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Ground vegetation covers increase grape yield and must quality in Mediterranean organic vineyards despite variable effects on vine water deficit and nitrogen status

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ABSTRACT

In the context of a warming climate and widespread soil degradation, successful soil management practices in Mediterranean vineyards should combine environmental (e.g., soil health) and productive (yield and must quality) objectives. With this objective, we tested five soil management practices in two organic farms in Chianti Classico (Italy) across three years. Five treatments were compared: conventional tillage (CT), spontaneous vegetation (S), soil-incorporated cover crop of pigeon bean (*Vicia faba* L. var. *minor* (Peterm. em. Harz) Beck. L.) (PBI), a cover crop mixture of barley (*Hordeum vulgare* L.) and clover (*Trifolium squarrosum* L.), either mulched (BCM) or incorporated in soil (BCI). We explored the effects of soil management practices on vine stress (SPAD and stem water potential), grape production (yield per plant; number of clusters per plant; cluster weight; berries weight) and must quality (titratable acidity; malic acid; pH; sugar concentration; yeast assimilable N; potential anthocyanins and total polyphenol index). Soil variability was taken into account in the statistical analysis, by testing two sets of soil covariates. A first dataset included the "raw" electrical conductivity and gamma ray total counts. The second dataset consisted in a set of soil covariates obtained by combining data collected by the proximal sensors with the results of the chemical analyses. We found that soil management affected SPAD and stem water potential with variable effects between farms and years. Mulched cover crops showed lower vine SPAD values than tilled treatments at both farms, especially in 2019 and 2020, while spontaneous vegetation effects varied considerably across farms and were comparable to tillage. Conventional tillage also decreased vine water stress compared with S, especially at the colder site in 2020. Mulched cover crops and tillage treatments had similar vine stem water potential at the warmer site. Significantly higher grape yields were found under PBI and S (about +30% compared with the other treatments), mainly due to higher cluster weight. The most productive treatments (PBI and S) also showed higher pH and malic acid concentration but lower anthocyanins and total polyphenol index as compared with the other treatments. Conventional tillage increased yeast assimilable N in 2019 while S showed the lowest values, probably due to a drop in the abundance of N-fixing plant species. On a methodological side we found that including soil parameters as covariates, instead of ECa readings and gamma ray total counts, improved regression models for all the dependent variables studied except for juice pH. Overall, our results indicate that groundcovers induced only a moderate and temporary stress that affected grape production and quality differently. While the barley-clover mixture significantly reduced grape production irrespectively of termination type, S and PBI were associated with higher grape yields. Overall, this study demonstrated that groundcovers can be profitably introduced in vineyards also in Mediterranean climates with positive effects on yields and quality.

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1. Introduction

Viticulture is a critical component of agriculture in Mediterranean areas. With a long-standing tradition in wine production, Mediterranean Europe hosts the three top producing countries – Italy, France and Spain – which accounts for ca. 33% of the world's vineyard area and almost half of the global wine production (OIV, 2016). In these countries, vineyards have been part of the landscape for more than 8000 years (Novara et al., 2021).

On a broader perspective, vineyards have been also identified as a key land use to deliver numerous ecosystem service (ES) (Brunori et al., 2016). Nevertheless, vineyard is to date one of the most erosive land uses in Mediterranean Europe (about 9.5 t eroded soil ha^{-1} $year^{-1}$ vs an average of 2.7 t eroded soil ha^{-1} $year^{-1}$ from the arable lands) (Panagos et al., 2015). Firstly, vineyards have been historically located on marginal soils (Lazcano et al., 2020). As a result, vineyard soils are often sloping, poorly developed and thus prone to degradation. Secondly, intensive tillage is often used in Mediterranean vineyards –particularly in organic wine production - as a mean to reduce weed-grapevine competition for nutrients and water (Delpuech and Metay, 2018). This practice has been widely shown to foster soil degradation due to the drastic reduction in soil cover (Gago et al., 2007), disturbance of soil life (Roger-Estrade et al., 2010; Fiera et al., 2020; Gonçalves et al., 2020), negative effects on soil structure quality and stability (Laudicina et al., 2017; Polge de Combret-Champart et al., 2013), increased soil organic matter (SOM) oxidation (García-Díaz et al., 2018; Prosdocimi et al., 2016) and soil erodibility (Novara et al., 2011; Rodrigo-Comino et al., 2018). Future projections indicate that water will be increasingly a limiting factor for grapevine production in the Mediterranean area, as temperatures are expected to increase while rainfalls are forecasted to be progressively more erratic and scarce in the vegetative season of grapevines (Fraga et al., 2012; Ramos, 2017). This is expected to have a direct detrimental impact on the quantity and quality of grape production (e.g. higher water stress, imbalances in grape maturation) (Santillán et al., 2019). As a response, viticulturists in dry areas could increase tillage frequency as a mean to increase water availability (e.g., by increasing infiltration or reducing evaporation caused by soil cracks), stimulating SOM mineralization rate and crop nutrient availability. Such additional intensification will further threaten the provision of key ES from vineyards. In this context new tools and practices should be sought and tested in collaboration with farmers to cope with the multiple challenges of climate change and soil degradation that the modern viticulture is facing.

Cover crops (CC) and spontaneous vegetation cover have been widely shown to improve soil and rehabilitate soil's capacity to deliver ES (Jian et al., 2020). Groundcovers represent a physical barrier to rain drop and sediment losses and are therefore instrumental to reduce soil erosion (Marques et al., 2010; Rodrigo Comino et al., 2016). Sown and spontaneous CC were also found to increase SOM through the combined effect of increased SOM input, reduced soil oxidation and erosion (Agnelli et al., 2014; López-Piñeiro et al., 2013; Peregrina et al., 2012; Priori et al., 2018; Ruiz-Colmenero et al., 2013). Physical soil health is also positively influenced by groundcovers which increase aggregation and improve soil structure depending on their production and root traits (Biddoccu et al., 2020; Garcia et al., 2019; Peregrina et al., 2010). Soil cover practices are also beneficial to the soil biological communities by improving their habitat and provide substrate and resources to sustain their life (Gonçalves et al., 2020; Hendgen et al., 2018; Schreck et al., 2012). CC and spontaneous vegetation also hold potential to rehabilitate other types of ES not strictly related to soil. A recent meta-analysis summarized the positive effects of extensive inter-row vegetation management on multiple ES, including pest control, soil health and biodiversity (Winter et al., 2018).

Specific policies are in place in Europe as national initiatives or under the umbrella of the Common Agricultural Policy to support farmers towards the adoption of sustainable soil management practices (Turpin et al., 2017). Nevertheless, it appears that farmers are still increasingly concerned about the potential competition between groundcovers (spontaneous or sown, both inter-row and beneath the row) and vineyards, as subsidies are not attractive enough and groundcovers are perceived to increase work load and risks for grape yield and quality (Schütte and Bergmann, 2019). Although a moderate water deficit and low N-supply is, in fact, beneficial for the production of high quality wines (Van Leeuwen and Seguin, 2006), in many situations including low vigor vineyards and dry years, vine water and nutrient uptake can be severely affected by groundcovers, thereby resulting in lower canopy development and yield reduction (Medrano et al., 2015). Cover cropping does in fact favor refilling of soil water during winter, but it increases transpiration during spring, thus likely causing water stress (Celette and Gary, 2013). Determining the nature of the CC-grapevine relationship (synergistic or competitive) is complex as this is determined by a variety of interacting factors, including soil type, CC species, climatic conditions and technique and timing of CC termination. Lower grape yields were indeed found under groundcovers in Italian vineyards (Muscas et al., 2017). Conversely, lack of or non-significant yield reduction were reported in more vigorous areas (DeVetter et al., 2015; Lopes et al., 2008), in vineyards where CCs were mown in early spring (Pérez-Álvarez et al., 2015) or when CC did not fully cover the soil (Delpuech and Metay, 2018). Groundcovers can also affect must quality mainly by anticipating ripening and hence increasing sugar concentration at the expenses of titratable acidity (TA) (Mattii et al., 2005; Lopes et al., 2008). Increased anthocyanin content was found under CC as compared to tillage while total polyphenol content was not affected (Pérez-Álvarez et al., 2013). Nevertheless, the effects of soil management on grape yield, and particularly on yield components, is still poorly understood and varies across climates, soils, CC species and termination strategies (Guerra and Steenwerth, 2012).

The variable response of groundcovers on grapevine performance, yield and must quality calls for additional on-farm studies. It is instrumental to explore with farmers the trade-off existing between soil conservation and productive goals. Such a work is particularly relevant in Chianti Classico DOP (Italy), where farmers are increasingly concerned about drought and the resulting yield reduction and decrease in wine quality.

On-farm experiments have increasingly gained attention by the scientific community as a mean to (i) engage with farmers, (ii) improve the relevance of agricultural experiments for end users; (iii) bridge scientific and farmers' knowledge; (iv) provide mutual learning experiences for researchers and farmers (Catalogna et al., 2018; Hoffmann et al., 2007). Nevertheless, on-farm soil variability may seriously affect the statistical power of these trials. Randomization has been often indicated as a panacea to manage soil variability, though complex randomized designs are often difficult to implement on-farm and especially on row and perennial crops. Moreover, studies based on chess board randomized designs are very rare in the viticulture literature where is common practice to randomize between -and not within- vine rows. Furthermore, in the scientific literature it is not common to report on the edaphic homogeneity within blocks and rows which, although is the main assumption for effective randomized designs, often remains untested. In this context, the use of proximal sensors has been shown to deeply improve the knowledge of soil variability and hence the statistical power of agronomic experiments (Heil and Schmidhalter, 2017). Sensors measuring apparent electrical conductivity (ECa) have been successfully used to improve blocking while "raw" ECa data were used as continuous covariates (Heil et al., 2018; Le Guen et al., 2017). Rudolph et al. (2016) demonstrated the statistical advantage of using ECa readings as continuous covariates in regression models over the "improved blocking" strategy. Moreover, the authors recommended the use of additional sensors such as gamma ray to improve statistical models (Pätzold et al., 2020). In addition, the comparison of different experimental designs with and without spatial information showed that including spatial covariates reduced Type I error regardless of the design and randomization (Alesso et al., 2019).

This work aimed at studying the effect on vine SPAD, water stress, yield and must quality of a set of different inter-row soil managements (including soil tillage on bare soil, different CC species managed as green manure or dead mulch, and spontaneous vegetation mowed on untilled soil), directly chosen by local farmers and tested for three years in two organic commercial farms on cv. Sangiovese. The two farms were located in two distinct areas of Chianti Classico, Tuscany, Italy. To the best of our knowledge, only one study was carried out on this topic in this area but not on cv. Sangiovese (Cataldo et al., 2020), which is the typical and most widespread vine cv. in the area,. On a methodological side, we used fine-scale variability soil maps to take into account the different edaphic conditions between and within experimental sites. Specifically, we did not only complement ECa measures with a gamma ray survey as recommended by Rudolph et al. (2016), but also obtained the values of a set of soil parameters in order to improve the statistical power of our models. We hypothesized that:

1. Including soil parameters as covariates improves regression models (lower BIC) compared with raw ECa and Gamma ray.
2. Groundcovers negatively affect vine SPAD and stem water potential compared to tillage due to higher competition for water and nutrients, with different degrees depending on cover crop composition (spontaneous flora > grass-legume mixture > legume pure stand) and termination strategy (mulching > soil incorporation).
3. Tillage increases grape yield compared with groundcovers as it reduces the competition for nutrients and water by the inter-row plant communities. Among groundcovers, the grass-legume mixture and the spontaneous vegetation limits yield due to the high biomass production, high presence of grass species and the resulting high competitive potential. Conversely, legume CC, either grown in pure stands or in mixture with grass species, when incorporated in the soil improves grape yields due to the recycling of the fixed N_2 accumulated in their biomass.
4. Tillage decreases sugar and polyphenol concentration while increases pH and TA concentration in grape's juice compared to groundcovers. We expect that competitive groundcovers, such as the grass-legume mixture and the spontaneous grassing, affect N and water stress thereby reducing yield and hence favoring sugar accumulation, reduction of TA and increase in grapes' polyphenols.

2. Materials and methods

2.1. Study site and experimental design

The experiment was conducted from 2017 to 2020 in two commercial organic farms located in two different areas of the Chianti Classico wine district (Tuscany, Italy):

(i) Fattoria San Giusto a Rentennano (SG) (43°22′14.1″ lat. N, 11º25′19.4″ long. E), is located in Gaiole in Chianti (Siena province) at 233 m a.s.l. Average annual rainfall and air temperature are 801 mm and 14.4 °C, respectively. Soils are loamy, moderately gravelly (5–15% w/w), developed on marine sands and Pliocene conglomerates with an average 1.6% w/w SOC concentration (0–30 cm).

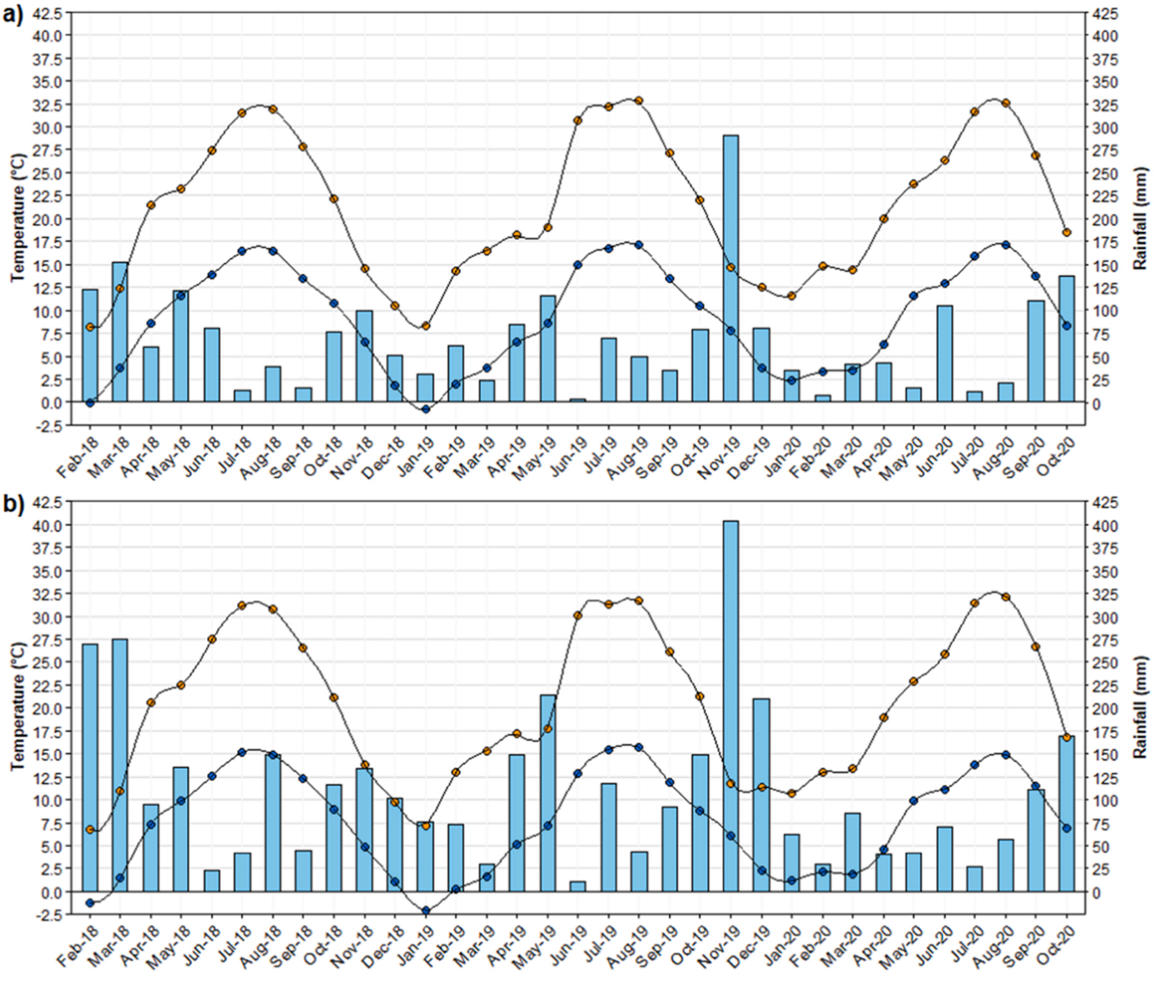


Fig. 1. Monthly rainfall, minimum and maximum air temperatures recorded in 2018, 2019 and 2020 at (a) San Giusto a Rentennano and (b) Montevertine.

(ii) Montevertine (MT) (43°30′06.2″ lat. N, 11°23′29.0″ long. E) is located in Radda in Chianti (Siena province) at 425 m a.s.l., where average annual rainfall and air temperature are 824 mm and 12.6 °C, respectively. Soils are stony, from silty clay loam to clay loam, developed on marls and limestone of the Sillano formation, with an average 1.2% w/w SOC concentration (0–30 cm).

Fig. 1 shows the rainfall, maximum and minimum air temperatures at both experimental sites across the three years of experimentation.

The average slope of the experimental vineyards is ca. 10% at both sites. The vines (*Vitis vinifera*, L. cv. Sangiovese R10, rootstock 420A) were planted in rows (2.50 × 0.8 m, i.e., 5000 plants ha^{-1}) with S-W and S-E orientation at SG and MT, respectively. The year of establishment of the vineyards is 1995 and 1991 at SG and MT, respectively. The training system is Guyot at SG and spurred cordon at MT. Five inter-row management practices were studied in both farms:

- Conventional tillage, performed once in autumn, spring and summer with a rigid tine cultivator at 15 cm depth (CT);
- Pigeon bean (*Vicia faba* L. var. minor (Peterm. em. Harz) Beck.) cover crop sown at 90 kg ha^{-1} in autumn and soil incorporated with a disc plow in late spring (PBI);
- Mixture of barley and squarrosum clover cover crop sown as above but soil incorporated with a disc plow in late spring (BCI);
- Mixture of barley (*Hordeum vulgare* L.) and squarrosum clover (*Trifolium squarrosum* L.) cover crop sown in autumn at 85 and 25 kg ha^{-1} respectively, mown in late spring and left as dead mulch on soil surface (BCM);
- Spontaneous vegetation mown in late spring and left as dead mulch on soil surface (S).

An in-row ventral plow was used to control weeds under the trellis during the growing season (late spring and summer) in all the treatments. Each experimental plot consisted of three rows and two inter-rows (about 5 × 100 m) and accounted for about 4.000 m^2 in each farm. Treatments including CC were allocated to alternate rows within the plot. The inter-row receiving a CC treatment was shifted every year, as this is common practice in the area. Conversely, CT and S were implemented on both inter-rows. Each experimental plot was divided in three replicates along the slope of the vineyard. Treatments were separated by a buffer inter-row.

2.2. Soil analysis and soil variability surveys

Soils were sampled in October 2017 prior to the establishment of the treatments. Soil was analysed for texture, SOM, total N, exchangeable K, exchangeable Mg, total carbonate and gravel. The two experimental sites were also surveyed with an electromagnetic induction sensor (EM38-Mk2, Geonics Ltd., Mississauga, ON, Canada) and a gamma-ray spectroradiometer (The Mole, Soil Company, the Netherlands) to study the soil variability of the sites.

Based on these surveys we obtained two datasets consisting of two sets of covariates to be included in statistical models. A first dataset contained the “raw” gamma ray total counts, shallow (ECa_1: 0–75 cm) and deep (ECa_2: 75–150 cm) electrical conductivity readings of the position of each plant sampled in the three experimental years. The second dataset, hereafter called the” soil parameters dataset”, contained the data on gravel, clay, sand, silt, K, Mg, SOM and total limestone. Details on the analytical methods, elaboration of soil maps and related analyses can be found in Warren Raffa et al. (2021).

2.3. Greenness index and stem water potential

The greenness index (SPAD) is related to leaf chlorophyll concentration. This index is strongly correlated with the total N content and is therefore used as an indirect indicator of the plant N status (Caruso et al., 2017; Muscas et al., 2017). SPAD was sampled with a SPAD-502 chlorophyll meter (Konica Minolta Sensing Europe B.V.) seven times in 2018 and 2019, from before termination of the CC (before grape flowering) until mid-September (maturation), and five times in 2020 in correspondence with stem water potential (Ψstem) measurements (from berry pea sized to maturation). Each sampling included five stocks per replicate from which three fully expanded median leaves were chosen (Taskos et al., 2015). Three points were measured and averaged on each leaf.

Stem water potential was measured five times per year (every two weeks from fruit set to maturation) using a pressure chamber (PMS 600D, PMS Instrument Company, USA). One undamaged leaf per stock was selected, enclosed in plastic bags covered with aluminum foil one hour before taking the measurement (Chonè et al., 2001). Measurements started at midday and were taken following the wrapping order. GPS coordinates of the sampled plants were taken at each SPAD and Ψstem sampling time.

2.4. Grapevine yield, berry sampling and must composition

Grapevine yield and yield composition were estimated on ten plants per replicate (300 plants per year) when the farm managers decided to harvest. Plants were chosen in 2018 and properly signed in order to sample the same plants every year. Nevertheless, some rootstocks were replaced in both experimental sites due to esca. The GPS positions of all the harvested plants were also taken. Number of clusters and weight of all clusters were recorded per each plant. At harvest, five berries were collected in different positions of all the clusters sampled in each replicate. From all those berries, we took one and three subsamples of 100 berries per replicate and weighted in 2018 and 2019–2020, respectively. Similarly, we picked one and three samples of 500 berries per each replicate in 2018 and 2019–2020, respectively. Berries from the first six plants of each replicate were included in the first and second sample. The rest formed the third subsample. All subsamples were analysed for pH (OIV-MA-AS313–15: R2011), titratable acidity (TA) (OIV-MA-AS313–01:R2015), sugar concentration (OIV-MA-AS2–02: R2012) and malic acid content (OIV-MA-AS313–11:R20099) according to the methods suggested by the International Organization of Vine and Wine (OIV, 2021). Yeast Assimilable Nitrogen was calculated as the sum of alpha-aminic N and ammonium-N obtained following the procedure illustrated by Dukes and Butzke (1998) and Bergmeyer and Beutler (1990), respectively. Total anthocyanins and total polyphenol index (TPI) were analysed following the method reported by Glories (1999).

2.5. Statistical analysis

The soil maps (clay, sand, silt, K, Mg, gravel, total limestone, gamma-ray total count, ECa1 and ECa2) were used to extract the values of the soil parameters, ECa1, ECa2 and gamma ray total counts according to the geographical coordinates of the plants which were sampled for SPAD, Ψstem, yield and yield composition variables. For must analysis we used the average of the soil properties of the plants from which the berries were taken. The extrapolation of soil covariates was carried out in QGIS 3.6.3 (“join by location” function).

We firstly used the bestglm function (bestglm package) to explore the variable subsets giving the models without interactions with the lowest Bayesian information criterion (BIC). The list of variables explored with bestglm can be found in Annex I. Those variables were then included in the Feasible Solution Algorithm (FSA –rFsa package) as fixed variables. We also included “treatment” as fixed variable when it was not specified by bestglm. FSA allows for interaction across variables and can be run both for generalized (glm) and linear models. FSA solutions are optimal in the sense that no single swap to any of the variables will increase the BIC. We tested bestglm and FSA both with the dataset containing ECas and gamma ray total count readings and with the soil parameters dataset, in order to identify which dataset performed better for each dependent variable. Overall, when FSA did not yield differences across linear and glm, we tested different glm distributions (Gaussian, Gamma) and link functions (identity, log, inverse) and selected the model with the lowest BIC (Annex 2). We used linear mixed effect model for SPAD, berries weight and total polyphenol index using "Replicate" as random factor (lme4 package). Stem water potential and potential anthocyanins were analysed through linear models. Generalized linear models using Gamma distribution were used for juice pH, TA, malic acid (link function = identity), plant yield and cluster weight (link function = log). Number of clusters per plant was analysed using a Poisson distribution. In all cases, residuals were assessed visually, and a Shapiro-Wilk test was performed. Goodness of fit of glm was also assessed through the Kolmogorov-Smirnov, dispersion and outlier tests (DHARMa package). Analysis of variance (type III SS) was used to check for statistically significant variables. Estimated marginal means were used to obtain p-value corrections, with Tukey's post hoc test ($\alpha = 0.05$). All statistical analyses were performed in R (version 4.0.3, 2020).

3. Results

3.1. Model selection

The outcomes of the FSA procedure showed that lower BIC were obtained using the soil parameters dataset for all the dependent variables but grape pH (Annex II).

3.2. SPAD and stem water potential

SPAD values were significantly affected by all the factors and interactions included in the model except for the treatment x farm interaction (Table 1). Overall, SPAD values were higher at MT than SG (Fig. 2). Treatments affected SPAD differently across the two experimental sites. S generally showed SPAD values higher than CT at MT, with two (BBCH = 65 and 75), one (BBCH = 13) and three (BBCH = 77, 83 and 85) significant differences between these treatments in 2018, 2019 and 2020, respectively. BCM had lower SPAD readings than CT especially in 2019 and 2020 but not in 2018 at MT. At this site, differences between BCM and the tilled CC (BCI and PBI) were more marked in 2019 and 2020 than in 2018. A different scenario was observed at SG (Fig. 1). Here, SPAD under CT was not higher than S only in one (BBCH = 75), three (BBCH = 15; 81 and 83) and in no sampling events in 2018, 2019 and 2020, respectively. Similarly, BCM often showed lower SPAD records than CT especially in 2019 and 2020. In particular, treatments differentiated quite strongly in 2020, which was a particularly dry and warm year at SG. In these conditions, tillage seems to play an important role in improving SPAD values.

Table 1
Results from the Analysis of variance (type III SS) for SPAD.

SPAD	Chisq	Df	Pr (>Chisq)
(Intercept)	3600.3390	1	***
Factors related to the experimental design			
Treatment	20.2551	4	***
Farm	0.0307	1	ns
Rep	13.9141	2	***
DOY	113.7008	3	***
Year	217.5439	2	***
Pedoclimatic factors			
Total limestone	68.7052	1	***
Gravel	113.7751	1	***
Interactions			
Treatment x Year	31.3900	8	***
Treatment x DOY	38.3966	12	***
Year x DOY	565.2254	6	***
Treatment x Farm	3.8227	4	ns
Year x Farm	283.7622	2	***
DOY x Farm	85.0877	3	***
Farm x Total Limestone	36.5280	1	***
Replicate x Gravel	398.1658	2	***
Treatment x Year	72.6791	24	***
Treatment x Year x Farm	23.6035	8	**
Treatment x Time x Farm	38.5895	12	***
Year x DOY x Farm	435.1481	6	***
Treatment x Year x DOY x Farm	105.3711	24	***
Distribution	Gaussian - Linear		

ns= not significant.
DOY= Day of the year
** significant at $p \leq 0.01$ respectively.
*** significant at $p \leq 0.001$, respectively.

Stem water potential (Ψstem) was significantly affected by the quadruple interaction (treatment × year × sampling time × farm] (Table 2).

Higher Ψstem values were observed in 2018 than in the other two years (Fig. 3). Overall, we found lower Ψstem values at MT (mean Ψstem= −0.84 MPa), but more significant differences across treatments emerged at SG (mean Ψstem= −0.77 MPa). At MT, treatments did not differ significantly in 2018. Instead, in 2019 CT (mean Ψstem= −0.80 MPa) showed higher values than S (mean Ψstem= −1.03 MPa) at the fourth sampling event. In 2020, tilled treatments showed higher Ψstem than mulched treatments.

At SG, in 2018 we found lower Ψstem values under S in comparison with CT in three out of five sampling events. BCM (mean Ψstem= −0.39 MPa) differed significantly from CT (mean Ψstem= −0.30 MPa) only at the beginning of the sampling season. Significant differences across treatments were only found in the last two sampling events at SG in 2019. CT still recorded the highest Ψstem values but it was significantly different only from BCI (at day 232) and PBI (at day 248). Similarly, in 2020 treatments were significantly different only at the end of the sampling campaign, but differences were found between CT, BCM and PBI.

3.3. Grapevine yield, berry sampling and must composition

Grape yields were significantly affected by treatment, year, farm and by the farm x year interaction (Table 3). Yields varied also across gravel and total limestone soil concentration. S and PBI increased significantly yields as compared with the other treatments (Fig. 4a). Despite the significant interaction, the post-hoc test did not reveal significant differences in yields across farms and years (data not shown).

Treatments significantly affected cluster weight and berries weight but not the number of clusters per plant (Table 3). Berries weight was higher under CT and S though those treatments were only significantly different from BCM (Fig. 4b). Clusters were significantly heavier under S and PBI as compared with the other treatments (Fig. 4c), thereby suggesting that the differences in yields across treatments were mainly driven by the weight of the clusters.

Must analysis revealed a significant effect of treatments on all the parameters analysed except for TA (Table 4). Must pH was significantly affected by treatment, farm, year, gamma ray and by the farm x year interaction (Table 4). Overall, differences in must pH across treatments were relatively small and mimicked the differences already found in the analysis of yield per plant and mean cluster weight. Specifically, juices produced by S (mean pH=3.39) and PBI (mean pH= 3.34) had significantly higher pH than the other treatments (Fig. 5a). pH also differed significantly across farms and years with MT showing larger differences across years than SG (Fig. 6a).

S showed the highest malic acid concentration (mean malic acid = 1.20 g l^{-1}) followed by PBI (mean malic acid = 1.11 g l^{-1}) which did not significantly differ from CT (mean malic acid = 0.98 g l^{-1}). The barley-squarrosum clover mixture reduced malic acid concentration, irrespectively of the termination strategy. Malic acid was also significantly affected by farm and year (Table 4). Significantly higher concentrations were found at SG (mean malic acid = 1.23 g l^{-1}) than at MT (mean malic acid = 0.70 g l^{-1}) and in 2019 (mean malic acid = 1.07 g l^{-}

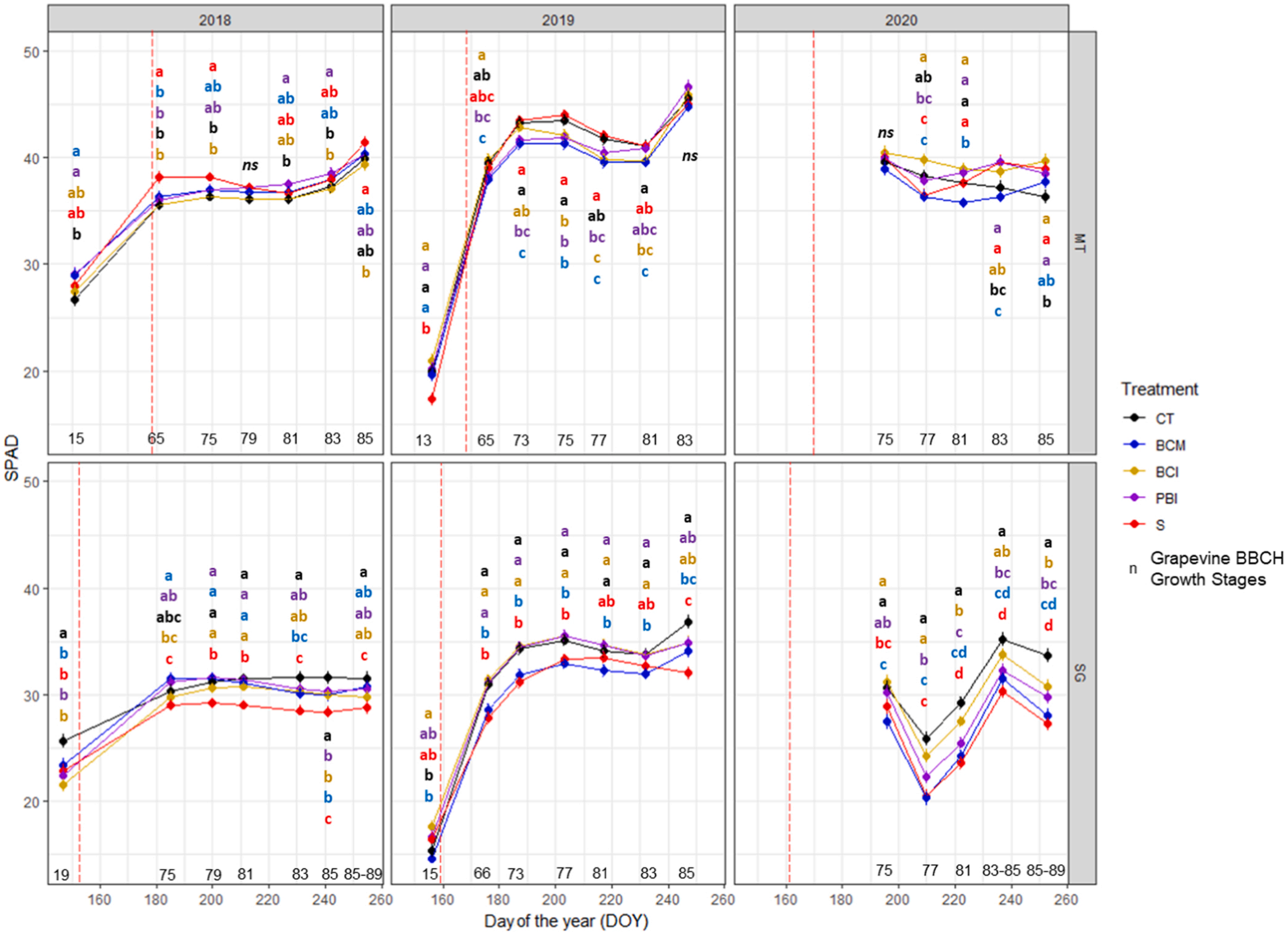


Fig. 2. SPAD values recorded in 2018, 2019 and 2020, averaged across total limestone, replicates and gravel (n = 8.550). Dashed red lines indicate the date when tillage and cover crop termination were carried out. CT= Conventional Tillage; BCM= Mulched cover crop of barley + squarrosum clover; BCI= Cover crop of barley + squarrosum clover incorporated in the soil; PBI= Pigeon bean cover crop incorporated in the soil; S= Mulched spontaneous vegetation. MT= Montevertine; SG= San Giusto a Rentennano. Points indicated by different letters are significantly different at $p < 0.05$ (Tukey test). Bars denote standard errors of the mean. BBCH Growth Stages of grapevines are also reported for each farm x year combination above x-axis. BBCH 13 = third leaves unfolded;BBCH 15 = fifth leaves unfolded; BBCH 19 = nine or more leaves unfolded; BBCH 65 = Full flowering: 50% of flower hoods fallen; BBCH 66 = 60% of flower hoods fallen; BBCH 73 = Berries groat-sized, bunches begin to hang; BBCH 75 = Berries pea-sized, bunches hang; BBCH 77 = Berries beginning to touch; BBCH 79 = Majority of berries touching; BBCH 81 = Beginning of ripening: berries begin to develop variety-specific color; BBCH 83 = Berries developing color; BBCH 85 = Softening of berries; BBCH 89 = Berries ripe for harvest.

^{1}) compared with 2018 (mean malic acid = 0.87 g l^{-1}).

Sugar concentration was significantly affected by treatment, total limestone and by the farm x year interaction. BCI produced musts with the highest sugar concentration (mean sugar= 243.1 g l^{-1}) which were significantly different from all the other treatments but S (mean sugar= 237.9 g l^{-1}) (Fig. 5c). Significant differences were observed across years at MT, with values higher in 2018 (mean sugar= 245.0 g l^{-1}) than in 2019 (mean sugar= 231.3 g l^{-1}) (Fig. 6b). A different trend was observed at SG, where the two experimental years did not highlight significant differences. Interestingly, we found a positive significant effect ($R^2 = 39.4\%$; $p < 0.001$) of total limestone on sugar concentration (data not shown).

Treatments significantly affected potential anthocyanins (Table 4), which were higher under the barley-squarrosum clover mixture, particularly when incorporated into the soil (mean potential anthocyanins = 1544 mg l^{-1}) (Fig. 5d). CT (1282 mg l^{-1}) had significantly lower anthocyanins than BCI and BCM (1423 mg l^{-1}), while the other groundcovers did not differ among them. Must anthocyanins concentration was on average 78% higher at MT than SG (1752 vs 979 mg l^{-1}).

Total Polyphenol Index was significantly influenced by treatment, year, farm, clay and by the farm x year interaction (Table 4). BCM was the treatment with the highest TPI (67.4) and was significantly different from all the other treatments but BCI (64.6) (Fig. 5e). TPI also varied significantly across farms and years (Fig. 6c). In 2018, TPI was on average 18% higher than in 2019 (74.0 vs 62.7) at MT. Conversely, at SG TPI was ca. 10% higher in 2019 than in 2018 (59.4 vs 55.0).

Yeast Assimilable Nitrogen (YAN) was significantly affected by treatment, farm, gravel, total limestone and by the treatment x year and replicate x gravel interactions (Table 4). Differences in must YAN across treatments were not found in 2018 (Fig. 5f). Instead, in 2019 we found higher YAN under tilled treatments than in the other treatments. Musts produced under S were 32% lower in YAN as compared with CT.

4. Discussion

4.1. Model selection is not explicit and including soil parameters as covariates improves regression models compared with raw ECa and Gamma ray

The comparison of the models obtained by the selection procedure

Table 2
Results from the Analysis of variance (type III SS) for stem water potential (Ψstem) ($n = 1.350$).

SWP	Sum Sq	Df	Pr (>F)
(Intercept)	5.1297	1	***
Treatment	0.1665	4	*
Year	1.0794	2	***
Event	1.6323	4	***
Farm	0.1233	1	**
Silt	0.5721	1	***
Gravel	0.0018	1	ns
Treatment x Year	0.1266	8	ns
Treatment x Event	0.4072	16	*
Year x Event	5.0540	8	ns
Treatment x Farm	0.0278	4	ns
Year x Farm	1.0050	2	***
Event x Farm	0.4788	4	***
Farm x Gravel	0.1659	1	***
Treatment x Year x Event	0.4144	32	ns
Treatment x Year x Farm	0.0839	8	ns
Treatment x Year x Farm	0.4491	16	**
Year x Event x Farm	2.5352	8	***
Treatment x Year x Event x Farm	0.9233	32	***
Distribution	Gaussian-linear		

ns= not significant.
[*] significant at $p \leq 0.05$ respectively.
[**] significant at $p \leq 0.01$ respectively.
[***] significant at $p \leq 0.001$, respectively.

using the two datasets (ECa + gamma ray vs soil parameters) highlighted that including the soil parameters as covariates yielded models with reduced BIC for all the dependent variables analysed but must pH (Annex II). This finding suggests that it can be advantageous to obtain the soil parameters based on proximal sensor surveys and their use as covariates in regression models as compared with raw ECa and gamma-ray readings. Still, additional research is needed to confirm our findings through more detailed methodological studies. Although our paper builds on innovative recent literature (e.g., Heil et al., 2018; Rudolph et al., 2016), it is not suitable to fully compare the statistical power of randomized vs non randomized design complemented with a set of continuous soil covariates.

4.2. Groundcovers negatively affect SPAD and stem water potential compared to tillage, with different degrees depending on cover crop mixture and termination strategy

SPAD has been shown to be a quick and cost effective methods to monitor plant health due to the strong correlation with N and chlorophyll content (Brunetto et al., 2012; Taskos et al., 2015). Although no differences across CC and tillage treatments were found in Chianti Classico on cv. Cabernet Sauvignon (Cataldo et al., 2020), our analysis showed that soil management significantly affected SPAD with a variable effect depending on farm, year, sampling time and soil characteristics (Table 2; Fig. 2). Overall, tillage played an important role in improving SPAD readings. Tillage indeed reduces weed competition, favors N turnover (Calderon et al., 2001) and improves soil water availability compared with CC in spring (Monteiro and Lopes, 2007). Muscas et al. (2017) reported higher SPAD values under tillage compared with spontaneous vegetation in a cv. Carignan vineyard over three years of experiment. Nevertheless, not all the groundcovers impose the same stress. Significantly different effects between legume and grass CC were reported in the literature (Muscas et al., 2017; Pérez-Álvarez et al., 2015). Similarly, in our experiment we observed that SPAD values were determined by the combined effect of groundcover management and species, interacting with the climatic conditions at the two sites. As an example, S consistently showed high SPAD values at MT. We hypothesize that such high SPAD values might be due to the higher biomass of spontaneous legumes found in the spontaneous groundcovers at MT (Medicago spp. accounted for 65% of total biomass in 2018) combined with the high availability of water which improved N turnover. Medicago spp were reported to fix about 125 kg ha^{-1} $year^{-1}$ (twice as much the usual N content in grapevine annual organs) hence significantly contributing to improve grapevine N status (Sulas et al., 2017). Likewise, the large amount of N potentially fixed by pigeon bean (Novara et al., 2013) may explain the increased SPAD readings under PBI at the MT site following incorporation in soil, especially in 2018 and 2020. A different scenario was observed at SG, which is characterized by warmer and drier climate. Here, mulched groundcovers resulted in significantly lower SPAD readings as compared with tilled treatments, especially in 2019 and 2020. In drier environments, water uptake by groundcovers can be high during spring, while the absence of tillage may hamper N mineralization and hence N availability. Indeed, reduction in N uptake by grapevine has been documented during drought periods as a results of the low mineralization rate in soils (Peregrina et al., 2012) and the drop in N-reductase in grapevine (Celette et al., 2009; Celette and Gary, 2013).

Stem water potential is considered a critical indicator for water stress in vineyards (Chonè et al., 2001), which can be significantly affected by soil management. Overall, the water stress found in our experiment was never severe (Ψstem<−1.4 MPa) (Van Leeuwen et al., 2009). Stem values classified between moderate and severe (−1.1 MPa< Ψstem<−1.4 MPa) were found at MT at the last sampling date in 2019 and 2020. We observed a lower water stress under CT as compared with the other treatments (Fig. 3). This effect of tillage have been commonly reported in the literature (Cataldo et al., 2020; Córdoba et al., 2015; Lopes et al., 2008; Monteiro and Lopes, 2007), and has been attributed to the combined effect of (i) reduced weed biomass, (ii) increased water infiltration after tillage operations and (iii) increased water availability through water loss reduction due to the interruption of capillary rise. Conversely, water uptake by groundcovers can significantly reduce soil water availability and increase grapevine water stress, with possible detrimental effects on vegetative and reproductive growth (Daane et al., 2018; Medrano et al., 2015; Novara et al., 2021). This is consistent with the results obtained in our study under natural groundcovers, especially in 2018 at MT and 2020 at SG. Nevertheless, despite the same termination strategy, the mulched CC showed higher Ψstem (lower water stress) than S. Multiple reasons can lay behind these results. Firstly, BCM biomass yield in spring was higher than S especially at SG (on average 3.2 vs 2.5 t d.m. ha^{-1}). Mulch has been shown to significantly affect evaporative losses depending on biomass amount (Myburgh, 2013). Prosdocimi et al. (2016) reported an immediate beneficial effect of barley straw which was able to reduce median water loss by about 25% at 750 kg of straw applied ha^{-1}. This further suggests that timely termination of CC may be critical to regulate the groundcover-grapevine competition. Secondly, the type of mulch strongly differed between S and BCM, with the latter having a high percentage of barley which notably produces straw which is harder to degrade (high C:N ratio) and hence last longer on the soil surface. Significant differences between BCM and CT were limited to only one sampling event at each farm. These results are not completely consistent with Cataldo et al. (2020), who found strong significant differences in Ψstem between tillage and CC, especially in a very dry year like 2017. In our study, the marginal differences found between mulched CC and tillage may be a result of timely mowing interventions. Indeed groundcovers termination remains a critical management lever to reduce grapevine-cover crop competition and needs to be adapted to the seasonal climatic conditions (Garcia et al., 2018). Reductions in evapotranspiration were indeed reported to range between 35% and 49% after mowing, thereby demonstrating the effectiveness of this practice in reducing CC evapotranspiration (Centinari et al., 2014). The very limited differences in Ψstem that we found between tillage and mulched-CC may be also related with the historical inter-row management of the farms, as CC have been grown at both sites for more than a decade. As a result, grapevines may have developed deeper soil roots which favored a complementary uptake of soil

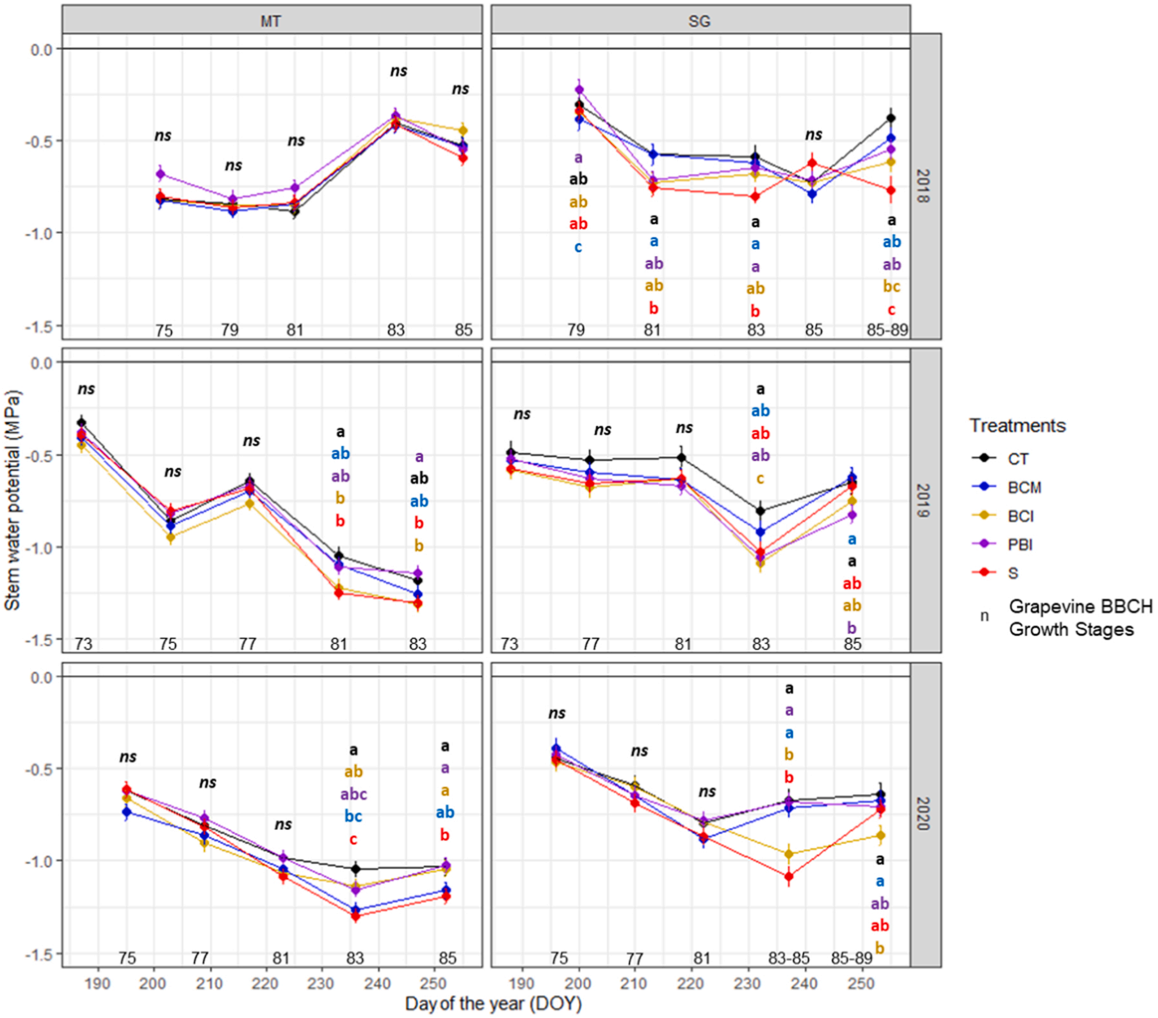


Fig. 3. Stem water potential recorded in 2018, 2019 and 2020, averaged across gravel and silt (n = 1.350). CT= Conventional Tillage; BCM= Mulched cover crop of barley + squarrosum clover; BCI= Cover crop of barley + squarrosum clover incorporated in the soil; PBI= Pigeon bean cover crop incorporated in the soil; S= Mulched spontaneous vegetation. MT= Montevertine; SG= San Giusto a Rentennano. Points indicated by different letters are significantly different at $p < 0.05$ (Tukey test). Bars denote standard errors of the mean. BBCH Growth Stages of grapevines are also reported for each farm × year combination above x-axis. BBCH 73 = Berries groat-sized, bunches begin to hang; BBCH 75 = Berries pea-sized, bunches hang; BBCH 77 = Berries beginning to touch; BBCH 81 = Beginning of ripening: berries begin to develop variety-specific color; BBCH 83 = Berries developing color; BBCH 85 = Softening of berries; BBCH 89 = Berries ripe for harvest.

resources with groundcovers (Celette and Gary, 2013; Linares Torres et al., 2018).

4.3. *Groundcovers do not always reduce grape yield in Mediterranean vineyards*

The effects of groundcovers on grape yield and must quality are notably the main concern which hampers the adoption of those practices by growers. Yield losses due to excessive competition for nutrient and water were reported especially in areas with total annual precipitation < 1000 mm (Medrano et al., 2015). Variable results of the effect of groundcovers on grape yield in non-irrigated vineyards are reported in the literature. No yield differences were found between grass, legume CC and tillage in La Rioja (~793 mm year^{-1}) (Pérez-Álvarez et al., 2015). Likewise, Monteiro and Lopes (2007) compared tillage vs sown and natural groundcovers in central Portugal (~760 mm year^{-1}) reporting no significant effects on grape yields. Conversely, grape production was severely affected by soil management in an arid Sardinian vineyard (~560 mm year^{-1}) (Muscas et al., 2017). In particular, tillage promoted higher grape yields in two out of three years compared with groundcovers while grass CC resulted in consistently lower yields compared with spontaneous vegetation and legume CC. In our study, we unexpectedly found significant higher yields under PBI and S (Fig. 4a). To the best of our knowledge, no studies have reported higher grape yields under groundcovers compared to tillage. Four main reasons can explain this finding. Firstly, in our trial the weeds growing on the vine row were timely removed by spading machines in all treatments twice a year. This practice may have improved soil resource acquisition by the grapevine as most of the competition between groundcovers and grapevine takes place in the vine row (Celette et al., 2008). Furthermore, it has been demonstrated that grape yield negatively correlates with soil vegetation cover. None of our treatments covered completely the soil and, following Delpuech and Metay (2018), PBI and S treatments correspond to 30% and 60% of soil cover, respectively. According to the authors, the 30% soil cover strategy represents a key strategy to combine soil protection with grape production in Mediterranean vineyards. Secondly, annual precipitations at our experimental sites accounted for > 800 mm year^{-1}, while studies reporting strong detrimental effects of groundcovers on grape yields were carried out in drier environments (e.g., Muscas et al., 2017; ~560 mm year^{-1}). Thirdly, the comparison of spontaneous vegetation across studies can be unfair as different weed assemblages carry different biomass production and functional traits which determine the type of relation - synergistic vs competitive - between spontaneous species and grapevine (Kazakou et al., 2016;

Table 3
Results from the Analysis of variance (type III SS) for grape yield, mean cluster weight, mean number of clusters per plant, mean weight of 100 berries.

	Yield	Cluster weight	Nr. of Cluster	Weight of 100 berries
(Intercept)	–	–	–	***
Treatment	***	***	ns	**
Year	*	***	***	***
Farm	***	***	***	–
Gravel	***	*	–	**
Replicate	***	***	**	ns
Clay	–	***	–	–
Total limestone	***	**	**	–
Soil organic matter	–	–	* *	–
Farm x Year	***	–	***	–
Replicate x Gravel	–	***	–	***
Distribution	Gaussian	Gamma	Poisson	Gaussian
Link function		Log		

ns= not significant.

[*] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

[**] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

[***] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

MacLaren et al., 2019). Fourthly, the choice of cover crop treatments implemented in this study always implied the presence of a legume species and this might have played a role in not depleting, and even increasing (e.g., in PBI) grape yields. Additionally, spontaneous legume species were also present in the S treatment, that also showed high grape yields. Nevertheless, the temporal dynamics of legume plant growth and the timing of their termination support the hypothesis that the yield-supporting effect of groundcovers was not due to legume N-fixation per se but rather considering the different N requirements across different grapevine phenological stages. Grapevine has two main N-demanding phases: from bud-burst to veraison and from late maturity to dormancy (Schreiner et al., 2006). N limitation during the former phase can severely affect yield while N shortage in the latter period can negatively affect N reserves and hence production in the following year (Guilpart et al., 2014). We hypothesized that pigeon bean and the natural vegetation may have not competed for N during bud bursts. Around harvest, the N fixed by groundcovers may have been mineralized and taken up by vines to build-up N reserves for the next year. Therefore, the possible N stress occurred under the spontaneous groundcover, as highlighted by SPAD readings during summer (especially at SG), may have not significantly affected yields as it occurred during a low N-demand stage. Conversely, the CC mixture, and particularly barley, may have competed more heavily for N during bud break (Pérez-Álvarez et al., 2013). Also, those groundcovers may have triggered higher N immobilization rate due to the higher C:N ratio of the residues, with consequent reduced N availability to grapevine during maturation and harvest. On the other hand, tillage did not provoke N stress in spring but may have stimulated a quick N mineralization of the few N input provided by the low weed biomass. Tillage was already reported to decrease total soil N as compared with CC (Steenwerth and Belina, 2008), and also in our trial we found lower total N under CT following harvest compared with groundcovers (Warren Raffa et al., 2021). As a result, the progressive depletion of soil N pool across the experimental years may have reduced yields under CT.

We also found a significant effect of soil management on berries weight and mean cluster weight (Figs. 4b and 4c, respectively). Berries formation and maturation is particularly affected by water availability (Garcia et al., 2018). We found no differences between CT and the most productive treatments (S and PBI). The lower water stress observed under CT during summer may have, therefore, increased individual berry weight. While number of clusters was not significantly affected by treatments, cluster weight was higher under PBI and S as compared to other treatments. This suggests that (i) PBI and S increased the number of berries per cluster and that (ii) cluster weight was the main responsible for yield formation.

Number of berries per cluster was reported to be significantly affected by N and water availability after bud burst (Guilpart et al., 2014). Moreover, this critical period influenced more than half of the yield of the following year. In our trial the higher stress imposed by the

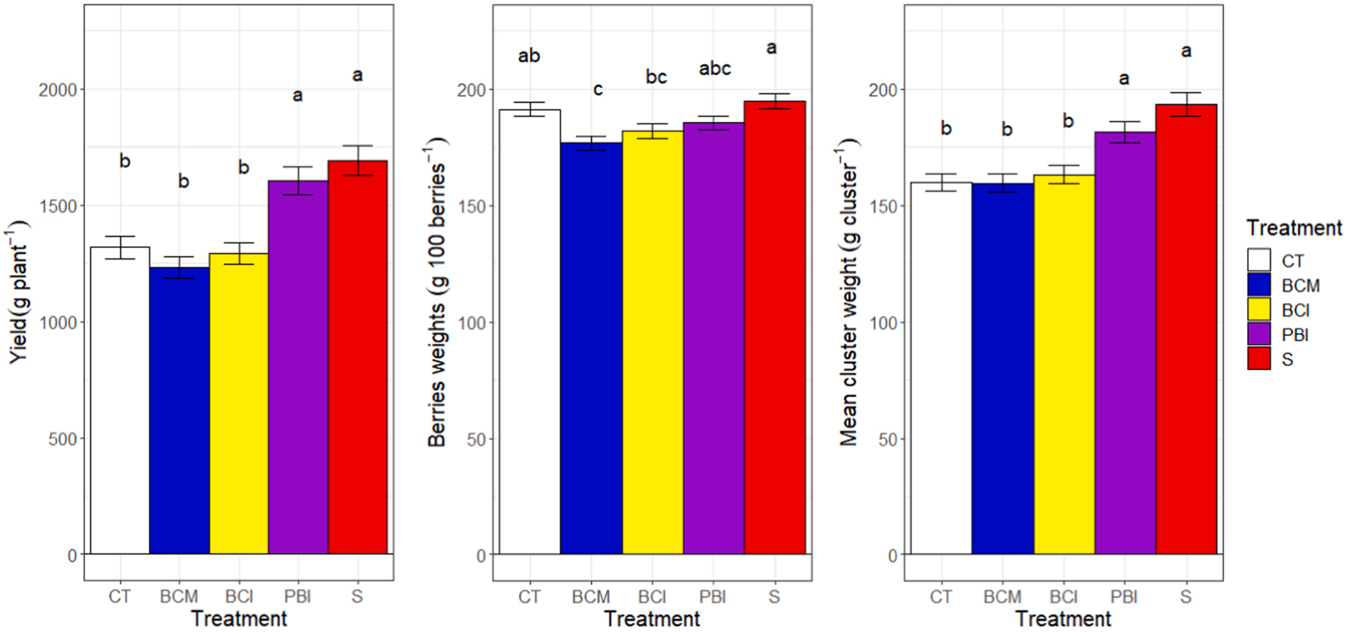


Fig. 4. (a) Yield (g plant^{-1}) averaged across year, farm, gravel, replicates and total limestone (n = 900); (b) berries weight (g 100 berries^{-1}) averaged across year, gravel and replicates (n = 210); (c) mean cluster weight (g cluster^{-1}) averaged across year, farm, gravel, replicates, clay and total limestone (n = 900). CT = Conventional Tillage; BCM = Mulched cover crop of barley + squarrosum clover; BCI = Cover crop of barley + squarrosum clover incorporated in the soil; PBI = Pigeon bean cover crop incorporated in the soil; S = Mulched spontaneous vegetation. Treatments indicated by different letters are significantly different at $p < 0.05$ (Tukey test). Bars denote standard errors of the mean.

Table 4
Results from the Analysis of variance (type III SS) for must pH, titratable acidity (TA), malic acid, sugar concentration, Yeast Assimilable Nitrogen (YAN), Potential anthocyanin, Total Polyphenol Index (TPI).

	pH	TA	Malic acid	Sugar	YAN	Potential anthocyanins	TPI
(Intercept)	***	–	–	***	***	***	***
Treatment	***	*ns*	***	**	*	***	***
Year	***	***	***	***	*ns*	*ns*	***
Farm	***	***	***	*ns*	***	***	***
Gravel	–	***	–	–	***	–	–
Replicate	–	**	–	–	*ns*	–	–
Clay	–	–	*	–	–	***	***
Total limestone	–	***	***	***	**	–	–
Sand	–	–	***	–	–	–	–
Gamma-ray	***						
Mg	–	–	–	–	–	***	–
Treatment x Year	–	–	*ns*	–	***	–	–
Farm x Year	***	–	–	***	–	–	***
Total limestone x Replicate	–	*	–	–	–	–	–
Year x Mg	–	–	–	–	–	***	–
Replicate x Gravel	–	–	–	–	***	–	–
Clay x Sand	–	–	*	–	–	–	–
Distribution	Gamma	Gamma	Gamma	Gaussian - Linear	Gaussian - Linear	Gaussian - Linear	Gaussian - Linear
Link function	Identity	Identity	Identity				

ns= not significant.

[*] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

[**] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

[***] significant at $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

barley-clover mixture during bud break and the depletion of the soil N pool under CT may have significantly decreased number of berries per cluster, cluster weight and hence grape yield.

4.4. *Groundcovers modulate must quality but without consistently increasing sugar accumulation at the expense of titratable acidity*

Several studies reported that must quality is significantly affected by soil management (Guerra and Steenwerth, 2012). Changes in juice quality due to groundcovers compared to tillage were reported both in case of diminished and no yield differences. Our analysis revealed a strong effect of soil management on all the must parameters considered but TA (Table 4; Fig. 5). We found higher pH under the two most productive treatments (PBI and S). Must pH was reported to increase under CC compared to tillage due to higher tartaric: malic acid ratio (Wheeler et al., 2005). Nevertheless, in our case the increased grape weight may have slowed down grape maturation and thus resulting in significant higher malic acid concentration under the most productive treatments. Still sugars did not accumulate more evidently in the less productive treatments, thereby suggesting a more balanced effect of soil management on sugars compared to other juice parameters. Moreover, the yield variations triggered by the different treatments in our study (1.2–1.7 kg f.m. plant^{-1}) were probably not large enough to severely affect the technological maturation of grape. As an example, Muscas et al. (2017) found a strong significant accumulation of sugar in a tillage treatment compared with a grass CC, with the two treatments yielding 3.6 vs 2.0 kg f.m. plant^{-1} and 4.9 vs 3.0 kg f.m. plant^{-1} in 2014 and 2015, respectively. In the same study, anthocyanins and polyphenols concentrations were also affected by groundcover management, with spontaneous vegetation and the legume CC that reduced anthocyanin and polyphenols concentration, respectively. Similarly, Cataldo et al. (2020) found higher sugar concentration, lower fruit setting and TA but higher anthocyanins under CC compared to tillage. Among the studies which did not report decreased yield under groundcovers, Pérez-Álvarez et al. (2013) observed higher anthocyanin content under a barley CC compared with tillage. In the same experiment, TA was not significant influenced by soil management (legume CC, barley CC, tillage) (Pérez-Álvarez et al., 2015) This result is consistent with our observations but not with Monteiro and Lopes (2007) who found groundcovers to increase sugar concentration while significantly reducing TA, total phenols and anthocyanins.

Overall, we found higher polyphenols and anthocyanin under the clover-barley mixture both when incorporated and when left as surface mulch. Higher polyphenols and anthocyanins in juices may be due to (i) a “concentration” effect of lower berry or cluster size (Guidoni et al., 2002; Košmerl et al., 2013), and/or (ii) a stimulating effect of low N and water stress on the synthesis of anthocyanins and polyphenols (Cataldo et al., 2020; Soubeyrand et al., 2014). In our case, we did observe lower yields under CT and the barley-clover CC mixture but slightly higher water stress and lower SPAD readings under BCM and BCI. The higher N and lower water stress reduced the anthocyanin and polyphenols content of CT compared with the other two treatments. These findings also likely reflect the effect of the competition of the barley-clover mixture on must quality. N availability has been also indicated as a lever for YAN concentration in grapes (Pérez-Álvarez et al., 2015). In our study, YAN was generally lower than the recommended values (140–150 mg l^{-1}) (Santamaría et al., 2020) and we found significant differences across treatments only in 2019. Spontaneous groundcovers showed the highest and the lowest YAN in 2018 and 2019, respectively. Interestingly, we found that resident vegetation consisted in a high share of N-fixing species in 2018 compared to 2019 in both farms. Legumes accounted for about 58% and 69% of the total plant biomass collected under S in 2018 in spring at MT and SG, respectively. Conversely, N-fixing species accounted for only 15% and 7% of the total plant biomass under S in 2019 at MT and SG, respectively. Our results are in agreement with previous studies which found reduced YAN concentration under CC compared to tillage but significant effects of legume CC on N must concentration (Giese et al., 2014).

5. Conclusion

This on-farm study monitored on-farm the effect of different ground covers, chosen by farmers, using an innovative approach based on the integration of fine scale soil variability into statistical models.

Soil management affected water stress and SPAD readings thereby indicating that competition between grapevine and CC can potentially affect grapevine performance. Nevertheless, our results showed significantly higher yields under two ground cover practices, namely mulched spontaneous vegetation and pigeon bean cover crop incorporated in spring. Such an increase in grape production appeared to be mainly

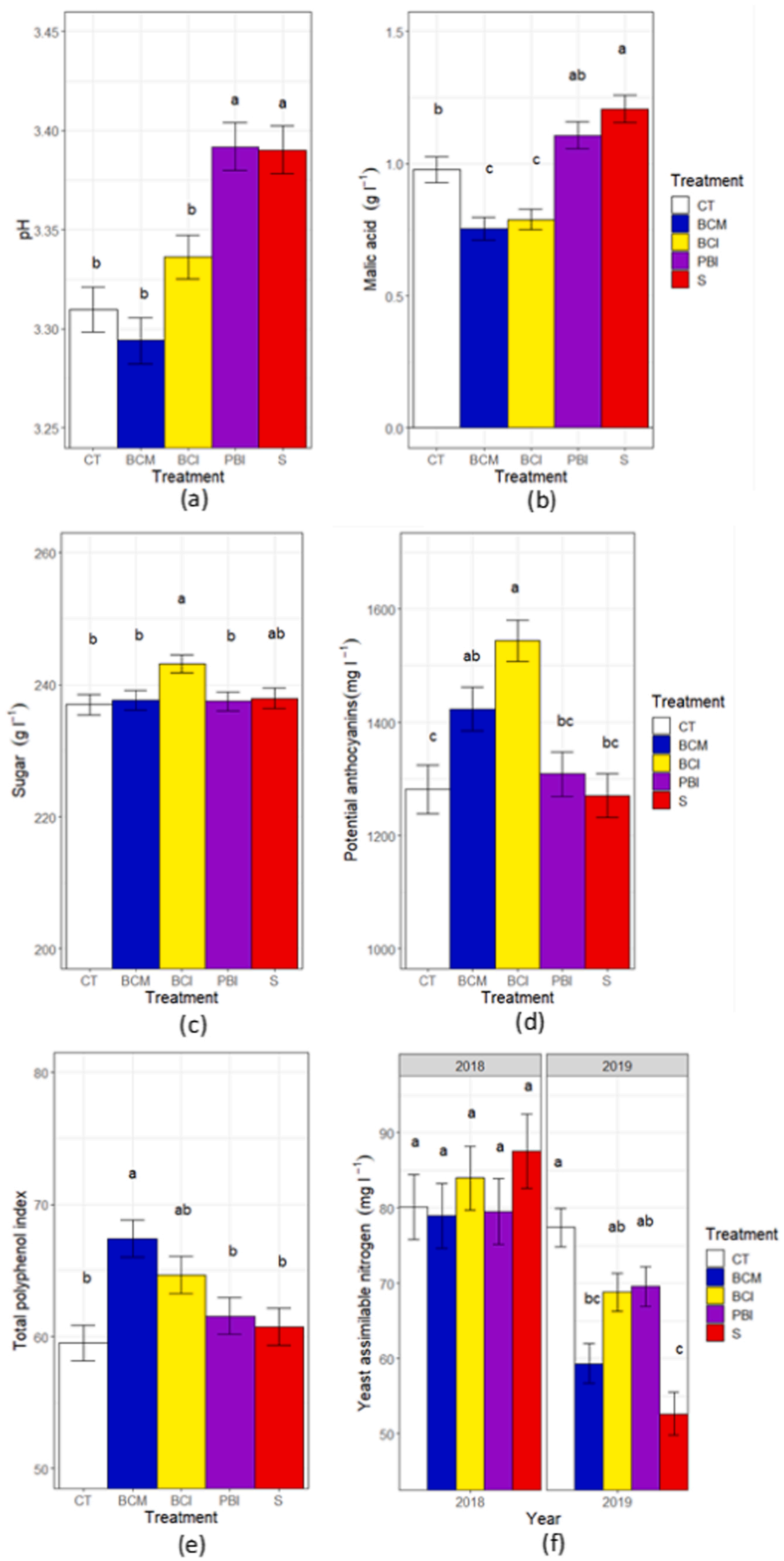
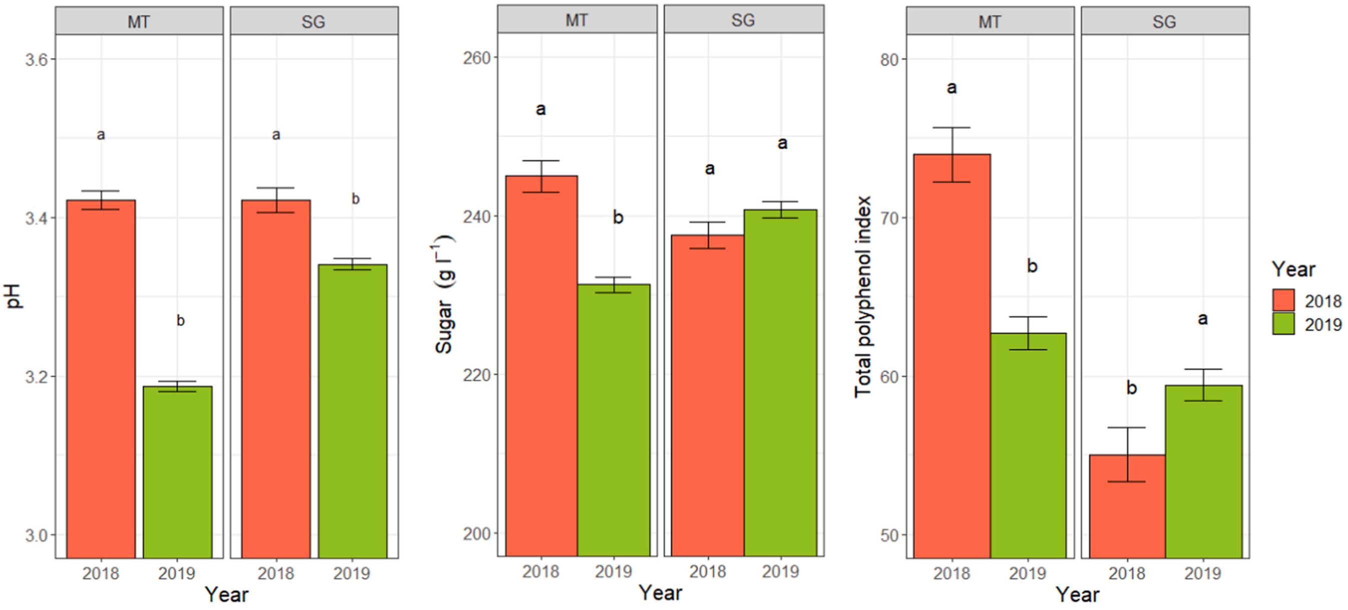


Fig. 5. (a) must pH averaged across year, farm and gamma-ray total count (n = 120); (b) malic acid concentration (g l^{-1}) averaged across year, farm, clay, total limestone and sand (n = 120); (c) sugar concentration (g l^{-1}) averaged across year, total limestone and farm (n = 120); (d) potential anthocyanin (mg l^{-1}) averaged across farm, clay year and Mg (n = 120); (e) Total Polyphenol Index averaged across year, farm and clay (n = 120); (f) Yeast assimilable nitrogen (mg l^{-1}) averaged across farm, gravel, total limestone and replicates (n = 120). CT= Conventional Tillage; BCM= Mulched cover crop of barley + squarrosum clover; BCI= Cover crop of barley + squarrosum clover incorporated in the soil; PBI= Pigeon bean cover crop incorporated in the soil; S= Mulched spontaneous vegetation. Treatments indicated by different letters are significantly different at $p < 0.05$ (Tukey test). Bars denote standard errors of the mean.



(a) (b) (c)

Fig. 6. Effects of the farm x year interaction: (a) must pH averaged across treatment; (b) sugar concentration ($g\ l^{-1}$) averaged across treatment and total limestone; (c) Total Polyphenol Index averaged across treatment and clay. MT= Montevertine; SG= San Giusto a Rentennano. Years indicated by different letters are significantly different at $p < 0.05$ (Tukey test). Bars denote standard errors of the mean.

driven by cluster weight rather than number of cluster or berries weight. Must quality was also significantly influenced by groundcovers. However, we did not find evidence of strong increases in sugar content and lower must acidity with groundcovers, the main concern of Mediterranean vine growers. Anthocyanins and polyphenols were significantly influenced by soil management as well as YAN, on which the N input from sown or spontaneous legumes likely played an important role. On a methodological side, we found that regression models explaining SPAD, Ψstem, grape production and must quality were improved when soil parameters were included as covariates, compared with ECa and gamma ray total counts. Overall, our results suggest that soil variability should be taken into account when analysing the effects of agronomic practices in vineyards. Generally speaking, the critical importance of soils in assessing viticulture practices should be further taken into consideration by future studies by including spatial covariates or, at least, by testing within-blocks and within-rows soil variability. Additional studies are therefore needed especially in vineyards to compare randomized-row design, randomized chess table with non-randomized designed coupled with continuous soil covariates. Further research is also needed to test (i) additional CC types and mixtures in different pedoclimatic areas and grape varieties, (ii) different termination timing of groundcovers according with grapevines phenological stages and climatic as a mean to modulate N and water stress, and (iii) plant and soil indicators to assist farmers decision making related to CC termination.

Finally, this study demonstrated that intercropping groundcovers in vineyards is possible also in Mediterranean climates without negative effects on yields. Soil management can also be conceptualized as a valuable strategy to modulate must quality according to specific enological objectives. The results of this work represent a basis to discuss with viticulturists the different options available to fine tune soil management practices according with their environmental and productive objectives.

CRediT authorship contribution statement

Dylan Warren Raffa: Conceptualization, Methodology, Investigation, Writing – original draft, Formal analysis, **Daniele Antichi**, Writing – review & editing, Supervision, Funding acquisition, Investigation, **Stefano Carlesi**, Writing – review & editing, Formal Analysis, **Àngela Puig-Sirera** Writing – review & editing, Investigation, **Giovanni Rallo**: Writing – review & editing, **Paolo Bàrberi**: Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stefano Carlesi reports financial support was provided by European Commission.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126483.

References

Agnelli, A., Bol, R., Trumbore, S.E., Dixon, L., Cocco, S., Corti, G., 2014. Carbon and nitrogen in soil and vine roots in harrowed and grass-covered vineyards. Agric., Ecosyst. Environ. 193, 70–82. https://doi.org/10.1016/j.agee.2014.04.023.

Alesso, C.A., Cipriotti, P.A., Bollero, G.A., Martin, N.F., 2019. Experimental designs and estimation methods for on-farm research: a simulation study of corn yields at field scale. Agron. J. 111, 2724–2735. https://doi.org/10.2134/agronj2019.03.0142.

Bergmeyer, Beutler, 1990. Ammonia. Methods of Enzymatic Analysis. VCH Publishers (UK) Ltd., Cambridge, UK.

Biddoccu, M., Guzmán, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J.G., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., Hoble, A., Cavallo, E., Gómez, J.A., 2020. Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. Int. Soil Water Conserv. Res. 8 (4), 337–353. https://doi.org/10.1016/j.iswcr.2020.07.003.

Brunetto, G., Trentin, G., Ceretta, C.A., Girotto, E., Lorensini, F., Miotto, A., Moser, G.R. Z., de Melo, G.W., 2012. Use of the SPAD-502 in estimating nitrogen content in leaves and grape yield in grapevines in soils with different texture. Embrapa Pecuária Sul-Artigo em periódico indexado (ALICE). https://doi.org/10.4236/ajps.2012.31118.

Brunori, E., Farina, R., Biasi, R., 2016. Sustainable viticulture: the carbon-sink function of the vineyard agro-ecosystem. Agric. Ecosyst. Environ. 223, 10–21. https://doi.org/10.1016/j.agee.2016.02.012.

Calderon, F.J., Jackson, L.E., Scow, K.M., Rolston, D.E., 2001. Short-term dynamics of nitrogen, microbial activity, and phospholipid fatty acids after tillage. Soil Sci. Soc. Am. J. 65, 118–126. https://doi.org/10.2136/sssaj2001.651118x.

Caruso, G., Tozzini, L., Rallo, G., Primicerio, J., Moriondo, M., Palai, G., Gucci, R., 2017. Estimating biophysical and geometrical parameters of grapevine canopies (‘Sangiovese’) by an unmanned aerial vehicle (UAV) and VIS-NIR cameras. Vitis 56, 63–70. https://doi.org/10.5073/vitis.2017.56.63-70.

Cataldo, E., Salvi, L., Sbraci, S., Storchi, P., Mattii, G.B., 2020. Sustainable viticulture: effects of soil management in Vitis vinifera. Agronomy 10, 1949. https://doi.org/10.3390/agronomy10121949.

Catalogna, M., Dubois, M., Navarrete, M., 2018. Diversity of experimentation by farmers engaged in agroecology. Agron. Sustain. Dev. 38, 1–13. https://doi.org/10.1007/s13593-018-0526-2.

Celette, F., Gary, C., 2013. Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. Eur. J. Agron. 45, 142–152. https://doi.org/10.1016/j.eja.2012.10.001.

Celette, F., Gaudin, R., Gary, C., 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur. J. Agron. 29, 153–162. https://doi.org/10.1016/j.eja.2008.04.007.

Celette, F., Findeling, A., Gary, C., 2009. Competition for nitrogen in an unfertilized intercropping system: the case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30, 41–51. https://doi.org/10.1016/j.eja.2008.07.003.

Centinari, M., Filippetti, I., Bauerle, T., Allegro, G., Valentin, G., Poni, S., 2014. Cover crop water use in relation to vineyard floor management practices. Wine Vitic. J. 29, 41. https://doi.org/10.5344/ajev.2013.13025.

Chonè, X., Van Leeuwen, C., Duborider, D., Gaudillère, J.-P., 2001. Stem water potential is a sensitive indicator of grapevine water status. Ann. Bot. 87, 477–483. https://doi.org/10.1006/anbo.2000.1361.

Córdoba, E.T., Cid, Y.B., Fernández, I.O., Losada, E.D., Avalos, J.M.M., 2015. Influence of cover crop treatments on the performance of a vineyard in a humid region. Span. J. Agric. Res. 13, 25. https://doi.org/10.5424/sjar/2015134-8265.

Daane, K.M., Hogg, B.N., Wilson, H., Yokota, G.Y., 2018. Native grass ground covers provide multiple ecosystem services in Californian vineyards. J. Appl. Ecol. 55, 2473–2483. https://doi.org/10.1111/1365-2664.13145.

Delpuech, X., Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. Eur. J. Agron. 97, 60–69. https://doi.org/10.1016/j.eja.2018.04.013.

DeVetter, L.W., Dilley, C.A., Nonnecke, G.R., 2015. Mulches reduce weeds, maintain yield, and promote soil quality in a continental-climate vineyard. Am. J. Enol. Vitic. 66, 54–64.

Dukes, B.C., Butzke, C.E., 1998. Rapid determination of primary amino acids in grape juice using an o-phthaldialdehyde/n-acetyl-l-cysteine spectrophotometric assay. Am. J. Enol. Vitic. 49, 125.

Fiera, C., Ulrich, W., Popescu, D., Buchholz, J., Querner, P., Bunea, C.-I., Strauss, P., Bauer, T., Kratschmer, S., Winter, S., 2020. Tillage intensity and herbicide application influence surface-active springtail (Collembola) communities in Romanian vineyards. Agric. Ecosyst. Environ. 300, 107006 https://doi.org/10.1016/j.agee.2020.107006.

Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Santos, J.A., 2012. An overview of climate change impacts on European viticulture. Food Energy Secur. 1, 94–110. https://doi.org/10.1002/fes3.14.

Gago, P., Cabaleiro, C., García, J., 2007. Preliminary study of the effect of soil management systems on the adventitious flora of a vineyard in northwestern Spain. Crop Prot. 26, 584–591. https://doi.org/10.1016/j.cropro.2006.05.012.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., Metay, A., 2018. Management of service crops for the provision of ecosystem services in vineyards: a review. Agric. Ecosyst. Environ. 251, 158–170. https://doi.org/10.1016/j.agee.2017.09.030.

Garcia, L., Damour, G., Gary, C., Follain, S., Le Bissonnais, Y., Metay, A., 2019. Trait-based approach for agroecology: contribution of service crop root traits to explain soil aggregate stability in vineyards. Plant Soil 435. https://doi.org/10.1007/s11104-018-3874-4.

García-Díaz, A., Marqués, M.J., Sastre, B., Bienes, R., 2018. Labile and stable soil organic carbon and physical improvements using groundcovers in vineyards from central Spain. Sci. Total Environ. 621, 387–397. https://doi.org/10.1016/j.scitotenv.2017.11.240.

Giese, G., Velasco-Cruz, C., Roberts, L., Heitman, J., Wolf, T.K., 2014. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. Sci. Hortic. 170, 256–266. https://doi.org/10.1016/j.scienta.2014.03.011.

Glories, Y., 1999. La maturità fenolica delle uve: primo parametro da controllare per una corretta vinificazione in rosso. Vignevini 3, 46–50.

Gonçalves, F., Nunes, C., Carlos, C., López, Á., Oliveira, I., Crespí, A., Teixeira, B., Pinto, R., Costa, C.A., Torres, L., 2020. Do soil management practices affect the activity density, diversity, and stability of soil arthropods in vineyards? Agric. Ecosyst. Environ. 294, 106863 https://doi.org/10.1016/j.agee.2020.106863.

Guerra, B., Steenwerth, K., 2012. Influence of floor management technique on grapevine growth, disease pressure, and juice and wine composition: a review. Am. J. Enol. Vitic. 63, 149–164. https://doi.org/10.5344/ajev.2011.10001.

Guidoni, S., Allara, P., Schubert, A., 2002. Effect of cluster thinning on berry skin anthocyanin composition of Vitis vinifera cv. Nebbiolo. Am. J. Enol. Vitic. 53, 224–226.

Guilpart, N., Metay, A., Gary, C., 2014. Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. Eur. J. Agron. 54, 9–20. https://doi.org/10.1016/j.eja.2013.11.002.

Heil, K., Schmidhalter, U., 2017. Improved evaluation of field experiments by accounting for inherent soil variability. Eur. J. Agron. 89, 1–15. https://doi.org/10.1016/j.eja.2017.05.004.

Heil, K., Heinemann, P., Schmidhalter, U., 2018. Modeling the effects of soil variability, topography, and management on the yield of barley. Front. Environ. Sci. 6, 146. https://doi.org/10.3389/fenvs.2018.00146.

Hendgen, M., Hoppe, B., Döring, J., Friedel, M., Kauer, R., Frisch, M., Dahl, A., Kellner, H., 2018. Effects of different management regimes on microbial biodiversity in vineyard soils. Sci. Rep. 8 https://doi.org/10.1038/s41598-018-27743-0.

Hoffmann, V., Probst, K., Christinck, A., 2007. Farmers and researchers: how can collaborative advantages be created in participatory research and technology development? Agric. Hum. Values 24, 355–368. https://doi.org/10.1007/s10460-007-9072-2.

Jian, J., Du, X., Reiter, M.S., Stewart, R.D., 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol. Biochem. 143, 107735 https://doi.org/10.1016/j.soilbio.2020.107735.

Kazakou, E., Fried, G., Richarte, J., Gimenez, O., Violle, C., Metay, A., 2016. A plant trait-based response-and-effect framework to assess vineyard inter-row soil management. Bot. Lett. 163, 373–388. https://doi.org/10.1080/23818107.2016.1232205.

Košmerl, T., Bertalanič, L., Maraš, V., Kodžulović, V., Šućur, S., Abramovič, H., 2013. Impact of yield on total polyphenols, anthocyanins, reducing sugars and antioxidant potential in white and red wines produced from Montenegrin autochthonous grape varieties. Food Sci. Technol. 1, 7–15. https://doi.org/10.13189/fst.2013.010102.

Laudicina, V.A., Palazzolo, E., Catania, P., Vallone, M., García, A.D., Badalucco, L., 2017. Soil quality indicators as affected by shallow tillage in a vineyard grown in a semiarid mediterranean environment. Land Degrad. Dev. 28, 1038–1046. https://doi.org/10.1002/ldr.2581.

Lazcano, C., Decock, C., Wilson, S.G., 2020. Defining and managing for healthy vineyard soils, intersections with the concept of terroir. Front. Environ. Sci. https://doi.org/10.3389/fenvs.2020.00068.

Le Guen, M.-E., Herrmann, L., Robain, H., Wiriyakitnateekul, W., de Oliveira, T., Robin, A., Srimawong, P., Bräu, L., Lesueur, D., 2017. Relevance of taking into account the fine scale soil variability to assess the effects of agricultural inputs on soil characteristics and soil microbial communities: a case study of biochar application in a rubber plantation in North East Thailand. Geoderma 305, 21–29. https://doi.org/10.1016/j.geoderma.2017.05.028.

Linares Torres, R., De La Fuente Lloreda, M., Junquera Gonzalez, P., Lissarrague García-Gutierrez, J.R., Baeza Trujillo, P., 2018. Effect of soil management strategies on the characteristics of the grapevine root system in irrigated vineyards under semi-arid conditions. Aust. J. Grape Wine Res. 24, 439–449. https://doi.org/10.1111/ajgw.12359.

Lopes, C., Monteiro, A., Machado, J., Fernandes, N., Araújo, A., 2008. Cover cropping in a sloping non-irrigated vineyard: II-Effects on vegetative growth, yield, berry and wine quality of ‘Cabernet sauvignon’grapevines. Ciência Téc. Vitiv 23, 37–43.

López-Piñeiro, A., Muñoz, A., Zamora, E., Ramírez, M., 2013. Influence of the management regime and phenological state of the vines on the physicochemical properties and the seasonal fluctuations of the microorganisms in a vineyard soil under semi-arid conditions. Soil Tillage Res. 126, 119–126. https://doi.org/10.1016/j.still.2012.09.007.

MacLaren, C., Bennett, J., Dehnen-Schmutz, K., 2019. Management practices influence the competitive potential of weed communities and their value to biodiversity in South African vineyards. Weed Res. 59, 93–106. https://doi.org/10.1111/wre.12347.

Marques, M., García-Muñoz, S., Muñoz-Organero, G., Bienes, R., 2010. Soil conservation beneath grass cover in hillside vineyards under Mediterranean climatic conditions (Madrid, Spain). Land Degrad. Dev. 21, 122–131. https://doi.org/10.1002/ldr.915.

Mattii, G., Storchi, P., Ferrini, F., 2005. Effects of soil management on physiological, vegetative and reproductive characteristics of Sangiovese grapevine. Adv. Hortic. Sci. 198–205.

Medrano, H., Tomás, M., Martorell, S., Escalona, J.-M., Pou, A., Fuentes, S., Flexas, J., Bota, J., 2015. Improving water use efficiency of vineyards in semi-arid regions. A review. Agron. Sustain. Dev. 35, 499–517. https://doi.org/10.1007/s13593-014-0280-z.

Monteiro, A., Lopes, C.M., 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agric. Ecosyst. Environ. 121, 336–342. https://doi.org/10.1016/j.agee.2006.11.016.

Muscas, E., Cocco, A., Mercenaro, L., Cabras, M., Lentini, A., Porqueddu, C., Nieddu, G., 2017. Effects of vineyard floor cover crops on grapevine vigor, yield, and fruit quality, and the development of the vine mealybug under a Mediterranean climate. Agric. Ecosyst. Environ. 237, 203–212. https://doi.org/10.1016/j.agee.2016.12.035.

Myburgh, P.A., 2013. Effect of shallow tillage and straw mulching on soil water conservation and grapevine response. South Afr. J. Plant Soil 30, 219–225. https://doi.org/10.1080/02571862.2013.867459.

Novara, A., Gristina, L., Saladino, S.S., Santoro, A., Cerdà, A., 2011. Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. Soil Tillage Res. 117, 140–147. https://doi.org/10.1016/j.still.2011.09.007.

Novara, A., Gristina, L., Guaitoli, F., Santoro, A., Cerdà, A., 2013. Managing soil nitrate with cover crops and buffer strips in Sicilian vineyards. Solid Earth 4, 255–262. https://doi.org/10.5194/se-4-255-2013.

Novara, A., Cerda, A., Barone, E., Gristina, L., 2021. Cover crop management and water conservation in vineyard and olive orchards. Soil Tillage Res. 208, 104896 https://doi.org/10.1016/j.still.2020.104896.

OIV, 2016. State of the Vitiviniculture World Market. Organisation Internationale de la Vigne et du Vine,, Paris.

OIV, 2021. Compendium of international methods of analysis of wines and musts.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, C., 2015. The new assessment of soil loss by water erosion in Europe. Environ. Sci. Policy 54, 438–447. https://doi.org/10.1016/j.envsci.2015.08.012.

Pätzold, S., Leenen, M., Heggemann, T.W., 2020. Proximal mobile gamma spectrometry as tool for precision farming and field experimentation. Soil Syst. 4, 31. https://doi.org/10.3390/soilsystems4020031.

Peregrina, F., Larrieta, C., Ibáñez, S., García-Escudero, E., 2010. Labile organic matter, aggregates, and stratification ratios in a semiarid vineyard with cover crops. Soil Sci. Soc. Am. J. 74, 2120–2130. https://doi.org/10.2136/sssaj2010.0081.

Peregrina, F., Pérez-Álvarez, E.P., Colina, M., García-Escudero, E., 2012. Cover crops and tillage influence soil organic matter and nitrogen availability in a semi-arid vineyard. Arch. Agron. Soil Sci. 58, SS95–SS102. https://doi.org/10.1080/03650340.2011.648182.

Pérez-Álvarez, E.P., Pérez-Sotés, J.L., García-Escudero, E., Peregrina, F., 2013. Cover crop short-term effects on soil NO3−-N availability, nitrogen nutritional status, yield, and must quality in a calcareous vineyard of the AOC Rioja, Spain. Commun. Soil Sci. Plant Anal. 44, 711–721. https://doi.org/10.1080/00103624.2013.748122.

Pérez-Álvarez, E.P., García-Escudero, E., Peregrina, F., 2015. Soil nutrient availability under cover crops: effects on vines, must, and wine in a tempranillo vineyard. Am. J. Enol. Vitic. 66, 311. https://doi.org/10.5344/ajev.2015.14092.

Polge de Combret-Champart, L., Guilpart, N., Mérot, A., Capillon, A., Gary, C., 2013. Determinants of the degradation of soil structure in vineyards with a view to conversion to organic farming. Soil Use Manag. 29, 557–566. https://doi.org/10.1111/sum.12071.

Priori, S., D'Avino, L., Agnelli, A.E., Valboa, G., Knapic, M., Schroers, H., Akca, E., Tangolar, S., Kiraz, M.E., Giffard, B., Fulchin, E., 2018. Effect of organic treatments on soil carbon and nitrogen dynamics in vineyard. EQA-Int. J. Environ. Qual. 31, 1–10. https://doi.org/10.6092/issn.2281-4485/7896.

Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A., 2016. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci. Total Environ. 547, 323–330. https://doi.org/10.1016/j.scitotenv.2015.12.076.

Ramos, M.C., 2017. Projection of phenology response to climate change in rainfed vineyards in north-east Spain. Agric. For. Meteorol. 247, 104–115. https://doi.org/10.1016/j.agrformet.2017.07.022.

Rodrigo Comino, J., Iserloh, T., Morvan, X., Malam Issa, O., Naisse, C., Keesstra, S.D., Cerdà, A., Prosdocimi, M., Arnáez, J., Lasanta, T., 2016. Soil erosion processes in European vineyards: a qualitative comparison of rainfall simulation measurements in Germany, Spain and France. Hydrology 3, 6. https://doi.org/10.3390/hydrology3010006.

Rodrigo-Comino, J., Keesstra, S., Cerdà, A., 2018. Soil erosion as an environmental concern in vineyards: the case study of Celler del Roure, Eastern Spain, by means of rainfall simulation experiments. Beverages 4, 31. https://doi.org/10.3390/beverages4020031.

Roger-Estrade, J., Anger, C., Bertrand, M., Richard, G., 2010. Tillage and soil ecology: partners for sustainable agriculture. Soil Tillage Res. 111, 33–40. https://doi.org/10.1016/j.still.2010.08.010.

Rudolph, S., Wongleecharoen, C., Lark, R.M., Marchant, B.P., Garré, S., Herbst, M., Vereecken, H., Weihermüller, L., 2016. Soil apparent conductivity measurements for planning and analysis of agricultural experiments: a case study from Western-Thailand. Geoderma 267, 220–229. https://doi.org/10.1016/j.geoderma.2015.12.013.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D.J., Marques, M.J., 2013. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. Catena 104, 153–160. https://doi.org/10.1016/j.catena.2012.11.007.

Santamaría, P., González-Arenzana, L., Garijo, P., Gutiérrez, A.R., López, R., 2020. Nitrogen sources added to must: effect on the fermentations and on the tempranillo red wine quality. Fermentation 6, 79. https://doi.org/10.3390/fermentation6030079.

Santillán, D., Garrote, L., Iglesias, A., Sotes, V., 2019. Climate change risks and adaptation: new indicators for Mediterranean viticulture. Mitig. Adapt. Strateg. Glob. Change 1–19. https://doi.org/10.1007/s11027-019-09899-w.

Schreck, E., Gontier, L., Dumat, C., Geret, F., 2012. Ecological and physiological effects of soil management practices on earthworm communities in French vineyards. Eur. J. Soil Biol. 52, 8–15. https://doi.org/10.1016/j.ejsobi.2012.05.002.

Schreiner, R.P., Scagel, C.F., Baham, J., 2006. Nutrient uptake and distribution in a mature Pinot noir ' Vineyard. HortScience 41, 336–345. https://doi.org/10.21273/HORTSCI.41.2.336.

Schütte, R., Bergmann, H., 2019. The attitudes of French and Spanish winegrowers towards the use of cover crops in vineyards. J. Wine Res. 30, 107–121. https://doi.org/10.1080/09571264.2019.1568975.

Soubeyrand, E., Basteau, C., Hilbert, G., van Leeuwen, C., Delrot, S., Gomès, E., 2014. Nitrogen supply affects anthocyanin biosynthetic and regulatory genes in grapevine cv. Cabernet-Sauvignon berries. Phytochemistry 103, 38–49. https://doi.org/10.1016/j.phytochem.2014.03.024.

Steenwerth, K., Belina, K., 2008. Cover crops and cultivation: impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Appl. Soil Ecol. 40, 370–380. https://doi.org/10.1016/j.apsoil.2008.06.004.

Sulas, L., Mercenaro, L., Campesi, G., Nieddu, G., 2017. Different cover crops affect nitrogen fluxes in mediterranean vineyard. Agron. J. 109, 2579–2585. https://doi.org/10.2134/agronj2017.05.0283.

Taskos, D.G., Koundouras, S., Stamatiadis, S., Zioziou, E., Nikolaou, N., Karakioulakis, K., Theodorou, N., 2015. Using active canopy sensors and chlorophyll meters to estimate grapevine nitrogen status and productivity. Precis. Agric. 16, 77–98. https://doi.org/10.1007/s11119-014-9363-8.

Turpin, N., ten Berge, H., Grignani, C., Guzmán, G., Vanderlinden, K., Steinmann, H.-H., Siebielec, G., Spiegel, A., Perret, E., Ruysschaert, G., Laguna, A., Giráldez, J.V., Werner, M., Raschke, I., Zavattaro, L., Costamagna, C., Schlatter, N., Berthold, H., Sandén, T., Baumgarten, A., 2017. An assessment of policies affecting sustainable soil management in Europe and selected member states. Land Use Policy 66, 241–249. https://doi.org/10.1016/j.landusepol.2017.04.001.

Van Leeuwen, C., Seguin, G., 2006. The concept of terroir in viticulture. J. Wine Res. 17, 1–10. https://doi.org/10.1080/09571260600633135.

Van Leeuwen, C., Tregoat, O., Choné, X., Bois, B., Pernet, D., Gaudillère, J.-P., 2009. Vine water status is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes. J. Int. Sci. Vigne Vin. 43, 121–134. https://doi.org/10.20870/oeno-one.2009.43.3.798.

Warren Raffa, D., Antichi, D., Carlesi, S., Frasconi, C., Marini, S., Priori, S., Bàrberi, P., 2021. Groundcover mulching in Mediterranean vineyards improves soil chemical, physical and biological health already in the short term. Agronomy. https://doi.org/10.3390/agronomy11040787.

Wheeler, S., Black, A., Pickering, G., 2005. Vineyard floor management improves wine quality in highly vigorous Vitis vinifera'Cabernet Sauvignon'in New Zealand. N. Z. J. Crop Hortic. Sci. 317–328. https://doi.org/10.1080/01140671.2005.9514365.

Winter, S., Bauer, T., Strauss, P., Kratschmer, S., Paredes, D., Popescu, D., Landa, B., Guzmán, G., Gómez, J.A., Guernion, M., Zaller, J.G., Batáry, P., 2018. Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: a meta-analysis. J. Appl. Ecol. 55, 2484–2495. https://doi.org/10.1111/1365-2664.13124.