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Integrated Weed Management in High Density Fruit Orchards

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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

1. 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 [1]. Therefore, proper weed management is vital in the fruit orchard to minimize weeds competition against fruit trees, assuring quality fruit yields [2,3], and supporting weed biodiversity in the orchard [4]. 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 [4,5]. Maintaining bare soil from 0.6 to 2.0 m along the tree row with herbicides [6] has proven to be easy, cost-effective, and favorable for tree growth and fruit yield [7]. 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 [8–10]. Additionally, these practices foster the development and evolution of herbicides resistant weed species [11] and favor an insurgence of soil sickness [12,13]. 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 [14]. 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 [15,16], by promoting functional agrobiodiversity in the orchard [17]. Hence, adopting a sustainable orchard management strategy is vital for enhancing weed biodiversity, which can provide ecological protection [18] by offering feed and shelter to beneficial organisms [19,20], and improving soil fertility by hosting mycorrhizae, and thereby promoting nutrient availability [21] and resilience in the soil [22]. 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 [23], while the opposite results may be found under the coverless ground system conditions [24]. 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 [25] that support covered soil with spontaneous, or selected living species by keeping them at a density level that does not negatively impact tree performances [4].

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 [26]. 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 [5,26,27].

The wide availability of sustainable management practices directed us towards seeking further advances in mechanical weed control [4]. 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 [18,28,29], tree roots [30], 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.

2. Materials and Methods

2.1. 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 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.

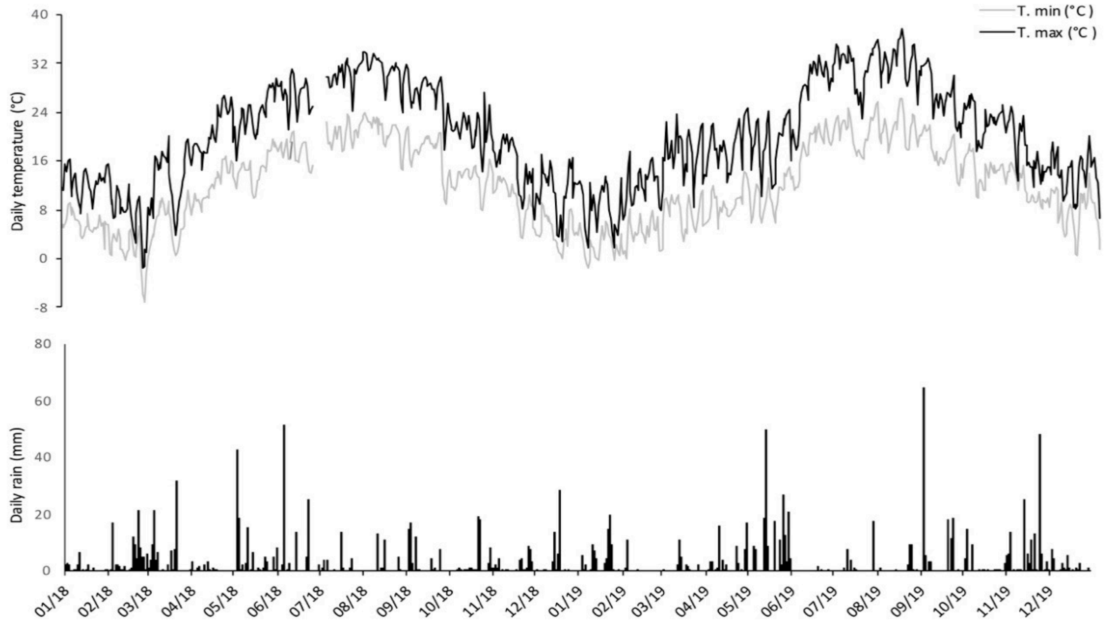

Figure 1. The daily rain (mm), and minimum and maximum temperature (°C) measured during the experiment (2018–2019) by a meteorological station located 3 km from the experimental field (Sistema Informativo Regionale Meteo-Idro-Pluviometrico).

For each species, a Randomized Complete Block Design (RCBD) was laid out with three blocks and three treatments (Table 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.

2.2. *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.

Table 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

2.3. 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 m^2 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 [31]. Visual weed ratings for each plot were recorded the day before the treatment application by randomly selecting 10 m^2 (4 m × 2.5 m) area in the tree row.

2.4. Gas Exchange Parameters

Gas exchange parameters such as the net photosynthetic rate (A, μmol CO_2 m^{-2} s^{-1}), the transpiration rate (E, mmol H_2O m^{-2} s^{-1}), the stomatal conductance (g_s, 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 [32]. The parameters were measured when the system reached equilibrium on July and August in 2018 and June, July, and August in 2019.

2.5. 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).

2.6. 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. Results

3.1. 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 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
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	

Table 2. *Cont.*

	Apple						Peach					
	2018			2019			2018			2019		
Species	**H**	**IT**	**IM**	**H**	**IT**	**IM**	**H**	**IT**	**IM**	**H**	**IT**	**IM**
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). 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.

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). 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). 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).

3.2. 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 4).

Table 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).

Table 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 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 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 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 5).

Table 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 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 5) without any change in the trend among treatments. There were no significant differences recorded among the treatments for SSC (Table 5), and fruit dry matter content in the apple (Table 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 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 5).

3.3. 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 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.

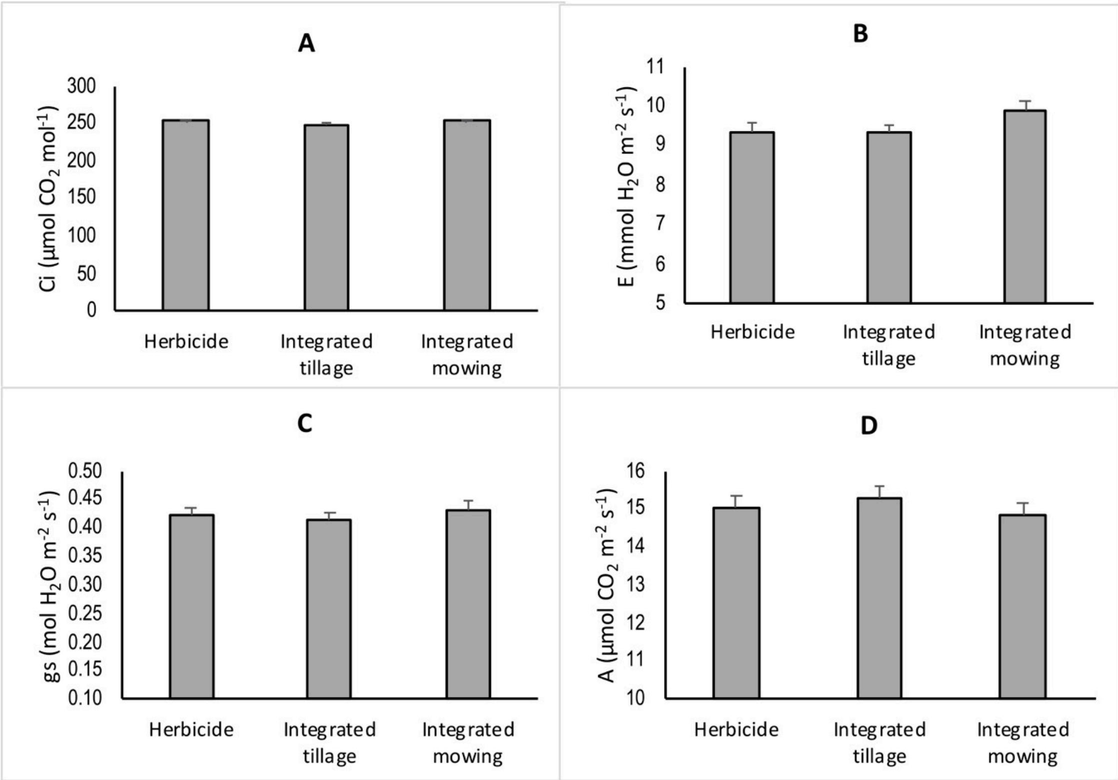

Figure 2. Effects of integrated weed management on different gas exchanges: (**A**) intercellular CO_2 concentration (Ci), (**B**) transpiration rate (E), (**C**) stomatal conductance (g_s), and (**D**) net photosynthetic rate (**A**) in leaves of apple and peach trees. Bars represent standard error.

3.4. Cost of Different Weed Control Methods

The more economical method of weed control was herbicide use (Table 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 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

4. 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). More weed biomass in the integrated plots signifies their vital role in soil physical and chemical quality improvement [33]. 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 [34]. 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 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 [35,36]. 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.

5. 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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