biodiversity, understanding of below-ground biodiversity, especially apple root responses under the presence of living mulching species is also crucial to avoid the risk of unwanted competition. Root architecture parameters, especially root dry weight density (RDWD), root length (RL), root surface area (RSA) and root diameter (RD) allow to infer the root activity and behaviour under different soil conditions (Kumar and Jose, 2018), particularly of fine roots, which are mainly responsible for absorption of water and nutrients (Polverigiani et al., 2013). Soil organisms present in the rhizosphere greatly depends on the exudates released by the plant roots for their nourishment (Hoagland et al., 2008; Wardle et al., 2001). Thus, plant roots stimulate the microbial activity in the soil, which in turn, leads to mineralization and make the nutrients available to plants (Hoagland et al., 2008). The key is to practice more sustainable weed control strategies (Chandran, 2018) that support covered soil with spontaneous, or selected living species by keeping them at a density level that does not negatively impact tree performances (Mia et al., 2020). Moving towards more sustainable management techniques implies the possibilities of providing sufficient weed control and multiple ecosystem services simultaneously (Lemessa and Wakjira, 2015).

In high density fruit orchards, fruit yields and quality are controlled primarily by soil and nutritional management. Fruit growers prefer a more sustainable approach for sustaining soil fertility with greater nutrients and water availability, in an attempt to reduce competition between understory vegetation and fruit trees, while striving for increasing biodiversity, orchard resilience, and reducing risks of soil sickness (Polverigiani et al., 2018, 2014). Recently, contamination of soil and aquifers has become a serious concern for the fruit growers, due to excess nitrate leaching, and consequent contamination of water bodies in the area (Cui et al., 2020). Therefore, effective weed management has to be done to balance N availability, since too little N results in lower crop productivity. On the other hand, too much N leads to environmental pollution and its concomitant threats to ecosystems' health and functioning (Zhang et al., 2015). However, maintaining ground vegetation along the tree row can be a viable solution for these problems, because plants are capable of absorbing N from the soil throughout their cycle, while sequestering it in their tissues. Thus, they can deliver N into the soil during the process of decomposition (Atucha et al., 2011; Wang et al., 2016). For this reason, an eradication of understory vegetation along the trees row is not desirable in sustainable orchard floor management (Mia et al., 2020a). Managing orchard floors with living vegetation is a good agricultural practice to reduce the risk of potential leaching of nitrates (Cui et al., 2020). The European Union (EU) introduced agri-environmental measures (AEMs) to support farmers and reduce the environmental risks in sustainable rural development (Toderi et al., 2017). Therefore, a more ecological approach is highly recommended, particularly in vulnerable agricultural areas like Valdaso (central Italy), where small landholders operate high-input and low-efficiency fruit production systems (Cui et al., 2018).

In this paradigm, the project was designed to identify more sustainable alternatives to chemicals that could facilitate the small landholder farmers in Valdaso (central Italy) in transitioning to sustainable fruit production. An orchard must be managed in such a manner as to be economically viable, environmentally sound and socially acceptable (Granatstein, Kupferman 2008). Considering these aspects, priority is given to the integrated mechanical approach for enhancement of long-term orchard sustainability. Two Integrated systems; integrated tillage and integrated mowing were evaluated with chemical herbicides (glyphosate) at apple and peach orchards in Valdaso. It is the most important fruit production area in the Marche region (Italy) due to the historical presence of a high number of specialized fruit growers, where smallholder intensive farming systems dominate the agricultural landscape. Finally, in one of the most crucial Northern apple production area in Skierniewice (PL), two selected living mulch species were tested to control weeds and increase biodiversity in organic apple orchards. Therefore, this PhD project was conducted in the selected areas based on the following objectives and hypotheses.

Objectives and Hypotheses

1) Evaluate the impact of alternative orchard floor management practices on tree growth, fruit yield and quality.

Hi. Alternative orchard floor management will not decrease the tree growth, fruit yield and quality.

2) Measure the orchard biodiversity in terms of species number and their coverage and weed biomass production.

Hii. Alternative orchard floor management will enhance overall orchard biodiversity.

3) Determine the effect of alternative orchard floor management on soil quality parameters including soil nitrogen and organic matter content.

Hiii. Alternative orchard floor management will have a positive effect on soil quality parameters.

4) Measures the weed biodiversity, tree physiological constituents and morphological root traits under selected living mulches in the tree row.

Hiv. Two selected living mulching species will not have a negative effect on apple growth and morphological root traits, but they could increase biodiversity.

The dissertation is written in six chapters to address the above-mentioned goals. Chapter 1 provides a general introduction to orchard floor management including problems with chemical and soil tillage, followed by the significance of achieving sustainable alternative practices in the tree row. Chapters 2, 3, 4, and 5 have been written in multiple paper formats. Chapter 2 has been published in Horticultural Science (Prague). This is a review paper that summerize literature on various sustainable alternative orchard soil management and their possibilities in the fruit orchard. Chapter 3 has been published in Agronomy (Basel). This paper focused on objectives 1 and 2, which assessed the effect of two integrated mechanical approaches on orchard biodiversity, fruit yield, and quality observed in 2018 to 2019. Chapter 4 has been published in Horticulturae (Basel), where we evaluated objective 3 about soil quality parameters and weed biodiversity from 2018 to 2019 under two orchard floor management practices. Chapter 5 covered objective 5, and it has been published to Horticulturae (Basel), where we discussed the effect of selected living mulching species on weed control, weed biodiversity, and root interactions between herbaceous species and apple trees, in 2020. Chapter 6 will provide a synthesis of the findings of the whole PhD project and describe the implications for growers looking to adopt more sustainable alternative orchard floor management practices in the tree row and propose directions for future research.

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Chapter 2

Sustainable alternatives to chemicals for weed control in the orchard – a Review

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2.1. Abstract

This review is designed to address various alternative weed control practices and their possibilities in the fruit orchard in terms of sustainability. Correct weed management and maintenance of adequate orchard biodiversity are crucial for sustainable orchard soil management. The key is to practice an alternative weed management approach (single or integrated) rather than to use possibly harmful chemicals only. Integration of modern equipment with a shallow tillage system can provide effective weed control in tree rows, including optimised tree performance and soil biodiversity. Living mulch suppresses weeds and enhances orchard biodiversity, while selection of less competitive and less pest-attracting species is crucial. Plastic covers offer long-term weed control, but additional nutrient amendments are required to maintain the balanced fertility of the soil. Wood chip mulch is suggested where the materials are available on or near the farm, and where there is lower incidence of perennial weeds. High pressure water and robotic systems are still in their infancy for fruit orchards and required more research to confirm their efficiency.

Keywords: biodiversity; soil quality; integrated mowing; mulching; precision weed control

2.2. Introduction

Chemical herbicides have dominated traditional weed management approaches in most perennial fruit orchards. The use of various chemicals such as herbicides and pesticides in fruit orchards might improve fruit yield, but this has been achieved at enormous costs to orchard biodiversity and soil and human health. Some herbicides have been shown to be detrimental to ecosystem health and sustainability (Shorette, 2012; Meng et al., 2016). Further problems have followed too, such as soil acidification (Kibblewhite et al. 2008), soil infertility and contamination of other natural resources, particularly the underground water table (Meng et al., 2016). Some studies have reported that chemical herbicides can substantially decrease the number of microbial communities (Grossbard and Davies, 1976) and the earthworm population (Gaupp-Berghausen et al., 2015), while the persistent effects of weed suppression can lead to reduction of nutrient availability and soil biodiversity (Gangatharan and Neri, 2012). Soil biodiversity has an important role in efficient root functioning, as has been demonstrated for monocultures, where monospecific organic residues can disrupt root behaviour for several species (Endeshaw et al., 2015a, b; Polverigiani et al., 2018 a, b). Thus, the persistent use of chemical herbicides and soil tillage can result in an impoverished soil quality, as well as decreased plant biodiversity (Yu et al., 2015; Robinson, Sutherland 2002; Meng et al., 2016). Moreover, another particular problem is that weeds are becoming more tolerant, and indeed resistant, to chemical herbicides due to their extensive application in farming systems (Pieterse, 2010). Taking the above into account, there is an urgent need to reduce and gradually overcome this reliance on chemical herbicides to sustain optimum soil health and orchard biodiversity.

Weed management in the fruit orchard is crucial to diminish competition for water and nutrients during the early critical period of tree growth, and to increase productivity of the fruit trees (Granatstein and Sánchez, 2009). Additionally, correct weed management in the orchard can have an important role towards operation of orchard machinery, reduction of pest habitats (e.g., for voles), and contributions to satisfactory economic benefit through the production of quality fruit (Hammermeister, 2016), as required by the market. In a fruit orchard, the trees are grown in rows where the soil can be categorised into four distinct zones: (i) the planting row; (ii) the zone immediately adjacent to the planting row; (iii) the area between the planting rows, known as the alleyway, where there is a clear area compacted by the tractor wheels; and (iv) the free intermediate zone (i.e., the area between the two-wheel tracks of the tractor). Usually, cover crops are maintained in the alleyway, with frequent mowing to provide physical protection to the soil through stabilising and reducing soil erosion, as well as to support the wheel traffic, minimise compaction, increase the habitat available for beneficial insects, and suppress weed growth. However, it is a serious challenge for fruit growers to manage weeds in the tree row area, where the weeds can strongly compete with the fruit trees for water and nutrients, because of the low root density of the trees compared to the weeds (Merwin 2003). Therefore, it is crucial to manage weeds in the tree row such that they do not have any adverse effects on tree performance.

The standard system for managing weeds in the tree row is to maintain a 0.6-m- to 2.0-m-wide vegetation-free strip in the tree row, which is managed using chemical herbicides in most orchards (Lisek, 2014). In this context, orchard biodiversity can be lost through complete eradication of the weeds from underneath the trees and between the tree row areas, which is not desirable for sustainable orchard floor management systems. Maintenance of vegetated soil in the tree rows might have a vital role for reduction of soil erosion, and provision of food for natural predators and a habitat for beneficial soil microorganisms. Therefore, it is essential to maintain vegetal soil with beneficial and less competitive plants in the tree rows. This can be achieved through different alternative methods to chemicals in sustainable orchard floor management systems, which when embraced appropriately, will not only protect from soil structure degradation and nutrient leaching, but also improve orchard biodiversity and root trophism.

Farmers have several alternative options available for weed control in the orchard, through which they can manage weeds in more sustainable ways. The selection of the correct weed-management method is crucial, as this can have significant effects on tree performance and fruit quality (Van Huyssteen and Weber, 1980; Guerra and Steenwerth, 2012), as well as on orchard biodiversity. The choice of the appropriate alternative strategy for sustainable weed management largely depends on type and age of the plants, the types of weeds present in the orchard, costs and availability of labour and materials, the kind of soil and its fertility, and the ideology of the farmers (Hammermeister, 2016). Furthermore, the weed management will depend on the critical weed-free period required for the orchard, and the ecological footprint of the strategy itself.

A sustainable orchard floor management system depends on the three pillars of economics, ecology and equity. These indicate that an orchard must be managed in such a manner as to be economically viable, environmentally sound and socially acceptable (Granatstein and Kupferman, 2008). To keep these pillars firm and steady, the use of alternative man- agement systems either alone or integrated with the more standard practices should be encouraged. The main purpose of this review is to address the different alternative weed-management strategies and their efficacy for management of weeds in fruit orchards in terms of sustainability, quality fruit yield, and satisfactory orchard biodiversity.

2.3. Alternative options to chemicals for orchard floor management

There are several alternatives to chemicals that have been proposed for orchard floor management over different periods. All orchard-floor options have both ‘pros’ and ‘cons’ (Granatstein et al., 2010). In this section, we discuss the key sustainable alternative weed-management strategies in fruit orchards. These include mechanical practices (e.g., tillage and integrated mowing, modern finger weeders), mulching (e.g., living mulch, organic mulch, plastic mulch), thermal weed control (e.g., flaming, steaming), high-pressure weed control (e.g., water jet blasting), and precision weed control (e.g., robotic systems).

2.3.1 Mechanical weed control

Adverse effects of chemical herbicides and the increasing popularity of organic farming have led to the need for further advances in mechanical weed control. These systems are mainly associated with different cultivation and tillage systems, integrated mowing (e.g., brush weeder plus mower), and modern finger weeders. Weed management with traditional mechanical systems can have a substantial number of negative effects on orchard soil health and biodiversity, but it is possible to minimise these problems by using advanced integrated mechanical systems.

2.3.1.1 Tillage

Tillage is one of the key primary alternative weed control methods for perennial fruit trees in many countries (Jordan, 1970; Lange, 1970; Giudice, 1981; Suzuki, 1981). This provides weed control in the tree row more effectively and conveniently compared to other approaches. However, different kinds of tillage operations need to be considered, including hand weeding, hand hoeing, harrowing, rotary hoeing, and the use of rototillers, cultiva- tors, brushes and discs (Bond, and Grundy, 2001).

Hand weeding and hand hoeing are the most ancient forms of weed control, and these continue to be used in some countries, as specifically in developing countries where manual labour is more readily available at relatively low cost (Hammermeister, 2016). The hoe is the simplest form of tillage implement, and it can be effectively used in the zone immediately around young trees, to avoid trunk injury during the operation of other mechanical equipment, and thus to increase the efficacy of the other tools used (Bradshaw, 2017). Hoeing is more useful for the control of annual and biennial shallow-rooted weeds, especially in areas where the field and/or climate are not favourable for mechanised systems or where there is a lack of technical knowledge (Bond, and Grundy, 2001).

Cultivators and rototillers are the main mechanised tillage equipment used. These are easy to operate, but they only provide weed control in the areas adjacent to the tree rows, and cannot provide weed control between the trees in the rows as they are fixed to the tractor (Hammermeister, 2016). However, modern tillage equipment, such as the ‘Wonder Weeder’ and the ‘Hydraweeder’, can access the areas between the trees using their hydraulic systems, and thus provide efficient weed control in this zone (Granatstein, Sánchez, 2009), while also

ensuring substantial reduction in the labour required (Granatstein et al., 2014). Similarly, other modern implements include the 'Weed Badger' (USA), the 'Rinieri Cultivator' (Italy), and the 'Weed Hoe' (Spain), which can cultivate the areas between the trees along the rows. Their operation can be maintained either automatically or manually, depending on the age of the trees and vines. For example, a hydraulic system can be used for established trees, and a manual system for small trees and bushes (Hammermeister, 2016).
Tillage has several beneficial factors. According to Hammermeister (2016), "it is less labour intense and capable of decomposing soil organic matter through soil disturbance, soil aeration, improved soil moisture status, and improved accessibility of decomposers to organic residues". However, as well as these benefits, excessive use of tillage can have substantial harmful effects on the soil quality parameters, including biological diversity, soil structure and water holding capacity (Merwin et al., 1994). Tillage reduces the supply of carbon and nitrogen nutrients to microbes (Sanchez et al., 2001; Hoagland et al., 2008). Granatstein and Sánchez (2009) also reported adverse effects of tillage for the soil cation exchange capacity and the available phosphorous nutrients, with the consequent reduction of 13% in the soil organic matter. The use of conventional tillage equipment close to the trees has also been associated with tree growth reduction, lower fruit yields and smaller fruit sizes (Neilsen et al., 2003; Granatstein and Sánchez, 2009; Granatstein et al., 2010). Furthermore, several studies have demonstrated detrimental effects of tillage on the soil microbial composition, enzyme activities and biological processes (Dick ,1984, 1992; García-Ruiz et al., 2008), as well as on trunk size and pruning mass of the trees (Wooldridge and Harris, 1989). Tillage also destroys the tree roots near the soil surface that are responsible for the absorption of moisture and nutrients (Hammermeister, 2016), thus reducing root abundance by 52.9% in comparison with herbicide control, and by 77.8% in comparison with straw mulch (Van Huyssteen, Weber 1980). For this reason, one of the major topics to be studied in this field is the depth of tillage, to find out the minimum depth at which the implements can be use so as not to adversely affect tree performance (Granatstein and Sánchez, 2009).
Some studies have shown that considering the overall pros and cons, tillage might represent the most economically sustainable method for weed control compared to other alternative approaches, such as steaming or use of organic herbicides (Shrestha et al., 2013). The key problem with tillage is the lack of environmental sustainability. In this regard, the practice of a shallow tillage system with advanced equipment might be the sustainable solution to the problems related to the more traditional tillage equipment. A blade weeder is such a kind of shallow tillage tool. This might provide an effective weed-control option for tap-root species, as it can be used horizontally at just 3 cm to 4 cm under the soil, and it causes little soil disturbance compared to other conventional tillage equipment. Therefore, studies are ongoing to investigate the integration of this practice with the other available options to provide an integrated tillage system for sustainable weed management in the fruit orchard.

2.3.1.2 Integrated mowing

Integrated mowing in terms of a brush weeder plus a mower can be an excellent sustainable alternative strategy for weed management in the tree rows. In this system, two advanced types of equipment are used simultaneously: a rotary brush weeder, and a mower. Brush weeders have a poly propylene brush mounted on a horizontal axis that is powered by the tractor power take-off. This can bend down the weeds even near to the tree trunk without any trunk damage, and at the same time the mower can cut and shred the weed plants just above the soil surface without disturbing the soil (ongoing research). Thus, the maintenance of the vegetal soil underneath and between the trees is possible, and this might also increase biomass production (Neri, 2013). The shredded weed plants can also serve as mulching material, as well as improving the soil nutrient status through the decomposition of the chopped plant materials in the soil, which can subsequently provide efficient erosion control and enhance the organic matter, to provide better soil structure. Also, only one person is required to operate this technique, and while it is new to the fruit orchard, it has been found to be useful on vegetable farms for weed management (Tei et al., 2003; Tei and Pannacci, 2005; Turner et al., 2007). In another comparative study, Vester and Rasmussen (1990) reported that a brush hoe is more efficient than a conventional hoe when compared to horticultural crops, and this might be due to the possibility to work very close to the plant row. In addition, the most important part of this integrated technique is that it can control weeds while also improving soil quality, biodiversity and tree productivity, which are the ultimate goals of sustainable orchard management.

2.3.1.3 Modern finger weeders

Finger weeders represent another advanced technology for weed management of perennial fruit trees, and their use is now achieving public acceptance due to their environmental sustainability and their high working efficiency. Finger weeders are available with two adjustable hydraulic widths, with the bearing frame equipped with two starshaped discs mounted at the ends. The first special steel disc positioned at the front of the frame works vertically on the ground and parallel to the plants, to break the soil crust and accumulate the soil under the tree row. The second rubber disc is positioned behind the frame, horizontal to the ground, and this eliminates the weeds between the plants (Source: Berti Macchine Agricole). Due to the use of rubber, this provides gentle weed control around the plant, just above the soil surface. These finger hoes are available in various versions with different hardnesses. The hardness of finger hoes is indicated using multiple colours; e.g., red indicates hard; yellow for medium; and orange for soft. The choice of a finger hoe thus depends on the type of soil and the type of weeds. In horticultural crops, some studies recommend their use in areas with loose soil and during the early stages of weed growth (Pannacci and Covarelli 2005; Panacci et al., 2008; Pannacci and Tei, 2014), because they perform poorly in heavily compacted soil, like clay, and the efficacy of this technique decreases with the age of the weed plants, and especially for grasses (Pannaci et al., 2017).

There have been recent advances in finger weeders for management of vineyard weeds, whereby different companies have developed various forms of finger hoes (e.g., Kress, Stekketi and Berti, in Germany, The Netherlands and Italy, respectively), through which farmers can control intra-row weeds in fruit orchards in the same way as in vineyards. It is expected that this advanced practice will provide excellent weed management in the tree rows with little soil disturbance, which will maintain orchard biodiversity with economic sustainability due to their efficiency, reasonable cost, and eco-friendliness.

2.3.2 Mulching

Mulching is one of the best alternatives to chemicals, as it minimises weed problems in the fruit orchard by suppressing weeds at an early growth stage. The main aim of mulching is to conserve the soil moisture and suppress weed growth. The additional advantage of mulching includes the management of temperature fluctuations, improved physical, chemical and biological characteristics of the soil, and the ultimate enhancement of orchard biodiversity (Polverigiani et al., 2013). However, mulches are available in different forms, which include natural mulches, such as living mulch, straw, sawdust, weeds, paper, and plant residues, and synthetic mulches, like plastic. These mulching forms can be used either alone or with integration with other practices in a 'sandwich system' (Tahir et al., 2015), with various combined techniques suggested (Granatstein and Sánchez, 2009) for effective weed management and maintenance of biological diversity in the orchard.

2.3.2.1 Living mulch

Living mulches might be one of the best sustainable practices for tree-row weed management. These are growing plants, and they have the potential to reduce nutrient leaching (especially of nitrates) along with the absorption of carbon and nitrogen (Żelazny and Licznar-Małańczuk, 2018).

Moreover, as well as reduction of nitrate leaching, the use of living mulches provides efficient control of soil erosion, builds up the organic matter for better soil structure, and provides a habitat for beneficial insects (Tedders, 1983; Liang and Huang, 1994; Lacey et al., 2006). Living mulches also contribute to root exudates and labile residues, to thus improve nutrient cycling and retention through stimulation of the soil biota (Rovira et al., 1990; Wardle et al., 2001). However, the benefits of this practice can come with certain drawbacks, such as competition with the fruit trees for water and nutrients, and reduced plant growth and yield (Granatstein and Sánchez, 2009; Tahir et al., 2015). One study reported that living mulches can prevent tree root development and distribution, by limiting their access to the soil surface moisture (Yao et al., 2009). Therefore, Hammermeister (2016) recommended this practice at areas with fertile soils, a sufficient water supply, and the absence of perennial weed species, conditions that will thus improve the efficiency of the living mulches. In addition, living mulches should be used only with established fruit trees, as the competition for water and nutrients is a lot greater at the early stages of tree growth.

The selection of the living mulch species has a significant effect on suppression of weeds and tree performance. Many plant species have been tested as living mulch, especially for vegetables, where more attention has been focussed on leguminous plants, and especially white clover (*Trifolium repens*), as these can supply nitrogen (Neilsen and Hogue, 2000) and provide improved soil biology through root exudates (Granatstein and Mullinix, 2008). One study indicated that yield losses for apple from 11% to 24% can occur depending on the living mulch species used (Hogue et al., 2010). Neilsen and Hogue (2000) tested white clover as the living mulch in an apple orchard, and they reported that while it supplied nutrients to the soil, it also reduced the fruit yield compared to a vegetation- free control. Freyman (1989) reported higher berry yields when mulching with white clover compared to perennial ryegrass (Lolium perenne L.). Competition between fruit trees and the vegetation underneath is the core problem for the use of live mulches (Granatstein and Sánchez, 2009). Fruit trees can be affected more here, because of their low root density per unit area of soil surface when compared to the vegetiton underneath (Merwin, 2003). For example, grassy vegetation can have a root density that is 100-fold that of apple trees (Neilsen and Neilsen 2003). However, this problem can be minimised by the selection of a less-competitive species (Meyer et al., 1992) and by frequent mowing (Neri, 2004).

Many studies have suggested that living mulches represent an excellent practice for weed suppression in sustainable agricultural systems and have recommended their use as an alternative method to the use of chemicals, particularly when integrated with other strategies (Bond and Grundy 2001; Teasdale et al., 2007; Kruidhof et al., 2008; Kitis et al., 2011). A sandwich system from Switzerland is a good example of integration of living mulch species with a tillage system. In this concept, the living mulch species are maintained as a 40 cm to 50 cm band within the tree line, with tilling on both sides of the tree rows to leave a competition-free zone for the tree roots (Weibel et al., 2007). The vegetation strip provides weed control around the tree trunk and reduces the competition. Some studies have indicated that this method as the most cost-effective weed-control practice, with good results obtained in terms of tree performance and fruit yield, compared to flaming and living mulches (Stefanelli et al., 2009).

2.3.2.2 Organic mulch

Organic mulches refer to mulches that derive from organic materials, such as bark, wood chips, leaves, grass clippings, sawdust, plant hulls, crop residues and weeds removed from the field. Here, wood chip mulches appear to be the best organic mulches for effective control of weeds in orchards (Granatstein and Mullinix, 2008; Ingels et al., 2013). A single application of wood-chip mulch can provide weed control for 1 year to 3 years, while also saving on irrigation water by over 20% (Granatstein and Sánchez, 2009). However, it can be an expensive method compared to other alternatives, as the wood chips need to be maintained as at least a depth of 10 cm for effective weed control, and their purchase costs can be unusually high (Lisek, 2014; Tahir et al., 2015), particularly if the materials are not available on the farm or near the farm. In addition, they are limited in terms of the control of established weeds, and especially for perennial weeds (Larsson, 1997). Granatstein et al. (2014) reported that the effectiveness of wood-chip mulch for suppressing perennial quackgrass (*Agropyron repens*) lasts only 1 year, as the weed competition increased after a couple of years. Thus, apart from the higher cost, the further main cons of this method are this limited efficiency in the control of perennial weeds, and the high carbon to nitrogen ratio, which reduces the availability of nutrients in the soil (Treder et al., 2004). This might be due to an immobilising effect of wood-chip mulch (Larsson, 1997), although this is not always the case (Forge et al. 2008; Granatstein, Mullinix 2008). Therefore, Hammermeister (2016) suggested the use of wood-chip mulches only in areas with at least moderate soil fertility, and for smaller numbers of perennial rhizomatous weeds in the field.

However, wood-chip mulch has a significant effect on tree growth and fruit yield. Some studies have reported improved tree growth with wood chip mulch, when compared to tillage or cover cropping, but they did not find any significant differences in terms of fruit yield (Teravest et al., 2010). In another study with blackcurrant, it was shown that the plants had relatively lower fruit yield under wood chip mulch compared to black plastic or bare soil (Larsson, 1997). Therefore, many studies have suggested additional soil amendments and or placing a green mulch on top of the wood chip, to minimise immobilisation problems and lower fruit yield (Neilsen et al., 2013). Granatstein et al. (2014) reported highest apple tree growth and economic return when wood-chip mulch was combined with flaming, compared to herbicide with flaming or tillage alone. However, the practice of wood-chip mulching can provide better tree growth compared to flaming or tillage, and compared to cover cropping alone (Hammermeister, 2016).

2.3.2.3 Plastic mulch

Plastic mulch. Plastic also represents an alternative weed-control method to chemical herbicides for fruit trees, and it can be especially effective at the early stages of plant growth (Mage, 1982; Camposeo and Vivaldi, 2011). Weed-management costs in the fruit orchard can be minimised using plastic because of the low cost and long-term efficiency (Hammermeister, 2016). As Schonbeck (2012) indicated, "The plastic fabric is an opaque film that reduces germination of light-responsive weed seeds by shading out and blocking the emergence of weeds physically". However, to prevent weeding issues, it is always critical to be sure of the correct placement of the plastic edge into the soil, to make sure that the weed roots remain under the plastic layer (Grieshop et al. 2012). This can also save on water use for irrigation by 75%, compared to non-mulch controls (Duncan et al., 1992) and thus reduce farm irrigation costs. Some studies have shown that plastic mulch influences soil nutrient status by stimulation of nutrient mineralisation from organic matter, although this does not supply nutrients to the soil (Schonbeck 2012). For this reason, Neilsen et al. (2013) suggested the additional of nutrient amendments, and especially nitrogen (N), to maintain the balanced fertility of the soil.

Plastic mulch can also affect fruit size and yield. For example, the yield of blackcurrants was 26% greater under plastic mulch when compared to a single application of chemical herbicide (Dale 2000). In another study, Neilsen et al. (2013) reported increased apple yield for black plastic compared to alfalfa mulch. However, Larsson (1997) indicated smaller berry size for blackcurrant with plastic mulch, compared to bare soil or wood-chip mulch.

Plastic has a large effect on the microclimate around the plant as its use results in changes to the above-ground and below-ground temperatures and water content (Tarara 2000). The extent of these microclimate modifications depends on the opacity and colour of the plastic (Lamont 2005), as well as the optical properties of the plastic and the connection between the plastic sheet and the soil (Hammermeister 2016). For example, black plastic has higher light absorption over white plastic, with this reversed in terms of light reflectivity. Some studies have investigated the combined practice of photo-degradable black plastic over white plastic mulch in vegetable crops, to keep the soil warm in spring and cool in summer; however, this did not increase yields over typical plastic mulch (Graham et al., 1995). The further alternative might be white plastic mulch over black plastic mulch, where the black plastic can block the light and thus supress the weeds, while the white plastic can reflect the light into the plant canopy and protect the soil from excess heating. Thus, different combinations of plastic mulch might represent good options for the growers, with the choice made based on the environmental conditions.

2.3.3 Thermal weed control

Modern technology has significantly improved the effectiveness of propane burners as an alternative weed-control method in the fruit orchard. Generally, this system requires one or two metal flame orifices to direct the heat at the weed strip and the base of the trees. These are connected to propane tanks (with a safety switch), which are pulled through the orchard at a speed whereby the heat provided breaks down the leaf cuticle of the weeds before they gain greater size or vigour, which causes their desiccation. In this system, a temperature of 60 °C to 70 °C can be maintained by using a propane flame with specialised equipment to heat the weed plants (Wei et al., 2010). According to Bond and Grundy (2001), an angle of 22.5° to 45.0° should be maintained between the burner and the ground for effective weed control. This system might also require several passes, and weeds should be flamed before reaching 5 cm in height (Bond and Grundy, 2001). Of note, the purpose of such flame weeding operations is not to burn off the weeds, but to apply enough heat to severely damage the plant cells, so that the plants will ultimately wither and die (Wei et al., 2010). Flaming is most effective in controlling erect and broad-leaved weeds in an early stage of growth, and it has been shown to be less effective in the control of grassy and prostrate weeds (Shrestha et al., 2012). As flame weeding is also a temporary weed-control practice, there is also the need for reapplication after 1 week to 3 weeks (Shrestha et al., 2013). The use of this method is not particularly widespread, however, due to its relative inefficiency in the control of some weeds and the limitations in the timing of the treatments for effective weed control (Guerra and Steenwerth, 2012). A large drawback of this method is also the fire haz- ard, which can lead to damage to the tree branches and to the irrigation line (Stefanelli et al., 2009). In another study, this method was shown to have relatively lower cost than herbicides and mulches, and similar costs to those of a tillage system (Granatstein et al., 2014). As an alternative to herbicides, the efficiency of flaming can be enhanced by its integration with tillage or mulching strategies (Granatstein et al., 2014). Thus, flaming represents a potentially good alternative to the use of chemicals considering all of the sustainability aspects, especially if a if biogas is used instead of fossil fuel for the flame operation.

2.3.4 High-pressure water

High-pressure water blast systems represent a modern revolution in technology for alternative weed management to chemicals, especially for weeds under vines. In this system, a high-pressure water blast is used rather than chemical herbicides, to avoid environmental degradation. This high-pressure water can break the foliage of the weed plants and bury this in the soil up to a few centimetres, thus also destroying the root system of the weed plants. ‘Grass Killer’ uses this kind of technology, as developed by an Italian company (Caffini) to control weeds under vines and orchards. This is composed of a very high-pressure pump (maximum pressure, 1 150 bar) that is managed using hydraulic devices, a tank for the water, and a rotating head that is positioned laterally with respect to the forward direction (Source: Caffini, Italy). The rotating head on a breakaway arm is equipped with nozzles that are powered by a very high-pressure pump that works in the same way as shrouded spray systems. The rotation speed of the nozzle is 600 rpm, which is combined with a forward speed of 2.5 km/h. This system requires approximately 2 000 L of water per hectare for 2.5-

m-wide vine rows. Weeds can be controlled for a year with only two applications (according to the manufacturer).
Although this represents an environmentally viable approach, there remain concerns in terms of the social and economic sustainability due to its high cost (over EUR 30,000). Therefore, increased working efficiency is crucial to provide a more reasonable balance in terms of this high purchasing cost.

2.3.5 Precision weed control

Precision weed control represents another modern and effective weed-management approach in the fruit orchard, where weeds in the tree rows can be controlled without harming the environment. Over the last few decades, rapid advances in automation have occurred for weed control in farming, and especially for field crops. Precision weed-control methods, such as 'robotic systems' might be the best modern technological intervention here (Bajwa et al., 2015). Peruzzi et al. (2017) provided a good overview of such precision weed control systems. In this case, the autonomous weed control approach was designed considering four key aspects: guidance, weed detection and identification, precision in-row weeding control, and mapping (Slaughter et al., 2008). Four kinds of intra-row robotic weeders are now available for precision weed-management systems: 'Robovator'; 'Robocrop'; 'IC-cultivator'; and 'Remoweed' (Peruzzi et al., 2017). Among these, Robovator appears to be the most effective intra-row weed management system for organic farming. It cuts the weeds at a shallow soil depth (1–2 cm) using a pair of tines, where each tine has a flat knife-like blade (Peruzzi et al., 2017). When the blades approach the crop plant, they move apart to avoid damaging the plant. As soon as the plant has been passed, the blades immediately close again to continue cultivating the area between the plants. The movement in and out of the crop row is operated by a hydraulic actuator connected to a front mounted camera. The camera recognition system defines each of the crop plants based on the difference in size between the crop plants and the weeds. Then, images are further processed by a computer to calculate the points at which the actuator of the blades need to be activated, based on the driving speed and the area that is always left uncultivated near the crop plants (Melander et al., 2015).
Bakker et al. (2010) suggested that such precision weed management systems might have a pivotal role in sustainable food production at lower cost. It would be a big challenge for the growers to use this kind of technique in sustainable fruit production. As an alternative to chemicals, studies carried out with these precision systems of weed management have indicated an optimistic future for their use not only for vegetables, but also in fruit orchards, to reduce weed management costs and the protect orchard biodiversity and soil health. Therefore, these precisions weed management approaches represent another possibility for sustainable weed management for perennial fruit trees.

2.4 Conclusion

Enhanced biodiversity and improved weed management in fruit orchards are crucial to increased orchard sustainability. It remains probably true that the use of herbicides is the most effective weed management practice in the fruit orchard, although many farmers are now seeking comprehensive alternative solutions (single or integrated) to protect soil health and orchard biodiversity, as well as to avoid other harmful effects of chemicals, as indicated above. Moving towards more sustainable orchard management practices is the desirable alternative option to offer eco-friendly management systems for maintenance of the vegetal soil, satisfactory orchard biodiversity, and adequate weed management in the orchard.

Mechanical methods are now one of the leading 'traditional' weed management approaches in both conventional and organic fruit orchards. Over the long-term, the typical tillage approach has adverse effects on soil quality and structure, as well as on the fruit trees. These problems can be minimised using more advanced mechanical equipment, such as fin- ger weeders, and brush weeders, along with a mower, rather than practicing conventional tillage. In addition, the timing and frequency of the treatments and the prevalent types of weeds are crucial factors for consideration for effective mechanical operations.

Using mulch in the tree rows can provide satisfactory weed control and promote orchard biodiversity and good soil biology and nutrient cycling. Living mulches can be used in established fruit orchards, as younger trees are more prone to competition with living mulch plants for moisture and nutrients. Therefore, the selection of a less competitive living mulch species is crucial to better tree growth and quality fruit yield. The European Core Organic project Domino is addressed to study the efficiencies of different living mulches for enhancement of fruit orchard biodiversity (http://www. domino-coreorganic.eu/).

Organic mulches are more effective for management of annual and biennial weeds and show low efficiency versus perennial vegetation. The use of some of these materials, such as wood chip and sawdust, greatly depends on the area to be cov ered and the availability of the materials, because of their high purchasing and transport costs. While plastic mulch can provide long-term weed control, it also requires additional nutrient amendments to maintain the soil nutritional status. Although the effectiveness of the various mulch materials in weed management is not as great as for herbicides, mulches can promote soil fertility and orchard biodiversity, as well as provide better economic returns with satisfactory weed management.

High pressure water blast and robotic weed control systems are still in their infancy in fruit orchards, although they have been shown to be particularly effective in the control of weeds in vegetable crops. In this context, it is expected that these techniques will provide good alternative weed management options in terms of improved sustainability. Future research is required to determine their long-term efficiency in fruit orchards.

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Chapter 3

Integrated weed management in high density fruit orchards

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3.1 Abstract

Despite the productivity, achieving long-term sustainability and maintaining plant biodiversity have become the pivotal goals in orchard floor management, especially along tree rows. Thus, the paradigm of eradicating weeds in the tree row using chemical herbicide or repeated soil tillage needs to be substituted with more sustainable alternatives. This study was conducted in two commercial apple and peach orchards in Marche region (Italy). Two integrated mechanical approaches, integrated mowing (mower and brush or disc) and integrated tillage (blade weeder and integrated mowing), were compared with the standard herbicide system in a 2-year trial. Weed species diversity, soil coverage, and weed biomass production, including, gas exchange parameters, trunk cross-sectional area (TCSA), fruit yield and quality were measured. Overall, both integrated practices demonstrated approximately 82%, 91% and 113% more species diversity, soil coverage, and weed biomass production, respectively, than herbicide systems. No significant differences were found in terms of tree gas exchange parameters, growth and fruit yield. However, a few fruit quality parameters such as fruit firmness, soluble solids content (SSC) and dry matter content responded positively to the integrated practices. These results suggest that the integrated mechanical approaches of weed management increased orchard biodiversity, and had no adverse effects on tree growth, fruit yield, and quality. The average costs per hectare associated with chemical weed control were 66.5% and 72% lower, respectively, compared to integrated tillage and integrated mowing. However, the government subsidies provided to the orchardists to encourage sustainable management practices were able to offset such additional costs.

Keywords: weed management; integrated tillage; integrated mowing; herbicide; weed biodiversity; fruit production

3.2 Introduction

Sustainable tree-row management in fruit orchards is not only crucial for healthy tree growth and quality fruit yield but also for sustaining soil quality and promoting orchard biodiversity. Tree-row management entails the management of orchard weeds as they can compete aggressively, with fruit trees for available nutrients and water, essential for plant growth. Fruit trees are poor competitors because of their low root density per unit of soil compared to weeds (Merwin, 2003). Therefore, proper weed management is vital in the fruit orchard to minimize weeds competition against fruit trees, assuring quality fruit yields (Cavender et al., 2014; Steenwerth and Guerra, 2012), and supporting weed biodiversity in the orchard (Mia et al., 2020). A common management method is to eradicate weeds, either permanently, or temporarily, through herbicide use, or traditional tillage along the tree row, or inter-row (Mia et al., 2020; Neri, 2013). Maintaining bare soil from 0.6 to 2.0 m along the tree row with herbicides (Lisek, 2014) has proven to be easy, cost-effective, and favorable for tree growth and fruit yield (Harrington et al., 2005).

However, the continuous use of chemicals is detrimental to human and environmental health. The consequences generated by herbicide applications include declines in weed biomass, weed biodiversity, and soil quality (Jiang et al., 2016; Robinson and Sutherland, 2002; Yu et al., 2015). Additionally, these practices foster the development and evolution of herbicides resistant weed species (Pieterse, 2010) and favor an insurgence of soil sickness (Polverigiani et al., 2018, 2014). Therefore, various herbicide mechanisms of action, especially using a mix of herbicides in the same tank, or practicing rotating herbicides from season to seasons, have been advocated to overcome the spread of herbicide resistant weeds (Beckie, 2006). Glyphosate was chosen in this study, as it is the most popular and economic weed control method in Valdaso. Residual herbicides were avoided in order to preserve the river water inside the vulnerable area.

Currently, the concept of weed management has achieved a broader meaning than in past decades, as it regulates the coenoses of orchard agroecosystems and turns into a consistent part of the agroecological approach in fruit orchards. Ground cover with living vegetation can deliver several agroecosystem services (Canali et al., 2015; Demestihas et al., 2017), by promoting functional agrobiodiversity in the orchard (Bianchi et al., 2013). Hence, adopting a sustainable orchard management strategy is vital for enhancing weed biodiversity, which can provide ecological protection (Granatstein et al., 2010) by offering feed and shelter to beneficial organisms (Bàrberi et al., 2018; Muscas et al., 2017), and improving soil fertility by hosting mycorrhizae, and thereby promoting nutrient availability (Kubota and Quideau, 2015) and resilience in the soil (Gangatharan and Neri, 2012). It can also play a crucial role in overall soil quality improvement by reducing soil erosion and increasing humification with improved organic matter in the soil (Rodrigues and Arrobas, 2020), while the opposite results may be found under the coverless ground system conditions (Keesstra et al., 2016). In this regard, maintaining soil vegetation, while augmenting biomass production and species diversity can be considered as fundamental goals in sustainable orchard management systems. The key is to practice more sustainable weed control strategies Chandran, 2018) that support covered soil with spontaneous, or selected living species by keeping them at a density level that does not negatively impact tree performances (Mia et al., 2020).

Several alternatives to chemical weed management, such as minimum tillage, mowing, mixtures of living mulching species, distribution of organic mulch, uses of plastic mulch, physical weed control (i.e., flaming and steaming), have been studied with relatively negative results (Granatstein and Kupferman, 2008). Therefore, researchers are still seeking a more sustainable strategy that might reduce weed competition and improve weed biodiversity without compromising fruit production and quality. Priority has been given to the integrated approach for enhancement of long-term orchard sustainability (Granatstein and Kupferman, 2008; Neri, 2013; Ponzio et al., 2013).

The wide availability of sustainable management practices directed us towards seeking further advances in mechanical weed control (Mia et al., 2020). These include integrated tillage, integrated mowing, and modern finger weeder as sustainable techniques that reduce soil disturbance. Weed control based on traditional soil tillage demonstrated several adverse impacts on tree growth, fruit production and quality (Granatstein et al., 2010; Granatstein and Sanchez, 2009; Neilsen et al., 2003), tree roots (Hammermeister, 2016), and soil fertility. However, it might be possible to minimize those problems and optimize orchard biodiversity by integrating advanced shallow tilling tools. In this study, two integrated mechanical practices: (i) integrated mowing (mower with brush or disc), (ii) integrated tillage (blade weeder and integrated mowing) were compared to a chemical herbicide (glyphosate) with the aim of investigating the effects of sustainable alternative weed management methods on orchard biodiversity, fruit yield, and quality. We hypothesized that the two integrated treatments would support species number, biomass production and vegetation coverage, without declining tree growth, fruit yield and quality in fruit orchards, managed with drip irrigation and a usual fertilization regimen.

3.3 Materials and Methods

3.3.1. Experimental sites and management practices

The experiment was started in March 2018 in two different private farms at Valdaso in the Marche region (central Italy, 43°00’13.70” N, 13°35’45.98” E). The area is characterized by a warm and temperate climate, with an average annual temperature of 15.4 °C and average annual precipitation of 794 mm during the 2018–2019 growing season (Figure 3.1). One farm had a three year old apple (Malus × domestica Borkh., cv. Crimson Crisp; rootstock M9) orchard, spaced at 4 × 1 m (2500 trees/ha) on an alkaline (pH = 8.25) sandy clay loam soil (sand 55% + silt 16.7% + clay 28.3%) with 1.29% soil organic matter. The trees were trained to spindle system and covered with a white high-density polyethylene net to protect them from insects and hailstorms. The other farm had a three year old peach (Prunus persica L. Batsch cv. Royal Sweet; rootstock GF677 hybrid peach × almond) orchard, spaced at 4 × 3 m (833 trees/ha) between row to row and plant to plant, respectively, on an alkaline (pH = 8.04) sandy clay loam soil (sand 46.7% + silt 26.7% + clay 26.7%) with 1.16% soil organic matter. The trees were trained to a palmette system. Both orchards were drip irrigated in the summer and fertilized at an annual rate of 45 kg N, 48 kg P, 75 kg K, and 12.25 kg Ca per ha in apple, and 84.2 kg N, 51.4 kg P, and 164 kg K per ha in peach. The total amount of fertilizer was split in two (winter and spring) in apple and in three (winter, spring and summer) in peach orchards.

For each species, a Randomized Complete Block Design (RCBD) was laid out with three blocks and three treatments (Table 3.1): (1) Integrated mowing (mower with polypropylene brush mounted on a horizontal axis or disc, Falconero Group S.R.L company, Faenza, Italy), (2) Integrated tillage (single blade weeder, mounted on Kubota M5091 tractor, ID-David S.L.U. company, Murcia, Spain, and integrated mowing), and (3) Herbicide (mixing 1 L glyphosate with 100 L of water, for 0.25 ha, with a total applied dose of 4.0 L/ha, where the amount of acid equivalent was 1.4 kg/ha). Each replication consisted of 32 trees for a total of 288 trees per species (9 replications × 32 trees). Three randomly selected trees per replication (total of 27 sampled trees per species) were sampled to measure the tree growth, fruit yield, and fruit quality parameters.

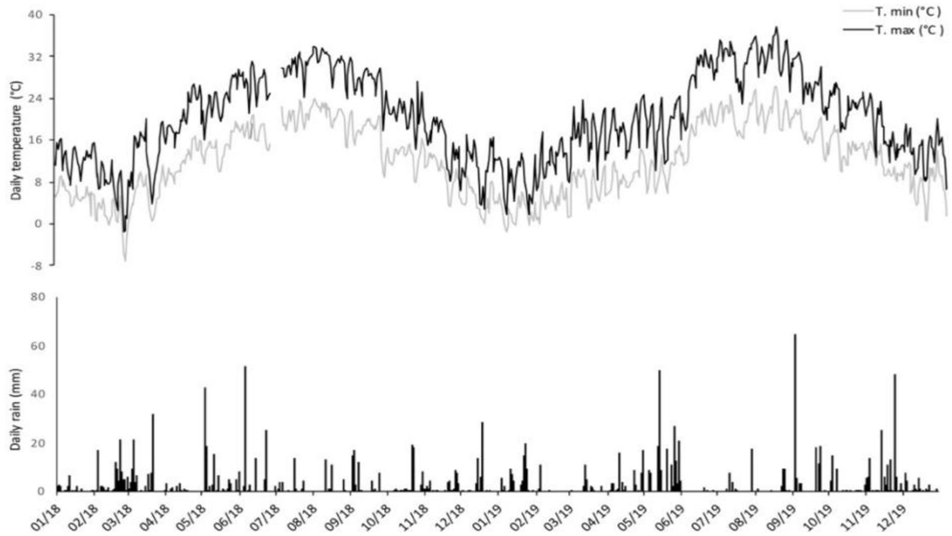

Figure 3.1. The daily rain (mm), and minimum and maximum temperature (°C) measured during the experiment (2018–2019) by a meteorological station located 3 km from the experimental field (Sistema Informativo Regionale Meteo-Idro-Pluviometrico).

Table 3.1 Treatments applied in the tree row over 2 years (2018–2019).

Treatment	2018	2019
Integrated mowing	5 times	7 times
Integrated tillage	Tilled with blade weeder 1 time, integrated mowing 4 times	Tilled with blade weeder 1 time, integrated mowing 5 times
Herbicide	Herbicide sprayed 2 times	Herbicide sprayed 2 times

3.3.2. Tree growth, fruit yield and quality

The tree growth was measured as the cross-sectional area of the trunk (TCSA) at 20 cm above the graft union on 27 sampled trees per species. Measurements were taken in March 2018, January 2019, and December 2019. Results are presented as the percent increase over 2 years. Fruit was harvested by hand; the total numbers of fruit from each plant were counted separately for each treatment, then fruit was weighed using a digital balance to measure the fruit yield (kg/plant). Three similar size fruits per plant (total twenty-seven fruits per treatment) were collected to measure fruit quality parameters: individual fruit weight, fruit firmness, dry matter content (DMC), and soluble solids content (SSC). The firmness was measured on two peeled sides in the equatorial plane of the fruit with a penetrometer (model 53200, Turoni, Italy), equipped with 11 mm plunger for apples and 8 mm for peaches. For the soluble solids content (SSC) determination, the pulp from three fruits from each selected plant was crushed and the intact juice was analyzed immediately, with an optical refractometer (model-53000 C, Turoni, Italy). For the determination of fruit dry matter content, 5 g of fruit flesh was collected from each fruit and kept in the oven at 60 °C until a constant weight was reached (approximately 48 h). The fresh and dry weights of fruits flesh were measured with a digital balance, only in 2019.

3.3.3. Weed biodiversity assessment

Weed biomass production, the total number of weed species present in the tree row and the percent of soil cover were considered to assess weed biodiversity in the orchard. Weeds were collected during the summer season (July–August) of each year, prior to treatment application, from three random zones per treatment, after selecting a 0.50 m2 sampling area (1 m × 0.5 m). Collected weeds were placed in a separate paper bag with a tag for each treatment, then the fresh weight of the weeds was recorded. For drying, weeds were kept in the oven for 48 h at 65 °C temperature. The fresh and dry weight of weeds were measured with a digital balance. Species abundance and their coverage rate in the tree row were estimated using the Braun-Blanquet method (Braun-Blanquet, 1928). Visual weed ratings for each plot were recorded the day before the treatment application by randomly selecting 10 m2 (4 m × 2.5 m) area in the tree row.

3.3.4. Gas exchange parameters

Gas exchange parameters such as the net photosynthetic rate (A, μmol CO2 m−2 s−1), the transpiration rate (E, mmol H_2O m^{-2} s^{-1}), the stomatal conductance (gs, mol H_2O m^{-2} s^{-1}), and the intercellular CO_2 concentration (Ci, μmol CO_2 mol^{-1}) were measured using a gas exchange measurement system (LCpro, ADC Bioscientific Ltd., Hodsden, UK), under environmental light (PAR= photosynthetically active radiation, ranging 1300–1650 μmol m^{-2} s^{-1}). Measurements were carried out on 2 leaves each from randomly selected 6 plants per treatment from 9–11 am to avoid the midday depression of photosynthesis and respective changes in stomatal conductance (Zhang et al., 2019). The parameters were measured when the system reached equilibrium in July and August in 2018 and June, July, and August in 2019.

3.3.5. Statistical Analysis

The experimental data were subjected to analysis of variance (ANOVA) considering two factors (treatment and year) on each species separately. For trunk cross-sectional area (TCSA) increase, fruit dry weight and gas exchanges, one-way ANOVA was performed on each species. Significant differences were compared using mean separation with the Tukey–Kramer HSD test ($p \leq 0.05$). Statistical analysis was conducted in JMP Software (Release 8; SAS Institute Inc., Cary, NC, USA, 200).

3.3.6. Cost of different weed control methods

The costs of different weed control methods were calculated, including herbicide costs and operating costs in herbicide treatment, while in integrated mowing and in integrated tillage treatments only the operating costs were calculated. Operating costs included fuel and operator costs (per hour) according to legal local prices and tariffs.

3.4. Results

3.4.1. Weed biodiversity assessment

A total of 48 weed species belonging to 22 families were identified with the abundance of annual species in both orchards over two years timeframe of the experiment (Table 2). None of them were listed in the red and blue list of Italian flora (composed of endangered and defended species). In both orchards, the most dominant weed species present in the tree row were the perennial dandelion (*Taraxacum officinale Weber*), especially under integrated mowing plot, the annual sow thistle (*Sonchus oleraceus L.*) under integrated tillage, and both broadleaved species of the Asteraceae family, and the annual birdeye speedwell (*Veronica persica Poir*.) under the herbicide plot, forming the prostrate ground cover. While white clover (*Trifolium repens L.*) was abundant in the inter-row area along with other perennial grasses, including bermudagrass (*Cynodon dactylon (L) Pers*.) and ryegrass (*Lolium perenne L*.). In the peach orchard, presence of cockspur *(Echinochloa crus-galli (L.*) Beauv., Poaceae), the plant that can grow up to 1 m tall), was abundant in June and July, especially under herbicide and integrated tillage plots.

Table 3.2 Weed species identified in the orchards over 2 years (2018–2019).

	Apple						Peach					
	2018			2019			2018			2019		
Species	**H**	**IT**	**IM**	**H**	**IT**	**IM**	**H**	**IT**	**IM**	**H**	**IT**	**IM**
Annuals												
Amaranthus retroflexus L.							x	x	x		x	x
Anagallis arvensis L.	x	x	x			x	x	x	x			
Anthriscus cerefolium (L.) Hoffm.				x								
Avena sativa L.							x	x	x			x
Cardamine hirsuta L.	x	x	x	x	x	x	x	x	x	x	x	x
Conyza canadensis (L.) Cronq.		x		x								x
Digitaria sanguinalis (L.) Scop.	x	x	x	x	x	x	x	x	x	x	x	x
Diplotaxis erucoides (L.) DC.	x											
Echinochloa crus-galli (L.) Beauv.	x	x	x	x	x	x		x	x	x	x	x
Fumaria officinalis L.	x	x	x	x	x	x	x	x	x			
Geranium pusillum L.				x								
Lamium purpureum L.		x	x		x	x	x	x	x	x	x	x
Lolium multiflorum Lam.		x	x				x	x	x		x	
Matricaria chamomilla L.							x	x	x		x	x
Mercurialis annua L.									x			
Oxalis corniculata L.						x						
Papaver rhoeas L.	x		x				x	x	x			
Picris echioides L.	x	x	x	x	x	x	x	x	x	x		x
Poa annua L.					x	x	x	x	x	x	x	x
Polygonum aviculare L.	x	x	x	x	x	x		x	x	x	x	x
Portulaca grandiflora Hooker	x	x	x	x	x	x	x	x	x	x	x	x

Table 3.2 (Continued)

Ranunculus arvensis L.			x									x
Scandix cerefolium L.		x	x	x								
Senecio vulgaris L.	x	x	x	x	x	x	x	x	x	x	x	x
Setaria glauca (L.) Beauv.			x		x	x		x	x		x	x
Setaria viridis (L.) Beauv.	x	x	x	x	x	x	x	x	x			
Solanum nigrum L.							x			x	x	
Sonchus oleraceus L.	x	x	x	x	x	x	x	x	x	x	x	x
Stellaria media (L.) Vill.			x	x	x		x	x	x	x		x
Veronica persica Poiret	x	x	x	x	x	x	x	x	x	x	x	x
Perennials												
Calystegia sepium (L.) R.Br.			x		x				x	x	x	x
Capsella bursa pastoris (L.) Medicus	x			x	x	x	x	x	x	x	x	x
Hyoseris radiata L.			x		x							
Lolium perenne L.				x	x	x					x	x
Malva sylvestris L.								x	x			x
Plantago lanceolata L.							x	x	x			x
Plantago major L.	x	x	x	x	x	x	x	x	x		x	x
Poa trivialis L.			x									
Potentilla reptans L.		x	x	x	x	x	x	x	x	x	x	x
Ranunculus ssp.		x			x							
Rumex obtusifolius L.		x	x		x	x	x	x	x		x	
Taraxacum officinale Weber	x	x	x	x	x	x	x	x	x	x	x	x
Trifolium repens L.		x	x	x	x	x					x	x
Urtica dioica L.											x	x
Geophytes												
Cirsium arvense (L.) Scop.	x	x	x	x	x	x	x	x	x	x	x	x
Convolvulus arvensis L.	x	x	x	x	x	x		x	x	x	x	x
Cynodon dactylon (L.) Pers.	x	x	x		x	x	x	x	x	x	x	x
Sorghum halepense (L.) Pers.												

Abbreviations: Herbicide (H); Integrated Tillage (IT); Integrated Mowing (IM).
*x= indicate the presence of weed species in the respective treatment plot.

The integrated weed management practices had a strong impact on the number of plant species present in the tree row, which was consistent both in the apple and peach orchards (Table 3.3). Over the two years, integrated practices showed a significantly higher number of plant species (p = 0.0001), which was 82% more compared to plots that were treated with herbicide, whereas integrated mowing and integrated tillage treatments showed a similar effect on weed species diversity considering Tukey–Kramer HSD test.

Table 3.3 Effects of integrated weed control methods, year and their interactions on apple and peach orchard biodiversity variables.

Apple	Soil Cover (%)	Weed Species Number (*n*)	Dry Weed Biomass ($g/m^2/day$)
Treatment			
Herbicide	48.5 b	4.1 b	2.7 b
Integrated tillage	86.8 a	6.5 a	5.9 a
Integrated mowing	85.7 a	6.8 a	6.2 a
p-value	0.0001	0.0001	0.0024
Year			
2018	71 a	6.1 a	5.0 a
2019	76 a	5.6 a	4.9 a
p-value	0.195	0.084	0.837
Interaction			
Treatment × Year	0.74	0.084	0.878
Peach			
Treatment			
Herbicide	41.5 b	3.7 b	1.8 b
Integrated tillage	85.1 a	7.2 a	3.9 a
Integrated mowing	86.8 a	7.9 a	3.2 ab
p-value	0.0001	0.0001	0.0223
Year			
2018	68.4 a	6.7 a	3.85 a
2019	73.9 a	5.9 a	2.57 b
p-value	0.131	0.017	0.025
Interaction			
Treatment × Year	0.159	0.428	0.307

Means with the same letter in a column for treatments or year are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

Likewise, the percentage of soil coverage with spontaneous vegetation was affected significantly by different weed management strategies, both in the apple and peach orchard (Table 3.3). Integrated mowing and integrated tillage treatments demonstrated approximately 85% to 87% soil coverage, compared to standard herbicide system (around 41% to 48%), at both apple and peach orchards. No significant effect was found between the two years, but the percent of soil coverage increased by about 5% in 2019.

The above-ground dry weed biomass production during the summer season varied significantly among different weed management practices (Table 3.3). In both orchards, the plots managed with integrated systems produced significantly higher dry weed biomass (p =

0.0024), compared to herbicide. The year had a significant effect on weed biomass productions (p = 0.025) in the peach orchard, where average weed biomass production was higher in 2018 than in 2019 (Table 3).

3.4.2 Tree growth, fruit yield and quality

There were no significant treatment effects on tree growth, as measured by percentage increase in trunk cross-sectional area (TCSA) at both orchards. The apple trees showed the highest TCSA increment (46%) in the herbicide plots and lowered in integrated mowing plots (38%). Similar tree growth (45%) was measured under all the treatments at the peach orchard, too (Table 3.4).

Table 3.4 Effects of integrated weed control methods on trunk cross-sectional area (TCSA) growth and fruit dry matter (%) in apple and peaches during two years experiments.

Treatments	**TCSA-2 Years (% Change)**		**Fruit Dry Matter (%)**	
	Apple	**Peach**	**Apple**	**Peach**
Herbicide	46 ± 4.6 a	45.6 ± 5.75 a	15.4 ± 0.15 a	13.7 ± 0.22 b
Integrated tillage	41.8 ± 7.44 a	45.1 ± 5.73 a	15.3 ± 0.21 a	14.5 ± 0.19 a
Integrated mowing	38.2 ± 4.08 a	45.3 ± 6.70 a	15.7 ± 0.26 a	14.6 ± 0.27 a
p-value	0.614	0.998	0.455	0.007

Data are expressed as mean ± standard error. Means with the same letter in a column are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

The average apple yield did not differ significantly among treatments (Table 3.5). In both years, a slightly higher apple yield was obtained from the herbicide plot (6.5 kg/plant) and the integrated tillage (6.4 kg/plant) than in the integrated mowing (5.6 kg/plant). Besides, there were no significant year effects on apple yield (Table 3.5). It indicates that the average apple yield was comparable among the treatments in both years. In peaches, a significant treatment effect was noticed on fruit yield (Table 3.5), where the herbicide plot obtained significantly higher yield (29.7 kg/plant) than integrated tillage (27.6 kg/plant) and integrated mowing plots (25.2 kg/plant). However, the peach yield was significantly higher in 2019 (p = 0.01) than in 2018 (Table 3.5).

Table 3.5 Effects of integrated weed control methods, year and their interactions on apple and peach yield and quality variables.

Apple	**Individual Fruit Weight (g)**	**Fruit Yield (kg/plant)**	**Fruit Firmness (kg/cm^2)**	**SSC (°Brix)**
Treatment				
Herbicide	218.5 a	6.5 a	9.6 b	13.8 a
Integrated tillage	208.1 ab	6.4 a	9.7 ab	13.8 a
Integrated mowing	206.5 b	5.6 a	10 a	14 a
p-value	0.0140	0.361	0.0041	0.375
Year				
2018	211.2 a	5.7 a	10.2 a	13.9 a
2019	210.9 a	6.6 a	9.3 b	13.8 a
p-value	0.925	0.1570	0.0001	0.764
Interaction				
Treatment × Year	0.0364	0.735	0.557	0.6284
Peach				
Treatment				
Herbicide	245.4 a	29.7 a	5.4 a	13.3 b
Integrated tillage	253.7 a	27.6 ab	5.4 a	13.5 ab
Integrated mowing	244 a	25.2 b	5.3 a	13.9 a
p-value	0.0831	0.0198	0.269	0.0542
Year				
2018	253.2 a	25.8 b	5.37 a	13.7 a
2019	242.1 b	29.2 a	5.34 a	13.5 a
p-value	**0.0039**	0.0105	0.810	0.558
Interaction				
Treatment × Year	0.553	0.879	0.471	0.274

Means with the same letter in a column for treatments or year are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test). SSC: soluble solids content.

Weed management practices showed a significant impact on fruit firmness ($p = 0.004$), and individual fruit weight ($p = 0.014$) in the apple orchard (Table 3.5), while apples obtained from integrated mowing and herbicide plots showed greater fruit firmness and higher individual fruit weight, respectively. In addition, fruit firmness was highly affected by year ($p = 0.0001$), while an interaction effect was found for individual fruit weight in apples (Table 3.5) without any change in the trend among treatments. There were no significant differences recorded among the treatments for SSC (Table 3.5), and fruit dry matter content in the apple (Table 3.4). However, fruits harvested from integrated mowing plots showed higher SSC and dry matter content. Among the peach quality parameters, a statistically significant treatment effect was found only for fruit dry matter content (p = 0.007), where integrated mowing resulted in a higher fruit dry matter content than other treatments (Table 3.4). Peach firmness, individual fruit weight, and SSC levels did not differ among treatments, even though, individual peach weight varied significantly between two years (Table 3.5).

3.4.3. Gas Exchange

Gas exchange data in both orchards did not significantly differ among the treatments. Intercellular CO_2 concentration (Ci), transpiration (E), stomatal conductance (g_s), and net photosynthetic rate (A) were statistically similar among all treatments (Figure 3.2). The results showed that maintaining a weed-free strip in the herbicide plot did not induce any physiological improvement of trees compared to alternative plots, under the same supplied cultural inputs.

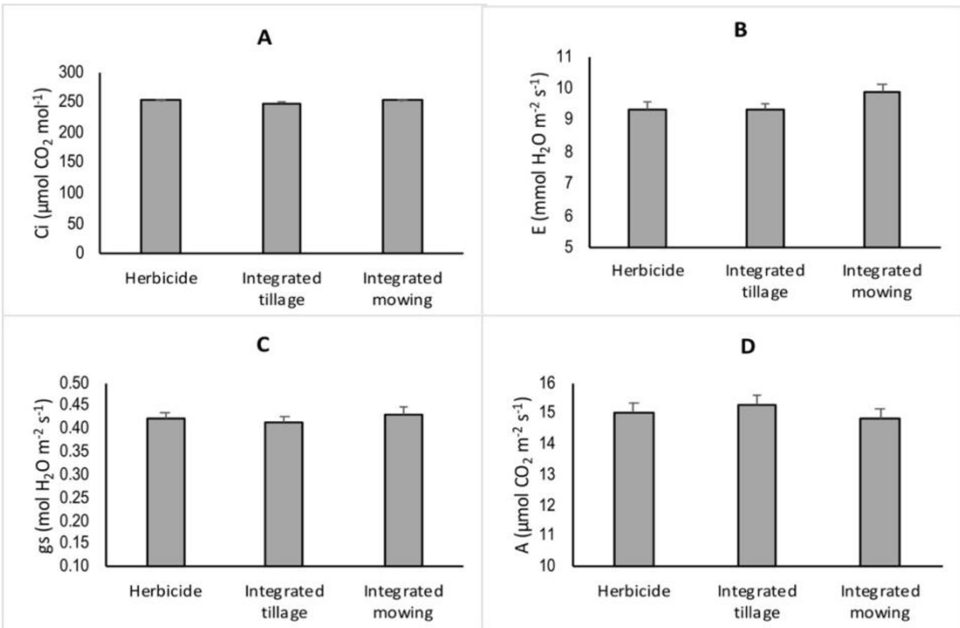

Figure 3.2 Effects of integrated weed management on different gas exchanges: (**A**) intercellular CO_2 concentration (Ci), (**B**) transpiration rate (E), (**C**) stomatal conductance (g_s), and (**D**) net photosynthetic rate (A) in leaves of apple and peach trees. Bars represent standard error.

3.4.4. Cost of different weed control methods

The more economical method of weed control was herbicide use (Table 3.6). However, the integrated tillage method showed a relatively lower cost than integrated mowing in both years due to the use of the blade weeder with the fastest tilling speed tractor.

Table 3.6 Costs of weed control methods in the two commercial apple and peach orchards in 2018 and 2019 in Valdaso (Italy).

Weed Control Methods	Number of Passes/Year	Duration of a Single Operation (h/ha)	Operating Cost ($/h)	Total Cost ($/ha/year)
2018				
Herbicide	2 times	2.5	27.85	160.50
Integrated tillage	Blade weeder 1 time	1.5	29.15	370.2
	Integrated mowing 4 times	2.8	29.15	
Integrated mowing	5 times	2.8	29.15	408.1
2019				
Herbicide	2 times	1.7	28.08	115.05
Integrated tillage	Blade weeder 1 time	1.4	29.50	454.3
	Integrated mowing 5 times	2.8	29.50	
Integrated mowing	7 times	2.8	29.50	578.2

3.5 Discussion

This research demonstrated that sustainable integrated weed management practices along the tree row enhanced understory species abundance, percent of soil cover and dry weed biomass, which ultimately led to an improvement in weed biodiversity in the orchard, in comparison with the conventional herbicide application. This is presumably due to the maintenance of spontaneous vegetation in both alternative plots, which was mowed frequently, with an integrated mowing system. In this system, two advanced types of equipment, a rotary brush weeder and a mower, were used simultaneously. A rotary brush weeder helps to bend down the weeds near the tree trunk without causing any trunk damage, while the mower can cut and chop weeds above the soil surface, without disturbing the soil. The chopped weed plants served as mulching materials in the tree rows. However, in the integrated tillage systems, the first application was conducted with a horizontal blade weeder, which is a shallow tillage implement (3 cm to 4 cm tillage depth) that cuts the tap roots of the noxious weeds without mixing the superficial soil layers, followed by an integrated mowing system for the rest of the season. It is worth noting that blade weeder works properly only in light (sandy loam) soils. On the contrary, chemical herbicide use maintained bare soil in the tree row, resulting in a lower number of spontaneous weed species, less percentage of soil coverage and reduced weed biomass production. While integrated weed management treatments established a substantial number of species (overall 82% more than herbicide) with a significantly higher percentage of soil coverage, approximately 91% higher than the herbicide treatment. The daily dry weed biomass during the summer season was substantially higher in the integrated treatment plots (approximately 124% and 97% more, in apple and peach orchard, respectively) than those that were treated with herbicides (Table 3.3). More weed biomass in the integrated plots signifies their vital role in soil physical and chemical quality improvement (Dabney et al., 2001). In this study, a similar impact of two integrated practices was observed on overall weed biodiversity improvement.

Integrated orchard management techniques at the ground level did not impair tree growth. Over two years, no treatment effects were found for TCSA increment. Herbicide use showed slightly better tree development in apple, but the divergence was limited among the treatments. This is probably due to the maintenance of partial bare ground in the herbicide plot, as this management system offers less competition between herbaceous vegetation and apple trees grafted on M9 dwarfing rootstock with fasciculated and superficial roots. Peach trees, grafted on GF677 vigorous rootstock, in integrated plots, reported similar growth increments as trees as in the herbicide plot. However, the average apple yield was not affected, either by different weed management systems or year. All the treatments showed an increased apple yield in the second year, with an increase of 13.8% in herbicide, 24.5% in integrated tillage, and 5.2% in integrated mowing. As a result, the average apple yield was increased by 15% in 2019. In the peach orchard, fruit yield was greatly impacted by different weed management practices, and years. The herbicide plot demonstrated a slightly higher yield than the integrated systems, over two years, but the rate of peach yield increment in the second year was higher in integrated plots (15.8%) compared to the herbicide system (8.8%), while overall peach yield increased by 13%. This rise in fruit yield correlated directly with less weed–tree competition (Hussain et al., 2018). It is also worth noting that weed–tree competition was under control in both orchards due to the consideration of different numbers of weeding interventions, based on the weather conditions and rain distribution during the summer season (Figure 3.1). These circumstances resulted in limiting the competition between weeds and fruit trees. In the second year, the precipitation was higher, which accelerated weeds' growth. As a result, two additional weeding interventions were done in the second year. Hence, sustainable alternative approaches did not have a negative impact on fruit production. In fact, there was a tendency of fruit yield increment in the integrated treatment plots. In this study, different ground management techniques affected apple and peach quality attributes to some extent. Despite the individual fruit weight in apple, integrated mowing and integrated tillage fruits were firmer compared to the herbicide fruits, which can play an important shift towards sustainability, by increasing consumer preferences in the marketplace (Peck et al., 2006; Slatnar et al., 2020). In the peach orchard, no fruit quality attributes varied significantly, among the management systems except fruit dry matter content. The integrated tillage alongside with herbicide exhibited a higher value of peach firmness than integrated mowing, even though differences were comparable among the treatments. However, sweeter apple and peach fruit with more dry matter content were obtained from integrated mowing plots. The overall results of this experiment illustrated a positive trend towards apple and peach quality improvement under both integrated approaches. Moreover, they had no negative impact on gas exchange parameters, which proved trees' ability to maintain similar physiological functions, as the trees do under the chemical herbicide system. The cost of integrated weed management approaches was about \$370 to \$580 per hectare per year, for five to seven passes, which is considerably higher than the cost of herbicide (about \$115 to \$160 per hectare per year, two passes). However, the project "Agri-environmental agreement–2014/2020 Rural Development Programme in Marche region" allotted \$950/ha/year to the farm for the advancement of more sustainable orchard management techniques while reducing chemical uses.

3.6. Conclusions

The worldwide eco-friendly guidelines, especially in the European Union, raise the popularity of embracing more sustainable orchard floor management practices. It is a challenge for researchers to find proper alternatives to chemical herbicides. However, this study revealed that both integrated mowing and integrated tillage practices were able to perform as more sustainable alternatives to herbicide, without impairing tree growth, fruit yield, quality, or photosynthetic performances of trees. Additionally, they supported a substantial number of plant species, a higher percentage of ground coverage, and a considerable amount of biomass production, compared to herbicide. These are the pivotal goals in achieving orchard biodiversity, improving soil quality, and eventually leading towards long-term sustainability. The cost of integrated mechanical systems was higher than herbicide cost but it is acceptable for the farmers, considering the positive externalities of the territory and the subsidies in the present transition to a reduced use of chemicals in the area (G.Eco. agreement). In sum, as an alternative to chemical herbicide use (twice a year), integrated mechanical strategies with repeated constraints by brush and disk mower (five to seven times depending on the orchard stage, type of soil and environmental conditions) and eventually blade tillage (in light soils, once a year early in the season) can be a more sustainable solution for intra-row management in high-density fruit orchards of central Italy.

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Chapter 4

Soil nitrogen and weed biodiversity: An assessment under two orchard floor management practices in a nitrogen vulnerable zone in Italy

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4.1 Abstract

Nowadays, understory vegetation along the tree row is considered a vital source of agroecosystem services and functional biodiversity improvement in the fruit orchard. Hence, current orchard floor management systems encourage practicing a more sustainable approach that supports vegetation cover rather than keeping bare soil herbicide use, or tillage. A two-year field trial was conducted using two different ground management techniques; integrated mowing (mower and brush or disc) and herbicide (glyphosate) in two commercial apple and peach orchards in a nitrogen vulnerable zone (NVZ) of the Marche region, Italy. This study aimed to evaluate the effects of these practices on soil N status, weed abundance, percent of soil cover, and dry weed biomass production. Weed management systems had no significant effect on soil organic matter and N availability; however, an improvement was noticed under integrated mowing when compared to the one treated with herbicides. Integrated mowing had a significant effect on species richness, soil coverage, and weed biomass production, which was approximately 2-times higher than in the herbicide-treated plots. The overall results showed that integrated mowing maintained a balance in the soil N status of both orchards, while supporting above-ground weed biodiversity and soil protection.

Keywords: soil management; nitrogen fertility; integrated mowing; herbicide; weed biodiversity

4.2 Introduction

Conventional weed management along the tree row in a fruit orchard relies heavily on herbicide use, which is applied during the production season to suppress ground vegetation, causing desiccation and death of herbaceous plants and roots. Herbicides can control weed competition effectively, although they leave chemical residues in the soil which decrease soil fertility and orchard biodiversity (Geiger et al., 2010; Mottes et al., 2014). We concede that such an approach may become a serious threat to environmental sustainability in the long run. A continuous application of herbicides results in augmenting soil erosion, diminishing soil organic matter content, and microbial activity, while impairing soil nutrients status due to the alteration of net N mineralization (Zhang et al., 2018). Herbicides may also disturb natural nutrient decomposition in the soil by interacting with earthworms, fungi, and bacteria (García-pérez et al., 2020). However, soil quality and biodiversity can be restored by practicing more sustainable weed management techniques that maintain the soil covered with spontaneous vegetation (Mia et al., 2020b; Neri, 2013). Above ground vegetation can deliver several ecosystem services including environmental protection (Granatstein et al., 2010), habitat for beneficial microorganism (Muscas et al., 2017), as well as sustaining soil fertility by hosting mycorrhizae (Kubota and Quideau, 2015). These improve soil organic matter content, aggregates stability, biological activity, and nutrient cycles (Dignac et al., 2017; García-pérez et al., 2020), through an accumulation of above ground biomass, root exudates, and other organic compounds into the soil. Thus, they ameliorate overall soil quality by accelerating the humification process (Neri, 2013) while increasing plant biodiversity and natural antagonists of crop pests and diseases (Simon et al., 2010). These benefits can be even more important for the growth of fruit trees because the 'niche effect' of having a part of their root system in optimal allelopathic condition can enhance resilience in the orchard, while reducing the self-residue impact (Giorgi et al., 2008; Polverigiani et al., 2014; Endeshaw et al., 2015).

Valdaso is the most important fruit production area in the Marche region (Italy) due to the historical presence of a high number of specialized fruit growers. Smallholder intensive farming systems dominate the Valdaso agricultural landscape, which is recognized to be a nitrate vulnerable zone (NVZ) (Vanni, 2014). Recently, contamination of soil and aquifers has become a serious concern for the fruit growers, due to excess nitrate leaching, and consequent contamination of water bodies in the area (Cui et al., 2020). However, maintaining ground vegetation along the tree row can be a viable solution for these problems, because plants are capable of absorbing N from the soil throughout their cycle, while sequestering it in their tissues. Thus, they can deliver N into the soil during the process of decomposition (Atucha et al., 2011; Wang et al., 2016). For this reason, an eradication of understory vegetation along the trees row is not desirable in sustainable orchard floor management (Mia et al., 2020a). Managing orchard floors with living vegetation is a good agricultural practice to reduce the risk of potential leaching of nitrates (Cui et al., 2020). The European Union (EU) introduced agri-environmental measures (AEMs) to support farmers and reduce the environmental risks in sustainable rural development (Toderi et al., 2017). Therefore, a more ecological approach is highly recommended, particularly in vulnerable agricultural areas like Valdaso where small land holders operate high-input and low-efficiency fruit production systems (Cui et al., 2018).

In high density orchards, fruit yields and quality are controlled primarily by soil and nutritional management. Fruit growers prefer a more sustainable approach for sustaining soil fertility with greater nutrients and water availability, in an attempt to reduce competition between understory vegetation and fruit trees, while striving for increasing biodiversity, orchard resilience, and reducing risks of soil sickness (Polverigiani et al., 2018, 2014). Ground cover management can be accomplished through a broad use of different techniques that impact soil nutritional status and plant biodiversity in different ways. Effective weed management has to be done to balance N availability, since too little N results in lower crop productivity. On the other hand, too much N leads to environmental pollution and its concomitant threats to ecosystems' health and functioning (Zhang et al., 2015). Therefore, an integrated mowing system was developed for sustainable orchard management with two advanced tools: a rotary brush weeder and a mower, where the rotary brush weeder facilitates bending the weed plant stems close to the tree trunk, avoiding any trunk damage. At the same time, mowing the weeds does not disturb the soil, and it deposits the mowed residues in the soil surface along the row (Brunetto et al., 2018; Mia et al., 2020a). Eventually, they are used as mulching materials, but in any case, ensure covered soil with spontaneous vegetation along the tree row.

In this study, we compared an integrated mechanical mowing system (mower with brush or disc) with a standard herbicide (glyphosate) application in two commercial fruit orchards (apple and peach). The aim of the study was to evaluate the effect of integrated mechanical weed management on soil quality parameters including soil nitrogen status and organic matter content, and on weed biodiversity, measurable as weed species number, percent of soil coverage, and weed biomass production.

4.3. Materials and Methods

4.3.1. Site descriptions, research design and management practices

The study was conducted from 2018 to 2019 in two different commercial orchards at Valdaso in the Marche region (central Italy, 43°00′13.70″ N, 13°35′45.98″ E). The region benefits from a warm and temperate climate, with the average annual temperature and precipitation of 15.4 °C and 794 mm, respectively (Figure 4.1). A three-year old apple (*Malus* × *domestica* Borkh., cv. Crimson Crisp; rootstock M9) orchard was established on a sandy clay loam (sand 55% + silt 16.7% + clay 28.3%, USDA classification) Holocene alluvial soil (soil service of Marche Region, Italy). It has 1.29% organic matter, 0.14% total N, with soil pH, and EC of 8.25 (alkaline) and 0.75 mS cm^{-1}, respectively. The trees were spaced at 4 × 1 m (2500 trees/ha), trained to a spindle system, and covered with a white high-density polyethylene net to protect them from insects and hailstorms. The second study site had a three year-old peach (*Prunus persica* L. Batsch cv. Royal Sweet; rootstock GF677) orchard, located adjacent to the apple farm. Peach trees were planted at the distance of 4 × 3 m (833 trees/ha) between row to row and plant to plant. The soil was classified as above: sandy clay loam (sand 46.7% + silt 26.7% + clay 26.7%) with a soil organic matter, total N, soil pH, and EC of 1.16%, 0.09%, 8.04 (alkaline), and 1.21 mS cm^{-1}, respectively. The trees were trained to a palmette system.

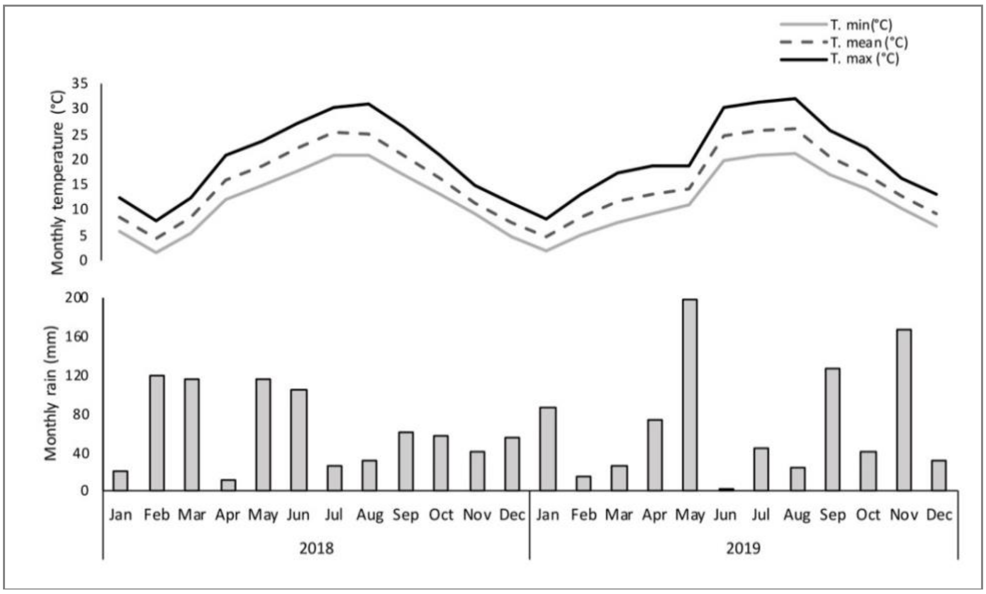

Figure 4.1. Monthly rain (mm.), minimum/maximum and mean temperature (°C) measured during the experiment (2018–2019) with a meteorological station located 3 km from the experimental field (Sistema Informativo Regionale Meteo-Idro-Pluviometrico, Marche, Italy).

In this study, two different weed management approaches were used;(1) Integrated mowing (mower with polypropylene brush mounted on a horizontal axis or disc, Falconero Group S.R.L company, Faenza, Italy), and (2) Herbicide (mixing 1 l glyphosate—360 g/l acid equivalent Fandango, Monsanto Agricoltura, Italy—with 100 L of water, for 0.25 ha sprayed surface area, with a total applied dose of 4.0 L/ha, where the amount of acid equivalent was 1.4 kg/ha). Herbicide was sprayed 2 times in each year while integrated mowing was applied 5 times in 2018 and 7 times in 2019. In both experimental sites, a randomized complete block design (RCBD) was laid out with three blocks and two treatments. Each treatment was replicated three times. Each replication was comprised of 32 trees for a total of 192 trees per species (6 replications × 32 trees). Both orchards were drip irrigated in the summer and fertilized at an annual rate of 45 kg N, 48 kg P, 75 kg K, and 12.25 kg Ca per ha in apple, and 84.2 kg N, 51.4 kg P, and 164 kg K per ha in peach. For NPK fertilizer, different products such as DUNG 3.5.7s + 18C (Fomet, Italy), and YaraMila PARTNER (Yara, Italy) were used, while Neobit new (Cifo, Italy) was used as Ca fertilizer. The total amount of fertilizer was split in two application times (at the beginning of December, and mid-April) in apple and three times (at the beginning of December, mid-April, and June) in the peach orchard.

4.3.2. Soil samples and analysis

Soil samples were taken with an auger soil sampler at 0–20 cm and 20–40 cm from each replication of the treatment on July 11 and September 24 in 2018; April 5, July 26, and October 10 in 2019. A total of 60 samples for each treatment were collected over two years. The soil was air-dried and ground to pass through a 2 mm and 0.5 mm sieve before analysis. All roots and visible plant residues were removed by hand-picking. The soil samples were then stored at 4 °C in the refrigerator.

Soil oxidable organic carbon (SOC) was measured according to the Walkley and Black method, as described by Nelson and Sommers (Nelson and Sommers, 1996). The soil organic matter (SOM) content was calculated by multiplying the determined organic carbon by 1.724. Total nitrogen (TN) concentration was determined on air-dried soil, where subsamples of 20 mg finely smashed soil were weighed in tin caps and analyzed with an elemental analyzer (CHNS-O Elemental Analyzer CE1110, ThermoQuest, Italy). Soil nitrate (NO_3^-) was extracted from 5 g of soil with a solution of 50 mL of KCl (0.01 M) (Mulvaney, 2018); the samples were agitated for 1 h followed by centrifugation, then the solutions were filtered and stored until analyzed through ion chromatography (Dionex ICS 1000, California, USA). Ammonium (NH_4^+) was determined from 5 g of soil using a solution of 20 mL of K_2SO_4 (0.5 M); then samples were prepared by following the same agitation and centrifugation procedure as for soil nitrate solutions and analyzed according to the modified Berthelot method (Mulvaney, 2018). Soil mineral N (Nmin) was calculated as the sum of the amount of nitrate (NO_3^-) and ammonium (NH_4^+), while soil organic N (org N) was determined by cutting off the total mineral N concentration from the total N.

To measure the level of NO_3^- in the leached water, high end suction lysimeters (Irrometer company, California, USA) equipped with a tube (OD 22 mm, ID 16 mm, and wall 3 mm) and a ceramic tip (7 cm) were installed at 15 cm and 45 cm soil depth, along the tree row in three replications in each of the treatments. They were installed to the respective depth by drilling the soil with an auger. A part of the removed soil was put back for the fixing of the lysimeters while adding the corresponding soil to each depth. Collections of the soil solutions were made using a manual pump (July 27 and September 24 in 2018) and May 25, June 27, July 26, and October 10 in 2019. The solution was removed from inside the lysimeters with a syringe attached to a hose. Thus, a total of 72 samples per each treatment were collected and stored in plastic test tube until analyzed by ion chromatography (Dionex ICS 1000, California, USA).

4.3.3. Weed biomass and biodiversity assessment

Dry weed biomass production, weed species number, and percentage of soil coverage were considered as weed biodiversity variables in our study. Above ground weed biomass measurements were collected prior to a weed control event, during the summer season of each year (July–August), from three random locations per treatment, using a frame of 0.50 m^2 (1 m × 0.5 m). Collected weed samples were placed in a separate paper bag before drying them in an oven at 65 °C for 48 h. Dry weed biomass was weighed using a digital balance. The measurements of species numbers and the percentage of soil cover along the tree row were estimated using the Braun–Blanquet method (1928). Visual weed ratings for each plot were recorded the day before the treatment application by randomly selecting 10 m^2 (5 m × 2 m) area along the tree row. A total of 48 samples for each treatment were considered for all weed biodiversity parameters.

4.3.4. Statistical analysis

A two–way analysis of variance (ANOVA) was the procedure employed for the data analysis. This considered four factors for soil data (orchard, treatment, soil depth, and sampling time) and three factors (orchard, treatment, and year) for weed biodiversity data. A one-way ANOVA was considered for the analysis of NO_3^- concentration in soil solutions. Significant differences were compared using mean separation with the Tukey–Kramer honestly significant difference (HSD) test ($p \leq 0.05$). Statistical analysis was carried out with JMP Software (Release 8; SAS Institute Inc., Cary, NC, USA, 2009).

4.4. Results

4.4.1. Soil organic matter (SOM)

Soil organic matter (SOM) did not differ significantly between the two treatments. However, it varied greatly, depending on the orchard, soil depth, and different sampling times (Table 4.1). Where SOM content was considerably higher in the apple orchard, at the upper soil surface (0–20 cm), in July 2018 and October 2019. However, no interaction effects were found among different factors.

Table 4.1 Two-way ANOVA for the effects of treatment, orchard, soil depth, sampling time, and their interactions on soil N variables and soil organic matter.

Parameters	**NO_3^- (mg kg^{-1})**	**NH_4^+ (mg kg^{-1})**	**Mineral N (mg kg^{-1})**	**Organic N (g kg^{-1})**	**Total N (g kg^{-1})**	**SOM (%)**
Orchard (O)						
Apple	58.2	10.5	68.7	1.25 a ^{z}	1.32 a	1.62 a
Peach	48.8	11.8	60.7	1.09 b	1.15 b	1.27 b
p-value	0.068	0.301	0.149	0.0001	0.0001	0.0001
Treatment (T)						
Herbicide	51.30	10.98	58.5	1.18	1.23	1.44
Integrated mowing	55.75	11.31	62.8	1.17	1.24	1.45
P-value	0.385	0.800	0.387	0.898	0.916	0.892
Soil depth (SD)						
0–20 cm	67.68 a	12.51	75.3 a	1.26 a	1.34 a	1.61 a
20–40 cm	39.36 b	9.78	46 b	1.08 b	1.13 b	1.28 b
p-value	0.0001	0.407	0.0001	0.0001	0.0001	0.0001
Sampling time (ST)						
July/18	37.7 bc	17.33 a	53.1 b	1.13 b	1.18 c	1.60 a
Sept/18	23.5 c	8.95 bc	24 c	0.98 c	1.01 d	1.32 b
April/19	113.8 a	14.08 ab	148 a	1.18 b	1.30 b	1.24 b
July/19	54.3 b	6.75 c	40.6 bc	1.38 a	1.44 a	1.46 ab

Table 4.1	(Continued)					
October/19	38.4 bc	8.62 bc	37.5 bc	1.19 b	1.24 bc	1.60 a
p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Interaction (*p*-value)						
O×T	0.914	0.919	0.93	0.083	0.08	0.32
O×SD	0.0001	0.544	0.78	0.834	0.55	0.85
O×ST	0.0001	0.0333	0.0003	0.089	0.103	0.07
T×SD	0.0622	0.199	0.0408	0.385	0.198	0.26
T×ST	0.0306	0.995	0.0762	0.293	0.6250	0.86
SD×ST	0.0001	0.442	0.0001	0.290	0.9017	0.68
O×T×SD	0.40	0.1139	0.244	0.680	0.916	0.4313
O×T×ST	0.4796	0.969	0.59	0.168	0.1820	0.194
O×SD×ST	0.0001	0.994	0.0001	0.678	0.944	0.915
T×SD×ST	0.08	0.203	0.185	0.964	0.96	0.88
O×ST×SD×T	0.120	0.0884	0.095	0.928	0.955	0.91

[z] Means with the same letter in a column for each parameter are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

4.4.2. Soil nitrogen status

Assessment of soil nitrogen availability is vital in the orchard, as fruit trees absorb N in both NO_3^- and NH_4^+ forms (Zoppolo et al., 2011). Soil NO_3^- concentration did not differ between the weed management treatments, though integrated mowing plots showed the highest concentrations of NO_3^- than herbicide treated plots (Table 4.1). The apple orchard soil had a higher concentration of soil NO_3^- (58.2 mg kg^{-1}) than peach (48.8 mg kg^{-1}). Nevertheless, at 0–20 cm soil depth in April 2019, there was a higher soil NO_3^- when compared to 20–40 cm at other sampling times (Table 4.1, Figure 4.2).

The concentration of NO_3^- in the soil solution varied significantly between treatments, at different sampling times and soil depths (Table 4.1, Figure 4.3). Integrated mowing showed the highest NO_3^- levels at 15 cm soil depth, at every sampling time, except May 2019, whereas under herbicide use, the highest NO_3^- values were measured at 45 cm, excluding July 2018. However, only traces of NO_3^- were detected in October 2019 under both treatments and soil depths.

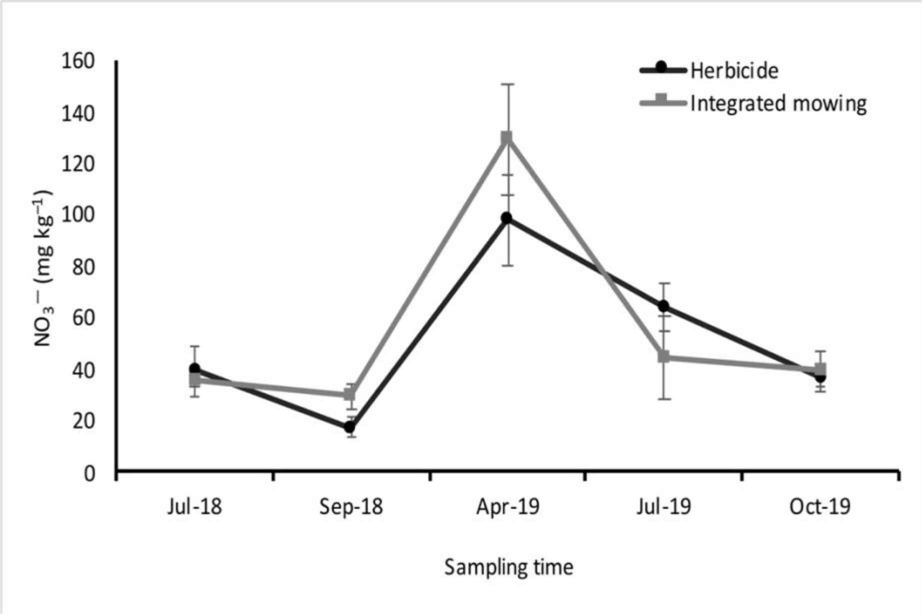

Figure 4.2 Interaction effects of treatment and sampling time on soil available NO_3^- in both apple and peach orchards. Bars represent the standard error.

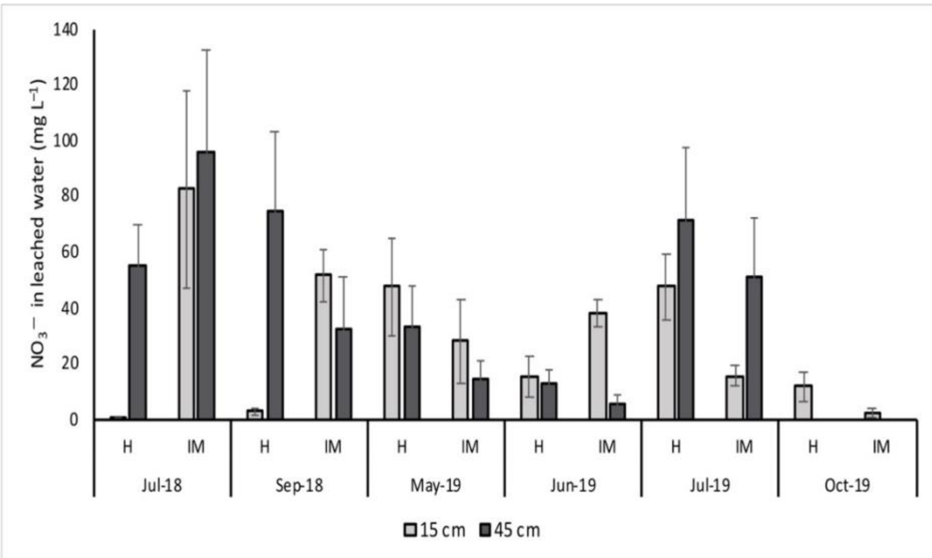

Figure 4.3 Treatment effect (H= herbicide and IM= integrated mowing) on the concentration of NO_3^- of leached water, in both apple and peach orchards. Bars represent the standard error.

These weed management approaches had a similar effect on ammonium (NH_4^+) concentrations in the soil, which averaged 11 mg kg^{-1} (Table 4.1). However, different sampling times showed that this N form (NH4+) was higher (17.3 mg kg^{-1}) in the sampling conducted in July 2018. In July 2019, the level of soil ammonium (NH_4^+) dropped to 6.75 mg kg^{-1}. Such a situation might be due to the depletion of the oxidation process of NH_4^+ into NO_2, and eventually into NO_3^-, known as nitrification (Wu et al., 2014).

Overall, soil mineral nitrogen did not vary significantly between the two treatments (Table 4.1). Integrated mowing exhibited a little more mineral N value (62.8 mg kg^{-1}) when compared to herbicide (58.5 mg kg^{-1}). At 0–20 cm soil depth, the concentration of soil mineral N was higher at depths of 20–40 cm, where integrated mowing and herbicide demonstrated highest mineral N at upper and lower soil depth (Table 4.1, Figure 4.4). Among the sampling times, April 2019 revealed higher mineral N concentrations over others.

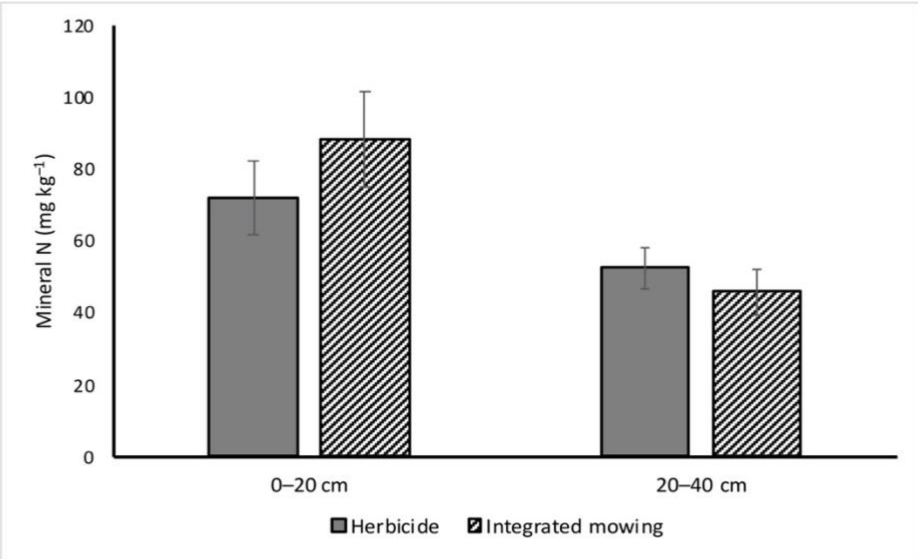

Figure 4.4. Interaction effects of treatment and soil depth on available mineral N in both apple and peach orchards. Bars represent the standard error.

Soil organic N was determined from total N after deducting of mineral N concentration. Both weed management methods showed a similar impact on soil organic N (Table 4.1). However, a significant effect was detected between two orchards, soil depth, and among different sampling times. For example, in the apple orchard, 12.8% higher organic N was produced than in the peach orchard. Again, upper soil layers (0–20 cm) had 14.3% more organic N than at 20–40 cm. Data collected from July 2019 demonstrated a considerably higher amount of organic N compared to others, while September 2018 displayed a reduced level of organic N.

Soil total N was highly affected by orchard soil, soil depth, and different sampling time, under two different weed management systems (Table 4.1). Apple orchard soil had higher total N content than peach soil, while upper soil layers possessed higher soil total N contents, throughout the experimental period. The concentration of total N in soil decreased with soil depth (Toselli et al., 2019). Among the sampling time, the highest total N was reached in July 2019, while the lowest in July 2018.

4.4.3. Weed biomass and species diversity

Soil cover (%) significantly differed between the treatments (Table 4.2). The integrated mowing plot maintained a higher percent of soil cover (92.3%), which was 2 times higher than the herbicide treatment. No year effect was observed, but soil coverage increased 12.8% in 2019, when compared to 2018. However, the apple orchard had a higher percent of vegetation coverage than the peach orchard.

Weed management practices had a significant effect on the number of weed species during the summer season of each year without differences among apple and peach orchards (Table 4.2). The results indicated that a substantial number of weed species were present in the integrated mowing plot, compared to the herbicide plot in each year without differences among apple and peach orchards (Figure 4.5). Nevertheless, weed species numbers were significantly reduced in the second year under both treatments.

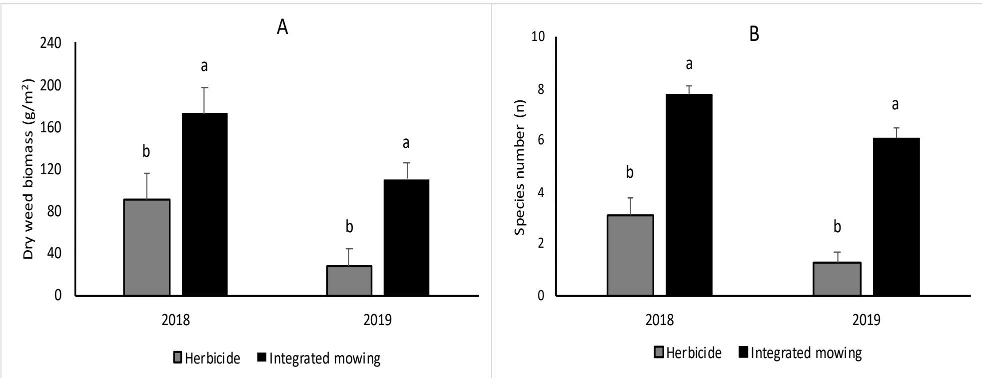

Figure 4.5 Effects of treatment on dry weed biomass (**A**) and species number (**B**) during the summer season. Bars represent standard error. Bars with different letters in a year are significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

A significantly higher above ground dry weed biomass during the summer season was recorded from integrated mowing plots (137.0 g/m^2), which indicates that the alternative treatment induced 59.5% more dry weed biomass compared to the herbicide system (Table 4.2). In the first year, weed biomass production was higher, but it decreased in the subsequent year. However, integrated mowing plots had significantly higher dry weed biomass in both years (Figure 4.5). Overall, both orchards yielded similar biomass production over two years.

Table 4.2 Two-way ANOVA for the effect of treatment, orchard, soil depth, sampling time, and their interactions on weed biodiversity parameters during the summer seasons in 2018–2019.

Parameters	Soil Cover (%)	Weed Species Number (n)	Dry weed Biomass (g/m^2)
Orchard (O)			
Apple	68.3	4.9	97.0
Peach	56.9	4.2	95.2
p-value	0.063	0.138	0.060
Treatment (T)			
Herbicide	32.9 b [Z]	2.2 b	55.5 b
Integrated mowing	92.3 a	7.0 a	137 a
p-value	0.0001	0.0001	0.0001
Year (Y)			
2018	58.3	5.5 a	131.7 a
2019	66.9	3.7 b	69.0 b
p-value	0.1654	0.0004	0.0001
Interaction (*p*-value)			
O×T	0.972	0.381	0.438
O×Y	0.040	0.019	0.0001
T×Y	0.396	0.930	0.988
O×T×Y	0.610	0.38	0.264

[Z] Means with the same letter in a column for each parameter are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

4.5 Discussion

Nitrogen is essential for nutrition and growth of trees (Ge et al., 2013), and soil organic carbon is a fundamental indicator of soil quality (Granatstein et al., 2014), including ecological system evolution (Qiu et al., 2018). For this reason, this research emphasized soil organic matter content and nitrogen status assessment, especially as the area is recognized as NVZ. In addition, the climatic conditions of the study sites may have played a role in the mineralization of organic matter and decomposition of plant residues (Leon et al., 2015), since temperature and rainfall distribution varied throughout the experimental period (Figure 1). However, no significant differences for soil organic matter were detected between soil management treatments and this is probably due to the short-term duration of the study and slow rate of change in behavior of organic matter content in the soil (Vance, 2000). Nevertheless, soil organic matter content was slightly higher in the apple orchard where the percent of soil cover by the weed was higher, resulting in the integrated mowing plot response as we hypothesized. This outcome could be also the consequence of maintaining soil cover with vegetation and a deposition of mowed residues along the tree row, benefiting soil physical and chemical properties (Dabney et al., 2001). The upper soil layer (0–20 cm) always maintained a higher SOM under all treatment conditions. In addition to this, different sampling times demonstrated a significant effect on SOM content. In 2018, the value was higher in July, then decreased in September, which was followed by a low value in April 2019, while it increased again in July and in October 2019. Seasonal and climatic factors could be responsible for this kind of variation among sampling times. For example, 77.4 mm higher rainfall was recorded in 2019 than in 2018, while the average monthly temperature varied from 15.3 to 15.6 °C between years. Thus, these climatic fluctuations could be responsible for temporary changes of SOM by changing the overall oxidizing condition of soil at different sampling time. Mineral N is the key source of N for fruit trees; yet, it should be managed carefully to avoid risks of environmental pollution (Toselli et al., 2019), especially when the trees are not absorbing nutrients from the soil (i.e., during the winter). For the management of soil mineral N in agroecosystems, the farmers are increasingly requesting for the development of an eco-friendly management system (Carranca et al., 2018). An assessment of mineral nitrogen can provide convincing evidence about available soil nitrogen (Baldi et al., 2020), where soil NO_3^- and NH_4^+ are the main forms. In this study, soil mineral N and NO_3^- concentrations showed the same patterns during the experiment, as described by Brunetto et al. (2018). Higher mineral N and NO_3^- concentrations were measured in the integrated mowing treatment compared to the herbicide (Table 4.1). In April 2019, the concentration of mineral N increased under both treatments (Figure 4.3) probably due to the effect of spring fertigation. In contrast, herbicide treatment showed lower NO_3^- concentrations because of a higher leaching occurrence in the bare ground, than in vegetation covered soil (Brunetto et al., 2018; Ventura et al., 2008). The level of soil NO_3^- at depths of 20–40 cm increased in the herbicide plot when compared to mowing, while the opposite response was observed at 0–20 cm soil depth. However, lower mineral N and NO_3^- concentrations were detected in September 2018 and October 2019, and this could be due to the end of the growing season, when trees require less nutrients to maintain their physiological function. Our results revealed that the mineral N comprises of 80–85% NO_3^-, while NH_4^+ contributed only 15–20% in both orchards. Likewise, soil organic N and total N showed the same trend under all the variables considered in this study (Table 4.1). Additionally, N availability and SOM were higher in the apple orchard, integrated mowing plot, upper soil layer, and in July 2019. A significant difference between July 2018 and July 2019 sampling times was detected because of climatic fluctuations that had occurred during the two years. Our results showed a positive trend of total N content in the vegetative cover soil plot, managed by integrated mowing. However, NO_3^- concentration in leached water differed greatly among different sampling times, whereas maximum NO_3^- leaching occurred during July with a minimum in October. This could have been the result of greater availability of NO_3^- during the productive growing season of the trees than the off-season. In addition, the NO_3^- concentration in leached water was higher in the deeper soil depths of the herbicide plot. Integrated mowing appeared to be able to limit NO_3^- leaching, which is not only crucial for healthy drinking water, but also for preserving the river water, within a vulnerable area (NVZ).

In sustainable orchard management systems, ground vegetations are considered as a source of enhancement of agroecosystem services and functional biodiversity (Bàrberi et al., 2018; Demestihas et al., 2017). The integrated mowing mimics a sustainable approach while supporting orchard biodiversity. This is crucial for diversifying residues which may buffer the presence of self-produced fruit crop residues (Giorgi eta al., 2008). Our results demonstrated that the integrated mowing technique maintained a significant percentage of soil coverage, species diversity, and dry weed biomass production in both orchards, which was approximately 2-times higher than in the herbicide system. This maintenance of covered soil using integrated mowing throughout the experimental period is advantageous for system sustainability, even though it needs to be controlled with repeated interventions to reduce the possible competition for water. In contrast, the soil remained bare in the herbicide plot, resulting in lower weed biodiversity, but it requires less weeding intervention and management cost (Mia et al., 2020a). It was worth noting that the year had a great effect on species diversity and weed biomass productions in both orchards (Table 4.2), and this could be due to the climatic variations and chemical residual effects. A total of 48 weed species were observed in both orchards over two years, where the total number of annual, perennial, and geophyte species were 30, 14, and 4, respectively (Mia et al., 2020a). The most dominant weed species in the integrated mowing and herbicide plots were perennial dandelion (*Taraxacum officinale Weber*) and annual birdeye speedwell (*Veronica persica Poir.*). However, a full list of weed species identified over two years can be found in our previous study by Mia et al. (2020 a). In 2019, the number of weed species was reduced in the apple but increased in the peach orchards, while an opposite result was obtained for weed biomass production. This response might have been due to the increased number of weeding interventions plus the short interval between two interventions during the summer season in peaches than in apple in 2019. This was probably because of the variation in other orchard management systems such as fertilizer application, supply of irrigation, and climatic conditions. For this reason, the apple orchard exhibited superior weed biodiversity than the peach orchard.

Fruit yield measured in our previous study (Mia et al., 2020a) demonstrated comparable apple production between the two treatments, while the herbicide treatment showed a significantly higher fruit production in peach. In both orchards, various fruit quality attributes such as fruit firmness, soluble solids content (SSC), and dry matter content (DMC) responded more positively to the integrated mowing than herbicide. In addition, the higher costs involving integrated practices was covered by EU subsidy under the agro-environmental agreement (AEA) of Valdaso area, which supported this transition phase (Mia et al., 2020a).

4.6 Conclusions

The findings of this study support the idea of maintaining vegetation coverage along the tree row. In comparison with herbicide-bare ground, the application of the integrated mowing technique (5–7 times per year) by combining the mower with a polypropylene brush or disc had no negative effect on overall soil N variables and organic matter content. Nitrate (NO_3^-) leaching was reduced considerably in leached water under the integrated mowing plot, which is of the utmost importance in a nitrogen vulnerable zone (NVZ). In addition, integrated mowing showed promising weed biodiversity (approximately 2–3 times higher than herbicide), including ground species number, percentage of soil coverage and aboveground dry weed biomass in both apple and peach orchards. In local agri-environmental agreements, government subsidies were given to the farmers to offset the additional costs needed for integrated technique. We believe that this study is the first step towards the possibility of supporting a balance of soil N and weed biodiversity in nitrogen vulnerable zone (NVZ) orchards in central Italy.

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Chapter 5

Living mulch with selected herbs for soil management in organic apple orchard

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5.1 Abstract

The establishment of living mulches in organic orchards could potentially improve the orchard biodiversity and, when specific plant species are selected, provide additional eco-services and functions, including adequate weed management. This study was conducted in an organically managed apple orchard in Skierniewice (Poland) to assess the effect of two selected living mulching species: *Alchemilla vulgaris* and *Mentha piperita*. They were assessed on weed control, weed biodiver- sity, tree nutritional status, root dry weight density (RDWD), and other root morphological traits compared to a natural soil cover (control). Overall, both living mulches produced 42.5% more dry biomass, increased weed species number (+29%), and increased soil coverage (+33%) compared to control mowed plots. The apple leaf chlorophyll index and nutrient content were higher in the presence of both living mulches than in the control. In addition, apple trees had 30–46% higher root dry weight densities, even though other root morphological traits were not affected by the treatments. The results suggested that the tree row can be managed with living mulches of herbs; these species have the potential to provide an additional income to the farmer, as well as beneficial effects for the orchard biodiversity, without impairing the tree root development and nutrient status.

Keywords: agroecology; biodiversity; root morphology; soil mulching; weed management

5.2 Introduction

The objective of soil orchard management in organic tree fruit production is to cre- ate optimal conditions for tree growth and production through increasing soil fertility, suppressing weeds, and minimizing biotic and abiotic stressors (Weibel, 2002). Mulches can provide several services in this respect: assisting in reducing weeds, maintaining soil moisture, increasing organic matter and nutrients, and improving the soil biological fertility (Marsh et al., 1996; Yao et al., 2005). However, mulching can also present some drawbacks such as increased rodent popula- tion (Merwin and Ray, 1999), nutrient competition, and the attraction of pests (Granatstein and Mullinix, 2008).

While tillage has demonstrated effectiveness in weed control and preventing rodent damage to trees (Granatstein and Sanchez, 2009), it has been associated with decreased tree growth, fruit yield, and fruit quality (Granatstein et al., 2010). The extensive use of soil tillage can reduce soil quality and plant biodiversity (Mia et al., 2020b; Jiang et al., 2016; Yao et al., 2005), as well as damage ethe tree roots, particularly in the case of low-vigor rootstocks which have a shallow root system (Hammermeister, 2016). These aforementioned issues are directly linked with orchard profitability and sustainability (Granatstein et al., 2014). To reduce these drawbacks, a modified tillage system that relies on grasses and leguminous plants was developed in Switzerland (the sandwich system–SSS) which is beneficial for biodiversity and nutrient cycling (Yao et al., 2005; Schmid and Weibel, 2000). It is easy to manage, and it leaves a competition-free zone for the tree roots (Weibel, 2002; Weibel and Häseli, 2003).

Moving towards more sustainable, agroecological management techniques in organic orchards explore the possibilities of enhancing multiple ecosystem services by maintaining fruit trees and herbaceous communities together. From this perspective, physical weed control or conventional soil tillage is not sufficient in the end. For this reason, holistic approaches are necessary for long-term sustainability (Mia et al., 2020a). Living mulch is considered a sustainable approach that may provide sufficient weed control and multiple ecosystem services simultaneously (Lemessa and Wakjira, 2015). Ecosystem services provided by the enhanced plant diversity of living mulches include in- creased beneficial organism populations (Bàrberi et al., 2018; Muscas et al., 2017); improved soil organic matter (Granatstein and Mullinix, 2008; Granatstein and Sanchez, 2009; Lemessa and Wakjira, 2015; Kremer et al., 2015), soil fertility, and resilience (Mia et al., 2020c; Neri, 2013); and reduced soil sickness (Polverigiani et al., 2013, 2018).

Despite these benefits, it is crucial to understand how apple roots respond to living mulch soil communities to avoid the risk of unwanted competition. Root architecture parameters, especially root dry weight density (RDWD), root length (RL), root surface area (RSA) and root diameter (RD) allow us to infer the root activity and behavior under different soil conditions (Kumar and Jose, 2018), particularly of fine roots, which are mainly responsible for absorption of water and nutrients (Polverigiani et al., 2013). Soil organisms present in the rhizosphere greatly depend on plant root exudates (Hoagland et al., 2008a; Wardle et al., 2001). Plant roots stimulate the microbial activity in the soil, which, in turn, leads to mineralization and makes the nutrients available to plants (Granatstein et al., 2002).

The selection of the living mulch species has a significant effect on weed management, tree performance, and biodiversity (Kumar and Jose, 2018). Farmers have various options for choosing mulch species, including grasses, legumes, or other broadleaf plants (Hammermeister, 2016). The emphasis has been given to less pest and disease-attractive species (Mia et al., 2020a) that can suppress weeds and maintain adequate soil coverage without competing with the main crop for water and nutrients (Granatstein and Sanchez, 2009). In this regard, the peppermint (*Mentha piperita L.*) and lady's mantle (*Alchemilla vulgaris L.*) show invasive characteristics that help to cover the ground rapidly, ensuring adequate weed management (Granatstein et al., 2002). Both mulch species can also be a source of a secondary economic benefits, being utilized for herbal or medicinal preparations (Boroja et al., 2018; Balakrishnan, 2015). Therefore, both species may be considered as second cash crops in the fruit orchards.

This study was carried out to assess the effect of two living mulch species (peppermint and lady's mantle) on weed control and above-ground biodiversity, while also taking into consideration the apple trees' nutrient status and the morphological traits of their roots. This was compared to natural soil cover under a mowing system. We hypothesized that the two selected living mulch species would enhance the overall orchard biodiversity, support weed control, and provide farmers an opportunity for additional income without negatively affecting apple growth physiology.

5.3 Materials and Methods

5.3.1 Experimental sites and management practices

The experiment was conducted at the Research Institute of Horticulture in Skierniewice experimental farm (central Poland, 51◦58′0” N, 20◦9′0” E). The area is characterized by the average annual temperature of 12◦C and an average annual precipitation of 512 mm. An eight-year-old apple (Malus × domestica Borkh., cv. Gala and Golden Delicious; rootstock M9) orchard was established on a loamy sand soil (sand 78%+ silt 14%+ clay 4%) with 3.22% soil organic matter and pH 6.2. The trees, trained according to spindle form, were spaced at 3.5 m × 1.6 m (1850 trees/ha). The orchard was drip irrigated, trees were managed according to organic farming rules (European Union Regulation 889/2008), and localized fertilization was provided with organic fertilizers (dry bovine manure and stillage), with a total of 12 g N/tree.

A Randomized Complete Block Design (RCBD) was laid out with three treatments and two replications. The treatments were (1) *Alchemilla vulgaris* (lady's mantle), (2) *Mentha piperita* (peppermint), and (3) control (natural cover with three-time mowing). Each replication consisted of 20 trees for a total row length of about 30 m. Both selected living mulching species were planted at the rate of 10 plants/m^2 randomly along the tree row (i.e., on the tree strip) in mid-May 2019. The plots were hand-weeded twice to promote the good establishment of the living mulches during the first growing season and during the experiment (on 22 May and 4 July 2020), after the assessments of soil coverage and weed population.

5.3.2 Weed biodiversity assessment

Living mulch species, weed biomass production, the number of weed species present in the tree row, and the percent of soil cover were considered to assess living mulch species and weeds development and biodiversity in the orchard. The plants comprised within a frame of 0.50 m^2 (1 m × 0.5 m) were collected in July from two random sites per replication (Domaradzki et al., 2001). After collection, the plants present in the samples were categorized as living mulch species and weeds. After air drying at 50◦C in an oven, weeds and living mulch species biomasses were measured separately by weighing them with a digital balance. Species abundance and percent of soil cover by selected mulch species and other weed species in the tree row were estimated separately in July by randomly selecting 12.5 m^2 (12.5 m × 1 m) areas in the tree row.

5.3.3 Root density and morphological traits

Soil samples were taken with an auger soil sampler (with the core length and diameter of 20 cm and 11 cm, respectively) at 0–20 cm and 20–40 cm depth three times during the growing season (2 June, 22 July and 29 September 2020), according to the method described by Böhm (1979) and adapted to row sampling as proposed by Frasier et al (2016). Each sampling time comprised of three samples per repetition at the two depths, thus a total of 36 samples for each treatment were collected during the experiment. The samples were collected along the tree row, after removing the superficial organic debris, on a randomly selected sampling site approximately 50–60 cm away from the tree trunk. No samples were taken from directly under an irrigation drip emitter. Once a core was taken from a point, and no further samples were taken in that area. The soil samples were stored at 4 ◦C in the refrigerator until analysis, which happened in the week following the sampling.

Apple, living mulch species, and weed roots were manually separated from the soil by washing the core in a 0.5 mm sieve. Roots were collected on filter paper and kept in plastic bags until analysis. The root length (RL), root diameter (RD), root surface area (RSA), and root volume (RV) of the whole sample (apple and herbaceous plants roots together) and of apple roots alone (recognized due to their different color and morphology) were measured by image analysis using the WinRhizo software (Regent Instruments Inc., Canada, 2009). To determine dry weight, the washed and cleaned roots were dried in an oven at 60 ◦C until the weight stabilized. Then, the root density was calculated as the ratio of dry root weight and soil volume of the core.

5.3.4 Leaf chlorophyl content and nutrient analysis

Apple leaf chlorophyll content (Chl) was measured using Dualex Scientific optical leaf-clip instrument at a 375 nm wavelength (FORCE-A, Orsay, France). The measurements were performed on 10 leaves from each randomly selected tree (total of 60 leaves per replication). The measurements were taken in July with the adaxial leaf side facing the light source (Cerovic et al., 2012). To measure the leaf nutrient content, leaf samples were collected randomly from each plot in July 2020. Each leaf sample contained 60 new midterminal mature leaves from current-year shoots from the central section of the tree. The leaves were washed with distilled water, dried at the temperature of 60 ◦C in a forced-air oven, then ground in a Wiley stainless-steel mill. The samples were microwave digested in HNO_3, using closed Teflon vessels. Inductively coupled plasma spectrometry (ICP Model OPTIMA 2000DV, Perkin Elmer, USA) was used to determine P, K, Na, Ca, and Mg, as described by Kowalczyk et al. (2020). The N content was determined using the Kjeldahl apparatus (Vapodest, Gerhardt, Germany) after mineralization in concentrated sulfuric acid in the presence of copper-potassium catalyst (Kowalczyk et al., 2020).

5.3.5 Statistical analysis

All the root trait data were subjected to analysis of variance (ANOVA) considering two factors (treatment and soil depth). For the biodiversity data, leaf chlorophyll content, and nutrient analysis data, one-way ANOVA was performed. Significant differences were compared using mean separation with the Tukey–Kramer HSD (Honestly Significant Difference) test ($p \leq 0.05$). Statistical analysis was conducted in JMP Software (Release 8; SAS Institute Inc., Cary, NC, USA, 2009).

5.4. Result

5.4.1. Weed biodiversity

A total of sixteen weed species were identified in the apple orchard in July 2020 (Table 1). The most dominant weed species present in the tree row were *Echinochloa crus- galli L.* and *Agropyron repens L.* in the *Alchemilla vulgaris* plot, *Hypochaeris radicata L.* in the *Mentha piperita* plot, and *Taraxacum officinale* Weber and *Trifolium arvense L.* in the control plot. Neither peppermint nor the control presented four weed species: neither presented *L. purpureum, V. persica,* nor two more species absent for each treatment (Table 1). White clover *(Trifolium repens L.)* was abundant in the inter-row area, along with other perennial grasses in all the treatments.

Table 5.1 Weed species identified along the rows of the apple orchard

EPPO Code	Scientific Name	Treatments		
		Alchemilla Vulgaris	Mentha Piperita	Control
AGRRE	*Agropyron repens (L.)*	✓	✓	✓
CAPBP	*Capsella bursa-pastoris (L.)*	✓		✓
ECHCG	*Echinochloa crus-galli (L.)*	✓		✓
EQUAR	*Equisetum arvense (L.)*	✓	✓	✓
ERICA	*Erigeron canadensis*	✓	✓	✓
EROCI	*Erodium cicutarium (L.)*	✓	✓	
GASPA	*Galinsoga parviflora*	✓	✓	
HRYRA	*Hypochaeris radicata (L.)*	✓	✓	✓
LAMPU	*Lamium purpureum (L.)*	✓		
POAPR	*Poa pratensis*	✓	✓	✓
RUMSS	*Rumex sp.*	✓	✓	✓
STEME	*Stellaria media (L.)*	✓	✓	✓
TAROF	*Taraxacum officinale Weber*	✓	✓	✓
TRFAR	*Trifolium arvense (L.)*	✓	✓	✓
VERPE	*Veronica persica Poiret*	✓		
VIOAR	*Viola arvensis (L.)*	✓	✓	✓

Note: The sign ✓ indicates the presence of the species in the respective treatment plot

The highest amount of above ground dry biomass (weeds + living mulch) was ob- tained in July from Alchemilla plots (500 g/m^2), followed by the peppermint (386 g/m^2), significantly higher (50% and 35% for Alchemilla and peppermint, respectively) than the control plot (Figure 1A). The living mulch treatments induced an increase in the number of weed species present in the tree row, which was 10% to 25% higher in peppermint and Alchemilla, respectively, compared to the control plots (Figure 1B).

The percentage of soil vegetation coverage was affected significantly by different soil management strategies (Figure 2). The soil coverage by weeds was significantly lower in the Alchemilla (12%) and peppermint (26%) plots, while the selected mulching species covered the soil up to 88% to 93% in total, respectively, compared to the control system (60.3%).

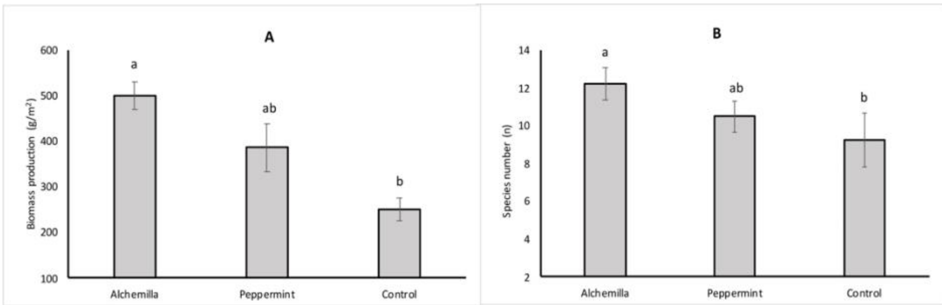

Figure 5.1 Effect of living mulching species on above ground dry biomass (A), and species number (B). Bars represent the standard error. Bars with different letters are significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

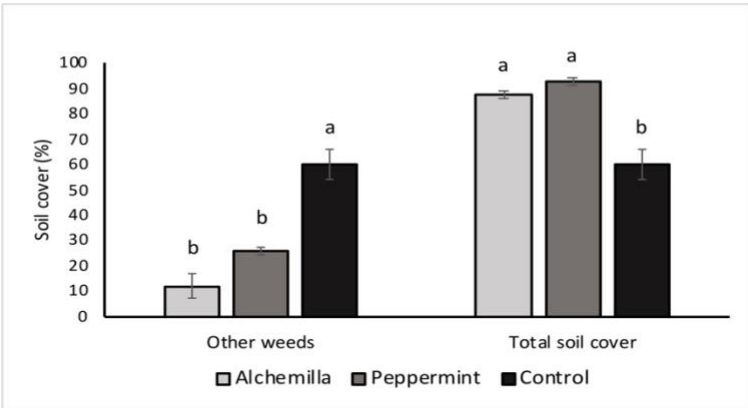

Figure 5.2 Effect of living mulching species on percentage of soil coverage by other weeds and total vegetation. Bars represent the standard error. Bars with different letters are significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

5.4.2 Leaf nutrients analysis and chlorophyll content

Data pertaining to leaf macronutrients (N, P, K, Ca, and Mg) and the micronutrient status of apple, as influenced by the soil orchard management during the experiment, are provided in Table 2. The highest content of leaf N (1.56%), P (0.15%), K (1.68%), Ca (2.12%), and Mg (0.29%) was recorded in trees growing in association with Alchemilla. Even though N content was different at a p level that could still be considered significant for field trials ($p = 0.066$), both P and K content showed no significant differences. However, Ca and Mg content was significantly lower (p = 0.015 and 0.0084, repectively) in the control in comparison to the two living mulch species. Leaf chlorophyll content was significantly higher (p = 0.0001) in Alchemilla in comparison to control and peppermint, which had a similar value (Table 2).

Table 5.2 Effect of different row living mulches on chlorophyll and leaf macro-nutrients content in apple leaves.

Parameters	Chlorophyll (μg/cm²)	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Treatment						
Alchemilla	27.9±0.66 a	1.56±0.06	0.15±0.01	1.68±0.08	2.12±0.02a	0.29±0.01a
Peppermint	22.9±0.44 b	1.42±0.05	0.13±0.01	1.42±0.06	2.0±0.07ab	0.29±0.01a
Control	21.7±0.50 b	1.37±0.04	0.14±0.01	1.54±0.06	1.61±0.07b	0.23±0.01b
p-value	0.0001	0.066	0.503	0.247	0.0150	0.0084

Data are expressed as mean ± SEM. Means with the same letter in a column are not significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

A strong positive correlation between the chlorophyll and N content (r = 0.99) and chlorophyll and dry biomass of ground vegetation (r= 0.92) was found (Figure 3). No correlation (r = 0.39) emerged between the leaf N and dry biomass production (Figure 3).

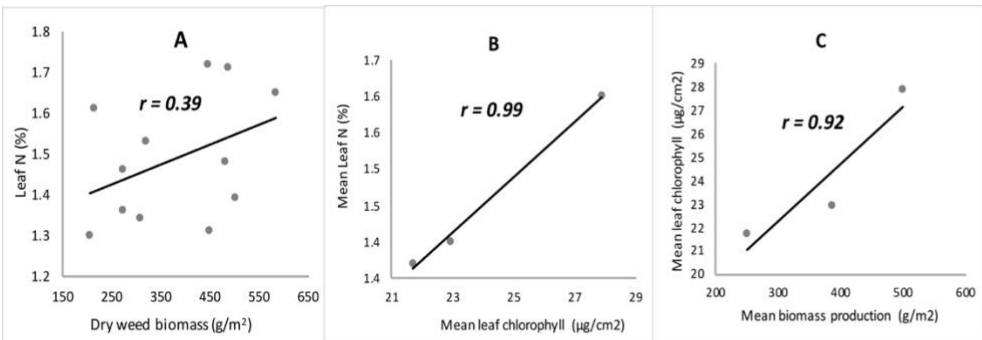

Figure 5.3 Correlation between leaf N and dry biomass (weed + mulching species) (A), between leaf N and leaf chlorophyll (B), and between leaf chlorophyll and dry biomass production (C).

5.4.3 Root morphological parameters

5.4.3.1 Analysis of overall soil root community

The root dry weight density (RDWD) of the samples, including both apple and herbaceous species together, varied significantly depending on the treatment, soil depth, and their interactions (Table 3). RDWD was significantly higher in peppermint mulched plots (1592.4 g/m^3), followed by Alchemilla (1191 g/m^3), compared to the control (895.9 g/m^3). The only root morphological parameter with a significant difference was the root surface area (Table 3). Nevertheless, all the parameters, except the root diameter, showed a significantly higher value for samples of the upper soil depth (0–20 cm) than of the lower depth (Table 3). The interaction between the two studied factors was significant only for RDWD (Table 3). Peppermint resulted in an average higher root dry weight density at both soil depths in comparison to the other two treatments, but significantly higher than control only at 0–20 cm depth (Figure 4).

Table 5.3 Effect of living mulches, soil depth, and their interactions on the density and morphological parameters of the total root community (herbaceous and apple roots).

Parameters	Root dry weight density (g/m^3)	Root length (cm)	Surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Treatment					
Alchemilla	1191.0 ab	700.0	156.0 ab	0.90	3.2
Mint	1592.4 a	619.9	167.5 a	0.90	3.8
Control	895.9 b	546.5	121.1 b	0.91	2.9
p-value	0.03	0.29	0.04	0.99	0.29
Soil depth					
0–20 cm	1551.6 a	885.9 a	205.8 a	0.86	4.2 a
20–40 cm	901.2 b	358.4 b	90.7 b	0.94	2.4 b
p-value	0.002	0.0001	0.0001	0.454	0.0002
Interaction					
Treatment*Soil depth (*p*–value)	0.042	0.640	0.724	0.515	0.224

Data are expressed as means ± SEM. Means with the same letter for treatments or year are not significantly different according to the Tukey HSD test ($p < 0.05$).

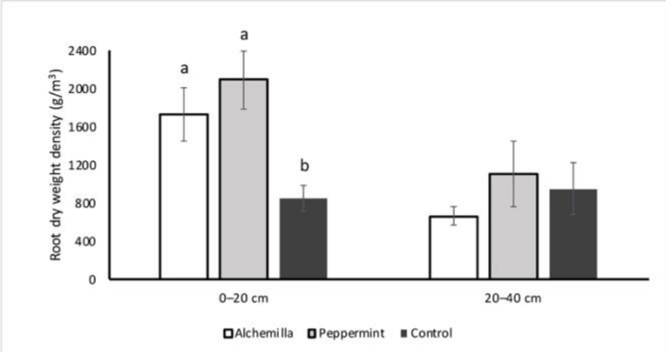

Figure 5.4. Effect of the interaction between living mulch treatment and soil depth on root dry weight density (g/m^3). Bars represent the standard error.

5.4.3.2 Apple root analysis

Apple RDWD and all other root morphological parameters did not significantly differ among the treatments nor between soil depths (Table 4). However, the root length could be considered significantly higher in the upper soil depth with a $p \leq 0.1$ significance level. Interestingly, the interaction between the two factors was significant for the RSA and RV. Alchemilla displayed higher apple RSA and RV values at a 0–20 cm soil depth, while peppermint showed a higher value for RSA and RV at the deeper soil layer (Figure 5).

Table 5.4 Effect of living mulches, soil depth, and their interactions on apple root dry weight density and morphological parameters.

Parameters	Root dry weight density (g/m^3)	Root length (cm)	Root surface area (cm^2)	Root diameter (mm)	Root volume (cm^3)
Treatment					
Alchemilla	556.8	186.3	35.3	0.40	0.61
Peppermint	624.3	104.9	23.3	0.51	0.50
Control	425.3	69.2	13.0	0.42	0.41
p-value	0.788	0.189	0.189	0.837	0.770
Soil depth					
0–20 cm	508	165.2	30.4	0.30	0.49
20–40 cm	563	75.1	17.3	0.60	0.51
p-value	0.819	0.094	0.191	0.109	0.921
Interaction					
Treatment*Soil depth	0.068	0.113	0.038	0.350	0.043

Data are expressed as means ± SEM. Means with the same letter for treatments or year are not significantly different according to the Tukey-HSD test ($p < 0.05$).

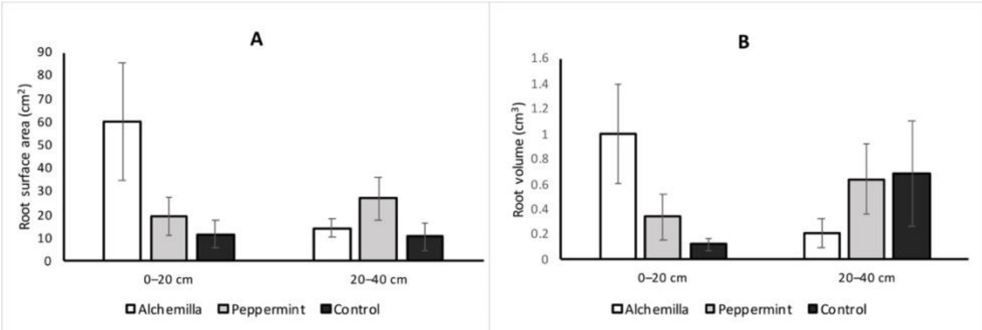

Figure 5.5. Interaction effect of treatment and soil depth on apple root surface area (cm^2) (A) and root volume (cm^3) (B). Bars represent the standard error.

5.5 Discussion

In this study, the results indicate that both selected living mulch species had a suppressive effect on weeds, achieving almost full coverage of the soil and control of the weed development by the beginning of summer of the second season after planting. Steinmaus et al. Steinmaus et al. (2008) found that keeping more than 50% soil coverage in the vineyard can increase weed management intensity proportionally. However, notwithstanding their potential in controlling weeds' development, their presence did not reduce the biodiversity of the weeds, as emerged from the higher number of species associated with peppermint and Alchemilla in comparison to the control, supporting a higher species diversity. Natural soil cover, as in the case of the control, particularly when managed with mowing, is reported to reduce species diversity (Tursun et al., 2018), which was also confirmed in our study. The high amount of above ground biomass produced in the living mulch plots was mainly comprised of Alchemilla and peppermint biomass, which suppressed, at the same time, the growth of other weeds. Prevention of weed emergence is exerted partly through competition for light, nutrients, and soil moisture by the living mulch, as well as the release of allelochemicals and modifications in the soil microenvironment (Qasem, 2013). Several plant species producing essential oils, including the mint family, have been considered and evaluated for weeds control (Cheng and Cheng, 2015). Mint essential oils are comprised of monoterpenes like menthone and menthol, which is the case for peppermint (Rohloff, 1999). These essential oils from peppermint show allelopathic potential particularly on monocotyledonous (Campiglia et al., 2007) and, as seen in our trial, on a species of *Echinocloa* (Mahdavikia and Saharkhiz, 2015). The inhibition of root growth by menthone targets cell microtubules (Sarheed et al., 2020), similarly to important herbicide classes, such as the dinitroaniline herbicides (Anthony et al., 1998) *Alchemilla mollis*, a species close to *A. vulgaris* and with a very similar growth and dense canopy of broad scalloped leaves, has been found to achieve a nearly complete weeds control as groundcover in roadsides (Eom et al., 2005): a reduction greater than 80% of the light reaching the soil surface was the major factor inhibiting weeds development. Considering the broad soil coverage of Alchemilla observed in our trial, it can be stated that the same mechanism of weed suppression would apply also for this species.

Moreover, Alchemilla and peppermint produced approximately 1.5 times higher biomass than weed plants, which has possible implications for the soil nutrient status and fertilization management. Nitrogen application rates, delivered as organic fertilizers as well (Costa et al., 2005), affected peppermint growth (Jeliazkova et al., 1999) and oil yields (Lawrence, 2006). Therefore, when considering the use of this species as living mulch and second cash crop, it is important to assure an adequate provision of nutrients to meet both the tree and mint requirements. The challenge would thus be finding a balance to avoid the risks posed by excessive fertilization, which could promote the growth of weeds and negatively impact on the main crop's (apple) physiology, nutrient and health status, and yield. Alchemilla is normally collected from the wild, and it is not grown as a crop, thus we were not able to find data about its productivity to compare the potential expressed in the trial. However, trials to cultivate *Alchemilla mollis* under different altitudes proved the high ecological plasticity of the species (Vitkova et al., 2011). Moreover, *Alchemilla vulgaris* was among the best biomass producers in field trials testing its suitability of roadside groundcover (Eom et al., 2005),

which, together with the data from the current trial, encourages consideration of this species as a good potential secondary cash crop for orchards.
It is noteworthy that the presence of the two mulching species in the tree row did not impair the apple leaf macronutrient content (N, P, K, Ca, and Mg); rather, they induced a higher leaf N content compared to the natural cover. Slow release of nutrients from organic sources should not result in increased competitive ability of weeds (Liebman and Davis, 2000), therefore also to a hypothetical competition of the two mulching species. However, the similar apple root dry weight density in the different treatments would result in a similar root uptake capacity. Therefore, a higher soil biological activity in the selected mulching plots could be hypothesized, which could result in a more rapid soil organic matter mineralization and nitrogen availability (Schütt et al., 2013). The incorporation of essential oils or their major constituents into soils has stimulatory effects on bacterial populations (Vokou et al., 2002). stimulatory or depressing effects on specific fungal populations (Kadoglidou et al., 2011; Konstantinou et al., 2019), and can stimulate soil respiration (Vokou and Liotiri, 1999). Moreover, a weekly addition of a minimum amount of mint essential oil for a month, which could mimic a natural contribution from the plants growing on the soil, enhanced the biomass of Gram-positive bacteria, fungi, and microeukaryotes, showing a priming effect of a low-intensity stimulus when applied repeatedly, which modified some enzymatic activities also linked with N cycle (Konstantinou et al., 2019). The removal of *Alchemilla monticola*, a species close to *Alchemilla vulgaris*, from a grassland strongly affected the bacterial community and weakly influenced mycorrhizal fungi, resulting in a decreased rate of plant litter decomposition and soil respiration (Mariotte et al., 2013). It could thus be speculated that, in our trial, a higher soil biological activity was also induced by Alchemilla. A noteworthy finding of this study was the positive correlation between dry biomass production and apple leaf chlorophyll content. This could be also associated to the hypothesized enhanced microbial activity deriving from the growth of the two mulching species, since plant physiology can be affected by soil microorganisms (Qu et al., 2020). The higher apple leaves content of P, K, Ca, and Mg in Alchemilla plots could be also an effect of a modified soil microbiome, leading to a higher solubilization and availability of these nutrients (Bardi and Malusá, 2012) also noticed highest leaf P contents in cherry trees with selected mulching species, such as *T. pratense* (red clover). However, the overall results showed that the primary leaf nutrient contents (N, P, and K) were slightly lower under all the treatments in comparison to data from other studies in apple (Hoagland et al., 2008; Żelazny and Licznar-Małańczuk, 2018). Even though the sandy-loamy texture of the soil of the orchard could account for such difference, the result is pointing to the need of a careful nutrient management of the orchard when living mulches are introduced.
Root dry weight density (RDWD) was significantly affected by the living mulch and the sampling depth as well. The high RDWD found with both living mulch species could likely be due to the size and architecture of their root system and the presence of stolons (Lawrence, 2006). These root architectural and morphological traits can be crucial in shaping orchard soil environment through a range of mechanisms, including the interaction with the soil microorganisms (Vassileva et al., 2020). Such hypothesis can be supported by considering that higher values of the morphological traits were found in the samples from the upper soil layer confirming the observations that roots of herbaceous plants are commonly found in this layer (Polverigiani et al., 2013). Even though no statistical differences were observed in terms of RDWD of apple roots between the different living mulches, on average, apple RDWD was

38% higher in the selected mulching species than in the natural vegetation cover, and 11% higher in the deeper soil layer compared to the upper one. Root plasticity in the response to the environment could be accounted for such observations (Polverigiani et al., 2014).

5.6 Conclusions

Proper soil management is a key challenge for growers in modern organic fruit orchards. A holistic approach can provide adequate weed and nutrients management as well as supporting orchard biodiversity. The cultivation of two mulching species (*Alchemilla vulgaris* and peppermint) on the tree row provided sufficient weeds control and ground coverage, according to organic farming standards, while significantly enhancing species number and producing a good amount of the herbs' dry biomass. These are the primary goals in improving biodiversity and long-term sustainability in organic fruit orchards. Both species allowed a normal nutrient uptake for the main crop without negatively affecting the apple root system development. Nevertheless, on the long term, their growth and biomass production would need to be sustained with a correct fertilization to avoid possible competition with the tree species. The good biomass production of the two living mulches also points to their use as a secondary income source, since their leaves and flowers are commercially used for making valuable medicinal products, as well as for aesthetic purposes. In case of mint, its features on diseases control could be exploited with a direct application of the essential oil extracted from the living mulch, implementing a circular economy approach. A repeated hand weeding (2 to 3 times during the summer) was required for an adequate establishment of the living mulching plots. However, this practice would become less necessary in the years following their establishment, as the plants reduce weed growth. Considering the potential additional economic value and the ecological benefits of these living mulches, they can represent a sustainable solution for row management in organic apple orchards.

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Chapter 6

Concluding Remarks

The project was developed under the agro-environmental agreement (AEA) in Valdaso area (central Italy) and in an organic apple orchard of the most important fruit production area in Skierniewice (Poland) to improve soil health and orchard biodiversity, without compromising fruit production. These goals are directly linked with all aspects of sustainability in both integrated and organic fruit orchards. Chemical herbicide and soil tillage are the most effective orchard floor management practices in the tree row, but both techniques have proved to be a tremendous threat to ecosystem health and sustainability. However, this research revealed that practicing more sustainable alternatives (either single or integrated) are able to restore orchard sustainability by improving biodiversity and soil quality while providing adequate weed control simultaneously. Two integrated mechanical systems; integrated mowing and integrated tillage have a great efficacy in increasing overall orchard biodiversity without compromising fruit production and quality. Yet, it requires a long-term experiment to confirm whether these systems can improve soil organic matter or not. But it can be predicted that the continuous use of these integrated techniques could improve soil organic matter in the soil as they did not have negative effect and might create favorable conditions for humification using mowed plant materials. These mowed residues could serve as mulches in the tree row, thus reduce on-farm cost and improve economic sustainability. Both integrated systems, especially integrated mowing was most effective against nitrate leaching, which was crucial in the nitrogen vulnerable zone (NVZ), especially in Valdaso (Marche region, Italy), for protecting groundwater. Therefore, it can be recommended that integrated mechanical strategies with repeated constraints by brush and disk mower (five to seven times, depending on the orchard stage, type of soil and environmental conditions) and eventually blade tillage (in light soils, once a year early in the season) can be a more sustainable solution for intra-row management in high-density fruit orchards of central Italy.

In the second study, the goal was to assess the efficacy of two selected herbal species in the tree row on weed control, apple leaves nutrient, weed biodiversity, and plant roots morphological traits. The idea was to introduce the herbal species; *Alchemilla vulgaris* L. and peppermint in the fruit orchard, not only for managing weeds but also for their potential economic value. Selected mulching species along the tree row provided sufficient weeds control and fostered above-ground biodiversity. They exhibited a positive association with apple trees, as a consequence, sufficient nutrient uptake and normal root activity emerged in the presence of selected mulches. However, they can be highly recommended in the established fruit orchards only, as younger trees are more disposed to competition. The presence of vole population can destroy their efficacy; therefore, further research is needed to find the way of minimizing vole problem, especially in the vole problematic area.

All the studies in this thesis highlight the potential benefits of practicing more eco-friendly alternative approaches for orchard floor management in the tree row with an aim to enhance orchard sustainability. The higher cost involved with these practices compared to chemical herbicide, covered by EU subsidy under the agro-environmental agreement (AEA) of the Valdaso area, which supported this transition phase to reduce the use of chemicals. Besides, selected living mulches, such as different herbal species used in the study are possibly able to provide additional source of income along with ecological benefits and weed control than the non-selective natural vegetations.

To disseminate our project findings to the national and international level, we published three peer reviewed articles in the international Journal and two technical articles in national (Italian) technical journal. In addition, several field demonstrations and seminars were organized by involving local farmers and private organizations with our university research body.