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Autonomous Mowing and Turf-Type Bermudagrass as Innovations for An Environment-Friendly Floor Management of a Vineyard in Coastal Tuscany

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Abstract: The establishment of permanent cover crops is becoming a common practice in vineyard floor management. Turfgrass science may provide species and techniques with a high potential for improving the sustainability of vineyard floor management. Based on this assumption, an experiment was carried out during 2018 and 2019 at the Donna Olimpia Vineyard, Bolgheri, Italy. The trial aimed at comparing an innovative floor management system based on a turf-type cultivar of bermudagrass mown with an autonomous mower with a conventional floor management system. Ground cover percentage, energy consumption, CO_2 emissions, grapevine water status, leaf nitrogen content, fruit yield and must composition have been assessed in order to perform the comparison. The innovative vineyard floor management produced an almost complete ground cover (98%) at the end of the second growing season, with the resident species reduced to a small percentage (4%). Resident species growing under-trellis were efficiently controlled without herbicide applications. A lower primary energy consumption and a reduction in CO_2 emissions were observed for the innovative management system compared to the conventional management system. Grapevine water status, leaf chlorophyll content, soil–plant analyses development (SPAD), fruit yields and must composition were similar between the different soil management systems. Based on results obtained in this trial, turf-type bermudagrass and innovative mowing machines may contribute to enhance the sustainability of vineyard floor management.

Keywords: soil protection; robotic mower; turfgrass; innovative agronomic practice; soil management

1. Introduction

Sustainable viticulture has been defined as a global strategy covering economic issues, product quality, environmental aspects and consumer health related to grape production and processing [1]. At the worldwide level, energy savings and pollutant reductions are the two main actions to improve viticulture sustainability [2]. Vineyard floor management sustainability can be improved adopting new techniques for vegetative covers' maintenance that require lower energetic and chemical inputs.

Cover crops have shown to improve physical and chemical soil properties, to enhance biodiversity [3] and to help control weeds [4] and pests [5]. The establishment of permanent cover crops is becoming a common floor management practice in vineyards, especially to prevent soil erosion and to facilitate machinery access [6,7]. Periodic mowing carried out on resident species is a simple technique to obtain a uniform ground cover. However, perennial or annual species may also be introduced. No matter what species is used as a cover crop, its growth needs to be controlled in order to prevent competition with the vine plants [8]. For the same reason, annual cover crops that grow during grapes' dormant season may be preferred [9–11]. Thus, conventional programs of vineyard floor management include soil tillage and periodical mowing of the interrow aimed at maintaining nutritional balance between vines and cover crop. Moreover, intrarow management is focused on preventing weeds growing inside vine canopies with repeated postemergence nonselective herbicides applications [6,8,12]. Bermudagrass (*Cynodon dactylon* (L.) Pers.) is not included among the list of species considered suitable as vineyards cover crops by various authors [6,8] and is conversely indicated as one the most aggressive vineyards weeds [4]. However, a fast establishment speed, high soil cover percentage and great persistency make bermudagrass a desirable species when it comes to competition against weeds, soil protection and trafficability [10,13,14]. The undesirable traits associated to bermudagrass refer mostly to the naturally occurring wild types, while turf-type cultivars have a reduced vertical growth, an increased density, an enhanced lateral growth, a higher wear resistance and a higher shade tolerance [15,16]. Few studies have been carried out on turf-type permanent cover crops in vineyard interrows, and this intercropping has shown to enhance the infiltration of winter rainwater [17]. Cover crops may also decrease vines' vegetative vigor [17] and promote a deeper vine root system [18]. The spring-summer vegetative cycle of bermudagrass overlaps with the vegetative cycle of the vine plants, so water may be an issue. Indeed, the adoption of cover crops is more frequent in vineyards provided with irrigation systems [13].

Grass mowing for agricultural purposes is commonly carried out with tractor-mounted flail mowers. More options are available from the turfgrass industry, such as battery-powered walk-behind rotary mowers and autonomous mowers. Battery-powered machinery has been reported to have a superior energetic efficiency compared to the equivalent gasoline-powered machinery [19]. Autonomous mowers are battery-powered machines designed to autonomously perform lawn mowing that offer high energy efficiency [20], with no local pollution from exhaust gasses and noise emissions, preventing operators from coming into contact with allergens [21,22]. Although not yet designed for agriculture purposes, autonomous mowers may improve vineyard floor management sustainability as a consequence of their reduced ground pressure [23], their high frequency of cut [24] and their ability to move between vine plants [25]. Continuous mowing has the potential to prevent weeds from excessive vertical development [26] and to encourage bermudagrass lateral growth [27]. The possibility to work both between the rows and under-trellis [25] allows to mow the entire cultivated area, reducing the need for chemical weed control.

The aim of this preliminary study was to compare an innovative vineyard floor management system with a conventional vineyard floor management system in terms of sustainability improvement. For the innovative system, a turf-type cultivar of bermudagrass was used as a cover crop and mown with an autonomous mower. The comparisons between the two management systems were based on assessments of energy consumption, CO_2 emissions and bermudagrass ground cover percentage. Productive and qualitative aspects of the vine plants have been determined in order to detect any early adverse effects on the cultivated plants.

2. Materials and Methods

The experiment was conducted from 22 May 2018 to 31 October 2019 at Donna Olimpia Vineyard, Bolgheri (Livorno), Italy (43°12′ N, 10°34′ E, 17 m.a.s.l.), in a flat commercial vineyard (*Vitis vinifera* L., cv. Petit Manseng) established in 2007, with a plant density of 5860 vines per hectare (0.8 × 2.2 m) and rows oriented north-south. Vines were trained on a vertical trellis with three fixed wires and spur-pruned on a single cordon system to 6–8 nodes per vine. The experimental design was a randomized block with two management systems (innovative and conventional) and four replications for a total of 8 experimental plots of 14 × 2.2 m (30.8 m^2). Each plot included the row and 1.1 m of the two adjoining interrows (Figure 1)

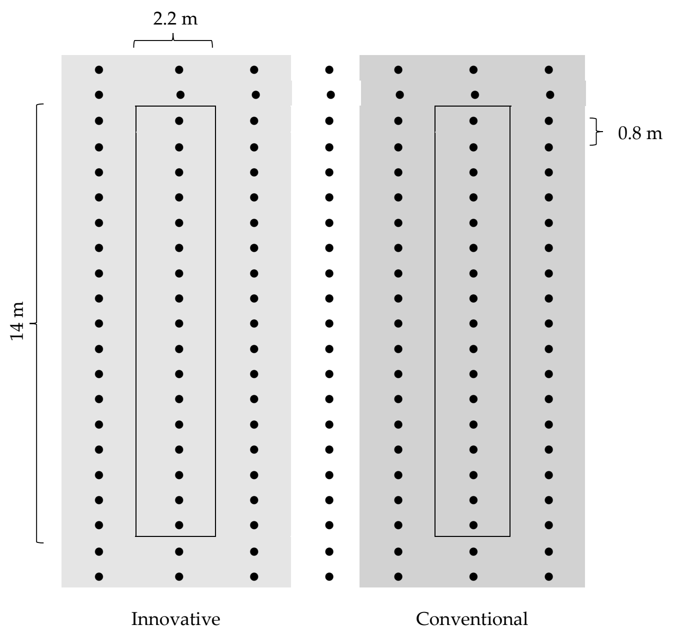

Figure 1. Sketch map of a single plot setup (14 × 2.2 m). Grapevines are identified as dots.

The main chemical and physical properties of the vineyard soil are shown in Table 1.

Table 1. Main chemical and physical soil properties.

Parameter	Method	Unit	Value
Sand (20–2000 µm)	Hydrometer ISSS	%	84.4
Loam (2–20 µm)	Hydrometer ISSS	%	8.1
Clay (<2 µm)	Hydrometer ISSS	%	7.5
pH	Extract 1:2.5		7.1
Organic Matter	Walkley-Black	%	1.2
Total Nitrogen	Kjeldahl	‰	0.9
C/N			7.6
Assimilable Phosphorus	Olsen	P_2O_5 ppm	99
Exchangeable Potassium	$BaCl_2$	K_2O ppm	535

Air temperature and rainfall were recorded on a iMETOS®IMT200 (PESSL Instruments GmbH, Weiz, Austria) weather station located in the vineyard. Monthly maximum and minimum temperatures and monthly cumulated rainfall are reported in Figures 2 and 3.

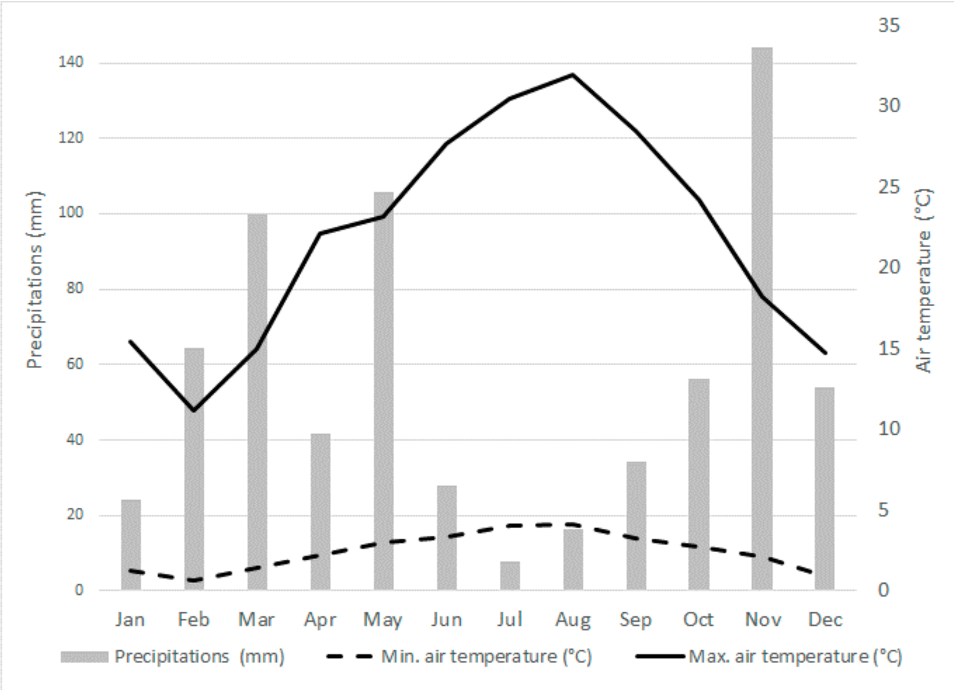

Figure 2. Monthly average minimum and maximum air temperatures and monthly rainfall: year 2018.

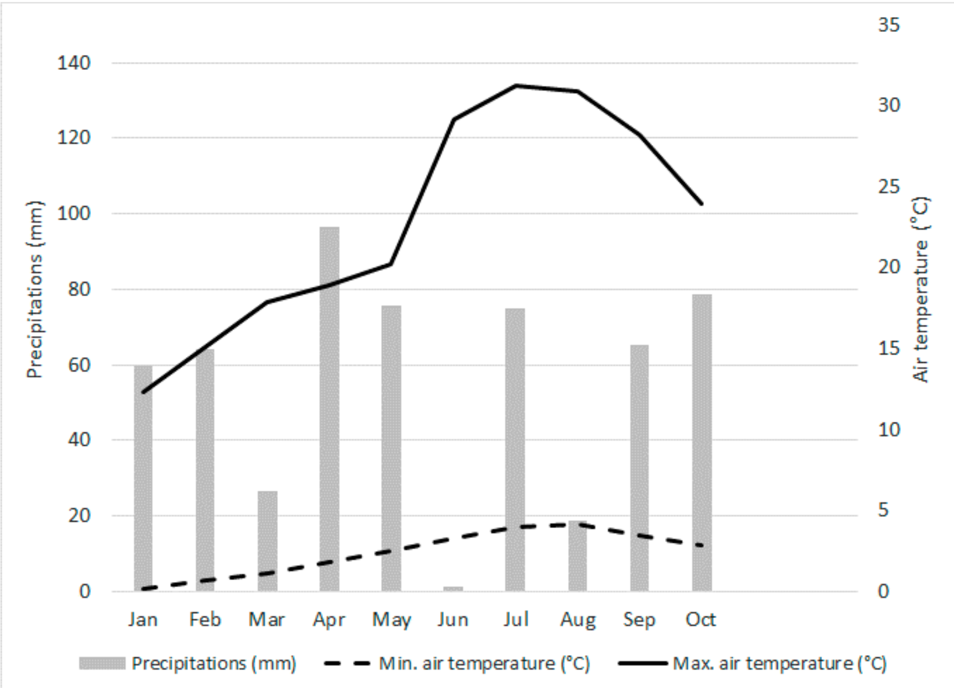

Figure 3. Monthly average minimum and maximum air temperatures and monthly rainfall: year 2019.

Water was supplied using drip lines (2.7 L h^{-1} pressure-compensated drippers spaced at 0.8 m) based on evapotranspiration demand. No irrigation was applied in 2019 due to abundant summer precipitations. According to vines' vigor, fertilization was broadcast-applied only on 15 March 2018 (22.5 kg ha^{-1} of N, 13.5 kg ha^{-1} of P_2O_5 and 54.0 kg ha^{-1} of K_2O from Fulet 5.3.12—Italpollina, Italia). No fertilization was applied in 2019.

2.1. Conventional Floor Management

Conventional vineyard management system was carried out in accordance to the vineyard integrated management protocol issued by the Tuscany Rural Development Program, (measure 10 of the Tuscany RDP 2014–2020). In particular, interrow rotary tillage was performed annually on alternated rows, with plant residues incorporated into the soil. Periodic flail mowing was used to control the development of resident species in the interrow. Flail mowing was carried out as close to the ground as possible, in order to remove most of the resident vegetation. The intrarow management had the aim of suppressing weeds with mechanical weeding and chemical applications of postemergence nonselective herbicides (2 applications of glyphosate from Roundup Platinum—Bayer, Rhein, Germany, with a dose of 0.8 kg ha^{-1} and one application of glyphosate from Gallup Biograde—Fitogest, Rome, Italy, with a dose of 0.9 kg ha^{-1}). A Spire S 105 tractor (Lamborghini Trattori SDF, Treviglio, Bergamo, Italy) was employed. The Spire S 105 tractor is equipped with a 4-cylinder diesel engine that has a displacement of 3849 cm^3 and a maximum power output of 102 hp (75 kW). To perform the different operations, the tractor was coupled to:

- a disc harrow with a working width of 150 cm (mod. PSME/P 17 16-51 Spedo Srl, Badia Polesine, Rovigo, Italy),
- a rotary harrow with a working width of 130 cm (mod. DL 1300 Maschio Gaspardo, Campodarsego, Padova, Italy),
- a flail mower with a working width of 135 cm (mod.SM135 Spedo Srl, Badia Polesine, Rovigo, Italy),
- a sprayer equipped with a 180-cm-wide spray bar (mod. PrM 800PBX Agri Perrone, Guagnano, Lecce, Italy) and
- an on-the-row mechanical weeder equipped with two lateral blades (mod. Expo Doppio H2 Arrizza Srl, Fossacesia, Chieti, Italy).

Details regarding the average duration and number of operations carried out during the trial period for the conventional management system are shown in Table 2.

Table 2. Average duration and number of operations carried out during the two years of the trial for the conventional vineyard management system.

Operation	Average Duration (h ha^{-1})	Number of Operations Per Year
2018		
Flail Mowing	1.53	3
Herbicide	1.40	1
Rotary Harrowing	2.21	1
2019		
Mowing	1.38	4
Herbicide	1.45	2
Rotary Harrowing	2.13	2
Disc Harrowing	1.33	1
Mechanical Intrarow weeding	1.50	1

2.2. Innovative Floor Management

The innovative management system consisted of bermudagrass establishment and management (*Cynodon dactylon* cv Celebration) as a permanent cover crop. Bermudagrass plants were obtained in a greenhouse from sprigs raised in peat-filled seed trays (5-cm^3 containers). On 22 May 2018, bermudagrass plants were manually transplanted into the field along the vine rows at 80-cm centers, with each bermudagrass plant in the middle of two vine plants (planting density of 5680 plants ha^{-1}). Planting bermudagrass in correspondence to the drip irrigation system ensures a fast establishment with low inputs [28]. The transplant was fulfilled on three adjacent vine rows, as shown in Figure 1.

From 1 June 2018, autonomous mowing of the innovative management plots was carried out every day using a Husqvarna Automower®430X (Husqvarna, Stockholm, Sweden) set at 10 h day^{-1} working time. The Automower®430X is a medium-sized autonomous mower (72-cm-long, 56-cm-wide, 31-cm-high) that has a 24-cm-wide cutting disc with three small, pivoting blades. The size of this machine allows it to pass between the vine plants of the experimental vineyard. The Automower®430X is designed to work inside an area defined by a shallow-buried boundary wire. The maximum working capacity of the machine is 3200 m^2 for a 24 h d^{-1} working time [29], while the overall size of the area managed by the autonomous mower (including the experimental plots) was 2500 m^2. The charging station was located outside the vine rows, so as not to interfere with other field operations. The working season of the autonomous mower during the first year of the trial ended on 31 October 2018 for a total of 153 working days. The working season of the autonomous mower during the second year of the trial started on 1 March 2019 and ended on 31 October 2019 for a total of 245 working days.

2.3. Assessments

2.3.1. Ground Cover

During both 2018 and 2019, from May to November, the ground cover percentage of transplanted and resident species was assessed monthly with visual assessments carried out by three expert evaluators [30] on sampling areas of 14 × 2.2 m (Figure 1). Plots were first evaluated to assess the total ground cover defined as the coverage given by plants as opposed to bare soil. The total ground cover value was subsequently attributed to the two components under investigation, namely the resident species and transplanted bermudagrass. Results are reported as ground cover percentage of the resident species or bermudagrass and their cumulated value, where applicable.

2.3.2. Energy Consumption

In order to measure the electric energy consumption of the autonomous mower (Table 3), a power consumption meter was used (EL-EPM02HQ; Nedis, MC, 's-Hertogenbosch, The Netherlands). The fuel consumption of the tractor (Table 3) was estimated using the equation of the hourly consumption of a tractor performing a specific operation:

$$\mathrm{Ch} = \mathrm{W} \cdot \mathrm{d} \cdot \mathrm{Cs}, \tag{1}$$

where Ch is the hourly consumption of the tractor (kg fuel h^{-1}), W is the power of the tractor (kW), d is the effort percentage of the tractor engine due to a specific operation (1 = maximum power required) and Cs is the energetic efficiency of the tractor (kg fuel kWh^{-1}). In this trial, considering the mechanical characteristics of the tractor, Cs was estimated at 0.25 kg fuel kWh^{-1}, while d was assigned depending on the operation carried out. The primary energy requirement of the autonomous mower was calculated considering the efficiency of the Italian National Electric System equal to 0.546 [31]. To estimate the primary energy consumption of the tractor, a conversion factor of 12.03 kWh/kg of fuel [32] was used.

2.3.3. CO_2 Emissions

To estimate CO_2 emissions produced by the two management systems, the following conversion factors were applied: 0.332 kg of CO_2 emission per kWh generated from the public electricity production in Italy [33] and 0.265 kg of CO_2 emission per kWh generated by the diesel fuel [33].

Table 3. Effect of different vineyard floor management systems on the ground cover percentage. Total ground cover percentage and ground cover percentage attributable to resident species and transplanted bermudagrass (*Cynodon dactylon* cv. Celebration) were assessed in Bolgheri during 2018 and 2019.

Management System	Ground Cover Percentage (%)					
	2018			2019		
	Total	Resident [1]	Bermuda [2]	Total	Resident [1]	Bermuda [2]
	22 May			15 May		
Conventional	35	35	na	25	25	na
Innovative	60	58	2	74	35	39
LSD (0.05)	10	18	-	9	ns	-
	20 June			12 June		
Conventional	12	12	na	15	15	na
Innovative	62	55	7	69	20	49
LSD (0.05)	7	10	-	11	ns	-
	25 July			10 July		
Conventional	38	38	na	28	28	na
Innovative	63	45	18	73	15	58
LSD (0.05)	12	ns	-	10	ns	-
	10 August			12 August		
Conventional	51	51	na	34	34	na
Innovative	67	35	32	82	11	71
LSD (0.05)	ns	ns	-	15	17	-
	10 September			16 September		
Conventional	55	55	na	54	54	na
Innovative	69	28	41	85	7	78
LSD (0.05)	ns	16	-	20	18	-
	10 October			16 October		
Conventional	81	81	na	87	87	na
Innovative	67	20	47	95	5	90
LSD (0.05)	15	13	-	ns	12	-
	07 November			05 November		
Conventional	84	84	na	94	94	na
Innovative	67	16	51	98	4	94
LSD (0.05)	12	15	-	ns	15	-

[1] = resident species, [2] = bermudagrass "Celebration", ns = not significant, na = not applicable and LSD = least significant difference.

2.3.4. Grapevine Assessments

On 28 June, 6 August and 7 September 2019, the vine plant water status was determined by measuring the stem water potential (SWP) on four grapevines (replicates) for each soil management treatment. The leaves were enclosed for at least 45 min in a nontranspiring, shaded bag to block transpiration and then sampled to determine the SWP once the potential reached equilibrium with the xylem. Leaves were excised with a razor blade and immediately put in the chamber cylinder (PMS Instruments, Albany, Oregon, USA), which was then pressurized with nitrogen gas.

On the same dates as the SWP, the greenness index was measured on one fully expanded leaf inserted on the median shoot for each replicate using a Minolta Soil-Plant Analyses Development—SPAD 502 portable greenness meter (Konica Minolta, Inc., Osaka, Japan).

Fruit yield per grapevine was determined on 10 September 2019. Grapevines were harvested using a Pellenc 3050 mechanical harvester (Pellenc sas, Pertuis, France). Fruit yield per grapevine was calculated by dividing the total yield production of each floor management system by the number of grapevines per system.

One homogeneous sample of berry juice was collected during harvest from each floor management system to assess the fruit quality. Soluble solids concentration (SSC, Brix) was determined using a refractometer. The pH was measured with a pH meter standardized to pH 7.0 and 4.0. In order to determine titratable acidity (TA), 10 mL of juice was titrated with 0.1-N NaOH to an endpoint pH of 8.2. Titratable acidity was expressed as grams of tartaric acid per juice milliliter.

3. Results and Discussion

During 2018, bermudagrass showed an increasing ground cover percentage from the date of transplant to the last assessments during October and November. During May and June 2018, ground cover percentage was composed primarily of resident species, with some differences between the two management systems due to the different operations performed (Table 3).

During June 2018 and June 2019, the decrease of ground cover percentage in the conventional management system was due to the flail mowing. During July 2018, both management systems showed a similar presence of resident species, while the innovative management system showed a higher total ground cover percentage because of bermudagrass spreading. During August and September 2018, the two management systems showed a similar total ground cover percentage. During August 2018, the majority of the ground cover percentage came from resident species, while during September 2018, the percentage of resident species decreased and bermudagrass reached 41% ground cover (Table 3). During September and October 2018, the resident vegetation cover percentage increased in the conventional management system, because mowing was not carried out, thus becoming significantly higher (more than 80 %) compared to the innovative management system. During the growing season of the second year (2019), the presence of resident species was similar among both management systems, but the innovative management system had a significantly higher total cover percentage due to the contribution of bermudagrass. During June and July 2019, the innovative management system continued to have a higher ground cover percentage, although the ground cover percentage of the resident species was similar to the conventional management system. During August and September 2019, the cover percentage of the innovative system (82% and 85%, respectively) was significantly higher than the cover percentage of the conventional system (34% and 54%, respectively). In 2018 and 2019, during October and November, the conventional system ground cover percentage increased and equaled the ground cover percentage values of the innovative system due to the mowing suspension. Both the autonomous mower and the mechanical weeding performed in the conventional management system were not able to control plants growing within 10–15 cm from the grapevine trunks or the trellis structures. In these specific areas, the resident species were observed growing into the grapevine canopies, while the bermudagrass remained shorter than 15 cm (data not reported in the tables).

Operative characteristics, energy consumption and gas emissions of the two management systems compared in the trial gave different values in the two years of observation (Table 4).

The large gap between the values of the two years depends on the difference of the working seasons, which were 153 days in 2018 (1 June–31 October) and 245 days in 2019 (1 March–31 October). The total working time was higher for the innovative management system. The random operating pattern of the autonomous mower turned into frequent overlapping, leading to an overall higher working time to mow a given area compared to a systematic operating pattern. The autonomous mowers' efficiency was close to 37% for a surface with no obstacles [34], while in an area with many obstacles, such as the vineyard, the working efficiency of the machine results were even lower [25]. Despite a higher working time, during both years, the primary energy consumption of the innovative management system was lower compared to the primary energy consumption of the conventional management system. Total CO_2 emissions were also lower for the innovative management system during both years.

Table 4. Operative characteristics, energy consumption and CO_2 emissions according to different vineyard floor management systems in Bolgheri during the two years of the trial.

Parameter	Unit	2018	2019
		Innovative	
Daily Mowing Time (no recharging)	h d^{-1}	7.86	7.82
Total Working Time	h y^{-1} ha^{-1}	4810.32	7663.60
Electric Energy Consumption	kWh y^{-1} ha^{-1}	188.56	301.54
Primary Energy Consumption	kWh y^{-1} ha^{-1}	345.34	552.26
Total CO_2 Emissions	kg y^{-1} ha^{-1}	114.65	183.35
		Conventional	
Total Working Time	h y^{-1} ha^{-1}	8.20	15.48
Total Fuel Consumption	kg y^{-1} ha^{-1}	59.63	111.73
Primary Energy Consumption	kWh y^{-1} ha^{-1}	717.40	1344.07
Total CO_2 Emissions	kg y^{-1} ha^{-1}	190.11	356.18

Grapevines yield and physiological parameters (vine water status, SPAD, yield and fruit quality) were not affected by the floor management systems. Grapevines showed high values of stem water potential during all the growing periods, indicating the absence of water stress for both management systems (Table 5).

Table 5. Stem water potential and Greenness Index with the soil–plant analyses development (SPAD) measured on fully expanded leaves of grapevines grown according to different vineyard floor management systems in Bolgheri. Values shown are means ± standard error of the four grapevines (replicates) per each management system.

Management System	Stem Water Potential (MPa)		
	28 June	**6 August**	**7 September**
Conventional	−0.27 ± 0.03	−0.28 ± 0.03	−0.30 ± 0.04
Innovative	−0.27 ± 0.03	−0.28 ± 0.07	−0.33 ± 0.03
LSD (0.05)	ns	ns	ns
	Greenness Index (SPAD)		
Conventional	45.6 ± 2.16	48.1 ± 2.47	46.3 ± 1.59
Innovative	45.1 ± 3.29	46.3 ± 1.59	45.2 ± 5.61
LSD (0.05)	ns	ns	ns

ns = not significant.

The fruit yield per vine was 1.07 and 1.36 kg for the conventional and innovative floor management systems, respectively. The soluble solid content (SSC), pH and titratable acidity in the two treatments were comprised between 24.5 and 24.8 Brix, 2.88 and 2.90 and 8.53 and 9.48 g mL^{-1}, respectively.

The innovative floor management system increased the total ground cover percentage during the vines' growing season, encouraging bermudagrass spreading and reducing the presence of the resident species. Furthermore, the innovative floor management showed an acceptable control of the under-trellis growing plants without herbicide applications. Reduced energy requirements, lower CO_2 emissions and the possibility to adopt a nonchemical weed control highlight the potential of this type of floor management to enhance vine crops' sustainability. These findings are in accordance with Slaughter [35] and confirm that using small, autonomous machines for weed control helps reducing human labor and herbicide applications. This trial showed that the different floor management systems did not affect the grapevines' yield and physiological parameters. The interaction between grapevines and permanent cover crops in general increase and then level off after four years [6]. However, Ripoche et al. [36] claim that one to two years may be an adequate period for a preliminary detection of a grapevines' response in terms of vegetative growth and yield.

4. Conclusions

The innovative vineyard floor management based on turf-type bermudagrass and autonomous mowing has shown an almost complete ground cover (98%) at the end of the second growing season, with the resident species reduced to a small percentage (4%). As expected, bermudagrass has shown its ability to spread from under-trellis to the interrow area. Furthermore, its aggressive growth results were competitive against the resident species. The high cutting frequency reduced the growth of the resident plants, thereby limiting their competitiveness against the grapevines. The innovative management system highlighted the possibility to maintain a permanent cover crop, requiring a lower amount of primary energy and lower CO_2 emissions, with no need for chemical weed control. Despite the encouraging results obtained in this trial, the autonomous mower used was not specifically designed to operate in field conditions. Therefore, improvements of the mowers' performances might be expected once purpose-built machinery becomes available.

Grapevine water status and leaf chlorophyll content (SPAD) were not affected by the different floor management systems in 2019. In the same year, the frequent rainfalls throughout the vegetative period probably ensured a nonlimiting soil water availability, leading to similar fruit yields and must composition in the two soil management systems.

Further investigations are needed to assess the possible water and nutrient competitions between grapevines and grass covers under drier climatic conditions.

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