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RESEARCH ARTICLE

Influence of soil management on vegetative growth, yield, and wine quality parameters in an organic "Pedro Ximénez" vineyard: field and UAV data

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Abstract

The use of cover crops in vineyards is expected to increase due to the strong encouragement by European agricultural policy and their contribution to reducing soil erosion. This paper presents the results obtained over three years in a vineyard of the "Pedro Ximénez" variety organically grown in southern Spain. The influence on production, vigor, and grape quality of a seeded cover crop versus tillage was compared using field data and imagery acquired by an uncrewed aerial vehicle. The vines under tillage showed greater vegetative development and yield than those with cover crops between rows. The grapes from the vines under the cover crop treatment ripened earlier and presented higher values of total soluble solids, characteristics that can be useful in the protected designation of origin where the study field is placed. However, the strong yield reduction caused by the cover crop treatment encourages future research to explore other cover crop species that could contribute to improving soil properties without compromising the profitability of the vineyard. This is the first time that the influence of cover cropping on the agronomic and oenological parameters of organically grown white vineyard varieties such as "Pedro Ximénez" has been assessed using field and UAV data.

Keywords Cover crop · Tillage · Remote sensing · *Vitis vinifera* L. · Berry composition

1 Introduction

The planting pattern in vineyards, especially on trellises, leaves a large amount of soil uncovered. Management of this part of the soil has a great influence on vineyard performance (Guerra and Steenwerth 2012; Abad et al. 2021a), soil properties (Abad et al. 2021b), vineyard biodiversity (Winter et al. 2018), and even on the aroma compounds of wine (Xi et al. 2011). There are two main types of treatments regarding soil management in vineyards: tillage of the interrow space (leaving the soil bare most of the year) and natural or sown cover crops between rows. Tillage or cultivation is the most traditional and commonly used soil management technique (Guerra and Steenwerth 2012). Spain is the country with the largest number of hectares dedicated to vineyard ("FAOSTAT" 2022), and traditional and minimum tillage are the soil management techniques used in almost 90% of the vineyard Spanish surface (Ministerio de Agricultura, Pesca y Alimentación, MAPA, 2020). Traditional tillage is the alteration and removal, by means of mechanical implements, of the soil profile to a depth of 20 cm or more, and minimum tillage is shallow tillage using cultivators, harrows, and chisel plows, to a depth of less than 20 cm. Frequent plowing of the soil often causes serious problems of erosion (Figure 1a), soil compaction, and a lower water-holding capacity and infiltration, which increase in sloping vineyards (Marques et al. 2010).

To alleviate these agro-environmental problems, soil management has changed over the last few decades in

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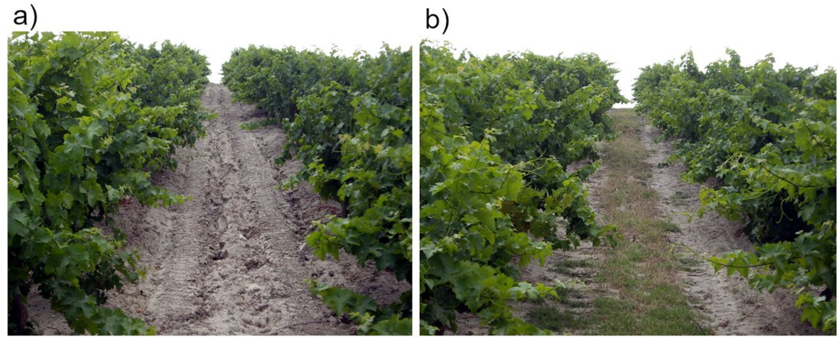

Fig. 1 Images of a vineyard showing the effect of different soil managements on erosion: conventional tillage (**a**) and cover crop (**b**).

some wine regions to a cultivation technique consisting of the maintenance of annual or perennial cover crops (CCs) between rows (Pardini et al. 2002). CCs can be implemented by sowing some broadleaved or grass species or allowing the natural vegetation to grow in vineyard alleys. The agronomic and environmental benefits of using ground covers are well known because they contribute to a set of ecosystem functions, such as decreasing soil erosion (Figure 1b), increasing organic matter, improving the structure, porosity, and water infiltration capacity of the soil, fixing atmospheric CO_2, increasing biodiversity (Winter et al. 2018; Abad et al. 2021b), reducing soil temperature (Pradel and Pieri 2000), mitigating the impact of excessive precipitation (Vanden Heuvel and Centinari 2021), or controlling competitive weeds during the first few years after planting (Cabrera-Pérez et al. 2022). At the plant level, CC helps regulate vine vegetative growth and vigor to maintain the balance with reproductive growth and improve grape quality in terms of health and composition in red varieties (Guerra and Steenwerth 2012; Abad et al. 2021a). However, inappropriate CC management may also have a negative effect on the vigor and yield of vines due to competition for water between the vines and the CC (Monteiro and Lopes 2007; Novara et al. 2021).

"Pedro Ximénez" is a white grape variety mostly cultivated in the southern Spain, and it is the main variety in the Montilla-Moriles protected designation of origin (PDO). This grape variety is mainly used in Montilla-Moriles for the production of "fino" and "Pedro Ximénez" wines, which have a high alcohol content. Although it is usually cultivated under tillage, this situation is expected to change in the coming years due to the importance given to cover cropping in the new European Common Agricultural Policy 2023–2027, according to Regulation (EU) 2021/2116. The use of spontaneous or sown cover crops in woody crops is one of the seven practices covered by the Low Carbon Farming eco-scheme, which has the main objectives of improving soil structure, reducing erosion and desertification, increasing the carbon content of soils, and reducing emissions. However, there is little information on the impact of vegetation cover on organic "Pedro Ximénez" vineyards (Ramírez-Pérez et al. 2018, 2021), and none of these works were published in scientific journals for a wider audience.

Although the use of CCs has proven advantages, special care must be taken in their management when rainfall is scarce and spring and summer temperatures are high, as is the case in most of the wine-growing areas in southern Spain. Therefore, it is necessary to further investigate the effects of different soil management practices on the agronomic and oenological behavior of the white "Pedro Ximénez" variety. In this context, the aim of this study was to compare the influence on production, vigor, and grape quality of a seeded cover versus tillage on "Pedro Ximénez" vines organically grown in a Mediterranean climate by using traditional on-ground sampling methods. As the analysis of remotely sensed imagery from uncrewed aerial vehicles (UAVs) has been reported to be an accurate and efficient way of measuring the canopy of vineyards (de Castro et al. 2018; Pádua et al. 2020), an assessment of the geometrical parameters of the vine canopy was performed by applying automatic algorithms to 3D models of the vineyard generated using UAV photogrammetry. Furthermore, an analysis of the gross income perceived by the vine-growers has been carried out to assess the influence of the soil management treatments from an economic point of view. The additional benefits derived from the commercialization of the wine were not included in this work because many of the vine growers in the Montilla-Moriles PDO are part-time farmers and sell their production to a cooperative (Schütte and Bergmann 2019).

The novelty of the present work is grounded in three pillars: (1) it provides new information about the influence of cover cropping on the agronomic and oenological parameters of organically grown white vineyard varieties such as "Pedro Ximénez," (2) the differences in grape maturation between soil management treatments have been taken into account by harvesting the grapes on two different dates, and (3) UAV remote sensing has been used to evaluate the influence of soil management treatments on the geometrical properties of the vine canopy.

2 Materials and methods

2.1 Study vineyard

This study was conducted between 2019 and 2021 in the experimental vineyard of IFAPA-Cabra Research Station (Andalusia, Spain). The vineyard is located at an altitude of 560 m above sea level, and its central geographical coordinates are 37° 30′ N, 4° 26′ W (WGS84). The climate is Mediterranean, with a certain continental character. The summers are hot, reaching temperatures of over 40 °C, and the winters are moderately cold, where temperatures do not usually fall below −4 °C. Data about precipitation and evapotranspiration during the studied seasons can be viewed in Figure 2. The soil of the experimental vineyard has a sandy-clay loam texture and is poor in organic matter.

The plant material used was "Pedro Ximénez" grafted on 140 Ru, a rootstock tolerant to drought and limestone, and one of the most commonly used in new plantations in the Montilla-Moriles PDO. The vineyard was planted in 2014 under a trellis system with a planting frame of 2.5 × 1.2 m, pruned in double cordon with a load of 16 buds per vine and with an east−west orientation. The crop was rainfed and organically managed in accordance with Regulation (EU) No. 2018/848 on organic production and labeling of organic products. Weeds growing in the vine line were controlled by tillage with intertillers in winter and a string weed cutter in spring. The soil management treatments applied were conventional tillage (CT) and CC. At the beginning of autumn and before planting the cover crop, the two treatments were fertilized in the same way at a dose of 20 l•ha^{-1} with a liquid organic fertilizer NK 3–6 of vegetable origin, authorized for organic farming.

A randomized design with four blocks was set up with each elementary plot consisting of a row of 75 vines with the same soil management treatment in the two lanes. In each of these rows, 10 vines were marked and georeferenced for sampling and monitoring to ensure that field and remote sensing measurements were performed on the same vines. Between plots, a guard line of vines was maintained.

The CC consisted of a combination of eight cultivated and wild native species with low growth rates (*Bromus parodii* Covas & Itria, *Lolium perenne* L., *Festuca rubra* L., *Bromus rubens* L., *Trifolium repens* L., *Centaurium erythraea* Rafn, *Anthemis arvensis* L., and *Papaver rhoeas* L.). The mixture was selected to protect the soil, provide nutrients, and introduce biodiversity, and it was sown at a rate of 250 kg•ha^{-1}. The CC treatment was seeded between the last days of October and the first days of November in the three studied years. After seeding, harrowing was carried out, and the soil was covered with a white net to avoid seed predation by rabbits and birds. The CC crop was controlled by mowing in the first fortnight of April in the three studied years. Two additional mowing treatments were carried out in 2019 and 2020, and only one was carried out in 2021. Tillage for the CT treatment was carried out in autumn, on the same date as the seeding of the CC treatment, and in spring. It was performed with a cultivator on both dates.

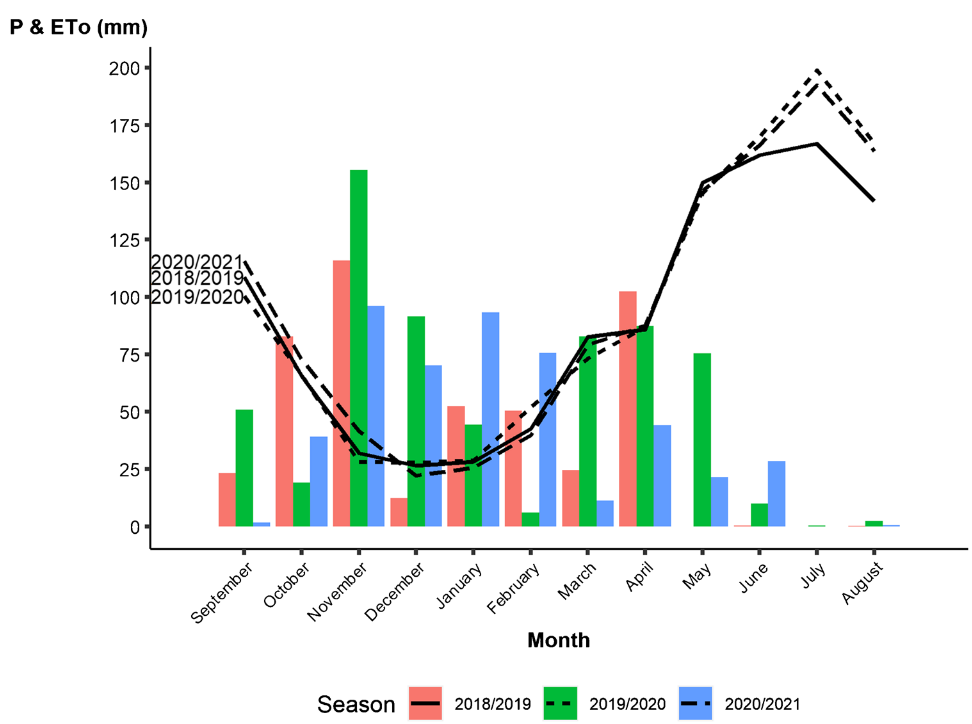

Fig. 2 Monthly precipitation (bars) and reference evapotranspiration (ET_o) (lines) for campaigns 2018/2019, 2019/2020, and 2020/2021 in the meteorological station located in the IFAPA-Cabra Research Station.

2.2 Vegetative growth and yield measurements

The assessment of vegetative growth and yield was performed using two kinds of measurements: field-based and UAV-based. The latter measurements were used to calculate the geometric parameters of the vineyard canopy due to the high efficiency of the UAV-based canopy measurement protocols developed in recent years (de Castro et al. 2018; Pádua et al. 2020).

2.2.1 Field measurements

From veraison to harvest, grape samples were taken weekly for ripening control. The soluble solid content, pH, total acidity, and weight of 100 berries were determined in these controls. Two harvest controls were carried out, one when the vines under the CC treatment reached a soluble solids concentration between 23.8 and 25.3 °Brix (14.0–15.0% v/v of probable alcohol) and another later one to check whether the vines under CT reached the CC concentration level without losing any quality. The following yield measurements were made at each harvest in the georeferenced vines: production, number of bunches, and weight of 100 berries. After leaf fall, the pruned wood was weighed in December.

2.2.2 UAV flights

The flight for 3D vineyard modeling was performed on July 12, 2019, using an MD4-1000 UAV (Microdrones GmbH, Siegen, Germany) equipped with a Sony ILCE-6000 (Sony Corporation, Tokyo, Japan) RGB camera with a 24 MP sensor and a 20 mm fixed focal length lens. The UAV was programmed to fly at a 30 m flight altitude with longitudinal and transversal overlaps of 89 and 60%, respectively. No UAV flights were performed in 2020 due to the difficulty of coordinating research teams because of the COVID-19 pandemic.

On July 22, 2021, in addition to the flight for photogrammetric reconstruction of the vineyard, a flight was also performed for the generation of spectral indices. The flight for 3D reconstruction of the vineyard was carried out with a DJI Mavic Pro 2 UAV platform (DJI, Shenzhen, China) equipped with a Hasselblad L1D-20c 20 MP RGB camera. The flight for obtaining a set of spectral indices was performed with a DJI Matrice 600 UAV carrying a Parrot Sequoia (Parrot SA, Paris, France) multispectral camera (green-G, red-R, red-edge, and near infrared-NIR bands). In both cases, the UAVs were programmed to fly at a 40 m altitude and with a forward and side image overlap of 80%. The images from the multispectral camera were radiometrically corrected using the reference panel provided by the camera manufacturer.

Agisoft Metashape Professional software (Agisoft LLC, St. Petersburg, Russia) version 1.5.3 was used to obtain the 3D photogrammetric point clouds from the RGB flights, and an orthomosaicked image from the multispectral flight. The generation of the photogrammetric products was almost automatic, with the exception of the manual location of five ground control points (GCPs) in the images located in the vineyard on the day of flights (one in each corner and one in the center of the field). The coordinates of these GCPs and the vines for monitoring were registered using a real-time kinematic (RTK) GNSS linked to a reference station from the GNSS network from the Institute for Statistics and Cartography of Andalusia (IECA), Spain. The accuracy of the GNSS-RTK system was approximately 0.02 m along the *X*–*Y* axis directions and 0.03 m along the *Z*-axis. At the end of the photogrammetric processes, the point cloud was stored in ".las" format, and the multispectral orthomosaic was stored in ".tiff" format.

2.2.3 Calculation of UAV-based parameters

The 3D characterization of the georeferenced vines was carried out automatically using the same methodology developed in a previous study (López-Granados et al. 2020); with the only difference being that in the present study, it was implemented using R computer language (R Core Team 2019). Following this automatic methodology, the area, maximum height, mean height, and canopy volume of each vine were extracted. The coordinates of the georeferenced vines were used to delimitate the sections of the vine rows corresponding to each vine in the 3D models and ensure that the UAV-based parameters corresponded to the same field-measured vines.

Using the abovementioned geometric parameters of the vines, the external surface area of each vine (SA) was calculated following Eq. 1. The SA calculated from UAV-based measurements of the vineyard canopy has been demonstrated to be highly correlated with the SA estimated using field measurements (Torres-Sánchez et al. 2022a), and it has the advantage of requiring less human labor. To take into account the height of the vine foliage and not that of the entire vine (stem and canopy), the average observed height from the soil to the first leaves (0.5 m) was extracted for the mean height of the vine in Eq. 1.

$$\mathrm{SA}\left(\mathrm{m}^2/\mathrm{m}^2\right) = \frac{\text{Area} + 2 * \text{Vine length} * (\text{mean height} - 0.5)}{\text{Distance between rows} \ * \ \text{Distance between vines}} \tag{1}$$

Three spectral (or vegetation) indices (Equations 2, 3, and 4) were calculated using the different bands from the multispectral orthomosaic generated in 2021. The spectral values were extracted using the delimitation of the vines created by combining the canopy detection performed in the 3D characterization of the vines and their coordinates. The vegetation indices used were NDVI (Rouse et al. 1974)

(Eq. 2), MSAVI (Qi et al. 1994) (Eq. 3), and CIg (Gitelson et al. 2005) (Eq. 4). These indices were selected among the plethora of existing vegetation indices because of their widespread use and simplicity of calculation. NDVI was one of the first vegetation indices used in satellite remote sensing and is known to be related to vegetation vigor. MSAVI is also related to vegetation vigor and was developed to reduce the influence of bare soil on the vegetation signal. CIg has been reported as an important variable for machine learning prediction of the LAI in vineyards using UAV data (Gao et al. 2022).

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - R}{\mathrm{NIR} + R} \tag{2}$$

$$\mathrm{MSAVI} = \frac{2\mathrm{NIR} + 1 - \sqrt{(2\mathrm{NIR} + 1)^2 - 8 * (\mathrm{NIR} - R)}}{2} \tag{3}$$

$$\mathrm{CI}g = \frac{\mathrm{NIR}}{G} - 1 \tag{4}$$

2.3 Must quality parameter determination

At harvest, a representative sample of approximately 3 kg of clusters was taken from each treatment and block. Must samples were extracted using a hand-operated crusher and press, and then, samples were centrifuged at 3000 rpm for 10 min. The following determinations were made for each must sample: total soluble solids (TSS), total acidity (ToA), pH, malic acid (MA) (OIV 2016), tartaric acid (TaA) (Rebelein 1973), gluconic acid (GA) (Möllering and Bergmeyer 1989), and easily assimilated nitrogen (EAN) (ammonia nitrogen) (Turbow et al. 2002).

2.4 Gross income analysis

The gross income per hectare has been calculated for both soil management treatments. In this analysis, the specificities of the Montilla-Moriles PDO were considered. In this PDO, the price of the grapes is calculated taking into account the probable alcohol content plus a percentage bonus. This bonus depends on the probable alcohol content and on the production area, being higher in two high-quality areas of the PDO: "Sierra de Montilla" and "Moriles Altos." The maximum bonus would be obtained in vineyards located in these quality areas whose grapes reach a probable alcohol content between 15 and 15.5% vol. at harvest (the level required to produce "fino" wine without the addition of wine alcohol). In this work, the only possible bonus is related to the probable alcohol content, since the study field is not located in the high-quality areas of the PDO.

2.5 Data analysis

An analysis of variance (ANOVA) for a randomized block design was performed on the field and laboratory data was obtained. Only the results for soil management are presented.

3 Results

3.1 Vegetative growth and yield

The vines under the CT treatment showed higher vegetative growth than those under the CC treatment (Table 1). Accordingly, pruning weight was significantly higher in the three studied years with values between 35% and 24% higher than those in the CC treatment. All the canopy geometric parameters extracted from the UAV photogrammetric models reflected this trend, with maximum and mean height, area, SA, and volume values being lower for the vines under the CC treatment in 2019 and 2021. Among these parameters, although all the detected differences were highly significant, height presented smaller differences between the CC and CT treatments (ranging from 7 to 10%), while differences between the treatments for volume, projected area, and SA ranged from 17 to 30%. Regarding the evaluation of vigor using the multispectral camera in 2021, the three vegetation indices calculated also distinguished the vines under CT treatment as being more vigorous, with MSAVI revealing more significant differences than NDVI and CIg.

Soil management also caused differences in the maturity of the grapes. Grapes in the CC treatment reached the optimum level of soluble solids for harvest before the grapes in the CT treatment. Consequently, the first harvest was always carried out when the grapes in the CC were ready for harvest, while the second harvest was performed when the grapes in the CT treatment reached the desired level of soluble solids. The first harvest was carried out on August 23 in 2019 and on August 21 in 2020. The second harvest was performed on September 3 in 2019 and on August 27 in 2020. In 2021, there was only one harvest because a heat wave lasting from August 13 to 16 caused earlier desiccation of the berries in both soil management treatments that caused them to quickly reach a high level of soluble solids.

Regarding the parameters related to vineyard production, the vines whose adjacent lanes were plowed more than doubled the production of the vines under the CC treatment in 2019 and 2021. Even in 2021, an anomalously warm year, the yield in the CT treatment was approximately 40% higher than that in the CC treatment. In the years in which a second harvest was possible, the differences between production weights were also highly significant, with vines in the CT treatment being the most productive. The berry weight was significantly higher for the CT treatment in the first harvest

Table 1 Mean and standard deviation of vegetative growth and yield parameters of the different soil management treatments (CT, conventional tillage; CC, cover crop). Results of the ANOVA are also presented. Significance level (s.l.): ***, 0.001; **, 0.01; *, 0.05; ns, not significant.

Data origin	Variable	2019 CC	2019 CT	2019 s.l.	2020 CC	2020 CT	2020 s.l.	2021 CC	2021 CT	2021 s.l.
Field	Pruning weight (kg)	0.46 ± 0.16	0.71 ± 0.22	***	0.74 ± 0.28	0.97 ± 29	***	0.63 ± 0.26	0.83 ± 0.24	***
Field	Yield 1st harvest (kg)	2.19 ± 1.23	4.98 ± 1.89	***	2.84 ± 1.67	5.91 ± 2.47	***	1.88 ± 1.33	3.12 ± 1.50	**
Field	Yield 2nd harvest (kg)	2.28 ± 1.54	4.11 ± 1.86	***	2.47 ± 1.20	5.70 ± 1.44	***	NA	NA	
Field	Berry weight 1st harvest (g)	222.50 ± 15.81	248.13 ± 14.83	**	190.80 ± 13.86	222.10 ± 13.73	*	197.68 ± 21.86	207.35 ± 13.34	ns
Field	Berry weight 2nd harvest (g)	188.50 ± 22.46	243.70 ± 20.56	*	205.15 ± 27.17	214.25 ± 22.56	ns	NA	NA	
UAV	Maximum height (m)	1.72 ± 0.12	1.85 ± 0.13	***	NA	NA		1.64 ± 0.11	1.77 ± 0.16	***
UAV	Mean height (m)	1.33 ± 0.10	1.47 ± 0.13	***	NA	NA		1.31 ± 0.10	1.41 ± 0.15	***
UAV	Area (m^2)	0.79 ± 0.14	0.98 ± 0.14	***	NA	NA		0.72 ± 0.16	0.97 ± 0.13	***
UAV	SA (m^2/m^2)	0.86 ± 0.13	1.03 ± 0.13	***	NA	NA		0.78 ± 0.14	0.97 ± 0.13	***
UAV	Volume (m^3)	1.05 ± 0.21	1.44 ± 0.21	***	NA	NA		0.94 ± 0.24	1.36 ± 0.21	***
UAV	NDVI	NA	NA		NA	NA		0.67 ± 0.03	0.69 ± 0.03	**
UAV	CIg	NA	NA		NA	NA		3.58 ± 0.48	3.85 ± 0.44	*
UAV	MSAVI	NA	NA		NA	NA		0.75 ± 0.03	0.77 ± 0.02	***
Mixed	SA/1st yield	1.59 ± 0.90	0.68 ± 0.24	***	NA	NA		1.94 ± 1.31	1.48 ± 1.75	ns
Mixed	SA/2nd yield	1.69 ± 1.33	1.01 ± 0.65	*	NA	NA		NA	NA	

of 2019 and 2020 and in the second harvest of 2019. Regarding the number of grape clusters, there was no clear trend. The number was significantly larger in the first harvest of 2020 and the second harvest of 2019 for the CC treatment, but it was higher for the CT treatment in the second harvest of 2020, and it presented no significant differences between treatments in the first harvest of 2019 and 2021.

3.2 Must quality parameters

Among the seven must quality parameters analyzed, three presented some significant differences between soil management treatments in the first harvest (Table 2). TSS was higher in the must from the vines under the CC treatment in all the studied years, and pH was higher for this soil management treatment only in 2020. The must from the CT treatment showed a larger concentration of MA in 2019 and 2021. There were no significant differences in any year for ToA, GA, or EAN.

As in the first harvest, TSS and pH also showed significant differences in the second harvest (Table 3). These differences showed the same trend as in the first harvest: the values of these parameters were significantly higher for the CC treatment in 2020. Contrary to the determinations performed in the first harvest, EAN showed significant differences in the second harvest, although only in 2019. The rest of the parameters (ToA, TaA, MA, and GA) were not significantly different between the treatments studied. The previous assessments of must quality parameters were carried out by comparing their values on the harvest date on which one of the treatments had reached the desired value of soluble solids.

Table 4 shows the comparison among the must quality parameters at the optimum maturity level for each treatment; i.e., it presents the parameters for the CC treatment in the first harvest compared to the parameters for the CT treatment in the second harvest. In this comparison, significant differences were detected for TSS and pH in 2020 but not in 2019; since in 2021, there was only one harvest date, and data from this year were not included in Table 4. As in the analyses presented in Tables 2 and 3 for one harvest date, the values for TSS and pH were higher for the CC treatment. There were no significant differences for the parameters related to the concentration of the acids studied or for the EAN.

3.3 Gross income analysis

The gross income per hectare was always higher in the CT treatment, independent of the study year or the harvest (Table 5). In the CT treatment, gross incomes ranged from 3912.33 to 4620.01 €•ha^{-1}, while the CC treatment led to gross income values ranging from 2425.16 €•ha^{-1} in the first harvest of 2019 to 2883.52 €•ha^{-1} in the second harvest of 2020. Taking the CC treatment as a reference, the gross incomes in the CT treatment were between 46.81 and 71.04% higher.

The CC treatment achieved the bonus based on probable alcohol content in the first harvest of 2019 and 2020 and in the second harvest of 2020. The probable alcohol content in the CT treatment was high enough to achieve the bonus only in 2021, a year with extreme weather conditions. However, the more frequent achievement of the bonus in the CC treatment did not in any case compensate for the yield loss from an economic point of view.

4 Discussion

The use of a cover crop resulted in a significant reduction in vegetative growth of the vines. The values of pruning weight measured in the field were higher for the CT treatment, in agreement with the different geometric parameters of the canopy (height, area, and volume) estimated with the photogrammetric products generated with the RGB sensor installed on the UAV. Furthermore, not only the measurements of the vine dimensions confirmed the influence of the soil management on the vegetative growth. The vegetation vigor estimates made with the three studied vegetation indices from the multispectral sensor also showed higher values for the CT treatment, with MSAVI, the one designed by its authors to reduce the effect of bare soil, showing the most significant differences between treatments. The detected reduction in growth was in line with the results obtained for other climates and varieties considered in the review about the use of cover crops reported by Abad et al. (2021a). This effect of the cover crop could be beneficial in vineyards with excessive growth, where it would reduce the necessity of canopy management operations. Furthermore, excessive canopy development can increase susceptibility to fungal diseases (Valdés-Gómez et al. 2011), although in the present study, both the CC and CT treatments presented good sanitary conditions, as reflected by the low values of GA detected in the must.

The reduction in growth caused by the cover crop could have been exacerbated because of the specificities of the study field. In organic farming, the management of CCs is limited to mechanical means, as it is not possible to use synthetic chemical products. Given that mechanical mowing does not eliminate plant cover but only temporarily limits its water and nutrient uptake, it would be necessary to carry out several mowings throughout the spring and even early summer. Accordingly, it should also be borne in

Table 2 Mean and standard deviation of must quality parameters of the different soil management treatments (CT, conventional tillage; CC, cover crop) in the first harvest (23/08 for 2019, 21/08 for 2020, and 17/08 for 2021). Results of the ANOVA are also presented. Significance level (s.l.): ***, 0.001; **, 0.01; *, 0.05; ns, not significant.

Variable	2019 CC	2019 CT	2019 s.l.	2020 CC	2020 CT	2020 s.l.	2021 CC	2021 CT	2021 s.l.
TSS (°Brix)	24.4 ± 1.6	20.7 ± 1.4	*	24.0 ± 1.9	18.8 ± 1.1	**	28.3 ± 2.0	27.2 ± 1.9	***
pH	3.61 ± 0.04	3.54 ± 0.11	ns	3.85 ± 0.08	3.65 ± 0.11	*	3.74 ± 0.08	3.74 ± 0.08	ns
ToA (tartaric acid g/l)	4.03 ± 0.05	4.29 ± 0.25	ns	3.28 ± 0.26	3.74 ± 0.39	ns	4.48 ± 0.35	4.70 ± 0.40	ns
TaA (g/l)	5.5 ± 0.0	5.2 ± 0.4	ns	5.9 ± 0.3	5.8 ± 0.4	ns	6.2 ± 0.4	6.0 ± 0.3	ns
MA (g/l)	0.7 ± 0.1	1.2 ± 0.3	*	0.7 ± 0.1	0.8 ± 0.1	ns	1.2 ± 0.2	1.8 ± 0.3	*
GA (g/l)	0.02 ± 0.01	0.01 ± 0.01	ns	0.02 ± 0.02	0.01 ± 0.01	ns	0.02 ± 0.01	0.03 ± 0.03	ns
EAN (mg/l)	201 ± 43	162 ± 33	ns	166 ± 49	138 ± 38	ns	215 ± 45	240 ± 62	ns

Table 3 Mean and standard deviation of must quality parameters of the different soil management treatments (CT, conventional tillage; CC, cover crop) in the second harvest (03/09 for 2019, and 27/08 for 2020). Results of the ANOVA are also presented. Significance level (s.l.): ***, 0.001; **, 0.01; *, 0.05; ns, not significant.

Variable	2019 CC	2019 CT	2019 s.l.	2020 CC	2020 CT	2020 s.l.
TSS (°Brix)	27.6 ± 3.5	23.3 ± 3.0	ns	26.4 ± 2.2	21.0 ± 1.5	**
pH	3.69 ± 0.19	3.57 ± 0.18	ns	3.89 ± 0.17	3.66 ± 0.07	*
ToA (tartaric acid g/l)	3.77 ± 0.47	3.80 ± 0.46	ns	3.24 ± 0.23	3.53 ± 0.18	ns
TaA (g/l)	5.8 ± 0.3	5.4 ± 0.3	ns	6.0 ± 0.1	5.9 ± 0.4	ns
MA (g/l)	0.6 ± 0.1	0.9 ± 0.2	ns	0.7 ± 0.2	0.5 ± 0.1	ns
GA (g/l)	0.01 ± 0.01	0.01 ± 0.01	ns	0.02 ± 0.02	0.02 ± 0.01	ns
EAN (mg/l)	235 ± 55	154 ± 47	*	180 ± 16	133 ± 40	ns

Table 4 Mean and standard deviation of must and wine quality parameters of the different soil management treatments (CT, conventional tillage; CC, cover crop) at the time of maturity for each treatment. Results of the ANOVA are also presented. Significance level (s.l.): ***, 0.001; **, 0.01; *, 0.05; ns, not significant.

Variable	2019 CC	2019 CT	2019 s.l.	2020 CC	2020 CT	2020 s.l.
TSS (°Brix)	24.4 ± 1.6	23.3 ± 3.0	ns	24.0 ± 1.9	21.0 ± 1.5	*
pH	3.61 ± 0.04	3.57 ± 0.18	ns	3.85 ± 0.08	3.66 ± 0.07	*
ToA (tartaric acid g/l)	4.03 ± 0.05	3.80 ± 0.46	ns	3.28 ± 0.26	3.53 ± 0.18	ns
TaA (g/l)	5.5 ± 0.0	5.4 ± 0.3	ns	5.9 ± 0.3	5.9 ± 0.4	ns
MA (g/l)	0.7 ± 0.1	0.9 ± 0.2	ns	0.7 ± 0.1	0.5 ± 0.1	ns
GA (g/l)	0.02 ± 0.01	0.01 ± 0.01	ns	0.02 ± 0.02	0.02 ± 0.01	ns
EAN (mg/l)	201 ± 43	154 ± 47	ns	166 ± 49	133 ± 40	ns

mind that, after mowing, the canopy continues to consume water and nutrients, although in smaller quantities than before mowing. Therefore, it is relevant to note that the presence of a CC must coincide with the latency period of vine growth (Compés López and Sotés Ruiz 2018); otherwise, the CC may have a negative effect on the vigor and yield of the vines. This is due to competition for water between vines and CCs in Mediterranean areas, where water availability is a limiting factor (Monteiro and Lopes 2007; Novara et al. 2021). One alternative to CCs that would fit the European Agriculture Policy (2021) is the use of mulching with straw or pruning vineyard residues as a cover since it has shown positive effects on the soil water content of the vineyard and the polyphenolic composition of red grapes (Göblyös et al. 2011; López Urrea et al. 2016; Intrigliolo et al. 2018). This would contribute to better integrated vineyard management by avoiding the traditional burning of vine pruning wastes. However, the use of pruning vineyard residues would not be feasible in vineyards with wood diseases, and the use of straw mulch can be a significant expense in certain areas due to purchase and spreading costs.

In this work, the UAV estimates were originally obtained only for the vines measured in the field, but the UAV technology and the procedure used have the advantage that all vines in the vineyard can be quickly and efficiently analyzed. Figure 3 shows a map in which the projected area has been calculated for 1.2 m segments (equal to the distance between vines) along the total length of the vine rows used as the experimental unit. It can be seen at a glance that the projected area values were lower along the entire length of the rows in the CC treatment (Figure 3). The application of remote sensing techniques to UAV imagery is able to support accurate multitemporal monitoring that opens the door to map canopy development. This is crucial, among other techniques, when it is necessary to plan canopy management practices to control excessive vigor and keep an appropriate right balance between vegetative and reproductive growth and even to supervise the application of timely green pruning treatments by temporary workers (López-Granados et al. 2020). The use of UAV remote sensing in viticulture also sets the stage for the estimation of yield, as has been demonstrated in red grape varieties (Di Gennaro et al. 2019; Torres-Sánchez et al. 2021) and, in a preliminary way, with

Table 5 Analysis of the influence of soil management treatments on gross income.

Year	Harvest	Treatment	Yield (kg•ha^{-1})	Alcohol by volume (% vol)	Basic value per ABV (€)	Basic value per kg (€)	Bonus (%)	Gross income (€•kg^{-1})	Gross income (€•ha^{-1})
2019	1st	CT	16,598	11.9	0.021	0.2499	0.00	0.2499	4147.93
2019	1st	CC	7299	14.4	0.021	0.3024	9.87	0.3322	2425.16
2019	2nd	CT	13,699	13.6	0.021	0.2856	0.00	0.2856	3912.33
2019	2nd	CC	7599	16.7	0.021	0.3507	0.00	0.3507	2665.05
2020	1st	CT	19,698	10.6	0.0194	0.2056	0.00	0.2056	4050.70
2020	1st	CC	9466	14.1	0.0194	0.2735	6.56	0.2915	2759.11
2020	2nd	CT	18,998	12.1	0.0194	0.2347	0.00	0.2347	4459.61
2020	2nd	CC	8232	15.8	0.0194	0.3065	14.27	0.3503	2883.52
2021	1st	CT	10,399	16.4	0.0258	0.4231	5.00	0.4443	4620.01
2021	1st	CC	6266	17.1	0.0258	0.4411	0.00	0.4412	2764.45

the "Pedro Ximénez" variety in the same study field (Torres-Sánchez et al. 2022b).

Soil management also affected the yield of the vines. The vines in the CT treatment were more productive during the years of study than those with cover crops. This result was expected since the reduction in yield caused by cover crops has been extensively documented, especially in warm climates (Abad et al. 2021a). Yield reduction should not always be viewed as a negative outcome. In humid regions, one of the objectives of installing cover crops is to reduce vegetative growth and yield in order to decrease the incidence of fungal diseases and produce higher-quality grapes. In the case of the studied vineyard, the yield of the vines in the CT treatment exceeded the production limits established by the Montilla-Moriles PDO (13,714 kg·ha^{-1}) in the years with less extreme weather conditions (2019 and 2020), while the yield of the CC treatment was within the production limits established by the PDO. However, the yield reduction in the CC treatment was such that the gross income from the sale of the grapes was about half that of the CT treatment, which could affect the profitability of the vineyard. On the contrary, in an analysis of the economic dimension of cover cropping in vineyards in a Mediterranean region, Mercenaro et al. (2014) reported that the adoption of intercropping was justified by private convenience criteria. This contradiction with the data presented here is due to the fact that the vineyard in the Mercenaro et al. study was irrigated, which reduced the competition between the cover crop and the vines, so that the presence of cover crop did not affect yield.

As reported by Ferrini et al. (1996) in the "Sangiovese" grape variety, the use of cover crops leads to an earlier harvest date. This result is of special interest in the PDO where the study field is located. A sizable portion of "Pedro Ximénez" grape production is dedicated to the production of sweet "Pedro Ximénez" wine, which implies the use of a technique called "asoleo" (traditional practice of over-ripening the grapes by direct exposure of the bunch grapes to the sun once they have been cut and spread out on the ground). Since the harvest in the CC treatment was earlier, grape bunches could be extended on the soil in August with less danger of rain and the associated risk of fungal infections than in September. Early ripening in conditions of high water stress could be problematic because of its influence on the aromatic richness, but in the Pedro Ximénez variety, the high sugar concentration is more important than the aromatic compounds, since it is mainly intended for "asoleo" to produce sweet wines, or for the production of "fino" wines with 15% vol. alcohol without the addition of wine alcohol.

In addition to the effects on vegetative growth and yield, soil management also affected the composition of the grapes. As reviewed by Guerra and Steenwerth (2012), the use of cover crops affects the must composition through competition for water and nutrients that lead to a reduction in vigor, causing an improvement in fruit exposure (Aerny and Maigre 2001; David et al. 2001), and to increased water stress which reduces berry size and yield (Wheeler et al. 2005; Tesic et al. 2007). In the study field, the TSS of the grapes was much higher in the CC than in the CT treatment as a result of yield loss. In the case of fortified wines with a high alcohol content (minimum 15° alcohol) produced in the Montilla-Moriles PDO, this is an advantage because there is a bonus in the prices of the grapes related to the probable

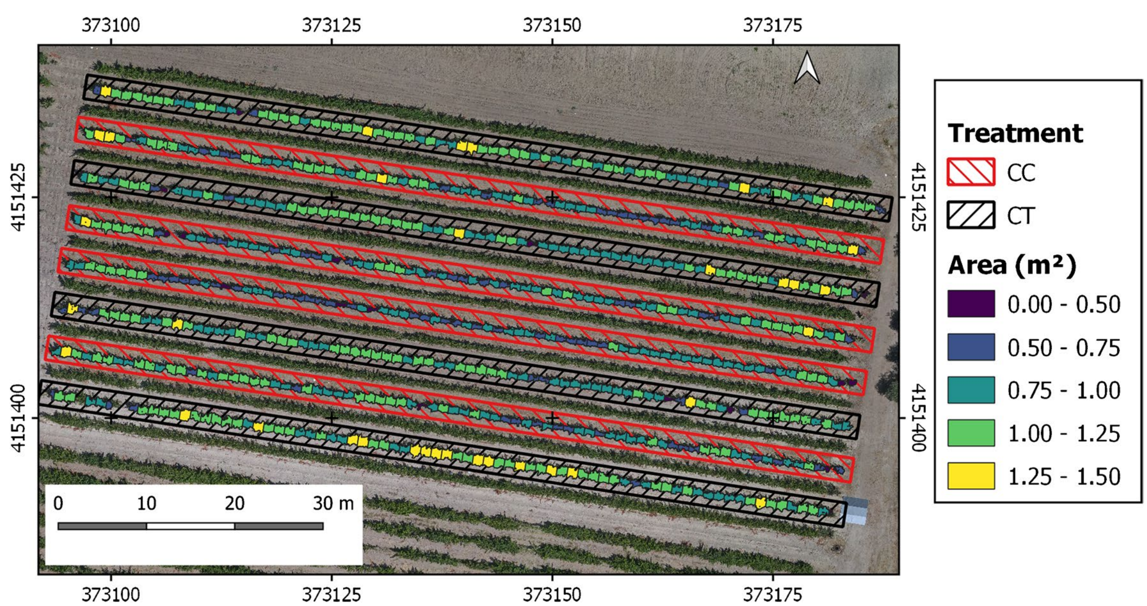

Fig. 3 Map representing the projected area of the vines in the study vineyard in 2021. Coordinate system: WGS84 UTM 30N.

alcohol content. However, in the study field, this bonus was not high enough to make up for the reduced yield from an economic point of view. The pH values were high, with a tendency to be higher in the CC treatment, although this difference was significant only in the first and second harvests of 2020. Perhaps more significant differences in TSS and pH values could have been detected if a larger number of must samples had been collected, but this was not possible due to limitations in the availability of the workforce.

The results concerning TSS and pH values contrast with the majority of the studies about the influence of cover crops on these parameters. According to a review by Abad et al. (2021a), TSS was not affected by cover crop in 30 out of 44 papers analyzed, and only in 8 of them TSS was higher in the treatment with cover crop. However, in one of the reviewed papers (Muganu et al. 2013), TSS was higher for vines with cover crop in samples taken during ripening of the grapes, but there were no differences at the moment of the harvest. The authors related the disappearance of the differences between cover crop and bare soil treatments to some rainfall before the harvest that could have relieved the water stress caused by the cover crop.

The differences in TSS found between the treatments when analyzing the first or second harvest separately were to be expected, since grapes at different stages of ripening were being compared (Tables 2 and 3). For this reason, a comparison was also made between the must parameters for the optimal ripening time of each treatment (Table 4), a practice that was performed in only 2 of the 44 articles reviewed by Abad (2021a) for TSS (Ferrini et al. 1996; Pérez-Bermúdez et al. 2016). Additionally, in that comparison, it was observed that the must from vineyards under CC treatment had higher values of TSS. This difference was significant only in 2020, but what was mentioned previously about the number of samples and the fact there was only one harvest in 2021 must be considered.

The management of plant covers in vineyards in areas with water limitation and particularly high temperatures during the growing season must be carried out with the utmost care to not compromise the profitability of the vineyards. Some advantages of the use of cover crops have been detected in this work, such as an increase in TSS and an earlier ripening, which favors the traditional practice of "asoleo." Probably, if they had been studied, other additional benefits evaluated in the scientific bibliography could be added to those previously commented, such as improvements in soil structure, increase in soil organic matter, or better water infiltration. However, the studied benefits of cover crops were not sufficient to compensate for the effect of cover crop on gross income, and the other benefits have their effect in the long term, without immediate effects on the profitability of the vineyard. As commented by Schütte and Bergmann (2019), in regions where vine growers are producers and direct sellers of their wine, and even organize tourist visits to their farms, the use of cover crops allows to economically compensate the yield loss. Wines produced with environmentally friendly practices such as cover cropping can be marked with a price premium, and according to Wratten et al. (2012), the presence of cover crops improves the esthetic value of farms, which could suppose a competitive advantage in attracting tourists. However, in the Montilla-Moriles PDO, many of the vine growers are part-time farmers and sell their grapes to cooperatives. As a result, they do not have access to the previously mentioned opportunities to compensate for the loss of yield caused by cover crops. Furthermore, although there are some subsidies to support the use of cover crops, they are not high enough to encourage vine growers to change their soil management practices. Therefore, to encourage winegrowers of arid and semiarid regions to use CCs, it is necessary to continue working to explore other cover crop species that achieve an appropriate soil coverage and fulfill their soil protection function and ecosystem services without compromising the profitability of the vineyards or while maintaining or improving the quality of grapes. Other research topics related to the adoption of cover crops in semiarid regions are the use of supplemental irrigation or different management strategies of the cover crop, such as earlier mowing, or variations in the cover crop width.

5 Conclusions

Soil management in vineyards is one of the most relevant questions, due not only to its effect on soil structure, erosion, or nutrients but also to its indirect effects on the plants and wine oenological properties. In the present work, the use of a cover crop between vineyard rows caused differences in the vegetative growth of the vines and in must quality parameters in an organic "Pedro Ximénez" vineyard in a Mediterranean climate. The vines with a cover crop growing between the rows presented lower vegetative growth and yield than the vines with plowed interrows. Yield in the vines under the conventional tillage treatment was over the production limit established by the PDO where the study field is located. Soil management also affected the harvest date, which was earlier for the vines under the cover crop treatment, and the composition of the grapes. The must from the vines with cover crop presented higher TSS values, which could be an advantage in the production of fortified wines such as those produced in Montilla-Moriles. Future research will focus on exploring other cover crop management techniques and considering cover crop species that compete less with the vines for water, to minimize the yield reduction and maintain or improve the quality of the grapes.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Ethical approval Not applicable.

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Consent for publication Not applicable.

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