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Title: Soil management in semi-arid vineyards: combined effects of organic mulching and no-tillage under different water regimes

Authors: Ignacio **Buesa**[1,2,*], José M. **Mirás-Avalos**[2,3], José M. **De Paz**[1], Fernando **Visconti**[1], Felipe **Sanz**[1,2], Antonio **Yeves**[1, 2], Diego **Guerra**[1,2], Diego S. **Intrigliolo**[1,2]

Affiliations:

[1] Instituto Valenciano de Investigaciones Agrarias (IVIA). Centro Desarrollo Agricultura Sostenible (CEDAS), Unidad asociada al CSIC "Riego en la agricultura mediterránea", Apartado Ofcial, 46113 Moncada, Valencia, Spain.

[2] Dept. Riego. Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC), Campus Universitario de Espinardo, PO Box 164, 30100 Murcia, Spain.

[3] Unidad de Suelos y Riegos (asociada a EEAD-CSIC). Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), 50059, Montañana, Zaragoza, Spain.

*** Corresponding author:**

Instituto Valenciano de Investigaciones Agrarias (IVIA): Unidad asociada al CSIC "Riego en la agricultura mediterránea"
Carretera CV-315, Km 10,7, 46113
Moncada, Valencia, Spain
Phone: +34 650578152
E-mail: igbuepue@gmail.com

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Abstract

Optimizing water use in vineyards is crucial for ensuring the sustainability of viticulture in semi-arid regions, and this may be achieved by minimizing direct water evaporation from the soil through the use of mulching. In this context, the current study aimed at assessing the combined effects of the vine-row application of an organic mulch (vine prunings) and no-tillage under two water regimes on soil properties, plant water and nutritional status, yield and must composition of grapevine (*Vitis vinifera* L.) cv. Bobal grown under semi-arid conditions. For this purpose, a field experiment in a split-plot design was carried out for three years (2016-2018) in a mature Bobal vineyard located in Eastern Spain. Two soil management strategies (tillage and organic mulching with no-tillage) were assessed under two water regimes (rainfed and deficit drip irrigation) with four replications per combination. Vine responses were determined by measuring midday stem water potential, leaf nutrient concentrations, pruning weight, yield components and grape composition. Soil properties were assessed at the end of the experiment. Mulching and no-tillage positively affected vine water status under both water regimes, resulting in reductions in grape phenolic composition. Interactive effects of both water regime and soil management on water use efficiency were found. Regardless of soil management practice, irrigation increased yield and pruning weight when compared to rainfed conditions. Soil management had slight effects on vine nutritional status. At the end of the experiment, soil compaction increased and infiltration decreased as a consequence of mulching and no-tillage. Organic mulch and no-tillage improved vine water status, however, considering the final soil surface compaction and low water infiltration rate, longer-term studies are necessary to assess the sustainability of combining both practices.

Keywords: Drip irrigation; Soil management; Sustainable viticulture; *Vitis vinifera* L.; Water relations.

Abbreviations: DO (Designation of Origin); ET_o (Reference evapotranspiration); WR (Water regime); SM (Soil Management); RT (Rainfed tilled); RM (Rainfed mulched and no-tilled); IT (Irrigated tilled); IM (Irrigated mulched and no-tilled); EU (experimental unit); Ψ_{stem} (midday stem water potential); CCE (Calcium carbonate equivalent); TSS (Total soluble solids); TA (Total acidity); ANOVA (Analysis of variance).

1. Introduction

In the current scenario of global change, sustainability is becoming a serious concern in viticulture due to the large extension of this crop in many different environmental conditions. Especially in semi-arid regions, vine water requirements generally exceed the average annual rainfall, making water the most important resource for the sustainability of viticulture (Medrano et al. 2015). Grapevine (*Vitis vinifera* L.) water requirements range between 300 and 700 mm to complete its growing cycle (López-Urrea et al. 2012; Medrano et al. 2015), which, under the Mediterranean climate, coincides with the driest months of the year, making irrigation scheduling and timing critical for vine performance and grape composition (Intrigliolo et al. 2012). In dry regions, irrigation competes for water with other uses and could result in an overexploitation of surface and groundwater resources, thus compromising the sustainability of viticulture (Chaves et al. 2007). Furthermore, evaporative demand is expected to rise due to the increased global air temperature and intensity of climatic anomalies, such as droughts and heat waves (Fraga et al. 2016). In response to the increase in temperature and evaporative demand, greater vine transpiration rates are expected, leading to further depletion of soil water content and/or increased vine water stress (Dayer et al. 2020; Flexas et al. 2010). In addition, to ensure viticulture sustainability, a balance between inputs and outputs of nutrients within the farm system is crucial, as grapevines strongly react to nutrient deficit in terms of vine yield and particularly grape composition (Keller et al. 2005). In this regard, soil nutrient storage capacity and accessibility are influenced by soil texture, rooting depth, and organic matter content, but the nutrient availability is modified by soil moisture and pH.

Nowadays, in most of the semi-arid regions of grapevine production, as well as many of the "new world" viticulture areas, minimum water and nutrition requirements are not met (García-Escudero et al. 2013; Medrano et al. 2015). Therefore, optimizing water use in vineyards and its interaction with vine nutrition is a subject of paramount importance to secure sustainability in viticulture (Quemada and Gabriel 2016). As a consequence, a great research effort has been made to determine the best strategies of irrigation (timing, schedule, rates) and its relation with crop nutrition that allow reasonable yields with good organoleptical quality (Buesa et al. 2017; Gaiotti et al. 2017; Intrigliolo et al. 2012; Jackson and Lombard 1993; Keller et al. 2005; Romero et al. 2013; Schreiner et al. 2013; Vos et al. 2004; Pérez-Álvarez et al. 2017). However, other agricultural practices besides irrigation and fertilization might improve water use efficiency (WUE) and increase soil nutrient availability in vineyards by reducing soil water evaporation and runoff, thus maximizing green water use (Medrano et al. 2015; Vos et al. 2004).

In this context, soil management (SM) practices allowing the control of weeds, the alleviation of soil compaction, the reduction of soil erosion, the enhancement of nutrients and water uptake, and the modulation of vine vigour and yield, amongst others (Celette et al. 2009; Guerra and Steenwerth 2012; Steenwerth and Belina 2008) are of special importance for grapevine performance and, consequently, for wine quality (Lopes et al. 2011; Trigo-Córdoba et al. 2015). Several SM practices can be used in vineyards to achieve the aforementioned goals, including tillage, application of herbicides, cover crops and organic/inorganic mulches (Gaudin et al. 2010; Guerra and Steenwerth 2012; Salomé et al. 2016). Whatever the case, to choose the best practice for each location the following factors have to be taken into account: vine age, vineyard plantation design, soil type, environmental regulations, objectives of the winery, and climatic conditions (Ripoche et al. 2011; Steinmaus et al. 2008).

In this regard, tillage is the most traditional soil management technique in vineyards worldwide because it is an effective way of controlling weeds (Guerra and Steenwerth 2012) and, at least initially, increasing water infiltration into the loosened soil and decreasing capillary continuity (Triplett and Dick 2008). In spite of this benefit, tillage has also several disadvantages including soil compaction and thus loss of structure, cumulative shrink of fertility and soil organic matter, increased risk of soil erosion and damage to vine roots as well as directional spread of soil pests and pathogens (Hamza and Anderson 2005; Steenwerth and Belina 2008; Garcia et al. 2019; Bordoni et al. 2019). The use of herbicides is another choice and though herbicides has been proven easy to use, cost-effective and more efficient than tillage for controlling weeds, the risk of toxicity and the potential of herbicide residues leaching into waterbodies (Tourte et al. 2008) limit their use for managing the soil in the vineyard inter-rows. As a third alternative, in the last decades, the use of cover crops has become a common vineyard SM practice because of its many benefits including soil protection against erosion, regulation of vine growth, weed suppression, habitat for beneficial predators and improved soil fertility and water-holding capacity (Gaudin et al. 2010; Fourie 2011; Linares-Torres et al. 2018; Morlat and Jacquet 2003; Pérez-Álvarez et al. 2015, Virto et al. 2012). Despite these advantages, the adoption of cover crops as a SM strategy in Mediterranean vineyards is limited by the concern of an excessive competition for nutrients and water between these crops and the grapevines (Celette et al. 2008, 2009; Monteiro and Lopes 2007). Finally, mulching may be an alternative for overcoming all these concerns and provide additional benefits to the soil and grapevines (Morlat et al. 2008; Prosdocimi et al. 2016). Indeed, organic mulching is a sustainable agronomic practice that is widely used for weed control, preventing soil erosion and improving general soil properties, including the minimization of water loss through evaporation and runoff, thus improving infiltration of water into the soil and increasing vineyard biodiversity (Morlat and Chaussod 2008; Pinamonti 1998; Varga and Májer 2004; Medrano et al. 2015). Moreover, this organic mulching has been reported to be positive not only for soil but also for grapevine yield and must composition (Mundy and Agnew 2002; Pinamonti 1998). Furthermore, mulching could contribute to a circular economy (recycling of pruning residues), increasing soil organic matter content and nutrients, water-holding capacity and inhibiting the growth of weeds (Ferrara et al. 2012; Montanaro et al. 2017). In addition, the use of pruning waste on soil would avoid the presently used, more conventional practice of burning pruning waste, and therefore, reduce emissions of CO_2 and other greenhouse gases into the atmosphere by increasing CO_2 capture into the soil (Montanaro et al. 2017). Other alternatives for the application of vine prunings are to compost them together with manure or winery wastes or even to carbonize them to obtain biochar (Mundy and Agnew 2002; Baronti et al. 2014; Gaiotti et al. 2017). In any case, increases in nutrient recirculation and release are interesting possible effects of mulching (Montanaro et al. 2017). Nonetheless, vine pruning waste's decomposition could compete with grapevines for nitrogen in the soil (Thomsen et al. 2008).

Furthermore, nutrient uptake is more influenced by the physical conditions of the soil, namely moisture and temperature, than by nutrient availability in the soil (Pinamonti 1998).

Recently, López-Urrea et al. (2020) determined in a weighting lysimeter the short-term effects of covering the entire vineyard floor with vine pruning waste (organic mulching) on the evapotraspiration of a fully irrigated vineyard and found that water use can be reduced by 17%. This moderate decrease in water use could be particularly relevant under rainfed conditions where vines normally experience more water stress that under irrigation and its alleviation could be more important for improving vine physiology (Romero et al. 2010). However, in rainfed vines, the effect of mulching on soil evaporation at mid-summer, when there is a lack of rainfall and the soil is dry, may be minimal. Thus, the reduction effect of mulching on ET is expected to be low in this period (Yunusa et al. 1997). In this sense, previous studies under mulching have been carried out mainly under a standard watering regime because they were more focused on exploring different soil management techniques (Guerra and Steenwerth 2012; Bavougian and Read 2018; Gil et al. 2018). Nonetheless, under a semi-arid climate, where vine water relations are a predominant factor affecting vine performance (Mirás-Avalos et al. 2017), it is important to determine how soil management with mulching is influenced by the watering regime, considering that drip irrigation only wets a small portion of the entire soil allotted to each vine.

In this context, the aim of the current study was to assess the effects of the application of an organic mulch (vine prunings) under no-tillage as compared to tillage, under two water regimes (WR, rainfed and deficit irrigation) on soil physical properties, plant water and nutritional status, yield and must composition of grapevine (*Vitis vinifera* L.) cv. Bobal grown under the semi-arid hot-summer Mediterranean climate of Eastern Spain. The working hypothesis was that mulching could improve vine water status and, particularly under rainfed conditions, increase yield and WUE. In parallel, the potential effects of mulching on the vineyard's nutrient balance were assessed at the grapevine level by determining leaf nutrient status and grape composition. Since the grapevine's nutrient uptake varies according to growth requirements, the response to the SM practice may differ between the different WR. Moreover, SM could cause microclimatic changes which affect the vineyard water and energy balances, and hence the grapevine's response to water regime. Therefore, the possible interaction between WR and SM was also explored.

2. Materials and Methods

2.1 Plant material and study site

The experiment was carried out during three consecutive seasons (2016 to 2018) in a commercial vineyard located in Requena (39º 29' N, 1º 13' W, elevation 750 m, Valencia, Spain) within the Designation of Origin (DO) Utiel-Requena. The vineyard was planted in 2002 with *Vitis vinifera* (L.) cv. Bobal on 110-R rootstock at a spacing of 2.6 by 1.4 m (2671 vines ha^{-1}). Vines were trained to a bilateral cordon system leaving six two-bud spurs per vine. Shoots were vertically trellised with a pair of steel catch wires. Rows were oriented from north to south and followed the slope of the ground which was on average 3.2%. The soil at this site was classified as a Typic Calciorthid according to the Soil Taxonomy (Soil Survey Staff, 1999), with a clay loam to clay texture according to USDA classification, highly calcareous (200 – 380 g kg^{-1}), with a pH of around 8.5, an electrical conductivity around 0.2 dS m^{-1}, and low in organic matter (3 – 20 g kg^{-1}) and nitrogen (0.4 g kg^{-1}). The available water capacity was ≈200 mm m^{-1} and the bulk density was 1.43 to 1.55 g cm^{-3}. The soil depth to the unaltered hard parent material (R horizon) exceeded 2 m. The climate of the area was classified as semi-arid hot-summer Mediterranean (de Paz et al., 2004; Rodríguez-

Ballesteros, 2016). The historical average annual rainfall was 390 mm and the reference evapotranspiration (ET_o) was 1120 mm (Supplementary Figure 1). Approximately 65% of rainfall occurs during the dormant period. Budbreak for Bobal in this area usually occurs by the end of April, flowering by June, veraison is reached by mid-August with harvest at the beginning of October (Salón et al. 2005).

2.2 Experimental design

Two treatments were established in the vineyard following a split-plot design. A given water regime (WR), either rainfed (R) or deficit-irrigated (I), was assigned to the main-plots, whereas a given soil management (SM), either tillage without mulching (T) or mulching with no tillage (mulch, M), was assigned to the sub-plots with four replicates per combination. Therefore, the combined treatments applied were RT, RM, IT and IM. Each subplot or experimental unit (EU) consisted of five rows with nine vines per row. The vines located in the center of the middle rows were used for measurements and samplings (21 vines), while the rest were left as buffers.

Deficit irrigation was applied in an attempt to maintain the midday stem water potential (Ψ_{stem}) of the IT treatment above the threshold values of -0.80 and -1.20 MPa at pre- and post-veraison, respectively. These degrees of water stress were considered as targets based onprevious research carried out in the area by Salón et al. (2005). The same irrigation regime was applied to the M and T treatments. Organic mulching consisted in the application, both in the rows and the inter-rows, of mechanically-chopped vine prunings corresponding to the theoretical amount that would be produced over 10 years by each vine (Supplementary Figure 2). That is, 4-5 kg of crushed pruning waste were spread over the 3.64 m^2 of vine spacing. Mulch was first applied in 2016 just before vine budburst and was seasonally reapplied in small quantities to maintain a 3-5 cm thick homogeneous layer without soil tillage. Treatments without mulch application were tilled using a cultivator twice per season, in autumn and spring. The ploughing depth was at most 15 cm during the experiment and also for at least 10 years before it began. The space between vines was manually weeded if necessary without applying herbicide, as was the occasional weed control in mulching treatments, since these were not tilled. All treatments received the same fertilization. At the beginning of the experiment, as a common practice in the area, buried manure was applied to the entire vineyard, containing 116, 93, 139 kg ha^{-1} of N, P_2O_5, K_2O, respectively. In addition, mineral fertilization was applied each season at a rate of 52.5-35-105 kg ha^{-1} year^{-1} of N, P_2O_5, K_2O, respectively. In the rainfed treatments, mineral nutrition was applied manually in solid form, whereas I treatments were fertigated. In addition, the rainfed treatments received 0.62 kg ha^{-1} of magnesium sulfate (Epsom salt) to compensate the Mg content of the irrigation water. Irrigation water was of adequate quality, with an EC $_{25^oC}$ of 0.79 dS m^{-1} and Magnesium content of 4.69 meq L^{-}.

2.3 Field measurements

Weather data were recorded at an automated meteorological station located within the vineyard studied. Reference evapotranspiration (ET_o) was calculated with the Penman-Monteith equation (Allen et al. 1998). The amount of water applied to the I treatments was measured with in-line water meters. Midday stem water potential (Ψ_{stem}) was determined on seven dates each growing season using a pressure chamber (Model 600, PMS Instruments Company, Albany, OR, USA) on bag-covered leaves from four representative vines per EU at midday (measurements were made between 11:30 and 12:30 solar time). Leaves were located on the west side of the row and were enclosed in hermetic plastic bags covered with aluminium foil for at least 1 h prior to measurement (Choné et al. 2001). The water stress integral, from June to October, that expresses the severity according to the duration of the stress above a minimum value was calculated for each treatment and year as defined by Myers (1988) using the Ψ_{stem} data.

The soil saturated hydraulic conductivity was measured in three places per EU only in the R treatments at the end of the experiment, specifically in January-February 2019, by using a single-ring infiltrometer and the calculation methods from Wu et al. (1999).

2.4 *Leaf, berry and soil samplings*

Twenty-one complete, disease-free and non-senescent leaves were taken in each EU (one per experimental grapevine) after veraison each year. The leaves were collected opposite to the second bunch from fruit-bearing shoots of average vigor (Romero et al. 2010).

Yield, number of clusters per vine and average cluster weight were determined at harvest on each experimental vine. In winter, pruning weight was recorded in four grapevines per EU (16 grapevines per treatment). Water use efficiency (WUE) was calculated as the ratio between grape yield and the amount of total rainfall plus irrigation applied to each EU.

The soil was characterized at the end of the experiment in the rainfed treatments only, specifically in January-February 2019, by taking disturbed and undisturbed soil samples and analyzing them in the laboratory. For the disturbed samples, three representing places were selected per EU and the soil was drilled with a Riverside auger to sample the 0-20 cm depth layer. Then, a composite sample was obtained from each EU by thorough manual mixing.

For the undisturbed samples two sets of soil cores per EU were taken from the 0-5, 10-15 and 40-45 cm depth layers. Specifically, two points close to the center of each EU were selected. A large cylinder (ø = 12 cm, h = 6 cm) was used for the soil surface, and small cylinders (ø = 5 cm, h = 5 cm) at depth by operating a 0753SA sampling equipment (Eijkelkamp, Giesbeek, The Netherlands).

2.4.1 Soil analyses

The disturbed soil samples were air-dried and gently deagreggated to pass a 2 mm mesh sieve for determining the textural fractions with the hydrometer method (Gee and Or, 2002), the organic matter with the Walkley-Black method (Nelson and Sommers, 1996) and the calcium carbonate equivalent (CCE) with the volumetric calcimeter method (Loeppert and Suarez, 1996). In addition, the percentage of sand-sized (0.05 – 2 mm) stable aggregates was determined according to Holz et al. (2000).

The undisturbed soil cores were weighed, then oven-dried at 105 ºC for 24 h and afterwards weighed again. Next, the soil cores were gently deaggregated to pass a 2-mm mesh sieve and the coarse elements (> 2 mm) were weighed and their volume measured by water displacement into a graduated cylinder. In this way, the fine-earth bulk density and soil water content were determined. Finally, the bulk density that would have been obtained using the large cylinder (ρ_{bL}) at the 10-15 and 40-45 cm depths was calculated from the small cylinder density (ρ_{bS}) by means of a previously calibrated equation ($\rho_{bL} = (\rho_{bS} - 0.9)/0.41$) (Visconti et al. 2014).

2.4.2 Leaf analyses

Leaves were thoroughly washed with tap water, rinsed with deionized water, and oven-dried in a Dry Big oven (J.P. Selecta, Barcelona, Spain) at 70°C for 48 h. Then, they were ground with a disc mill enough to pass a 1-mm mesh and stored at room temperature. The nitrogen content was determined by the automated combustion method (Horneck and Miller, 1998) using a TruSpec CHNS (LECO TruSpec Micro Series, St. Joseph, MI, USA). For the determination of P, K, Ca, Mg, Fe, Mn, Cu, S, B, and Zn concentrations, the dry-ashing method was used (Miller, 1998) followed by inductively coupled plasma-optical emission spectroscopy in an Optima 4300DV (PerkinElmer, Norwalk, CT, USA). Deionized water was used for all dilutions. Concentrations were expressed in terms of dry weight.

2.4.3 Berry analyses

Berry fresh weight was determined from a random sample of 200 berries per EU. Then, 150 berries were crushed and hand-pressed through a metal screen filter to assess must characteristics including total soluble solids (TSS), pH, total acidity (TA), and malic and tartaric acid concentrations. Must TSS were determined by refractometry with a PR-101 refractometer (Series Palette, Atago, Tokyo, Japan), pH and TA were measured in an automatic titrator (Metrohm, Herisau, Switzerland), this latter one using 0.1 N NaOH to an end point of pH 8.2 following the official methods of the Office International de la Vigne et du Vin (OIV 1990). Berry ripening was assessed using the TSS to TA ratio at harvest as the maturity index (Al-Kaisy et al. 1981). The concentrations of tartaric and malic acids were measured via infrared spectroscopy with a Bacchus II IR spectrometer (Tecnología Difusión Ibérica, Barcelona, Spain) according to García-Romero et al. (1993).

The remaining 50 berries were homogenized with a blender (Ultraturrax T25, IKA-Werke, Staufen, Germany) for determining phenolic maturity. Anthocyanin and phenolic substances (expressed in malvidin equivalents) were determined in duplicate by UV/VIS spectrophotometry (Iland et al. 2004).

2.5 Statistical analyses

Data were checked for normality using the Shapiro-Wilk test and homogeneity of variances of the residuals using the Bartlett's test. A logarithmic transformation of the original data was used when the requirements of normality and homogeneity of variance were clearly not met, i.e., at a 99% confidence level. A three-way analysis of variance (ANOVA) was used to assess the effects of the factors (water regime, soil management and year), along with their interactions, on the plant variables. From this first analysis, we detected that year exerted a significant influence on all the variables studied (leaf nutrient contents, pruning, yield components and berry composition), and showed significant interactions with either soil management or water regime for many of the variables considered (Supplementary Table 1). Therefore, data from each year was analysed separately using a split-plot ANOVA with water regime and soil management and their interaction, namely a factorial experiment but with two plot sizes and two different error variances, one for each plot size. Note that when analizing data about soil properties, there was only one treatment, i.e., soil management, at two levels, i.e. tillage and mulching and, therefore, Student's two-means comparison t-test was used instead of ANOVA for the different soil layers separately. All the statistical analyses were performed with the R software v.3.4.1 (R Core Team 2017).

3 Results

3.1 Vine water and nutritional status

The results presented correspond to 2 dry seasons, 2016 and 2017, and a wetter one, 2018. Rainfall and irrigation amounts applied from April 1st to September 30th each year are displayed in Table 1, showingthat deficit irrigated (I) vines received 2.86, 2.01 and 1.30 times more water than rainfed (R) vines in 2016, 2017 and 2018, respectively. Off-season rainfall was much higher in 2017 than in 2016 and 2018 (Table 1).

Water stress integral values (Figure 1) differed seasonally, being lower in 2018 than in the dryer seasons. This indicator differed significantly in response to both factors, WR and SM, without interaction between them. Nonetheless, irrigation improved vine water status compared to rainfed to a greater extent than mulching compared to tillage.

Differences in vine water status between both water regimes were observed during the entire growing season in 2016 (Figure 2a). In contrast, these differences were observed later in the season in 2017 and 2018 (Figure 2b and c). Minimum values were observed by the end of August, and there was a recovery towards the end of the season with the decrease of evaporative demand and the occurrence of rainfall events. Vine water status was better in M treatments from mid-August in all seasons studied (Figure 2). In 2016, IM vines showed less negative Ψ_{stem} values over the growing season, which were significantly different from the values of IT vines (Figure 2a). In that year, mulching seems to have significantly improved the vine water status in the R treatments only on some dates.

In general, differences in leaf contents of N, K and Mg among treatments were very small (Table 2). In the first season, the Ca content was significantly increased by both irrigation and mulching, but in subsequent seasons there was an interaction between factors on this nutrient. In contrast, both irrigation and mulching tended to increase the contents of P in leaves (Table 2).

In general, the contents of B, Cu, Fe, Mn and Zn in leaves did not show significant differences between either the SM or WR treatments (Table 3), with some remarkable exceptions depending on the season for specific elements. For instance, the contents of Mn were higher under irrigation in two out of the three seasons studied. In contrast, the B and Zn contents were lower in the vine leaves under irrigation in 2016. Note that in that season, the leaf contents of both microlements were the highest in the whole trial. Differences in the response to the SM were barely significant with the sole exception of B and Fe. The latter was significantly higher in the mulching treatments in 2016 and 2017, whereas B was higher only in 2016, when there was an interactive effect between factors for this element (Table 3).

3.2 Vine performance and berry composition

Pruning weight was greater in vines from the I treatments in most of the years studied. However, no effect of the SM on pruning weight was observed (Table 4). The number of clusters per vine was significantly greater in I than in R vines in 2017, while no differences among treatments were observed in 2016 and 2018. In addition, cluster weight was significantly higher in the I treatments, leading to higher yields. Cluster weight was also significantly higher in the M treatments in 2017, although in 2018 the opposite was observed. Berry weight was higher in the I treatments in 2016 but not in 2017 and 2018. No significant differences were observed regarding SM practices. In 2017, WUE was significantly affected by both SM and WR. In this season, significant interactions between SM and WR were detected for cluster weight, yield and WUE (Table 4).

Berry composition differed primarily depending on the WR and secondarily on the SM (Table 5). The TSS were lower in the irrigation treatments, while no differences were found between SM treatments. In contrast, total acidity (TA) and pH behaved differently depending on the season. The malic acid concentration was higher in the irrigation treatments and also in the mulched ones in 2017. Tartaric acid concentration in berries was lower in the I treatments in 2016 but higher in 2017, while no clear effects were observed in 2018. On the other hand, SM caused a consistent reduction in tartaric acid concentration over the whole study period. The maturity index (TSS-to-TA ratio) was significantly lower in 2017 in response to I and M. Concentrations of phenolic compounds (total polyphenols and anthocyanins) in most seasons were lower in both the I and M treatments. No significant interactions between SM and WR were detected for any of the berry compositional traits (Table 5).

3.3 Effects of mulching on soil properties

No significant differences were observed in soil surface basic properties such as textural fractions and organic matter content between tillage and mulching under rainfed conditions at the end of the experiment (Table 6).

Contrary to the basic soil properties, the bulk density, water content and saturated hydraulic conductivity did differ between SM practices. The bulk density was significantly higher under mulch at the soil surface by the end of the experiment with negligible differences in deeper layers (Figure 3a and Supplementary Table 2). Also, the soil water content was significantly higher under mulch in the surface layer with differences again vanishing with depth (Figure 3b and Supplementary Table 2). The aggregate stability in the soil surface layer was the same regardless of the soil management (Figure 3c). Interestingly, the saturated hydraulic conductivity was the soil property for which differences between the T and M treatments were larger. Specifically, its value under mulching was found to be one order of magnitude lower than under tillage (Figure 3d).

4 Discussion

In this three-year study we focused on the effects of the soil and irrigation management mainly on vine performance, plant water and nutrient status considering that at the vine level it is possible to integrate both the effect of the soil resources availability and the vine-environment interactions. While the effects of irrigation on the soil water balance are easy to predict and assess, the implications that soil mulching and no tillage may have on the vineyard water balance are more difficult to predict. This is because the soil management strategies tested here can affect many components of the soil water balance including evaporation, water infiltration, soil water holding capacity, vine microclimate, vineyard energy balance and also vine root growth and activity and therefore the vine plant water and nutrient uptake capacity. Indeed, the mulch application seemed to be effective for improving grapevine water status, both under R and I conditions (Figure 2). This can be due to the fact that mulching increased the soil water content at a depth of 0-5 cm as revealed by the measurement made at the end of the experiment under rainfed conditions (Figure 3). This can be attributed to the lower water losses through soil evaporation (Davies et al. 2011; Myburgh 2013; Cao et al. 2012). Montoro et al. (2016), using a weighing lysimeter, estimated that direct soil evaporation accounts for 26-31% of the vineyard evapotranspiration under drip-irrigated conditions in a semi-arid region from South-Eastern Spain. Consequently, employing mulches for covering vineyard soil surface may provide substantial water savings (López-Urrea et al. 2020). Nonetheless, research on the assessment of the effects of mulching on crop water use efficiency in grapevines provided contrasting results (Montoro et al. 2016). In the case of vineyards, Pinamonti (1998) reported 2% increments of soil water availability under mulching when compared to bare soil in a Merlot vineyard. Agnew et al. (2002) found that mulches allowed for retaining soil moisture early in the season, reporting soil water contents 5% higher under mulch in the first 30 cm of the soil profile. In our study, the increase was as high as 35% on average in the first 20 cm. In Mediterranean vineyards, Medrano et al. (2015) indicated that direct soil evaporation may account for 20% of water consumption, so the reduction in evaporation observed in mulched soil could result in a greater water availability for vines (Davies et al. 2011). In the current study, the water stress integral values reflected an average improvement of 5% in vine water status over the growing season when mulch was applied, in comparison with vines under tilled soil (Figure 1). Under irrigation, the improvement was even higher: 13% on average for the three studied years. As expected, greater improvements were observed in dry seasons (2016 and 2017). In addition, the 2017 season in which rainfall was highest during the off-season period, WUE was improved by 11% in mulch treatments (Table 4). These results are in accordance with previous research on the effects of organic mulching on crop water use efficiency (Buckerfield and Webster 2001; Fourie 2011; Guerra and Steenwerth 2012; Nguyen et al. 2013). Moreover, an improved vine water status coud be also due to differences in the root system provoked by mulching, mainly due to the proliferation of fine roots (Gaiotti et al. 2017; Morlat 2008; Linares-Torres et al. 2018).

On the other hand, both mulching and irrigation regimes can affect vine performance by modifying the vineyard nutrient balance (Keller et al. 2005). In the present research, we focused on determining the end effects at the vine level via a detailed analysis of the leaf macro- and micro-nutrient status. Despite other authors reported improvements in vine nutrient status in response to mulch application (Agnew et al. 2005; Nguyen et al. 2013), leaf nutrients did not show a consistent response to the treatments imposed in the current work (Table 2). In fact, the effect of WR and SM on vine nutrition was minimal and not fully consistent over the study period. For instance, deficit irrigation did not lead to nutritional deficiencies due to increased vigor as compared to rainfed treatments. Only the slight increases detected in P in response to the application of mulch may be linked to improved soil water content in these treatments (Mpelasoka et al. 2003), rather than to any effect on the incorporation of nutrients into the soil from pruning waste. This increase in P contents allowed for correcting a nutritional deficiency in the soil that existed prior to the application of mulching (Poni et al. 2003; Romero et al. 2005; Navarro et al. 2008; García-Escudero et al. 2013). Leaf micronutrients behaved inconsistenly with SM and WR. It should be noted that in 2017, the Cu values must have been affected by fungicide residues so they have no physiological meaning. On the other hand, the high levels of B found in the first experimental season, which were far from optimal (García-Escudero et al. 2013), may be due to the application of manure in this season. Although the nutrient levels in the manure were standard (Supplementary Table 3), it cannot be ruled out that the trial conditions favoured a high absorption of B, which is an essentially passive nutrient in contrast with other compounds such as Fe (Reid 2001). However, in some seasons, leaf contents of both nutrients were increased by the effect of mulching, most likely due to the increased soil water content (Keller et al. 2005). Other studies assessing the effect of vine pruning mulch on foliar nutrient status showed similar results in Cabernet franc on 3309C rootstock in the medium-term (Morlat 2008). Nevertheless, in the long-term (28 years) a trend towards a favorable influence of mulching on grapevine nutrition was observed (Morlat 2008), likely due to the increase of the soil organic matter content (Morlat and Chaussod 2008) which increased, in turn, the soil water holding capacity and, consequently, improved nutrient uptake by plants.

In our study, the worsened soil hydrophysical properties under mulching were the consequences of soil compaction, which was reflected in the increased bulk density at 0-5 cm (Figure 3), similar to the response to non-tillage reported by other authors (Álvaro-Fuentes et al. 2008a; Hansen et al. 2011). Contrary to the upper topsoil, the soil layers below the depth reached by the cultivator's tines, i.e., 10 cm, tended to be more compact under tillage, which is an undesirable effect known to be caused by repeatedly ploughing at the same depth (Tripplett and Dick 2008). The differences in bulk density in the 0-5 cm layer of the soil were reflected in differences in the saturated hydraulic conductivity of the soil surface (Figure 3), in accordance with previous studies (Curtis and Claassen 2009). However, in treatments where infiltrability was increased, this had no consequences on the soil water content below the surface layer (Figure 3).

Aggregate stability was not affected by soil management (Figure 3). The stability of aggregates increase with the build-up of binding agents (Álvaro-Fuentes et al. 2008b; Virto et al. 2012). In the Typic Calciorthid soil featured in the current study these binding agents are mainly calcium carbonate and organic matter. Nevertheless, on the one hand, the calcium carbonate content of soils under semi-arid Mediterranean climate only significantly changes in the very long-term and, on the other hand, even though the organic matter had increased due to mulching, as observed in other vineyards (Ferrara et al. 2012; Peregrina et al. 2012), it may be also a very short time for structural stability to increase (Table 6). In order to be able to change this parameter in a soil with poor aggregate stability as this, the mulching should definitely increase the organic matter content more than 2 g kg^{-1}. Perhaps it takes a much longer time for the mulching to incorporate into the soil, since the functioning of calcareous soils does not rapidly change in Mediterranean vineyards, thus limiting the effects of soil improving practices (Salomé et al. 2016).

In addition to the effects on plant water and nutrient status, the present research carried out a comprehsive agronomic assessment of vine performance and grape composition in order to integrate the effects of the soil mulching and irrigation on soil characteristics and vine physiology at the whole vine level. Although previous research showed that employing mulches increased vine vegetative growth (Gaiotti et al. 2017; Pinamonti 1998; Agnew et al. 2002), no clear effects were observed in the current study (Table 4). Despite the reports indicating that the use of organic mulches increases grape yields (Fourie 2011; Guerra and Steenwerth 2012; Nguyen et al. 2013), in the current study, yield increased by irrigation but not by the application of mulching. Nonetheless, cluster weight did increase in M treatments in 2017, but the contrary was observed in 2018, with no effect in 2016. In 2017, there was an interactive effect between SM and WR in yield and WUE, suggesting that the increase in soil water content under mulching during the off-season period of 2017 was enough for enhancing vine performance and WUE in the most stressed vines (rainfed) but not in irrigated vines. It is noteworthy that this interactive effect did not occur in all seasons (Supplementary Table 1). These irreproducible effects indicate that the environmental conditions the grapevines must cope within this semi-arid region are rather restrictive and the improvements generated by mulching and no-tilling are not sufficient for having a consistent impact on grapevine performance, at least in a three-year span. In addition, the beneficial increase in the soil water content promoted by mulching could be offset by the detrimental soil surface compaction effect due to no tillage methods (Figure 3). Although these findings contradict previous research on which mulching clearly increased vine yield (Porter 1999; Agnew et al. 2002), they may be explained by the different environmental conditions in which these studies were conducted. Environmental conditions are of paramount importance on grapevine response to management practices (Jackson and Lombard 1993) and, in fact, other studies reporting no significant effects on vineyard yield are not rare. For instance, Ferrara et al. (2012) did not observe significant effects of mulching application on grapevine yield after two years of research, in accordance with the results found in the current study.

Grape composition parameters were more clearly affected by WR than by SM (Table 5). For instance, irrigation decreased TSS and increased malic acid concentration, which is in accordance with previous research on irrigation effects on this variety (Salón et al. 2005). In contrast, SM only consistently affected the concentration of tartaric acid in the grapes which in turn showed an increased pH in 2016 and 2017. This contradicts previous works in which the application of mulch significantly increased TSS and TA (Mundy and Agnew 2002; Varga and Májer 2004). These contrasting results among studies may depend on the cultivar and the pedoclimatic conditions (Ferrara et al. 2012; Salomé et al. 2016). Notably, both WR and SM affected grape phenolic composition, with deficit irrigation and mulching reducing the concentration of polyphenols and anthocyanins in some seasons (Table 5). This can be explained by the effects that I and M had on alleviating vine water stress (Fig.1) and thus on regulating phenolic ripening (Castellarin et al. 2007; Romero et al. 2010). The observed effect of mulching on phenolic compounds was in agreement with previous evidences showing that organic amendments, such as crushed pruned vine-wood, decreased grape phenolic compounds in the long-term (Morlat and Symoneaux 2008).

5 Conclusions

Yield components were mostly unaffected by the combined effects of mulching with vine prunings and no-tillage under both water regimes. Vine nutritional status was not consistently affected. However, vine water status was enhanced under mulching, leading to water stress integral values over the season that were 5 and 13% lower than those from the tilled soil under rainfed and irrigation regimes, respectively. This enhancing effect, which is a result of the higher soil water content under mulching and no-tillage, resulted in reductions in grape phenolic composition. In one of the studied seasons, the soil management and water regime had an interactive effect on water use efficiency, highlighting the importance of environmental conditions on vine response to management practices. At the end of the experiment, however, soils from the mulched and no-tilled treatments also showed a higher bulk density in the shallower soil layer, along with a lower saturated hydraulic conductivity. According to these results, combining an organic mulch and no-tillage seems to have been useful in reducing direct soil water loss and limiting early transpiration losses, which were eventually revealed by the better vine water status. Nevertheless, the final higher compaction and lower infiltration ability of soils under mulching and no-tillage suggests that these positive effects may be unrepeatable along different seasons and therefore, complementary soil improvement practices should be adopted. Furthermore, the amount of material needed for mulching and its cost of establishment are additional factors that might constrain the use of pruning waste as organic mulching.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Tables

Table 1. Total amount of water received by rainfall and irrigation during the growing season (from 1st April to 30th September) in Bobal onto 110-R vines in Requena, Valencia, Spain, along with off-season rainfall (from 1st October of previous season to 31st March of the current season). RT, Rainfed Tilled; RM, Rainfed Mulched and no-tilled; IT, Deficit Irrigated Tilled; IM, Deficit Irrigated Mulched and no-tilled.

Treatment	2016		2017		2018	
	Rainfall	Irrigation	Rainfall	Irrigation	Rainfall	Irrigation
RT RM	166.0	0	118.6	0	231.9	0
IT IM	166.0	259.8	118.6	120.4	231.9	68.9
Off-season	109.0	-	383.8	-	175.3	-

Table 2. Contents of N, Ca, K, Mg and P at veraison in leaf blades from *Vitis vinifera* (L.). cv. 'Bobal' onto 110-R under two different soil management and water regime strategies during 2016, 2017 and 2018. RT, Rainfed and Tilled; RM, Rainfed and Mulched and no-tilled; IT, Deficit Irrigated and Tilled; IM, Deficit Irrigated and Mulched and no-tilled.

<table>
<tr><th rowspan="4">Parameter</th><th rowspan="4">Year</th><th colspan="4">Water Regime (WR)</th><th colspan="3" rowspan="3">Significance of effects</th></tr>
<tr><th>R</th><th>I</th><th>R</th><th>I</th></tr>
<tr><th colspan="4">Soil Management (SM)</th></tr>
<tr><th colspan="2">T</th><th colspan="2">M</th><th>WR</th><th>SM</th><th>WR × SM</th></tr>
<tr><td rowspan="6">N
(g kg^{-1} DW)</td><td rowspan="2">2016</td><td>19.4</td><td>21.8</td><td>19.3</td><td>21.7</td><td rowspan="2">**0.007**</td><td rowspan="2">0.854</td><td rowspan="2">0.941</td></tr>
<tr><td colspan="2">20.6</td><td colspan="2">20.5</td></tr>
<tr><td rowspan="2">2017</td><td>17.9</td><td>18.1</td><td>18.7</td><td>19.7</td><td rowspan="2">0.311</td><td rowspan="2">**0.009**</td><td rowspan="2">0.241</td></tr>
<tr><td colspan="2">18.0</td><td colspan="2">19.2</td></tr>
<tr><td rowspan="2">2018</td><td>18.0</td><td>19.0</td><td>18.9</td><td>19.6</td><td rowspan="2">0.178</td><td rowspan="2">0.282</td><td rowspan="2">0.858</td></tr>
<tr><td colspan="2">18.5</td><td colspan="2">19.2</td></tr>
<tr><td rowspan="6">Ca
(g kg^{-1} DW)</td><td rowspan="2">2016</td><td>26.3</td><td>30.5</td><td>27.8</td><td>32.5</td><td rowspan="2">**0.003**</td><td rowspan="2">**0.004**</td><td rowspan="2">0.491</td></tr>
<tr><td colspan="2">28.4</td><td colspan="2">30.1</td></tr>
<tr><td rowspan="2">2017</td><td>29.0</td><td>35.6</td><td>33.3</td><td>32.2</td><td rowspan="2">0.116</td><td rowspan="2">0.678</td><td rowspan="2">**0.008**</td></tr>
<tr><td colspan="2">32.3</td><td colspan="2">33.3</td></tr>
<tr><td rowspan="2">2018</td><td>27.9</td><td>24.9</td><td>24.7</td><td>31.0</td><td rowspan="2">0.610</td><td rowspan="2">0.279</td><td rowspan="2">**0.008**</td></tr>
<tr><td colspan="2">26.4</td><td colspan="2">27.8</td></tr>
<tr><td rowspan="6">K
(g kg^{-1} DW)</td><td rowspan="2">2016</td><td>6.7</td><td>6.1</td><td>6.6</td><td>6.8</td><td rowspan="2">0.684</td><td rowspan="2">0.279</td><td rowspan="2">0.150</td></tr>
<tr><td colspan="2">6.4</td><td colspan="2">6.7</td></tr>
<tr><td rowspan="2">2017</td><td>4.5</td><td>5.4</td><td>6.4</td><td>6.3</td><td rowspan="2">0.247</td><td rowspan="2">**0.006**</td><td rowspan="2">0.203</td></tr>
<tr><td colspan="2">5.0</td><td colspan="2">6.4</td></tr>
<tr><td rowspan="2">2018</td><td>6.1</td><td>6.4</td><td>5.8</td><td>7.8</td><td rowspan="2">0.097</td><td rowspan="2">0.412</td><td rowspan="2">0.237</td></tr>
<tr><td colspan="2">6.2</td><td colspan="2">6.8</td></tr>
<tr><td rowspan="6">Mg
(g kg^{-1} DW)</td><td rowspan="2">2016</td><td>3.3</td><td>3.9</td><td>3.2</td><td>4.1</td><td rowspan="2">**0.009**</td><td rowspan="2">0.663</td><td rowspan="2">0.577</td></tr>
<tr><td colspan="2">3.6</td><td colspan="2">3.6</td></tr>
<tr><td rowspan="2">2017</td><td>3.7</td><td>4.2</td><td>3.6</td><td>3.4</td><td rowspan="2">0.358</td><td rowspan="2">0.078</td><td rowspan="2">0.145</td></tr>
<tr><td colspan="2">4.0</td><td colspan="2">3.6</td></tr>
<tr><td rowspan="2">2018</td><td>2.9</td><td>3.0</td><td>2.8</td><td>3.2</td><td rowspan="2">0.540</td><td rowspan="2">1.000</td><td rowspan="2">0.098</td></tr>
<tr><td colspan="2">3.0</td><td colspan="2">3.0</td></tr>
<tr><td rowspan="6">P
(g kg^{-1} DW)</td><td rowspan="2">2016</td><td>0.9</td><td>1.2</td><td>0.9</td><td>1.3</td><td rowspan="2">**< 0.001**</td><td rowspan="2">**< 0.001**</td><td rowspan="2">**< 0.001**</td></tr>
<tr><td colspan="2">1.1</td><td colspan="2">1.1</td></tr>
<tr><td rowspan="2">2017</td><td>0.6</td><td>0.9</td><td>0.8</td><td>1.1</td><td rowspan="2">**0.005**</td><td rowspan="2">**0.006**</td><td rowspan="2">0.834</td></tr>
<tr><td colspan="2">0.8</td><td colspan="2">1.0</td></tr>
<tr><td rowspan="2">2018</td><td>0.7</td><td>0.8</td><td>0.7</td><td>1.0</td><td rowspan="2">0.087</td><td rowspan="2">**0.033**</td><td rowspan="2">0.331</td></tr>
<tr><td colspan="2">0.7</td><td colspan="2">0.9</td></tr>
</table>

Statistical significance effect of SM, WR and their interaction is also indicated by means of p-values. SM = Soil Management; WR = Water regime.

Table 3. Contents of B, Cu, Fe, Mn and Zn at veraison in leaf blades from *Vitis vinifera* (L.). cv. 'Bobal' onto 110-R under two different soil management and two water regime strategies during 2016, 2017 and 2018. RT, Rainfed and Tilled; RM, Rainfed and Mulched and no-tilled; IT, Deficit Irrigated and Tilled; IM, Deficit Irrigated and Mulched and no-tilled.

Parameter	Year	Water Regime (WR)				Significance of effects		
		R	I	R	I			
		Soil Management (SM)						
		T		M		WR	SM	WR × SM
B (mg kg^{-1} DW)	2016	129.5	102.6	161.1	110.0	**0.004**	**0.002**	**0.020**
		116.0		135.5				
	2017	21.3	22.5	22.4	24.3	0.081	0.118	0.671
		21.9		23.3				
	2018	20.9	19.8	18.4	24.4	0.269	0.028	0.418
		20.3		21.4				
Cu (mg kg^{-1} DW)	2016	4.6	5.0	5.0	6.0	0.142	0.105	0.389
		4.8		5.5				
	2017	41.5	63.9	57.1	48.5	0.475	0.992	0.055
		52.7		52.8				
	2018	4.5	3.9	3.1	5.6	0.433	0.874	0.111
		4.2		4.3				
Fe (mg kg^{-1} DW)	2016	139.1	134.0	443.7	193.8	0.099	**0.023**	0.088
		136.6		318.7				
	2017	101.7	124.6	130.8	135.5	0.246	**0.029**	0.244
		113.2		133.1				
	2018	115.1	78.5	86.3	105.4	0.648	0.964	0.235
		96.8		95.8				
Mn (mg kg^{-1} DW)	2016	97.7	146.3	99.3	167.0	**0.004**	0.157	0.215
		122.0		133.1				
	2017	93.2	146.9	124.5	130.3	**0.021**	0.511	0.062
		120.1		127.4				
	2018	91.4	94.1	76.5	112.9	0.144	0.795	0.053
		92.8		94.7				
Zn (mg kg^{-1} DW)	2016	20.1	13.7	18.5	14.4	**0.015**	0.553	0.139
		16.9		16.4				
	2017	14.5	19.3	18.2	18.7	**0.018**	0.285	0.151
		16.9		18.4				
	2018	13.5	12.4	13.5	13.3	0.660	0.832	0.825
		13.0		13.4				

Statistical significance effect of SM, WR and their interaction is also indicated by means of p-values.SM = Soil Management; WR = Water regime.

Table 4. Pruning weight and yield components in a Bobal onto 110-R vineyard under two soil management and two water regime strategies over the 2016-2018 growing seasons. RT, Rainfed and Tilled; RM, Rainfed and Mulched and no-tilled; IT, Deficit Irrigated and Tilled; IM, Deficit Irrigated and Mulched and no-tilled.

Parameter	Year	Water Regime (WR)				Significance of effects		
		R	I	R	I			
		Soil Management (SM)						
		T		M		WR	SM	WR × SM
Pruning weight (kg/vine)	2016	0.30	0.61	0.30	0.73	**0.023**	0.204	0.181
		0.46		0.52				
	2017	0.52	0.76	0.55	0.89	**0.043**	0.071	0.341
		0.64		0.73				
	2018	0.58	0.77	0.51	0.80	0.114	0.671	0.323
		0.68		0.65				
Clusters per vine	2016	10.3	12.6	9.7	12.4	0.108	0.265	0.845
		11.3		10.9				
	2017	7.3	13.1	8.0	12.4	**0.004**	0.963	0.145
		10.0		10.0				
	2018	8.7	10.4	9.1	9.6	0.356	0.622	0.172
		9.5		9.3				
Yield (kg/vine)	2016	2.1	6.7	2.3	7.1	**0.044**	0.623	0.896
		4.2		4.4				
	2017	2.5	6.3	3.3	6.0	**0.010**	0.134	**0.013**
		4.3		4.5				
	2018	3.1	4.5	2.9	4.0	0.088	0.133	0.594
		3.8		3.4				
Cluster weight (g)	2016	211.7	538.3	234.2	591.0	**0.029**	0.283	0.629
		361.7		393.4				
	2017	337.7	479.6	404.6	494.4	**< 0.001**	**0.005**	**0.038**
		403.8		444.9				
	2018	354.7	431.6	312.5	396.6	**0.046**	**0.025**	0.761
		390.2		349.1				
Berry weight (g)	2016	1.41	3.20	1.47	3.56	**0.001**	0.117	0.252
		2.30		2.51				
	2017	3.44	3.26	3.55	3.49	0.323	0.114	0.578
		3.35		3.52				
	2018	2.63	3.04	2.66	3.21	0.069	0.450	0.581
		2.84		2.94				
WUE (kg/m^3)	2016	3.5	4.4	3.8	4.6	0.069	0.706	0.945
		3.9		4.1				
	2017	5.8	7.3	7.5	6.9	**0.035**	**0.025**	**0.008**
		6.5		7.3				
	2018	3.7	4.1	3.5	3.7	0.160	0.160	0.773
		3.9		3.5				

Statistical significance effect of SM, WR and their interaction is also indicated by means of p-values. SM = Soil Management; WR = Water regime.

Table 5. Parameters of berry composition at harvest for Bobal grapes from two soil management and two water regime strategies over the 2016-2018 growing seasons. RT, Rainfed and Tilled; RM, Rainfed and Mulched and no-tilled; IT, Deficit Irrigated and Tilled; IM, Deficit Irrigated and Mulched and no-tilled.

Parameter	Year	Water Regime (WR)						Significance of effects		
		R	I		R	I				
		Soil Management (SM)								
		T			M			WR	SM	WR × SM
Total soluble solids (ºBrix)	2016	22.5	19.7	21.1	22.1	19.5	20.8	**0.011**	0.264	0.773
	2017	22.7	18.5	20.6	21.5	18.4	20.0	**0.004**	0.119	0.132
	2018	21.9	20.2	21.0	21.7	19.7	20.7	**0.036**	0.466	0.762
Total acidity ($g L^{-1}$ as tartaric acid)	2016	7.2	5.7	6.4	7.0	5.7	6.4	**0.071**	0.735	0.481
	2017	5.1	5.7	5.4	5.6	5.9	5.8	**0.012**	0.062	0.520
	2018	6.0	6.0	6.0	5.7	6.1	5.9	0.426	0.886	0.576
pH	2016	2.72	2.88	2.80	2.75	2.95	2.85	**0.011**	**0.024**	0.213
	2017	3.48	3.30	3.39	3.50	3.41	3.46	**0.011**	**0.014**	0.063
	2018	3.57	3.59	3.58	3.62	3.64	3.63	0.482	0.186	0.971
Malic acid ($g L^{-1}$)	2016	1.0	5.3	3.2	1.1	4.8	2.9	**0.001**	0.127	0.050
	2017	2.6	2.7	2.7	2.8	3.2	3.0	**0.014**	**0.008**	0.112
	2018	2.1	2.2	2.2	2.2	2.6	2.4	**0.018**	0.067	0.304
Tartaric acid ($g L^{-1}$)	2016	9.7	7.3	8.5	9.2	7.0	8.1	**0.002**	**0.008**	0.266
	2017	7.1	8.0	7.6	6.8	7.5	7.2	**0.009**	**< 0.001**	0.186
	2018	7.9	8.0	8.0	7.5	7.6	7.5	0.054	**0.009**	0.992
Ratio TSS/TA	2016	3.2	3.5	3.3	3.2	3.4	3.3	0.448	0.599	0.544
	2017	4.4	3.3	3.9	3.9	3.1	3.5	**0.004**	**0.041**	0.166
	2018	3.7	3.4	3.5	3.8	3.2	3.5	**0.101**	0.887	0.403
Total polyphenolic index	2016	4.9	3.8	4.3	4.7	3.5	4.1	**0.006**	0.270	0.698
	2017	4.9	4.7	4.8	4.5	4.4	4.5	0.100	**0.009**	0.953
	2018	4.2	5.1	4.6	3.9	4.9	4.4	**0.003**	**0.026**	0.901

Anthocyanins (g L^{-1})	2016	1.9	1.3	0.7	1.7	1.1	0.6	**0.003**	0.218	0.830
	2017	1.0	0.9	0.7	0.9	0.7	0.6	**0.011**	**0.023**	0.725
	2018	1.2	1.0	0.9	1.1	1.0	0.8	**0.029**	0.356	0.620

Statistical significance effect of SM, WR and their interaction is also indicated by means of p-values.

SM = Soil Management; WR = Water regime; TSS = Total soluble solids; TA = Total acidity.

Table 6. Statistical summary of the comparison of the 0-20 cm soil layer basic properties under rainfed conditions at the end of the experiment between tillage and mulching

Parameter	**USDA textural fractions**			**Organic matter content ($g\ kg^{-1}$)**	**Calcium carbonate equivalent ($g\ kg^{-1}$)**
	Clay ($g\ kg^{-1}$)	**Silt ($g\ kg^{-1}$)**	**Sand ($g\ kg^{-1}$)**		
Tillage treatment descriptive statistics					
Count	4	4	4	4	4
Mean	199	306	496	9.7	320
Standard deviation	30	18	43	7.4	80
Maximum value	237	326	552	19.9	379
Minimum value	165	284	452	2.8	202
Mulching treatment descriptive statistics					
Count	4	4	4	4	4
Mean	218	298	484	11.7	296
Standard deviation	33	42	56	4.4	45
Maximum value	247	351	529	15.2	355
Minimum value	190	251	403	5.4	258
Student's t-test of the comparison of tillage against mulching					
Weighted Standard Deviation	31	30	49	5.9	62
Std. Error of the Difference of Means	22	21	35	4.2	44
t value	-0.88	0.36	0.34	-0.46	0.54
p value	0.41	0.73	0.75	0.66	0.61

Figures

Figure 1. Effects of the soil management and water regime on the water stress integral over the three studied growing seasons. Values reported are treatment means ± standard error of 8 experimental units per factor. Asterisks on the columns indicate significant differences between levels within each factor. WR, Water Regime: R, Rainfed and I, Irrigated; SM, Soil Management: T, Tillage and M, Mulched and no-tilled.

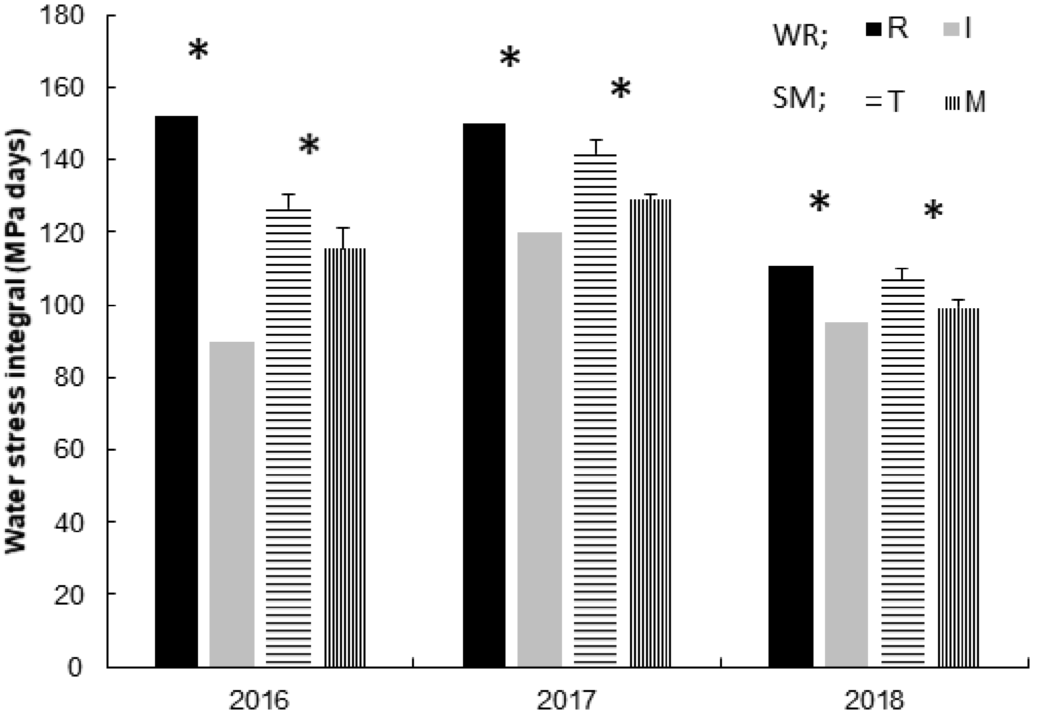


Figure 2. Seasonal (2016-2018) variations of midday stem water potential in a Bobal vineyard subjected to two different types of soil managements and two water regimes. Values reported are treatment means ± standard error of 16 determinations. RT, Rainfed and Tilled; RM, Rainfed and Mulched and no-tilled; IT, Deficit Irrigated and Tilled; IM, Deficit Irrigated and Mulched and no-tilled.

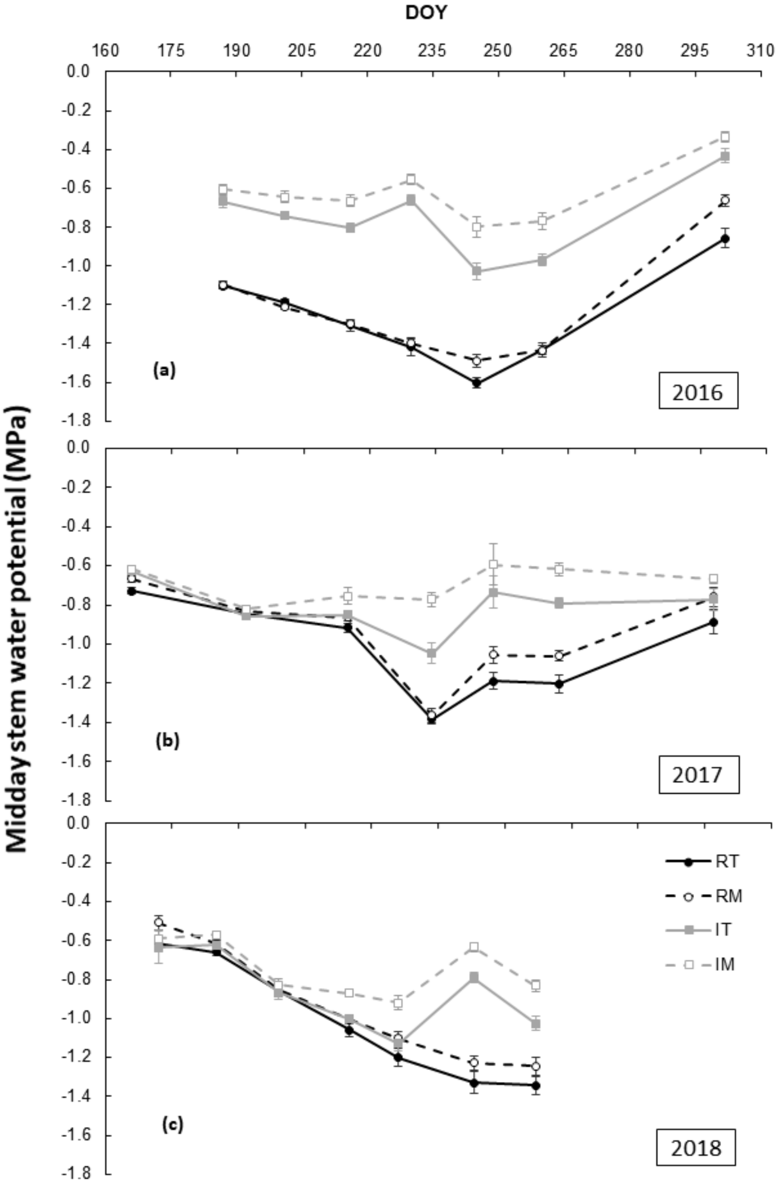
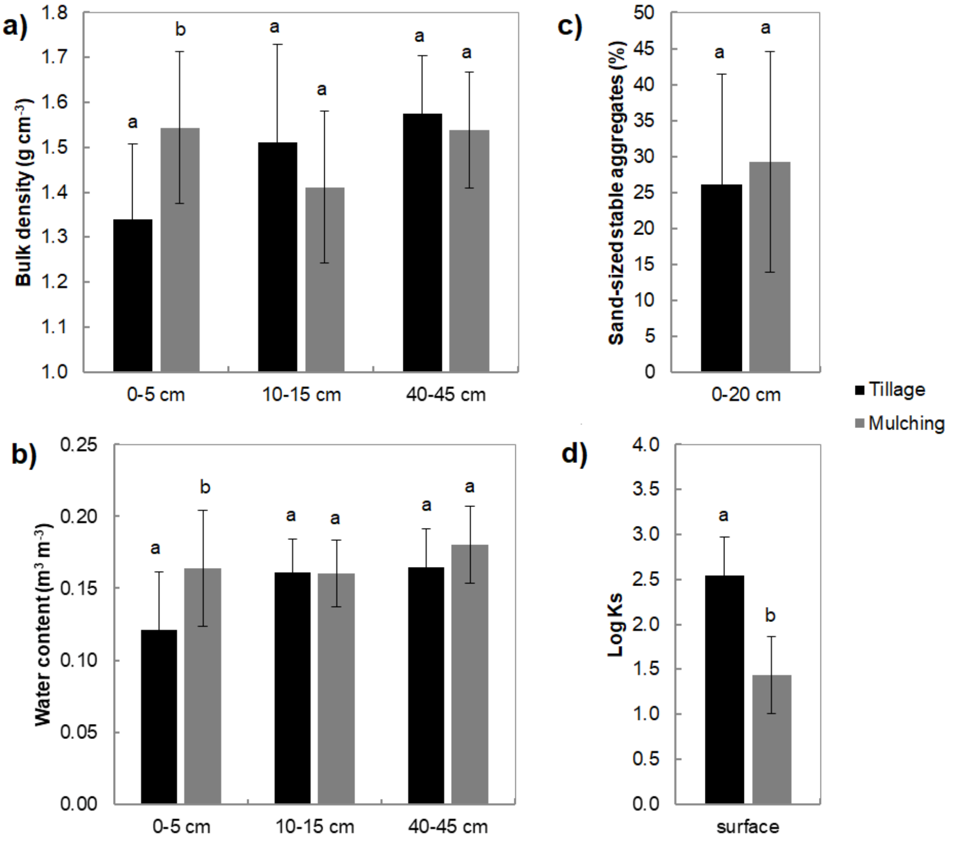
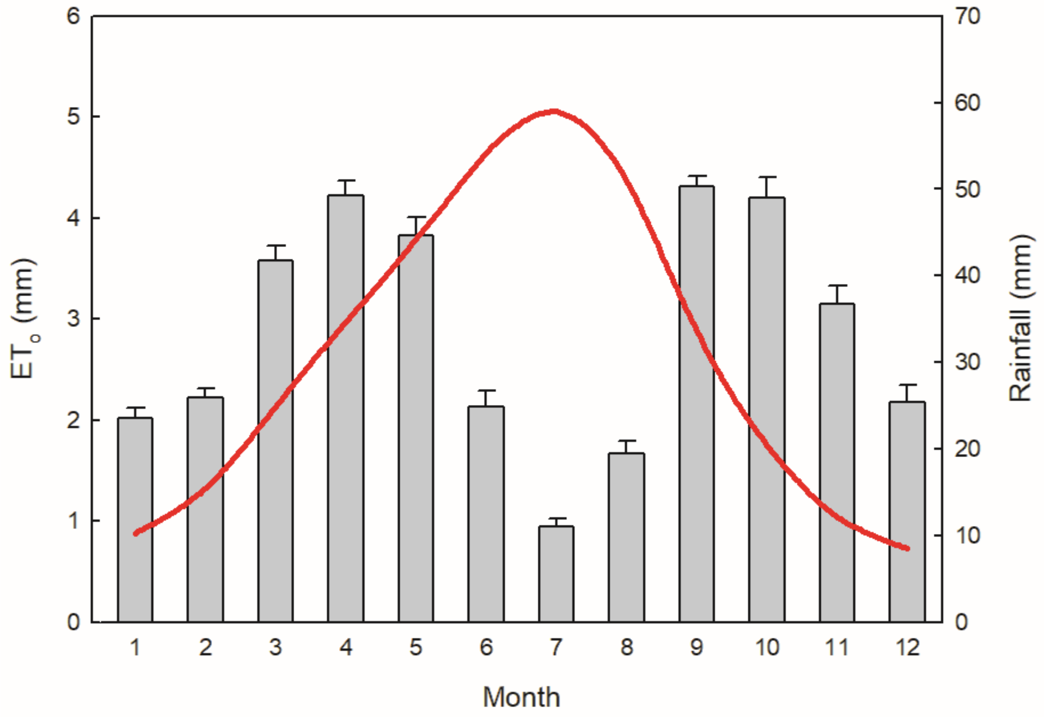


Figure 3. Effect of soil management on bulk density (a), water content (b), aggregate stability (c) and surface saturated hydraulic conductivity (d) at the end of the experiment under rainfed conditions. Values reported are treatment means ± 95% confidence intervals for the difference of means in the pairwise comparisons for the same depth. Different letters indicate significant differences at the 95% confidence level according to the Student's t-test between treatments for the same depth.



Supplementary material

Supplementary Figure 1. Monthly averages of reference evapotranspiration and total rainfall in Requena, Valencia, Spain for the 2001-2015 period.



Supplementary Figure 2. Detail of the soil mulching applied in the cv. Bobal vineyard located in Requena, Valencia, Spain.

Supplementary Table 1. Results of the ANOVA (*p* value) conducted to assess the effects of the soil management (SM), water regime (WR), year of study and their interaction on the parameters assessed on *Vitis vinifera* (L.). cv. 'Bobal' grafted onto 110-R.

	Variable	**SM**	**WR**	**Year**	**SM x WR**	**SM x Year**	**WR x Year**	**SM x WR x Year**
Elements in leaves	**N**	0.073	**< 0.001**	**< 0.001**	0.721	0.249	0.052	0.797
	Ca	0.951	**0.002**	**0.026**	0.832	0.339	0.428	**0.001**
	K	0.066	0.111	**< 0.001**	0.919	0.062	0.204	0.110
	Mg	0.185	**0.007**	**< 0.001**	0.390	0.342	0.185	0.350
	P	**< 0.001**	**< 0.001**	**< 0.001**	0.770	**< 0.001**	0.074	0.278
	B	**0.001**	**< 0.001**	**< 0.001**	**0.002**	**< 0.001**	**< 0.001**	**0.016**
	Cu	0.977	0.607	**< 0.001**	0.387	0.998	0.873	0.384
	Fe	**0.010**	**0.049**	**< 0.001**	**0.024**	**< 0.001**	**0.014**	**0.031**
	Mn	0.898	**< 0.001**	**< 0.001**	0.266	0.300	**0.008**	**0.006**
	Zn	0.301	0.155	**< 0.001**	0.224	0.806	**< 0.001**	0.383
Yield components and vegetative growth	**Pruning weight**	0.216	**< 0.001**	**< 0.001**	0.100	0.383	0.250	0.981
	Clusters per vine	0.483	**< 0.001**	**< 0.001**	0.229	0.840	**< 0.001**	0.438
	Yield	0.937	**< 0.001**	**< 0.001**	0.201	0.198	**< 0.001**	0.226
	Cluster weight	0.224	**< 0.001**	**< 0.001**	0.866	**< 0.001**	**< 0.001**	0.161
	Berry weight	0.082	**< 0.001**	**< 0.001**	0.319	0.875	**< 0.001**	0.907
	WUE	0.197	**0.005**	**< 0.001**	**0.038**	**0.041**	0.460	**0.047**
Berry composition	**TSS**	0.073	**< 0.001**	**0.047**	0.452	0.857	**0.009**	0.434
	TA	0.578	0.070	**< 0.001**	0.574	0.375	**< 0.001**	0.645
	pH	**0.002**	0.156	**< 0.001**	0.187	0.895	**< 0.001**	0.539
	Malic acid	0.155	**< 0.001**	**< 0.001**	0.912	**0.018**	**< 0.001**	**0.045**
	Tartaric acid	**< 0.001**	**< 0.001**	**< 0.001**	0.891	0.883	**< 0.001**	0.560
	TSS/TA	0.115	**< 0.001**	**0.008**	0.902	0.236	**< 0.001**	0.252
	Total Polyphenols	**< 0.001**	**0.006**	**< 0.001**	0.688	0.619	**< 0.001**	0.732
	Anthocyanins	**0.001**	**< 0.001**	**< 0.001**	0.861	0.344	**< 0.001**	0.803

Bold values indicate statistically significant effects for each factor on a given parameter. WUE = Water use efficiency; TSS = Total soluble solids; TA = Total acidity

Supplementary Table 2. ANOVAs conducted to assess the effect of the soil management, soil depth and their interaction on the bulk density and soil water content under the rainfed treatment in the plantation of *Vitis vinifera* (L.). cv. 'Bobal' grafted onto 110-R

Source of variance	**Sum of squares**	**Degrees of freedom**	**Mean squares**	**F**	**p-value**
Bulk density ---					
Soil management	0.0062	1	0.0062	0.2124	0.647
Soil depth	0.1217	2	0.0609	2.0899	0.136
Interaction	0.2060	2	0.1030	3.5373	0.038
Residual	1.2233	42	0.0291		
Total	1.5572	47			
Soil water content ---					
Soil management	0.0045	1	0.0045	5.1641	0.028
Soil depth	0.0072	2	0.0036	4.1693	0.022
Interaction	0.0039	2	0.0020	2.2729	0.116
Residual	0.0362	42	0.0009		
Total	0.0518	47			

Supplementary Table 3. Nutritional composition of the buried manure applied at the beginning of the experiment in a *Vitis vinifera* (L.). cv. 'Bobal' vineyard grafted onto 110-R.

Parameter	**Manure**
N (% DW)	2.5
P (% DW)	1.35
K (% DW)	2.79
Ca (% DW)	6.3
Mg (% DW)	1.33
Na (% DW)	0.58
B (mg kg^{-1} DW)	53.4
Fe (mg kg-1 DW)	4036
Cu (mg kg-1 DW)	50,0
Mn (mg kg-1 DW)	198
Zn (mg kg-1 DW)	273