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Living Mulch with Selected Herbs for Soil Management in Organic Apple Orchards

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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 biodiversity, 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

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1. Introduction

The objective of soil orchard management in organic tree fruit production is to create optimal conditions for tree growth and production through increasing soil fertility, suppressing weeds, and minimizing biotic and abiotic stressors [1]. 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 [2,3]. However, mulching can also present some drawbacks such as increased rodent population [4], nutrient competition, and the attraction of pests [5].

While tillage has demonstrated effectiveness in weed control and preventing rodent damage to trees [6], it has been associated with decreased tree growth, fruit yield, and fruit quality [7]. The extensive use of soil tillage can reduce soil quality and plant biodiversity [8–10], as well as damage ethe tree roots, particularly in the case of low-vigor rootstocks which have a shallow root system [11]. These aforementioned issues are directly linked with orchard profitability and sustainability [12]. 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 [3,13]. It is easy to manage, and it leaves a competition-free zone for the tree roots [1,14].

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 [15]. Living mulch is considered a sustainable approach that may provide sufficient weed control and multiple ecosystem services simultaneously [16]. Ecosystem services provided by the enhanced plant diversity of living mulches include increased beneficial organism populations [17,18]; improved soil organic matter [5,9,16,19], soil fertility, and resilience [20,21]; and reduced soil sickness [22,23].

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 [24], particularly of fine roots, which are mainly responsible for absorption of water and nutrients [25]. Soil organisms present in the rhizosphere greatly depend on plant root exudates [26,27]. Plant roots stimulate the microbial activity in the soil, which, in turn, leads to mineralization and makes the nutrients available to plants [28].

The selection of the living mulch species has a significant effect on weed management, tree performance, and biodiversity [24]. Farmers have various options for choosing mulch species, including grasses, legumes, or other broadleaf plants [11]. The emphasis has been given to less pest and disease-attractive species [15] that can suppress weeds and maintain adequate soil coverage without competing with the main crop for water and nutrients [6]. 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 [28]. Both mulch species can also be a source of a secondary economic benefits, being utilized for herbal or medicinal preparations [29,30]. 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.

2. Materials and Methods

2.1. 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.

2.2. 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 [31]. 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.

2.3. 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 [32] and adapted to row sampling as proposed by Frasier et al [33]. 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.

2.4. Leaf Chlorophyll 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 [34]. 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. [35]. 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 [35].

2.5. 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).

3. Results

3.1. 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 1. Weed species identified along the rows of the apple orchard.

EPPO Code	Scientific Name	Treatments		
		A. vulgaris	***M. piperita***	**Control**
AGRRE	*Agropyron repens* L.	✓	✓	✓
CAPBP	*Capsella bursa-pastoris* L.	✓		✓
ECHCG	*Echinochloa crus-galli* L.	✓		✓
EQUAR	*Equisetum arvense* L.	✓	✓	✓
ERICA	*Erigeron canadensis* L.	✓	✓	✓
EROCI	*Erodium cicutarium* L.	✓	✓	
GASPA	*Galinsoga parviflora* Cav.	✓	✓	
HRYRA	*Hypochaeris radicata* L.	✓	✓	✓
LAMPU	*Lamium purpureum* L.	✓		
POAPR	*Poa pratensis* L.	✓	✓	✓
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 obtained 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%).

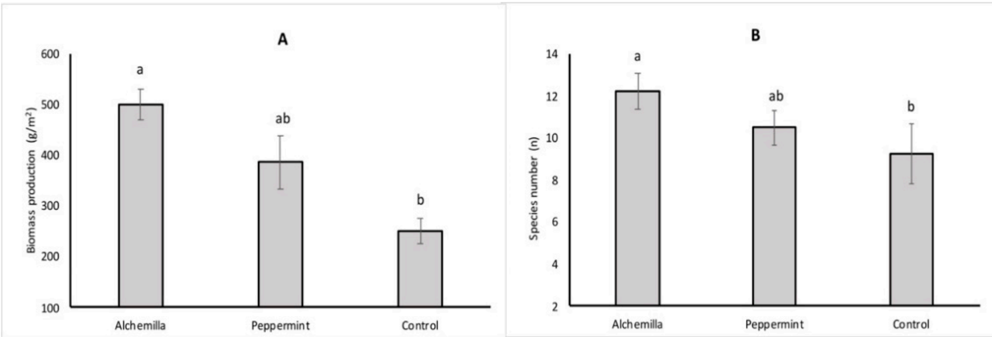

Figure 1. Effect of living mulching species on above ground dry biomass (**A**), and species number (**B**). Bars represent the SEM. Bars with different letters are significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

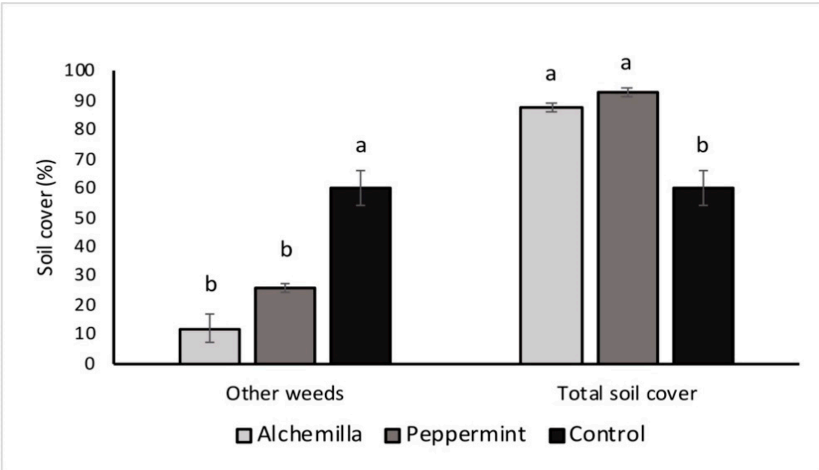

Figure 2. Effect of living mulching species on percentage of soil coverage by weeds and total vegetation. Bars represent the SEM. Bars with different letters are significantly different at $p \leq 0.05$ (Tukey–Kramer HSD test).

3.2. 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, respectively) 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 2. Effect of different row living mulches on chlorophyll and leaf macro-nutrients content in apple leaves.

Parameters	Chlorophyll (μg/cm^2)	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 ± 0.01 a
Control	21.7 ± 0.50 b	1.37 ± 0.04	0.14 ± 0.01	1.54 ± 0.06	1.61 ± 0.07 b	0.23 ± 0.01 b
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).

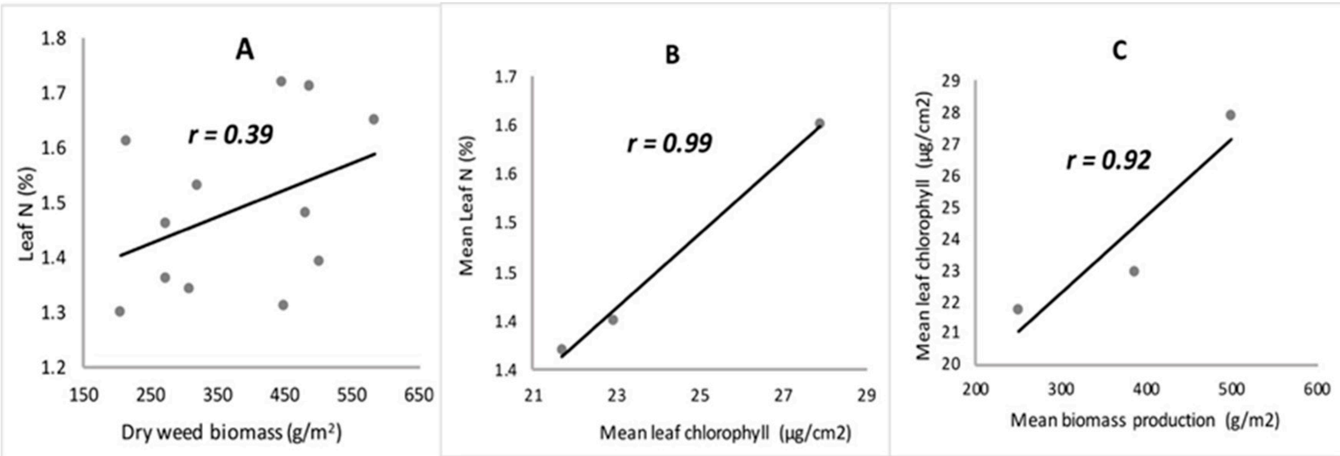

Figure 3. Correlation between leaf N and dry biomass (weed + mulching species) (**A**), between leaf N and leaf chlorophyll (**B**), and between leaf chlorophyll and dry biomass production (**C**).

3.3. Root Morphological Parameters

3.3.1. 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 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)	Root 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
Peppermint	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 ($p < 0.05$).

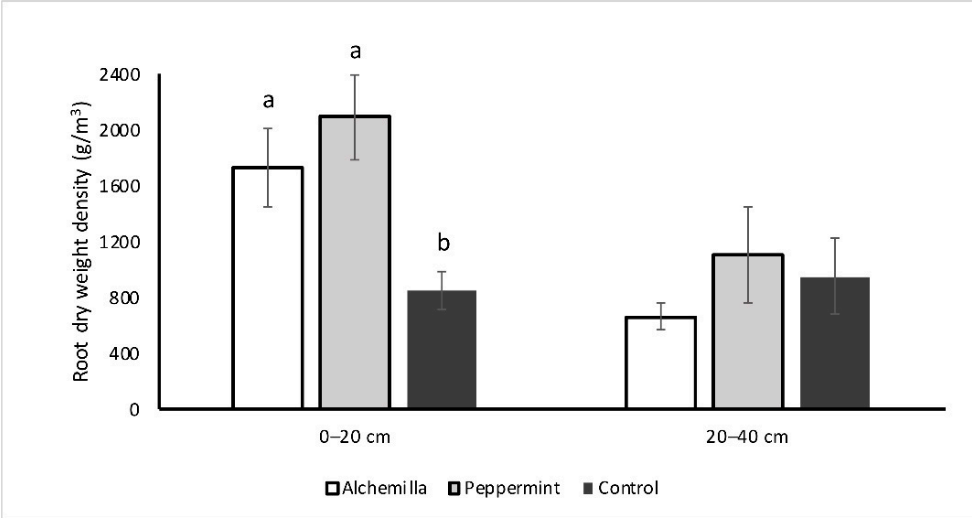

Figure 4. Effect of the interaction between living mulch treatment and soil depth on root dry weight density (g/m^3). Bars represent SEM.

3.3.2. 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).

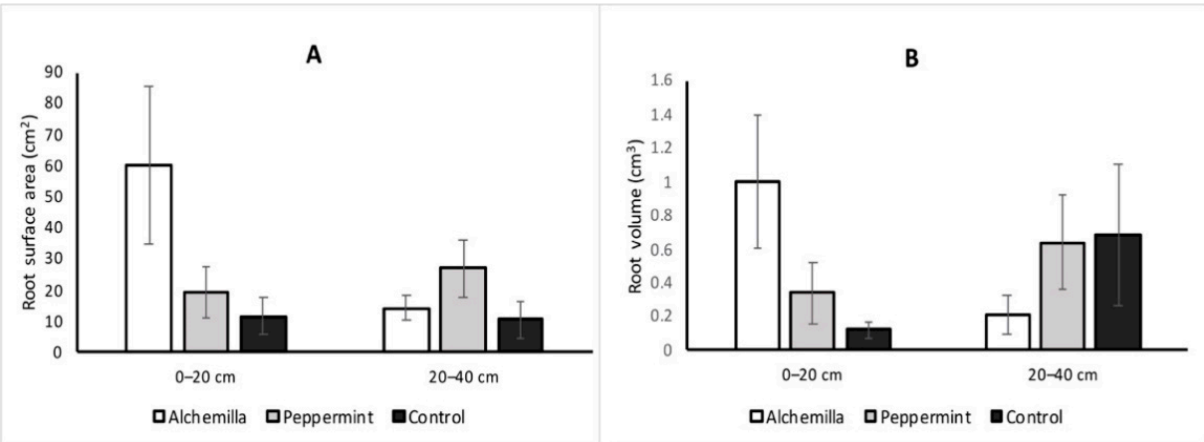

Figure 5. Interaction effect of treatment and soil depth on apple root surface area (cm^2) (**A**) and root volume (cm^3) (**B**). Bars represent the SEM.

Table 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 (*p*-value)	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 ($p < 0.05$).

4. 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. [36] 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 [37], 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 [38]. Several plant species producing essential oils, including the mint family, have been considered and evaluated for weeds control [39]. Mint essential oils are comprised of monoterpenes like menthone and menthol, which is the case for peppermint [40]. These essential oils from peppermint show allelopathic potential particularly on monocotyledonous [41] and, as seen in our trial, on a species of *Echinocloa* [42]. The inhibition of root growth by menthone targets cell microtubules [43], similarly to important herbicide classes, such as the dinitroaniline herbicides [44] *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 [45]: 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 [46], affected peppermint growth [47] and oil yields [48]. 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 [49]. Moreover, *Alchemilla vulgaris* was among the best biomass producers in field trials testing its suitability of roadside groundcover [45], 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 [50], 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 [51]. The incorporation of essential oils or their major constituents into soils has stimulatory effects on bacterial populations [52], stimulatory or depressing effects on specific fungal populations [53,54], and can stimulate soil respiration [55]. 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 [54]. 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 [56]. 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 [57]. 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 [58]. Hoagland et al. [27] 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 [27,59]. 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 [48]. 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 [60]. 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 [25]. 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 [22].

5. 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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