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ORIGINAL RESEARCH ARTICLE

Cover Crops and No-Tillage Show Negligible Effects on Grapevine Physiology in two different California Vineyard Agroecosystems

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ABSTRACT

This study evaluated the effects of annual or perennial cover crops and tillage regimes on whole grapevine physiology and berry composition. We studied the interactive effects of tillage and cover crops on grapevine water status, leaf gas exchange, components of yield, berry composition and resulting water footprint in two contrasting production regions (Fresno County-hot climate and Napa County-warm climate) of California. The treatments included perennial grass (PG), resident vegetation (RV), and an annual grass (AG) grown under conventional tillage (CT) and no-till (NT) settings. Neither cover crop nor tillage affected grapevine leaf gas exchange. However, at the Napa County vineyard, NT detrimentally affected grapevine water status compared to CT. Grapevine mineral nutrition, when assessed during anthesis, revealed no effects of cover cropping in either year or at either location. Cover crop type did not affect yield components or berry composition; however, CT increased titratable acidity (TA) at both sites. The water footprint of vineyards at either location was not affected by cover crops or tillage. Under our experimental conditions, it was evidenced that both in a hot and warm climate, vineyard cover cropping had negligible beneficial effects on grapevine physiology, mineral nutrition or productivity with no detrimental effects on vineyard water footprint. Furthermore, this study showed that tillage was beneficial in younger vineyards to improve plant water status in semi-arid regions.

KEYWORDS: grape composition, nutrients, yield components, vineyard management, water status

INTRODUCTION

In the last decade, there has been a rise in the adoption of sustainable soil management practices that reduce soil erosion and bolster soil organic matter to counter the impacts of climate change on agricultural soils (Lal, 2004a; Powlson *et al*., 2011a; Lal, 2012a; Lazcano *et al*., 2020a). Traditionally, vineyard rows were kept bare with the use of herbicides and tillage. However, there is disagreement on the utility of this practice due to the detrimental effects of tillage on air quality and soil physical, chemical, and biological properties (Patiño-Zúñiga *et al*., 2009a; Ferreira *et al*., 2020; Gatti *et al*., 2022a). Thus, the adoption of cover crops and reduced tillage is considered a sustainable alternative to the traditional management of vineyard floors (Alsina *et al*., 2013b). Furthermore, environmental regulations and public perception serve as an additional incentive to adopt climate-smart practices (Guerra and Steenwerth, 2012).

The benefits of cover crops on the properties of soils are well documented. They can increase soil organic matter (SOM), total nitrogen, microbial biomass, β-glucosidase, and alkaline phosphomonoesterase, improve water infiltration and aggregate stability, reduce soil erosion and greenhouse gas emissions (GHG), and increase vineyard biodiversity (Ingels *et al*., 2005; Steenwerth and Belina, 2008b; Gattullo *et al*., 2020; Abad *et al*., 2021, Zumkeller *et al*., 2023). Nevertheless, the adoption of cover crops in vineyards is limited by the concern of excessive competition between the cover crop and grapevine for water and nutrients (Smith *et al*., 2008; Steenwerth and Belina, 2008a; Celette *et al*., 2009a; Steenwerth *et al*., 2013; Pérez-Bermúdez *et al*., 2016). Thus, the presence of a cover crop is generally reported to affect grapevine water status detrimentally (Naor *et al*., 1997; Monteiro and Lopes, 2007; Hatch *et al*., 2011a; Pou *et al*., 2011; Steenwerth *et al*., 2016; Tomaz *et al*., 2021). Despite wide acceptance of this particular effect, results depended on the specific conditions of the study, as some studies have shown that cover crops may improve early-season water status (Ingels *et al*., 2005; Delpuech and Metay, 2018; Reeve *et al*., 2016); yet others have concluded that cover cropped vineyards do not display better water status compared to those with bare soil (Celette *et al*., 2005; Costello, 2010; Daane *et al*., 2018, Torres *et al*., 2017). Ultimately, previous works agree that changes in grapevine physiological response to cover crop adoption are largely driven by the climatic conditions and irrigation regime at a given site (Delpuech and Metay, 2018; Tomaz *et al*., 2021).

There is an agreement in the literature that cover crops may reduce vegetative growth, with more pronounced yield losses in warmer regions. However, some studies had found no effect (Monteiro and Lopes, 2007; Lopes *et al*., 2008a; Smith *et al*., 2008; Costello, 2010; Jordan *et al*., 2016; Steenwerth *et al*., 2016) or yield increases when vineyards were planted with annual species such as oats or legumes (Fourie and Freitag, 2010; Ovalle *et al*., 2010; Steenwerth *et al*., 2013, 2016; Messiga *et al*., 2016; Fourie *et al*., 2017). These effects were dependent on the experimental conditions (Morlat and Jacquet, 2003; Ingels *et al*., 2005; Tesic *et al*., 2007; Lopes *et al*., 2008a; Smith *et al*., 2008; Costello, 2010; Pou *et al*., 2011; Steenwerth *et al*., 2013; Giese *et al*., 2015a; Gattullo *et al*., 2020), the cover crop species (reviewed by Abad *et al*., 2021) and the cover surface (Reeve *et al*., 2016). Consequently, any changes to berry composition as a result of cover crop adoption were closely associated with changes in yield, such as smaller berry size and purportedly greater content of berry flavonoids (Lopes *et al*., 2008b; Lopes *et al*., 2011; Lee and Steenwerth, 2013; Tomaz *et al*., 2021).

Cover cropping and reduced tillage management are two practices that directly alter the growing environment of grapevines. Thus, the selection of appropriate vineyard floor management practices is critical to maximise benefits to the soil while minimising the impact on grapevine function and productivity. This selection involves decisions in space (cover crop in vineyard rows vs under-vine), type (grasses vs broadleaves; monoculture or species mixture), and time including perennial vs annual species selection and timing of termination (Bowles *et al*., 2017b; Gatti *et al*., 2022b). Factors such as cultivar, vineyard age, macroclimate, soil physiochemical characteristics, and the overall goals for the use of the selected cover crop and tillage system must also be considered. These elements have been shown to contribute to the effect of the practices on grapevine functioning and production (Ingels *et al*., 2005; Sweet and Schreiner, 2010; Steenwerth *et al*., 2013; Abad *et al*., 2021). The adoption of reduced or no-till management preserves SOM, reduces soil erosion, improves soil structure, and is considered integral to reducing GHG emissions from the agriculture sector (Álvaro-Fuentes *et al*., 2008b; Gaudin *et al*., 2010; Dobrei *et al*., 2015; Wolff *et al*., 2018a). A greater amount of SOM exerts positive effects not only on the structure of the soil but also on the crops, even reducing many negative effects (i.e., mutagenic) of chemical compounds adopted in agriculture (Ferrara *et al*., 2000; Ferrara *et al*., 2004; Ferrara *et al*., 2006). Thus, the influence of tillage on soil properties, while not entirely understood, is more studied than the impact on crops themselves, and few reports have investigated the influence of tillage on grapevine physiology under the presence of a cover crop. Thus, according to previous studies, there is little evidence of tillage having a direct influence on grapevine stomatal conductance and net leaf photosynthesis (Pou *et al*., 2011), and although no-till practices are often promoted for their positive influence on soil infiltration and conservation of soil water, few studies have found that this effect translated to ameliorated plant water status in grapevine (Pool *et al*., 1990; Patiño-Zúñiga *et al*., 2009b; Myburgh, 2013; Steenwerth *et al*., 2016; Van Huyssteen and Weber, 2017). The grapevine vegetative growth has been reported to be greater under conventional tillage, while yield reductions are typically associated with no-till management, despite research that indicated no effect on production (Myburgh, 2013; Steenwerth *et al*., 2013; Wolff *et al*., 2018a). Similarly, previous studies reported a limited impact of tillage on berry composition (Van Huyssteen and Weber, 1980; Lee and Steenwerth, 2013; Reeve *et al*., 2016; Chrysargyris *et al*., 2018; Buesa *et al*., 2021).

Therefore, the objective of this work was to investigate the interactive effects of tillage and cover crops on grapevine water status, leaf gas exchange, components of yield, berry composition and resulting water footprint in two contrasting production regions in California, USA.

MATERIALS AND METHODS

1. Site description and experimental design

Field experiments were conducted at two sites (Figure 1A) for two consecutive growing seasons (2019-2020 and 2020-2021). The first site was located at a Winkler Index V vineyard in Fresno, CA (36.671°N, –119.925°W) in a Ruby Cabernet/Freedom (27 % *V. vinifera* hybrid) vineyard. Grapevines were planted in 2012 with a spacing of 3.0 × 1.2 m (row × vine) with a row orientation of E-W. The grapevines were cane-pruned and trained to quadrilateral cordons at 1.38 m with catch wires at 1.54 m and at 1.68 m above the vineyard floor. The soil texture of the site was classified as Hanford fine sandy loam. Hanford fine sandy loam is a coarse-loamy, mixed, super active, non-acid, thermic Typic Xerothents. (websoilsurvey.sc.egov.usda.gov). The A1 horizon is 0 to 30 cm deep with a moist, weak fine granular structure; slightly hard, very friable, nonsticky and nonplastic; many fine roots in the upper few inches; many fine interstitial pores; slightly acid; with gradual smooth boundary between 15 and 35 cm thick. The C1 horizon is 30 cm to 96 cm moist; massive; slightly hard, very friable, nonsticky and nonplastic; common fine interstitial pores; neutral; diffuse boundary 25 to 60 cm thick. The vines were drip-irrigated with two emitters per plant, delivering 4.0 L/h each at 100 % crop evapotranspiration replacement. Irrigation was scheduled daily to meet the vineyard demand according to methods reported by Torres *et al*. (2021) and 2900 m^3/ha and 3073 m^3/ha of irrigation water were applied in 2020 and 2021, respectively. The second site was located at a Winkler Index III vineyard in Oakville, CA (38.428 °N, –122.409 °W) in a Merlot (clone 181)/3309 C (*V. riparia* × *V. rupestris*) vineyard. Grapevines were planted in 2018 at a spacing of 3.0 by 2.0 m (row × vine) with a row orientation of E-W. The grapevines were spur-pruned and trained to quadrilateral cordons 1.38 m above the vineyard floor with catch wires at 1.68 m. The soil of the site was classified as Baley clay loam. The Bale soil series consists of very deep, somewhat poorly drained soils formed in stratified, gravelly and sandy alluvium from mixed sources. In these soil series, the Ap horizon is distributed from 0 to 0.15 m deep, the B horizon is distributed from 0.15 to 0.61 m, the Ab horizon is distributed from 0.61 to 1.12 m, and the C horizon is distributed from 1.12 to 1.47 m. (websoilsurvey.sc.egov.usda.gov). The vines were drip-irrigated with two emitters per plant, delivering 2 L/h each at 80 % crop evapotranspiration replacement. Irrigation at this location was scheduled weekly (Torres *et al*., 2021). In 2020 and 2021, 978.5 m^3/ha and 824 m^3/ha of irrigation were applied, respectively, at this location.

At both experimental sites, the experiments were arranged as a split-plot 3 × 2 factorial arrangement of treatments (three cover crops and two tillage managements) with four (Oakville) and three replications (Fresno). Each treatment replicate consisted of 15 grapevines. Three grapevines in the middle of each replicate were used for measurements, and the distal plants on either end served as buffer plants. Treatments included tillage as the main plot [conventional tillage (CT) and no-till (NT)], and the sub-plot was randomly applied within the main plots as i) Perennial grass (*Poa bulbosa* hybrid cv. Oakville Blue) (Figure 1B); ii) Annual grass (Barley, *Hordeum vulgare*) (Figure 1C); iii) Resident vegetation (natural weed population) (Figure 1D). Resident vegetation was mainly composed of grasses from the Poaceae family, *Plantago* sp., *Trifolium* sp., *Convolvulus* sp., and *Barbarea vulgaris*. The cover crop seed was drilled in a 1.5 m wide strip with a 1.5 m wide Frontier GS1160 (John Deere &Co. Deerfield, IL USA) seed drill according

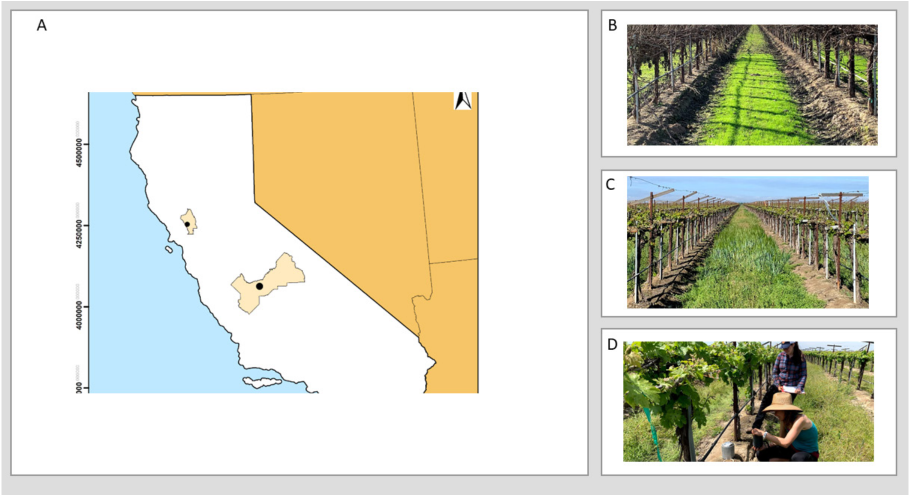

FIGURE 1. Location of experimental sites in the state of California, U.S.A. (A), Perennial grass (*Poa bulbosa* hybrid) (B), Annual grass (*Hordeum vulgare*) (C), Native vegetation (D) in the vineyard.

to the seed manufacturer's recommended rate prior to receiving fall/winter rains in 2019 (19 November 2019 in Napa County, 26 November 2019 in Fresno County) and 2020 (16 October 2020 in Napa County and 23 October 2020 in Fresno County) at a rate of 605 kg/ha and 84 kg/ha for the perennial grass (PG) and annual grass (AG) treatments, respectively. Resident vegetation (RV) was allowed to grow within the 1.5 m strip and mowed once with a 1.5 m wide Rears IFA60 (Rears Mfg. Co. Coburg, OR USA) flail mower (6 April 2020 and 11 April 2021 in Napa County; 12 March 2020 and at the vineyard manager's discretion. Conventional tillage was performed with a Schmeiser TSN60 tandem disk (Schmeiser Co. Selma, CA USA) within the 1.5 m planted strip according to the vineyard manager´s discretions once per year (22 April 2020 and 2 May 2021 in Napa County; 18 April 2020 and 21 April 2021) and removed cover crop was left on the field. All other cultural practices, including weed control on the berm once during March of each year with glyphosate (Zumkeller *et al.*, 2023), were conducted according to University of California Cooperative Extension guidelines (Christensen, 2000).

2. Weather conditions

Weather data at both sites was obtained from California Irrigation Management Information System (CIMIS) stations nearest the experimental vineyard (station #77 in Napa County, CA and station #2 in Fresno County, CA). Growing degree day values were calculated using a base of 10 °C from 1 April through 30 September of each year.

3. Grapevine water status and leaf gas exchange (Ψ, Anet, gs)

Plant water status was measured as stem water potential (Ψ_S) every 2 weeks (Oakville) and 4 times (Fresno) during each growing season within 1.5 h of solar noon, and integrals were calculated as previously reported (Yu *et al.*, 2021). Two fully expanded leaves exposed to the sun and without signs of disease and/or damage were selected per treatment-replicate. For Ψ_S, leaves were then covered 1.5 hours before measurements with a reflective foil-lined zip-top plastic bag to suppress transpiration. The Ψ_S was measured with a pressure chamber (Model 610 Pressure Chamber Instrument, PMS Instrument Co., Corvallis, OR USA).

Leaf gas exchanges of stomatal conductance (g_s) and net carbon assimilation (A_{net}) were measured at solar noon on three fully expanded and sun-exposed leaves with a CIRAS-3 infra-red gas analyser (PP Systems, Amesbury, MA, USA) equipped with a leaf chamber with a 4.5 cm^2 window. The reference CO_2 was set to 400 µmol/mol CO_2 at a flow rate of 100 mL/min. The window of the chamber was oriented perpendicularly toward the sun to allow for saturating light conditions, and the cuvette was left attached to the leaf for 40-60 s until a steady state was reached. Three grapevines were measured from each treatment replicate.

4. Grapevine mineral nutrient status

Grapevine petiole samples were collected for nutrient analysis at bloom at both sites. Bloom (Oakville: 29 May 2020, 25 May 2021; Fresno: 10 May 2020, 15 May 2021) was defined as when > 50 % of flowers opened. Leaves with petioles were collected from the north side of the three middle data vines in each replicate, and the blade was removed. Petioles were delivered to a commercial laboratory for mineral analysis which was carried out by using coupled plasma-mass spectrometry. Nitrogen (N) was determined via automated combustion analysis (method B-2.20), while phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), boron (B), iron (Fe), and copper (Cu) were analysed via Nitric/Perchloric Acid Digestion (method B-4.20) as described by Gavlak *et al*. (1994).

5. Leaf area and components of yield

At the Fresno site, leaf area index (LAI) was measured in late spring to characterise grapevine canopy growth and converted into leaf area by a smartphone program, VitiCanopy, via iOS system (Apple Inc., Cupertino, CA, USA) (De Bei *et al*., 2016). The gap fraction ranged from 0 % to 100 % and was set to 75 %, meaning that if 75 % of pixels from each of the sub-images (25 in total) correspond to the sky while the light extinction coefficient (k), was set at 0.7 by default since this value has been described to be the most accurate for grapevine canopies following developer´s recommendations (De Bei *et al*., 2016). A telescoping mounting device was used to position the device 75 cm underneath the canopy effectively. The device was positioned with the maximum length of the screen being perpendicular to the cordon and the cordon in line with the middle of the screen, according to previous work (De Bei *et al*., 2016; Yu and Kurtural, 2020). In each experimental unit, three images were taken to capture half canopy of each vine and analysed by the software. The relationship between leaf dry mass and area was determined on a subsample of leaves using a leaf area meter (Li-Cor 3300, Lincoln, NE, USA). This subsample was also used to calculate the leaf area per vine after defoliating a vine and measure by using the leaf area meter.

Harvest commenced when the fruit reached approximately 25 °Brix in Oakville (August 25, 2020, and September 1, 2021) and 21° Brix in Fresno (October 6, 2020, and September 7, 2021). At harvest at both sites, clusters from three data vines per treatment replicate were manually removed, counted, and weighed on a top-loading balance. The leaf area to fruit ratio was calculated by dividing leaf area by crop weight.

6. Berry composition

At harvest, fifty berries were randomly collected from the three middle grapevines within each replicate and immediately processed. Berries were weighed and gently pressed by hand to squeeze the juice. Total soluble solids (TSS) were determined using a temperature-compensating digital refractometer (Atago PR-32, Bellevue, WA, USA). Must pH and titratable acidity (TA) were determined with an autotitrator (Metrohm 862 Compact Titrosampler, Herisau, Switzerland). TA was determined by titrating with 0.1 N sodium hydroxide to an end point of 8.3 pH and reported as g/L of tartaric acid.

Berry skin anthocyanin content was determined at harvest from 20 berries randomly collected from each treatment replicate. Berries were gently peeled, and skins were freeze-dried (Cold Trap 7385020, Labconco, Kansas City, MO, USA). Freeze-dried tissue was ground with a tissue lyser (MM400, Retsch, Germany). Fifty milligrams of the resultant powder were extracted in methanol: water: 7 M hydrochloric acid (70:29:1, V:V:V) to determine anthocyanin content. Extracts were filtered using a 0.45 µm filter (Thermo Fisher Scientific, San Jose, CA, USA) and analysed using an Agilent 1260 series reversed-phase high-performance liquid chromatography (HPLC) system (Agilent 1260, Santa Clara, CA, USA) coupled to a diode array detector. Separation was performed on a reversed-phase C18 column LiChrospher 100, 250 mm × 4 mm with a 5 µm particle size and a 4 mm guard column of the same material at 25 °C with elution at 0.5 mL per minute. The mobile phase consisted of a constant 5 % of acetic acid and the following gradient (v/v) of acetonitrile in water: 0 min 8 %, at 25 min 12.2 %, at 35 min 16.9 %, at 70 min 35.7 %, 65 % between 70-75 min, and 8 % between 80-90 min. The identification of compounds was conducted by determining the peak area of the absorbance at 520 nm for anthocyanins and made by comparison of the commercial standard retention times found in the literature as previously reported (Martinez-Luscher *et al*., 2019). A commercial standard of oenin (Extrasynthese, Genay France) was used for the quantification of anthocyanins.

7. Water footprint assessment

Water footprint (WF) was calculated following the methods described in Zotou and Tshrintzis (2017) with minor modifications explained in Torres *et al*. (2021) and below. Total WF was derived as the sum of the green, blue and grey WFs and expressed in m^3 of water consumed per ton of fruit harvested. Cover crop WF was derived in the same manner and expressed in m^3 of water consumed per kg of cover crop biomass. Green, blue, and grey components were given by the following equations:

Eq. 1: $_{green}WF = \frac{\sum Pm}{Y}$

where P_m is the monthly effective precipitation was calculated from the data obtained from the CIMIS stations (station #77 in Napa County, CA and station #2 in Fresno County, CA, USA) and expressed in $m^3 \cdot ha^{-1}$ after applying a conversion factor of 10 and Y is the yield of grapevines expressed in $tonne \cdot ha^{-1}$.

Eq. 2: $_{blue}WF = \frac{\sum WUm}{Y}$

where WU_m is the total amount of irrigation water received by the grapevines monthly expressed in $m^{3-} \cdot ha^{-1}$ and Y is the yield of grapevines expressed in $tonne \cdot ha^{-1}$

Eq. 3: $_{grey}WF = \frac{\alpha AR}{(cmax - cnat)\, Y}$

where α is the percentage of fertiliser that leaches to the receiving aquatic system; AR is the amount of fertiliser applied to the grapevines expressed in $kg \cdot ha^{-1}$; c_{max} is the maximum acceptable concentration of fertiliser in the aquatic system ($mg \cdot L^{-1}$); and c_{nat} is the natural concentration of the pollutant in the aquatic system ($mg \cdot L^{-1}$). For grey component calculation, only nitrogen fertilisation was considered, given that N use in agriculture presents the largest environmental concern (UC Davis, 2016). The percentage of nitrogen entering the water system of the area was assumed to be 10 %, according to Mekonnen and Hoekstra (2011). The maximum acceptable concentration of nitrogen ($45\ mg \cdot L^{-1}$) was obtained from CDFA (2020). According to Hoekstra *et al*. (2011), the natural concentration of pollutants was taken equal to zero, as proposed when data were missing.

8. Statistical analyses

Statistical analyses were conducted with R studio Version 3.6.1 (RStudio: Integrated Development for R., Boston, MA, USA) for Mac OS. After normality assessment, data were submitted to a three-way analysis of variance (ANOVA) to assess the statistical differences between the different cover crop and tillage treatments and the respective interaction effects over two years. Means ± standard errors (SE) were calculated, and when the F value was significant ($P \leq 0.05$), a Tukey's 'Honest Significant Difference' (HSD) post hoc test was executed by using "agricolae" 1.2-8 R package. Plots were made using GraphPad Prism v8.1.2 for Windows (Graph Pad Inc., San Diego, CA, USA).

RESULTS

1. Weather conditions at the experimental sites

Temperature minima, maxima, and their average were calculated daily (air and soil) and annually (air) from the CIMIS station data for the 2019-20 and 2020-21 seasons (Table 1). In comparison to the ten-year average (2011–2021), both sites experienced warmer and drier conditions over the course of the experiment. During both years in Fresno, total precipitation was lower than the ten-year average for the same period. Specifically, the 2019-20 season received 10.6 mm less precipitation, while the 2020-21 season received 57.1 mm less. Average daily air temperature during the growing season was also 0.1 °C higher in 2020 and 0.4 °C higher in 2021 compared to the ten-year average. Average daily soil temperatures were 0.3 °C and 0.5 °C higher in 2020 and 2021, respectively. Despite one-degree increases in average monthly temperature between the two years, mean daily air and soil temperatures were similar. The greatest number of growing degree days in Fresno were accumulated in 2021 (2488 GDD_{10}), compared to 2020 (2358 GDD_{10}).

In Oakville, drought conditions were more pronounced, as the 2019-20 season received 343.6 mm less precipitation than the ten-year average and 299.5 mm less during the 2020-21 year (Table 1). However, there was a 43.8 mm increase in precipitation received in the second year of the experiment compared to the first year. The average daily temperature during the growing season was 0.4 °C higher in 2020 and 0.3 °C lower in 2021 compared to ten-year average values. Average daily soil temperatures were 0.5 °C and 0.4 °C higher in 2020 and 2021, respectively. As was observed at the Fresno vineyard, average daily air and soil

TABLE 1. Site conditions at two commercial vineyards in Fresno and Napa Co. from experimental years (2019–2021) compared to long-term mean values (2011–2021) [a, b, c].

Year		Air Temperature (°C)			Soil Temperature (°C)			Precipitation (mm)	Growing Degree Days
		Daily Max	Daily Min	Daily Average	Daily Max	Daily Min	Daily Average	Total	Total
Fresno County									
2020	Mean	25.6	9.1	17.3	25.7	10.7	22.6	199.0	2358
	Annual max	35.8	18.0	27.3	–	–	–	–	–
	Annual min	15.6	0.6	7.6	–	–	–	–	–
2021	Mean	25.8	9.2	17.6	26.6	10.4	22.8	152.5	2488
	Annual max	37.8	18.7	28.5	–	–	–	–	–
	Annual min	12.5	3.1	7.7	–	–	–	–	–
2011–2021	Mean	25.4	9.4	17.2	25.6	10.1	22.3	209.6	2259
Napa County									
2020	Mean	24.4	7.0	14.9	22.5	10	16.5	234.2	1647
	Annual max	31.8	12.3	21.1	–	–	–	–	–
	Annual min	17.1	2.0	8.5	–	–	–	–	–
2021	Mean	23.1	6.3	14.2	22.8	10.2	16.4	278.3	1519
	Annual max	30.0	10.8	19.2	–	–	–	–	–
	Annual min	12.5	2.6	7.6	–	–	–	–	–
2011–2021	Mean	23.2	7.1	14.5	22.8	7.9	16.0	577.8	1504

[a] Annual maximum (max) and annual minimum (min) indicate the greatest or lowest value observed during the respective year.

[b] Total precipitation occurred during the annual winter rainy season, calculated from October of the preceding year through September of the following year (e.g., 2020 values were calculated from October 1, 2019-September 30, 2020).

[c] Abbreviations: –: not applicable.

temperatures were similar between the two years of the study. Contrarily, the greatest number of growing degree days in Oakville (1647 GDD$_{10}$) were accumulated in the 2020 growing season compared to 2021 (1519 GDD$_{10}$).

2. Leaf gas exchanges and plant water status over the season

In Fresno, no treatment effects were observed on season-long integrals of g_s (Table 2). Likewise, season-long integrals of A_{net} were also not affected by the treatments applied. However, in 2020 both gs and A_{net} were significantly lower than in 2021 in Fresno.

In Oakville, g_s was significantly lower among grapevines grown with AG compared to RV and PG in 2020, 96 DAF and 110 DAF (Table 3). However, a similar effect was not evident throughout the rest of the experiment. Additionally, no differences were measured in A_{net} , although 2020 values were lower than in 2021. A similar response was observed at the Fresno vineyard.

In Fresno, Ψs values ranged from –1.68 to –0.70 MPa in 2020 and –1.75 to –0.73 MPa in 2021. The cover crop and tillage treatments did not affect $\Psi_{s.\text{integrals}}$, and there was not an interaction of cover crop and tillage or an effect of the year (data not shown). Conversely, at Oakville, $\Psi_{s\ integrals}$ ranged from –1.49 to –0.64 MPa in 2020 and –1.46 to –0.77 MPa in 2021. As presented in Figure 2, in 2020, $\Psi_{S\ integrals}$ were affected by cover crops. Grapevines grown with AG displayed the most negative $\Psi_{s\ \text{integrals}}$, with PG the least negative. However, this effect was not observed in the second year of the study, nor was there an interaction effect between the cover crop and tillage system. Tillage was more effective in eliciting a $\Psi_{S\ integrals}$ response more so than cover crop type. Grapevine water status was significantly lower in NT vines (–1.07 MPa) than in CT vines (–1.01 MPa) over both years at the Oakville vineyard.

3. Grapevine mineral nutrient status

Grapevine mineral nutrition was assessed at bloom, and there were year-to-year differences at both locations. At the Fresno vineyard, nitrogen (%), phosphorus (%), and zinc (mg/kg) concentrations in petioles were greater in 2020 than in 2021 (Table 4). There was also an interaction of year and tillage where calcium concentration was greater than tillage during 2020. In Fresno, manganese, magnesium, iron, and copper values were greater in 2021 than in 2020.

In Oakville, N, Mg, and Fe petiole concentrations were greater in 2021 than in 2020 (Table 5). Conversely, petiole concentrations of P, Zn, Mg, and Cu values were greater in 2020 compared to 2021. At Oakville, we measured lower petiole N concentrations with NT (1.18 %) when compared to CT (1.25 %). Again, an interaction of year and tillage within Ca was measured in 2020 in Oakville as well.

TABLE 2. Stomatal conductance and net carbon assimilation values of Ruby Cabernet grapevines subjected to different cover crops and tillage systems, as collected at various points in the 2019-20 and 2020-21 growing seasons[a, b].

Fresno County						
Treatment	Stomatal conductance (mmol m^{-2} s^{-1})			Net carbon assimilation (μmol CO$_2$ m^{-2} s^{-1})		
2020	78 DAF	184 DAF	–	78 DAF	184 DAF	–
No Till - AG	259.5 ± 23.4	266.7 ± 54.5	–	10.2 ± 1.6	13.4 ± 0.7	–
No Till - RV	308.7 ± 34.7	230.8 ± 21.6	–	12.2 ± 1.9	13.5 ± 3.7	–
No Till - PG	380.1 ± 60.1	252.5 ± 7.4	–	15.7 ± 0.5	14.5 ± 1.9	–
Till - AG	281.2 ± 30.1	260.2 ± 24.4	–	16.2 ± 1.7	12.9 ± 1.9	–
Till - RV	262.7 ± 24.4	301.8 ± 59.9	–	14.5 ± 0.9	11.3 ± 3.9	–
Till - PG	403.0 ± 64.2	189.8 ± 3.5	–	14.8 ± 0.2	9.97 ± 2.9	–
Cover crop (CC)	ns	ns	–	ns	ns	–
Tillage (T)	ns	ns	–	ns	ns	–
CC x T	ns	ns	–	ns	ns	–
2021	26 DAF	91 DAF	128 DAF	26 DAF	91 DAF	128 DAF
No Till - AG	178.4 ± 41.92	415.0 ± 68.0	349.8 ± 56.5	12.2 ± 3.6	15.8 ± 2.9	18.5 ± 2.7
No Till - RV	139.9 ± 22.21	352.1 ± 55.8	349.6 ± 30.2	6.33 ± 1.9	16.1 ± 0.9	20.8 ± 2.7
No Till - PG	149.5 ± 18.10	293.5 ± 68.2	382.0 ± 60.8	8.67 ± 1.5	18.1 ± 3.1	19.8 ± 1.8
Till - AG	133.2 ± 16.63	418.4 ± 51.2	318.0 ± 59.9	9.27 ± 1.2	18.5 ± 1.4	20.4 ± 3.0
Till - RV	137.7 ± 30.52	360.5 ± 70.7	413.9 ± 42.5	5.57 ± 1.6	17.2 ± 1.9	19.1 ± 2.1
Till - PG	137.9 ± 7.87	421.2 ± 89.4	407.0 ± 73.9	9.07 ± 1.7	19.7 ± 2.7	19.8 ± 1.9
Cover crop (CC)	ns	ns	ns	ns	ns	ns
Tillage (T)	ns	ns	ns	ns	ns	ns
CC x T	ns	ns	ns	ns	ns	ns
Year		ns			**	
Year x CC		ns			ns	
Year x T		ns			ns	
Year x CC x T		ns			ns	

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: AG: Annual grass; RV: resident vegetation; PG: perennial grass; DAF: days after flowering; na: not applicable; ns: not significant; –: not applicable.

3. Yield and yield components

In Fresno, there were no differences in cluster number per vine, average cluster mass, yield per vine, or leaf area to fruit ratio (Table 6). On average, the number of clusters per vine was higher in 2021 than in 2020, although the average cluster mass was lower in 2021 compared to 2020. Year-to-year differences were also observed at the Oakville site, whereby cluster number per vine, average cluster mass and yield per vine were greater in 2021 compared to 2020, while the leaf area to fruit ratio was greater in 2020. There was no treatment effect of cover crop or tillage, nor an interaction measured at either site.

4. Grape berry composition

In Fresno juice, pH, TA, TSS, total anthocyanin content, average berry mass, and average skin mass were not affected by the cover crop, or tillage system applied. The TSS and TA were higher in 2021, and TA was lower under NT (5.92 g/L) compared to CT (6.53 g/L) (Table 7).

At Oakville, the TSS and average berry mass were higher in 2020 than in 2021. Total anthocyanin content and average skin mass were higher in 2021 than in 2020. There was a main effect of tillage on juice pH, as mean values were lower in CT (3.43) compared to NT (3.46) over the two seasons. Furthermore, there was also a year-by-tillage interaction among pH due to a greater difference between tillage treatments in 2021. Conversely, mean juice TA values were lower in NT (6.48 g/L) compared to CT (7.13 g/L) in only 2021, resulting in a year-by-tillage interaction and without the main effect of tillage.

5. Vineyard water footprint

The analysis of the effect of treatments applied on WF components indicated the same pattern regardless of the

TABLE 3. Stomatal conductance and net carbon assimilation values of Merlot grapevines subjected to different cover crops and tillage systems, as collected at various points in the 2019-20 and 2020-21 growing seasons [a, b].

Napa County								
Treatment	Stomatal Conductance (mmol m^{-2} s^{-1})				Net Carbon Assimilation (µmol CO_2 m^{-2} s^{-1})			
2020	61 DAF	96 DAF	110 DAF	145 DAF	61 DAF	96 DAF	110 DAF	145 DAF
No Till - AG	136.6 ± 18.9	141.5 ± 6.3 b	147.7 ± 18.2 b	220.4 ± 22.2	10.0 ± 1.35	13.1 ± 0.96	19.2 ± 7.99	16.5 ± 1.6
No Till - RV	161.3 ± 27.6	195.5 ± 26.5 a	213.7 ± 14.0 a	217.0 ± 29.1	7.7 ± 0.72	17.3 ± 0.94	14.4 ± 1.04	16.6 ± 1.7
No Till - PG	174.0 ± 28.5	182.5 ± 17.1 a	217.0 ± 29.1 a	205.4 ± 17.3	11.7 ± 2.01	14.3 ± 1.85	17.1 ± 1.67	17.0 ± 0.9
Till - AG	109.2 ± 13.0	124.3 ± 19.3 c	167.8 ± 11.7 b	159.0 ± 18.9	7.7 ± 0.24	11.4 ± 1.31	13.2 ± 0.95	14.8 ± 1.0
Till - RV	143.0 ± 25.1	194.2 ± 32.5 a	229.2 ± 10.8 a	184.4 ± 10.8	6.3 ± 2.58	16.0 ± 2.32	16.0 ± 1.75	17.2 ± 0.3
Till - PG	172.2 ± 26.3	167.2 ± 30.0 b	201.4 ± 24.5 a	237.0 ± 20.8	10.4 ± 2.44	12.9 ± 2.07	14.0 ± 2.14	19.0 ± 0.9
Cover crop (CC)	ns	*	*	ns	ns	ns	ns	ns
Tillage (T)	ns	ns	ns	ns	ns	ns	ns	ns
CC x T	ns	ns	ns	ns	ns	ns	ns	ns
2021	56 DAF	74 DAF	98 DAF	109 DAF	56 DAF	74 DAF	98 DAF	109 DAF
No Till - AG	198.3 ± 26.4	191.7 ± 18.1	179.0 ± 17.9	150.3 ± 15.9	9.0 ± 2.06	13.1 ± 2.01	13.6 ± 1.51	12.4 ± 1.2
No Till - RV	180.9 ± 23.2	156.6 ± 25.1	155.0 ± 24.4	173.6 ± 18.7	9.4 ± 1.42	11.9 ± 1.41	11.5 ± 1.15	13.2 ± 1.3
No Till - PG	209.0 ± 28.9	146.5 ± 13.3	165.7 ± 16.9	177.1 ± 25.6	11.5 ± 2.08	13.2 ± 0.47	13.2 ± 1.63	12.2 ± 1.8
Till - AG	193.5 ± 19.2	160.5 ± 32.8	194.2 ± 21.5	163.2 ± 27.1	9.5 ± 1.31	14.8 ± 1.70	11.9 ± 1.51	12.1 ± 2.0
Till - RV	231.0 ± 24.6	168.7 ± 32.1	177.4 ± 26.7	193.3 ± 23.3	10.8 ± 1.87	13.4 ± 1.29	10.9 ± 1.85	13.3 ± 1.6
Till - PG	199.3 ± 26.2	171.4 ± 38.6	145.8 ± 18.3	181.2 ± 20.3	10.5 ± 1.73	12.5 ± 2.72	10.3 ± 1.59	13.9 ± 1.1
Cover crop (CC)	ns	ns	ns	ns	ns	ns	ns	ns
Tillage (T)	ns	ns	ns	ns	ns	ns	ns	ns
CC x T	ns	ns	ns	ns	ns	ns	ns	ns
Year	ns				***			
Year x CC	ns				ns			
Year x T	ns				ns			
Year x CC x T	ns				ns			

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: AG: Annual grass; RV: resident vegetation; PG: perennial grass; DAF: days after flowering; na: not applicable; ns: not significant.

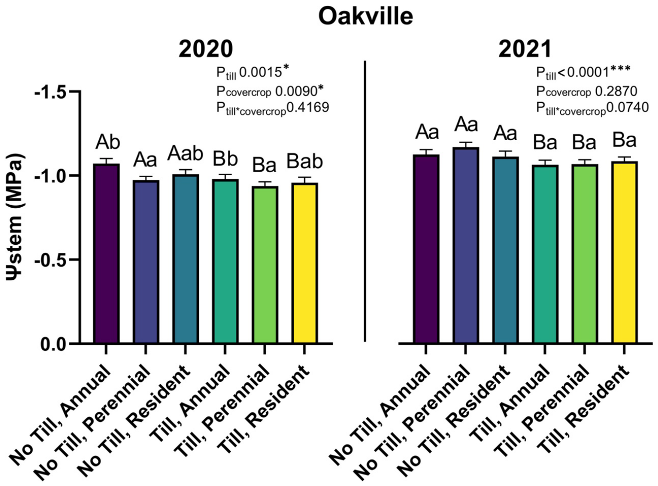

FIGURE 2. Mid-day stem water potential *integrals* of Merlot grapevines subjected to different cover crop and tillage systems at the Oakville vineyard (Napa County) over the course of the 2019-20 and 2020-21 growing season [a]

[a] ANOVA to compare data (p-value of the respective factor indicated). The interaction between the till and cover crop factor was not significant and upper(tillage) and lower case (cover crop). Letters above treatment bars indicate significant mean separation according to *Tukey's honest significance difference (HSD)* test for tillage and cover crop factors, respectively, at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

TABLE 4. Mineral nutrition measured on petioles at bloom of Ruby Cabernet grapevines subjected to different cover crops and tillage systems collected in the 2019-20 and 2020-21 seasons [a, b]

		Fresno County									
	Treatment	N (%)	P (%)	K (%)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Ca (%)	Mg (%)	Fe (mg/kg)	Cu (mg/kg)
2020	No Till - AG	0.76 ± 0.06	0.13 ± 0.01	3.17 ± 0.24	30.3 ± 0.3	46.0 ± 14.6	31.3 ± 1.5	1.35 ± 0.07	0.88 ± 0.03	48.3 ± 6.6	3.00 ± 0.58
	No Till - RV	0.69 ± 0.06	0.15 ± 0.02	3.51 ± 0.17	30.7 ± 3.2	48.0 ± 14.8	31.3 ± 0.1	1.31 ± 0.12	0.82 ± 0.08	46.7 ± 2.2	2.00 ± 0.03
	No Till - PG	1.01 ± 0.35	0.17 ± 0.06	2.89 ± 0.47	33.0 ± 6.7	68.7 ± 19.4	32.0 ± 2.1	1.47 ± 0.04	0.86 ± 0.09	101.3 ± 54.9	2.33 ± 0.67
	Till - AG	0.95 ± 0.24	0.17 ± 0.03	3.56 ± 0.43	34.3 ± 6.2	65.0 ± 19.4	34.0 ± 0.6	1.44 ± 0.07	0.84 ± 0.08	94.0 ± 52.0	2.33 ± 0.33
	Till - RV	0.72 ± 0.02	0.19 ± 0.05	3.59 ± 0.10	27.7 ± 4.4	43.3 ± 14.1	30.7 ± 0.9	1.28 ± 0.05	0.79 ± 0.05	48.0 ± 5.3	2.33 ± 0.33
	Till - PG	0.86 ± 0.23	0.18 ± 0.04	3.41 ± 0.19	32.0 ± 4.4	65.8 ± 18.2	32.3 ± 0.7	1.37 ± 0.19	0.86 ± 0.21	98.0 ± 50.5	2.67 ± 0.33
	Cover crop (CC)	ns	ns	ns	wns	Ns	ns	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
2021	No Till - AG	0.65 ± 0.03	0.12 ± 0.01	3.16 ± 0.07	26.7 ± 4.3	68.7 ± 5.1	31.3 ± 0.4	1.79 ± 0.05	1.09 ± 0.05	155.1 ± 15.9	3.3 ± 0.44
	No Till - RV	0.63 ± 0.03	0.11 ± 0.01	3.46 ± 0.17	26.7 ± 1.6	81.0 ± 15.2	31.7 ± 1.9	1.85 ± 0.05	1.14 ± 0.03	133.0 ± 24.6	3.33 ± 0.44
	No Till - PG	0.72 ± 0.10	0.13 ± 0.04	3.06 ± 0.27	29.3 ± 5.2	64.3 ± 4.9	34.3 ± 3.1	1.58 ± 0.03	0.91 ± 0.10	143.0 ± 41.7	4.00 ± 0.76
	Till - AG	0.66 ± 0.01	0.11 ± 0.01	3.49 ± 0.11	32.0 ± 5.9	84.7 ± 23.5	29.0 ± 1.3	1.72 ± 0.11	1.04 ± 0.07	192.1 ± 38.6	4.00 ± 0.76
	Till - RV	0.64 ± 0.02	0.11 ± 0.02	3.37 ± 0.09	27.3 ± 1.8	83.3 ± 6.5	34.3 ± 5.1	1.70 ± 0.12	1.06 ± 0.07	138.0 ± 15.6	4.00 ± 1.32
	Till - PG	0.64 ± 0.03	0.10 ± 0.01	3.81 ± 0.56	26.3 ± 1.9	84.3 ± 19.0	31.3 ± 1.6	1.88 ± 0.17	1.16 ± 0.75	134.0 ± 6.5	3.00 ± 0.44
	Cover crop (CC)	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
	Year	***	***	ns	***	***	ns	ns	***	***	***
	Year x CC	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns
	Year x T	ns	ns	ns	ns	Ns	ns	*	ns	ns	ns
	Year x CC x T	ns	ns	ns	ns	Ns	ns	ns	ns	ns	ns

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: N: Nitrogen; P: Phosphorus; K: Potassium; Zn: Zinc; Mn: Manganese; B: Boron; Ca: Calcium; Mg: Magnesium; Fe: Iron; Cu: Copper; na: not applicable; ns: not significant.

TABLE 5. Mineral nutrition measured on petioles at bloom of Merlot grapevines subjected to different cover crops and tillage systems collected in the 2019-20 and 2020-21 seasons [a, b].

Napa County											
	Treatment	N (%)	P (%)	K (%)	Zn (mg/kg)	Mn (mg/kg)	B (mg/kg)	Ca (%)	Mg (%)	Fe (mg/kg)	Cu (mg/kg)
2020	No Till - AG	1.07 ± 0.09	0.43 ± 0.03	3.19 ± 0.18	98.8 ± 4.33	39.0 ± 4.64	43.5 ± 2.60	1.73 ± 0.14	0.63 ± 0.06	32.3 ± 3.60	10.00 ± 1.56
	No Till - RV	0.88 ± 0.06	0.53 ± 0.06	3.12 ± 0.10	100.8 ± 3.57	37.3 ± 4.01	44.5 ± 1.37	1.99 ± 0.23	0.65 ± 0.05	32.0 ± 3.16	12.50 ± 1.20
	No Till - PG	0.92 ± 0.09	0.51 ± 0.03	3.02 ± 0.36	101.0 ± 3.68	37.3 ± 3.07	48.0 ± 3.09	1.87 ± 0.20	0.79 ± 0.02	36.3 ± 2.18	13.00 ± 0.81
	Till - AG	0.88 ± 0.04	0.51 ± 0.02	3.12 ± 20	99.5 ± 1.11	35.8 ± 0.55	46.3 ± 0.29	1.90 ± 0.08	0.68 ± 0.07	40.0 ± 1.16	12.50 ± 0.58
	Till - RV	0.96 ± 0.09	0.46 ± 0.06	3.22 ± 0.17	96.3 ± 5.94	40.8 ± 4.63	45.0 ± 3.86	1.65 ± 0.14	0.60 ± 0.09	33.0 ± 5.27	10.25 ± 1.66
	Till - PG	1.11 ± 0.12	0.46 ± 0.02	3.17 ± 0.19	91.8 ± 7.78	35.8 ± 4.86	47.0 ± 374	1.66 ± 0.10	0.63 ± 0.09	34.3 ± 3.31	11.00 ± 0.67
	Cover crop (CC)	ns	Ns	ns	Ns	ns	Ns	ns	ns	ns	Ns
	Tillage (T)	ns	Ns	ns	ns	ns	Ns	ns	ns	ns	Ns
	CC x T	ns	Ns	ns	ns	ns	Ns	ns	ns	ns	Ns
2021	No Till - AG	1.39 ± 0.07	0.38 ± 0.02	3.04 ± 0.28	43.0 ± 2.45	63.0 ± 7.96	45.8 ± 1.91	1.74 ± 0.15	0.51 ± 0.05	46.3 ± 1.91	8.75 ± 0.29
	No Till - RV	1.45 ± 0.07	0.39 ± 0.02	3.16 ± 0.29	40.3 ± 3.10	66.0 ± 5.06	45.8 ± 1.09	1.86 ± 0.14	0.51 ± 0.02	46.0 ± 0.82	8.75 ± 0.55
	No Till - PG	1.39 ± 0.06	0.41 ± 0.02	3.09 ± 0.23	45.8 ± 1.52	65.0 ± 13.76	47.5 ± 1.67	1.80 ± 0.05	0.56 ± 0.01	51.3 ± 5.42	9.00 ± 0.82
	Till - AG	1.54 ± 0.03	0.38 ± 0.02	3.17 ± 0.10	39.5 ± 2.33	70.0 ± 12.82	45.8 ± 1.28	1.95 ± 0.11	0.56 ± 0.04	44.8 ± 3.60	8.75 ± 0.33
	Till - RV	1.50 ± 0.11	0.42 ± 0.04	2.99 ± 0.07	40.3 ± 4.01	77.5 ± 16.93	46.8 ± 1.44	1.92 ± 0.15	0.54 ± 0.01	42.8 ± 4.25	8.75 ± 0.55
	Till - PG	1.51 ± 0.04	0.42 ± 0.03	3.44 ± 0.18	43.0 ± 1.33	79.0 ± 13.56	48.8 ± 1.36	1.98 ± 0.05	0.52 ± 0.02	52.5 ± 3.67	9.25 ± 0.55
	Cover crop (CC)	Ns	ns	ns	ns	ns	Ns	ns	ns	ns	Ns
	Tillage (T)	*	ns	ns	ns	ns	Ns	ns	ns	ns	Ns
	CC x T	ns	ns	ns	ns	ns	Ns	ns	ns	ns	ns
	Year	**	**	ns	***	***	Ns	ns	***	***	***
	Year x CC	ns	ns	ns	ns	ns	Ns	ns	ns	ns	ns
	Year x T	ns	ns	ns	ns	ns	Ns	*	ns	ns	ns
	Year x CC x T	ns	ns	ns	ns	ns	Ns	ns	ns	ns	*

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: N: Nitrogen; P: Phosphorus; K: Potassium; Zn: Zinc; Mn: Manganese; B: Boron; Ca: Calcium; Mg: Magnesium; Fe: Iron; Cu: Copper; na: not applicable; ns: not significant.

TABLE 6. Yield components of Ruby Cabernet (Fresno County) and Merlot grapevines (Napa County) subjected to different cover crops and tillage systems, collected in the 2019-20 and 2020-21 seasons [a, b].

	Fresno County					Napa County				
	Treatment	Cluster No.	Cluster Mass (g)	Yield (kg/vine)	Leaf Area: Fruit (m2/kg)	Treatment	Cluster No.	Cluster Mass (g)	Yield (kg/vine)	Leaf Area: Fruit (m2/kg)
2020	No Till - AG	139 ± 9.92	128.6 ± 7.9	5.92 ± 0.98	1.94 ± 0.11	No Till - AG	18 ± 1.29	64.5 ± 6.5	0.40 ± 0.17	1.74 ± 0.41
	No Till - RV	122 ± 20.17	128.4 ± 16.9	5.11 ± 0.77	1.42 ± 0.68	No Till - RV	19 ± 2.67	74.2 ± 12.4	0.47 ± 0.28	1.38 ± 0.23
	No Till - PG	115 ± 20.13	145.6 ± 16.8	5.44 ± 0.95	1.55 ± 0.66	No Till - PG	17 ± 1.57	73.1 ± 7.1	0.41 ± 0.08	1.54 ± 0.10
	Till - AG	139 ± 25.89	112.8 ± 18.7	5.32 ± 0.62	1.72 ± 0.25	Till - AG	17 ± 1.57	82.6 ± 15.4	0.47 ± 0.32	1.37 ± 0.26
	Till - RV	146 ± 26.35	121.9 ± 9.9	5.86 ± 1.02	1.58 ± 0.25	Till - RV	17 ± 1.06	80.0 ± 10.9	0.46 ± 0.26	1.54 ± 0.32
	Till - PG	129 ± 36.47	157.1 ± 11.6	6.58 ± 0.98	1.60 ± 0.45	Till - PG	18 ± 0.50	78.9 ± 7.8	0.47 ± 0.24	1.41 ± 0.28
	Cover crop (CC)	ns	ns	ns	ns	*Cover crop (CC)*	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	*Tillage (T)*	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	*CC x T*	ns	ns	ns	ns
2021	No Till - AG	111 ± 15.59	160.2 ± 14.2	5.85 ± 0.67	1.97 ± 0.12	No Till - AG	34 ± 4.71	100.6 ± 19.0	1.16 ± 1.05	0.65 ± 0.12
	No Till - RV	106 ± 23.11	134.4 ± 25.4	4.53 ± 0.75	1.64 ± 0.94	No Till - RV	32 ± 5.52	79.8 ± 5.3	0.83 ± 0.24	0.70 ± 0.13
	No Till - PG	100 ± 9.33	147.7 ± 33.2	4.83 ± 0.46	1.59 ± 0.58	No Till - PG	37 ± 0.50	81.0 ± 2.7	0.88 ± 0.06	0.72 ± 0.45
	Till - AG	124 ± 28.06	168.9 ± 21.3	6.71 ± 0.81	1.40 ± 0.26	Till - AG	32 ± 1.22	105.1 ± 26.6	1.09 ± 0.74	0.60 ± 0.09
	Till - RV	137 ± 16.52	131.8 ± 28.5	5.91 ± 0.22	1.52 ± 0.40	Till - RV	41 ± 7.80	104.0 ± 17.1	1.52 ± 0.78	0.57 ± 0.10
	Till - PG	116 ± 26.39	172.8 ± 45.0	6.66 ± 0.10	1.63 ± 0.48	Till - PG	40 ± 7.17	82.9 ± 11.3	1.11 ± 0.85	0.76 ± 0.32
	Cover crop (CC)	ns	ns	ns	ns	*Cover crop (CC)*	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	*Tillage (T)*	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	*CC x T*	ns	ns	ns	ns
	Year	*	*	ns	ns	*Year*	***	**	***	***
	Year x CC	ns	ns	ns	ns	*Year x CC*	ns	ns	ns	ns
	Year x T	*	***	ns	ns	*Year x T*	*	***	ns	ns
	Year x T x CC	ns	ns	ns	ns	*Year x T x CC*	ns	ns	ns	ns

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: ns: not significant; AG: Annual grass; RV: resident vegetation; PG: perennial grass.

TABLE 7. Berry composition of Ruby Cabernet (Fresno County) and Merlot (Napa County) grapevines subjected to different cover crops and tillage collected in the 2019-20 and 2020-21 seasons [a, b].

		Treatment	Juice pH	TA (g/L)	TSS (°Brix)	Total Anthocyanins (mg/g Berry FM)	Average Berry Mass (g/berry)	Average Skin Mass (g)
Fresno County	2020	No Till - AG	3.89 ± 0.04	5.37 ± 0.38	21.8 ± 1.5	1.45 ± 0.23	1.83 ± 0.09	1.31 ± 0.07
		No Till - RV	3.84 ± 0.04	5.73 ± 0.23	17.2 ± 4.3	1.44 ± 0.24	1.78 ± 0.05	1.41 ± 0.12
		No Till - PG	3.88 ± 0.05	5.68 ± 0.71	19.5 ± 2.6	1.48 ± 0.27	1.54 ± 0.08	1.24 ± 0.22
		Till - AG	3.80 ± 0.06	6.30 ± 0.50	20.4 ± 1.3	1.20 ± 0.21	1.72 ± 0.22	1.32 ± 0.21
		Till - RV	3.89 ± 0.02	5.60 ± 0.27	20.4 ± 1.2	1.55 ± 0.04	1.80 ± 0.02	1.42 ± 0.17
		Till - PG	3.88 ± 0.02	5.77 ± 0.56	20.8 ± 0.8	1.40 ± 0.03	1.77 ± 0.12	1.51 ± 0.34
		Cover crop (CC)	ns	ns	ns	ns	ns	ns
		Tillage (T)	ns	ns	ns	ns	ns	ns
		CC x T	ns	ns	ns	ns	ns	ns
	2021	No Till - AG	3.86 ± 0.03	6.18 ± 0.24 b	21.1 ± 1.4	1.85 ± 0.44	1.74 ± 0.11	1.37 ± 0.29
		No Till - RV	3.87 ± 0.03	5.92 ± 0.61 b	22.2 ± 1.3	1.41 ± 0.39	1.67 ± 0.08	1.25 ± 0.20
		No Till - PG	3.82 ± 0.04	6.13 ± 0.78 b	19.6 ± 2.4	1.60 ± 0.30	1.68 ± 0.11	1.34 ± 0.12
		Till - AG	3.77 ± 0.06	6.98 ± 0.86 a	20.8 ± 1.1	1.27 ± 0.10	1.75 ± 0.14	1.28 ± 0.23
		Till - RV	3.82 ± 0.09	6.95 ± 0.95 a	21.9 ± 0.9	1.80 ± 0.35	1.78 ± 0.07	1.45 ± 0.23
		Till - PG	3.88 ± 0.09	6.35 ± 1.33 a	22.1 ± 1.2	2.04 ± 0.42	1.68 ± 0.04	1.62 ± 0.20
		Cover crop (CC)	ns	ns	ns	ns	ns	ns
		Tillage (T)	ns	*	ns	ns	ns	ns
		CC x T	ns	ns	ns	ns	ns	ns
		Year	ns	***	**	ns	ns	ns
		Year x CC	ns	ns	ns	ns	ns	ns
		Year x T	ns	ns	ns	ns	ns	ns
		Year x T x CC	ns	ns	ns	ns	ns	ns
Napa County	2020	No Till - AG	3.33 ± 0.02	7.70 ± 0.43	25.9 ± 1.0	1.16 ± 0.08	0.94 ± 0.06	0.78 ± 0.08
		No Till - RV	3.32 ± 0.01	7.65 ± 0.29	25.2 ± 0.6	1.50 ± 0.44	0.94 ± 0.05	0.61 ± 0.07
		No Till - PG	3.30 ± 0.01	7.85 ± 0.05	24.8 ± 0.5	1.37 ± 0.48	1.02 ± 0.08	0.63 ± 0.11
		Till - AG	3.31 ± 0.02	7.50 ± 0.13	25.4 ± 0.2	1.49 ± 0.30	1.00 ± 0.10	0.61 ± 0.09
		Till - RV	3.33 ± 0.02	7.50 ± 0.24	24.7 ± 1.6	1.42 ± 0.12	0.96 ± 0.06	0.59 ± 0.06
		Till - PG	3.32 ± 0.02	7.68 ± 0.24	25.7 ± 0.5	1.36 ± 0.11	0.94 ± 0.07	0.57 ± 0.09
		Cover crop (CC)	ns	ns	ns	ns	ns	ns
		Tillage (T)	ns	ns	ns	ns	ns	ns
		CC x T	ns	ns	ns	ns	ns	ns
	2021	No Till - AG	3.58 ± 0.05 a	6.58 ± 0.43	24.1 ± 0.5	2.40 ± 0.44	0.91 ± 0.13	1.14 ± 0.13
		No Till - RV	3.65 ± 0.10 a	6.73 ± 0.11	24.7 ± 0.5	1.20 ± 0.32	0.99 ± 0.05	1.26 ± 0.26
		No Till - PG	3.59 ± 0.03 a	6.30 ± 0.30	25.6 ± 0.9	2.93 ± 0.89	0.83 ± 0.04	1.37 ± 0.08
		Till - AG	3.54 ± 0.01 b	7.00 ± 0.32	24.9 ± 0.6	1.91 ± 0.39	0.96 ± 0.03	1.40 ± 0.29
		Till - RV	3.54 ± 0.03 b	7.30 ± 0.33	24.4 ± 0.5	2.28 ± 0.41	1.04 ± 0.05	1.18 ± 0.21
		Till - PG	3.54 ± 0.01 b	7.08 ± 0.23	24.1 ± 0.4	2.05 ± 0.19	0.89 ± 0.04	1.05 ± 0.15
		Cover crop (CC)	ns	ns	ns	ns	ns	ns
		Tillage (T)	*	ns	ns	ns	ns	ns
		CC x T	ns	ns	ns	ns	ns	ns
		Year	***	***	*	***	ns	***
		Year x CC	ns	ns	ns	ns	ns	ns
		Year x T	*	***	ns	ns	ns	ns
		Year x T x CC	ns	ns	ns	ns	ns	ns

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's HSD test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001. [b] Abbreviations: TA: titratable acidity; TSS: total soluble solids; ns: not significant; AG: Annual grass; RV: resident vegetation; PG: perennial grass.

TABLE 8. Water footprint (m3/ton) of the Ruby Cabernet (Fresno County) and Merlot (Napa County) vineyard subjected to different cover crops and tillage collected in the 2019-20 and 2020-21 seasons [a, b].

	Fresno County					Napa County				
	Treatment	Green Water Footprint (m^3/ton)	Blue Water Footprint (m^3/ton)	Grey Water Footprint (m^3/ton)	Total Water Footprint (m^3/ton)	Treatment	Green Water Footprint (m^3/ton)	Blue Water Footprint (m^3/ton)	Grey Water Footprint (m^3/ton)	Total Water Footprint (m^3/ton)
2020	No Till - AG	170 ± 9.3	248 ± 13.6	50 ± 2.7	468 ± 25.7	No Till - AG	2803 ± 369.3	1170 ± 154.1	116 ± 15.2	4088 ± 538.7
	No Till - RV	197 ± 10.2	288 ± 14.9	58 ± 3.0	542 ± 28.0	No Till - RV	2344 ± 376.1	978 ± 157.0	97 ± 15.5	3419 ± 548.6
	No Till - PG	180 ± 9.3	263 ± 13.5	53 ± 2.7	496 ± 25.5	No Till - PG	2347 ± 173.5	979 ± 72.4	97 ± 7.2	3423 ± 253.0
	Till - AG	211 ± 63.2	308 ± 92.4	62 ± 18.5	500 ± 174.1	Till - AG	2316 ± 274.0	966 ± 114.3	95 ± 11.3	3378 ± 399.6
	Till - RV	173 ± 18.4	254 ± 26.8	51 ± 5.4	478 ± 50.6	Till - RV	2366 ± 337.9	987 ± 141.0	98 ± 13.9	3451 ± 492.9
	Till - PG	159 ± 29.4	233 ± 43.0	47 ± 8.6	439 ± 81.0	Till - PG	2281 ± 319.5	952 ± 133.3	94 ± 13.2	3328 ± 466.0
	Cover crop (CC)	ns	ns	ns	ns	Cover crop (CC)	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	Tillage (T)	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	CC x T	ns	ns	ns	ns
2021	No Till - AG	137 ± 13.9	276 ± 28.1	52 ± 5.3	466 ± 47.3	No Till - AG	1213 ± 332.9	359 ± 98.6	87 ± 23.8	1659 ± 455.3
	No Till - RV	187 ± 32.6	377 ± 65.6	72 ± 12.5	635 ± 110.6	No Till - RV	1481 ± 97.4	439 ± 28.9	106 ± 7.0	2026 ± 133.3
	No Till - PG	177 ± 38.2	357 ± 77.1	68 ± 14.6	603 ± 129.9	No Till - PG	1417 ± 142.5	420 ± 42.2	101 ± 10.2	1938 ± 194.9
	Till - AG	121 ± 9.8	244 ± 19.8	46 ± 3.8	412 ± 33.4	Till - AG	1231 ± 225.8	365 ± 66.9	88 ± 16.2	1684 ± 308.8
	Till - RV	133 ± 28.1	277 ± 56.7	51 ± 10.8	452 ± 95.5	Till - RV	932 ± 106.4	276 ± 31.5	67 ± 7.6	1275 ± 145.6
	Till - PG	138 ± 56.6	278 ± 114.1	53 ± 21.7	469 ± 192.4	Till - PG	1208 ± 229.1	358 ± 67.9	87 ± 16.4	1653 ± 313.4
	Cover crop (CC)	ns	ns	ns	ns	Cover crop (CC)	ns	ns	ns	ns
	Tillage (T)	ns	ns	ns	ns	Tillage (T)	ns	ns	ns	ns
	CC x T	ns	ns	ns	ns	CC x T	ns	ns	ns	ns
	Year	*	ns	ns	ns	Year	**	**	**	**
	Year x CC	ns	ns	ns	ns	Year x CC	ns	ns	ns	Ns
	Year x T	ns	ns	ns	ns	Year x T	ns	ns	ns	ns
	CC x T x Year	ns	ns	ns	ns	CC x T x Year	ns	ns	ns	ns

[a] ANOVA to compare data (p-value indicated); Letters within columns indicate significant mean separation according to Tukey's honest significance difference (HSD) test at p-value < 0.05, where "*": p-value < 0.05; "**": p-value < 0.001, "***": p-value < 0.0001.

[b] Abbreviations: ns: not significant; AG: Annual grass; RV: resident vegetation; PG: perennial grass.

growing season at both sites. In Fresno, the green water footprint was greater in 2020 than in 2021 (Table 8). However, the treatments applied did not affect the WF components at Fresno. At Oakville, year-to-year differences were observed in all WF components, with 2020 values greater than 2021 which was expected due to differences in yield between the two years (Table 6). The treatments applied did not affect the WF of the vineyard at Oakville in 2020 or 2021 either.

DISCUSSION

1. Cover crop and tillage system did not affect leaf gas exchange

At both sites, there were no effects of cover crop or tillage on g_s or A_{net} over the two seasons monitored in this paper. This may indicate that despite different climatic and site conditions, whole grapevine physiology was not affected by the presence of a cover crop or tillage. These results are corroborated with previous work that has measured leaf gas exchange between grapevines grown with and without inter-row cover crops and found negligible differences (Celette *et al*., 2009b; Sweet and Schreiner, 2010; Hatch *et al*., 2011b; Reeve *et al*., 2016). Previous works that reported changes to leaf gas exchange of the grapevine have either contrasting applied water amounts (Torres *et al*., 2021), variation in leaf area to shoot ratio (Martinez-Lüscher and Kurtural, 2021) or soil spatial variability that affected grapevine water status (Brillante *et al*., 2018, Yu *et al*., 2021). Since neither factor had a significant effect on these variables, it is plausible that cover crops or tillage would not affect grapevine leaf gas exchange in the short term in warm climate viticulture.

2. Tillage was more influential than cover crop type on grapevine water status and mineral nutrition

Much of the literature regarding competition between cover crops and grapevine suggested that the presence of a cover crop increased the competition for nutrients, namely nitrogen (Calderón *et al*., 2001; Celette *et al*., 2009b; Reeve *et al*., 2016) and, consequently, we hypothesised that RV and AG would decrease grapevine mineral nutrition status; however, no effects of cover crop on grapevine mineral nutrition were found under our experimental conditions. In Fresno, the nutrient status of the grapevines at bloom only differed between years and was not affected by treatments, indicating little to no competition with the cover crop for nutrients in mature vineyards under arid conditions.

However, Oakville tillage appeared to have an effect on grapevine mineral nutrition, and CT grapevines demonstrated a higher nitrogen content at bloom compared to NT in both years. Higher N in both leaves and juice in response to tillage was previously reported (Rodriguez-Lovelle *et al*., 2000b; Guerra and Steenwerth, 2012). In one particular three-year study, NO_3-N petiole values of grapevines with inter-row tillage were found to be up to 2 × greater than those of no-till grapevines, suggesting a possible temporal offset between soil N availability and plant uptake related to tillage (Steenwerth *et al*., 2013b; Reeve *et al*., 2016). It was well demonstrated that soil tillage affects the decomposition and mineralisation of N from plant residues and existing pools which regulates the inorganic N pool available for uptake by the grapevines (Guerra and Steenwerth, 2012). The type of cover crop did not influence nitrogen content in the present study, nor was there an interaction between cover crop and tillage. Similarly, small differences in P and S contents have been noticed between a tilled and cover-cropped table grape vineyard in the Puglia region, southern Italy, with higher values in the leaves of the cover-cropped vineyard (Tarantino *et al*., 2020).

It was also hypothesised that PG would improve grapevine water status due to spatial and temporal complementarity, whereby the shallow rooting depth would be less likely to compete with grapevines, and peak water use of PG would occur during grapevine dormancy. In Fresno, no treatment effects were observed on grapevine water status nor among WF components. This result is particularly important as it indicated that despite different growth cover crops (AG is a tall stature grass and, thus, produces more biomass than the low stature PG, Figure 1), there was no competition with the grapevines for water due to vineyards were sufficiently irrigated, as also indicated by a lack of differences in Ψs between treatments. In Oakville, PG did improve grapevine water status compared to RV and AG in one instance during 2020, but this effect was not observed in the second year of the study nor over the two seasons. Furthermore, there was no interaction effect between the PG cover crop, and NT factor, which is particularly important as the greatest benefits to the soil from a permanent cover crop were observed under no-till environments (Rodriguez-Lovelle *et al*., 2000a; Morlat and Jacquet, 2003; Volaire and Lelièvre, 2010).

While under our experimental conditions, the type of cover crop again had little influence on grapevine water status in contrast with previous studies (Ingels *et al*., 2005), CT improved grapevine water status (i.e., more positive Ψs) compared to grapevines under NT. Thus, although it is commonly accepted that cover crops may exert some competition with grapevines for soil water, Steenwerth *et al.* (2016) previously reported reduced soil water content under no-till settings, and no association was found with Ψs. While contradictory to some reports that indicated tillage did not affect grapevine water status (Van Huyssteen and Weber, 1980; Steenwerth *et al*., 2013; Myburgh, 2013), this result provided further evidence of tillage in semi-arid regions to preserve water in the soil through early season cultivation. This was based on the notion that while evaporative losses of the upper tilled layer of soil immediately increase, overall losses are minimised as a barrier that restricts capillary water movement is created, which preserves moisture in the deeper layers of the soil (Hillel, 1998; Myburgh, 2013b). Furthermore, seasonal grapevine water status in irrigated viticulture was shown to be more influenced by subsoil conditions than the topsoil, which dries quite early in California vineyards (Yu *et al*., 2021). As the presence of vegetation was shown to deplete water out of the upper portion of the soil more rapidly than bare soil (Monteiro and Lopes, 2007b; Celette *et al*., 2008; Novara *et al*., 2018), it is possible that the complete termination and incorporation of vegetation helped preserved moisture in the soil compared to NT, where vegetation was able to remain in competition with the grapevines. However, no conclusions can be made as to the mechanism of reduced water stress under CT vines, as root structure was not examined in the present study (Hunter, 1998; Myburgh, 2013b). Ultimately, these differences in vine water status between tillage systems in Oakville did not affect WF components, as irrigation amounts remained unchanged.

3. Minimal effects observed on yield components and berry composition

Regarding grapevine yield and berry composition, most differences were observed between years at the Fresno vineyard. Although no yield components were affected by cover crop or tillage, minimal effects of tillage on berry composition were seen. The TA was significantly higher in CT compared to NT in both years, as has been previously reported when permanent grass was compared to conventionally tilled soil (Reeve *et al*., 2016), even in a table grape vineyard (Ferrara *et al*., 2021). This may suggest that tillage hastens the ripening process; however, no statistically significant effects were observed on Brix, which would support such a claim as the climate keeps warming in the study areas (Kennedy, 2002; Gambetta and Kurtural, 2021). Other studies that investigated the influence of vineyard floor management in mature vineyards reported similar findings with reduced effect of soil management practices as grapevines aged. It was possible that mature grapevines may be more resilient to the adoption of cover crops due to their well-established root systems that can more effectively compete with the cover crop (Van Huyssteen and Weber, 1980; King and Berry, 2005; Steenwerth *et al*., 2013b; Fourie *et al*., 2017b; Gattullo *et al*., 2020). Combined, these results provided evidence that the use of annual or perennial grass cover crops and/or no-till practices may be implemented in mature irrigated vineyards in the San Joaquin Valley with little to no effect on production.

In the Oakville vineyard, TA was again significantly higher under CT compared to NT in 2021. However, this effect was only seen in the second year of the study resulting in a year-by-tillage interaction without a significant main effect. The juice pH was also reduced under CT grapevines, which has been a reported effect of cover crop adoption rather than tillage as a result of the release of potassium (K) when the cover crop decomposed (Wheeler *et al*., 2005; Guerra and Steenwerth, 2012; Chrysargyris *et al*., 2018b; Cataldo *et al*., 2020). While several studies have reported no reductions to yield in response to cover crops, others that assessed permanent cover crops observed decreased yield after 2 to 3 years (Morlat and Jacquet, 2003; Tesic *et al*., 2007; Lopes *et al*., 2008a; Steenwerth and Belina, 2008b; Hatch *et al*., 2011b; Giese *et al*., 2015b). It is not clear whether competition for water or N was the primary cause, as the two factors are interconnected (Celette *et al*., 2008, 2009b). The absence of effect on yield, as seen in this study and in others, may be a result of the shorter length of the experiment and/or shallower rooting depth of the perennial grass used compared to deeper rooting and higher biomass-producing grasses investigated in the aforementioned studies. However, even considering 3-year trials, effects on yield are generally limited and mainly at the beginning of the trial when the cover crops are sowed. Ultimately, the adoption of cover crops under both tillage systems in the present study did not affect production despite great differences in soil type, vineyard age, and climate between the two sites.

CONCLUSIONS

Under the experimental conditions of this study, the use of inter-row cover crops had negligible beneficial effects on grapevine physiology, mineral nutrition or productivity, with no detrimental effects on vineyard water footprint, in both hot and warm climate vineyards. Additionally, differences between the cover crop species used in this study were not evident. The main effects of inter-row management were evidenced when comparing conventional tillage vs no tilling. Thus, conventional tilling accounted for increased pH and, consequently, decreased must acidity, and decreased water stress over the season, especially, when studying tillage on younger vineyards where it was beneficial to improve vine water and nutritional status in Napa Valley.

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