Effects of Various Vineyard Floor Management Techniques on Weed Community Shifts and Grapevine Water Relations

Kerri L. Steenwerth,[1] Arturo Calderón-Orellana,[1,2] Robert C. Hanifin,[1]
Chris Storm,[3] and Andrew J. McElrone[1]*

Abstract: Adoption of permanent cover crops and no-till systems is considered integral to achieving the California state air quality standards regulating airborne particulate matter, as indicated in Senate Bill 656. Imposition of such management techniques in a vineyard could create competition with vines for limited water resources. We evaluated the effects of cover crops that were either tilled or just mowed on vineyard floor composition, weed populations, vine water relations and growth, and fruit composition over three years within a mature commercial Merlot vineyard subjected to deficit irrigation in Lodi, San Joaquin Valley, California. The vineyard floor in this experiment supported resident vegetation that was tilled (standard grower practice), an oat cover crop, or a legume/oat cover crop. The two planted cover crops were either tilled or mowed (i.e., no-till). Biomass of cover crops, weeds, and legumes varied by year and treatment, but consistent effects among treatments were not observed. Weed species composition and cover segregated with the presence or absence of tillage rather than cover crop type and the weed species composition of the resident vegetation was distinct from those in the cover crop treatments. Some treatments, like 'Oats/Legumes + NoTill', 'Oats + NoTill', 'Oats/Legumes + Till', and 'Resident Vegetation + Till' reduced soil water content (Θ_v) in at least one of the three shallow soil layers spanning 0 to 30 cm, 30 to 60 cm, and 60 to 100 cm in 2008, and 'Oats/Legumes + NoTill' also dried the two upper layers in 2009, but these differences had no consistent influence on plant water status. Distinctions in Θ_v between years were attributed partly to the cessation of rainfall two months earlier in 2008 than in 2009, despite similar total annual quantities. Significant reductions in Θ_v imposed by the 'Oats/Legumes + NoTill' treatments reduced vine vegetative growth in two of three years, but these effects did not manifest in yield and fruit composition. Values for the Ravaz index for two of the three years indicate that the vineyard was overcropped for all treatments, but maximizing production in this region is a common practice. Weak competitive effects of the cover crops for water were likely associated with the use of a well-established mature vineyard and demonstrated that these management strategies could be employed to improve air quality to meet California air quality regulations with limited effects on vine water status and production.

Key words: legume, no-till, permanent cover crops, soil nitrogen availability, tillage, vineyards

Vineyard floor management includes a broad spectrum of cultural practices that produce important benefits for grapegrowers like improving soil organic matter content and aggregation, reducing weeds, managing nutrients and water, and enhancing biodiversity (Guerra and Steenwerth 2012). The selection of the most appropriate floor management practices for each vineyard must consider factors like vine age, soil type, management, climate, and temporal complementarity between vines and cover crops for resource acquisition to avoid potential drawbacks (Celette et al. 2008, Ripoche et al. 2010, Guerra and Steenwerth 2012). Among these techniques, winter cover cropping, with or without tillage, is widely practiced in California vineyards. While winter cover cropping can improve water holding capacity of shallow soils under nonirrigated conditions, cover crops can compete strongly for water and cause important reductions in yield, vegetative production, and nutrient concentrations, and can even change vine rooting patterns in Mediterranean climates with summer drought and autumn and winter rainfall (Van Huyssteen 1989, Ripoche et al. 2011, Guerra and Steenwerth 2012). For example, in a six-year-old, nonirrigated vineyard of Arenal on Fercal rootstock in Montpellier, France, the deeper rooting of a summer perennial grass led to the grapevines' use of soil water below the perennial grasses over four years (Celette et al. 2008); nitrogen reserves in these same grapevines were reduced compared to vines grown with an annual cover crop or no cover crop (Celette et al. 2009). In this same vineyard, impacts of newly established vineyard floor treatments on vine vegetative growth and yield were delayed for one to two years, but also depended on the preceding year's vineyard floor management practice (Ripoche et al. 2011). In an irrigated Merlot vineyard on 5BB rootstock in Sacramento, CA, the use of no-till, native annual grasses in winter led to a consistent reduction in pruning weights and slightly affected juice characteristics compared to a tilled cereal mixture, a tilled green manure mix, and a no-till clover mix, yet there

---

[1] USDA/ARS Crops Pathology and Genetics Research Unit, Davis, CA; [2] Department of Engineering and Soils, University of Chile, Chile; and [3] Vino Farms, Inc., Lodi, CA.

*Corresponding author (andrew.mcelrone@ars.usda.gov; tel: 530-754-9763; fax: 530-752-0382)

Acknowledgments: This research was funded by USDA-ARS Sustainable Viticulture Production Systems (Project 2032-21220-006-00, NP305 Crop Production). The authors thank C. Manuck, W. Collatz, and D. Sullivan for technical assistance.

Manuscript submitted Jun 2015, revised Aug 2015, Nov 2015, accepted Dec 2015

doi: 10.5344/ajev.2015.15050

were neither effects on fruit yields nor consistent effects on plant water status over three years (Ingels et al. 2005). However, in a six-year-old irrigated Merlot vineyard in Napa, CA, winter season vineyard floor treatments consisting of no-till annuals, no-till perennials, tilled annual grain, or a tilled control with no cover crop did not impact pruning weights, plant nutrition, or yield over a three year period, but notably, soil and vine water status were not assessed (Baumgartner et al. 2008). Competition between vines and cover crops for resource acquisition likewise emerges in more mature vineyards, as demonstrated by diminished growth in vegetative structures and fruit production in a 12-year-old own-rooted Chardonnay vineyard in New South Wales, Australia, in the third and fourth year of exposure to mown resident vegetation with either partial or complete floor coverage (Tesic et al. 2007). Together, these findings demonstrate that the choice to use irrigation and the corresponding soil water status, temporal and spatial complementarity between vine and cover crops, and duration of vine exposure to the respective floor management practice all influence the vine's response. While lower vegetative growth rates might be translated into reduced fruit shading and improved canopy aeration in vigorous vines in the Loire Valley, France (Morlat and Jacquet 2003, Tesic et al. 2007), excessive canopy openness during fruit development could expose berries to temperatures that might compromise quality. Although winter cover cropping in mature vineyards is gaining popularity among growers in California, the appeal may be less for those concerned about excessive competition for soil resources among cover crops and vines, especially under water-limited conditions.

Cover crops and tillage influence other key components of vineyard floor management (Guerra and Steenwerth 2012). Tillage can provide effective weed control and influence mineralization of cover crop residue and compost (Chauhan et al. 2006, Jackson 2000), but it can also lead to soil compaction and generation of particulate matter associated with air pollution (Baker et al. 2005). Although tillage may reduce potential competition between floor vegetation and the crop for limited resources like nutrients and water, it causes mineralization of inorganic nitrogen (N) from recently incorporated and protected soil organic matter within aggregates (Calderón et al. 2001). In turn, this reduces the soil's capacity to store organic nitrogen (N) for later mineralization and plant uptake (Steenwerth and Belina 2008a, 2008b). Changes in these soil attributes coupled with physical disturbance like tillage may be linked to observed shifts in seedbanks and weed communities in annual and perennial cropping systems (Chauhan et al. 2006, Baumgartner et al. 2008, Steenwerth et al. 2010).

No-till practices and cover crops have been promoted recently for their beneficial effects on minimizing dust production from vineyards to meet California regulations for air quality (Senate Bill 656), especially in the San Joaquin Valley where the current study occured, and as soil carbon storage to mitigate greenhouse gas emissions to meet goals of Assembly Bill 13, the Global Warming Solutions Act of 2006 (Steenwerth and Belina 2008a, 2008b). Despite these benefits, there are tradeoffs associated with these practices on weed community composition, and potential competition between permanent vineyard floor vegetation and the vines for water and nutrients may occur. Here, we ask how tillage and cover crop selection affect vineyard weed communities and whether the anticipated changes in weed communities lead to changes in soil water and nitrogen concentration. We then examined whether vine water stress correlated to differences in cover crop, weed biomass, and associated shifts in soil and weed attributes among treatments.

Materials and Methods

Site description. The study site was conducted in a commercial Merlot vineyard (clone 3 on 110R rootstock) originally planted in 1995 (15.5 ha, 3.1 m between vine rows × 2.1 m between vines, width of floor management treatment centered between the vine rows was 2.5 m) within the Lodi American Viticultural Area, just east of Lodi and north of Lockeford, San Joaquin County, CA (lat. 38°11′43″N; long. 121°08′59″W). Mean daily high and low temperatures were as follows: 13.6 and 3.35°C in winter, 22.8 and 7.4°C in spring, 32.4 and 13.1°C in summer, and 24.8 and 8.0°C in autumn, respectively, in 2008 to 2010. Average annual precipitation was 443 mm (1999 to 2008); annual precipitation during the study was 321 mm in 2008, 354 mm in 2009 and 468 mm in 2010 (see Table 1 for monthly totals). The vineyard was composed of two soil types: San Joaquin series (fine, mixed, thermic Abruptic Durixeralf) and Exeter series (fine-loamy, mixed, thermic Typic Durixeralfs). The series both have 0 to 2% slopes, a thick surface, and a duripan that was disrupted through deep ripping to 1.5 m prior to vineyard establishment. Soil characteristics from April 2008 (n = 40) were as follows: total N concentration by combustion: 0.10%; total carbon by combustion: 1.03%; Olsen phosphorus (P): 18.72 µg/g; exchangeable or X-potassium (K): 0.58 cmolc/kg;

Table 1 Total monthly precipitation as rainfall (mm) per water year from October 2007 through the conclusion of the experiment in September 2010.

	Precipitation (mm)[a]		
Month	**2008**	**2009**	**2010**
October[b]	13.72	21.34	78.49
November[b]	23.11	35.31	12.45
December[b]	67.06	45.21	61.21
January	178.05	49.78	103.89
February	36.58	108.97	88.14
March	2.03	43.18	45.72
April	0.51	23.37	67.31
May	0.00	26.92	10.41
June	0.00	0.00	0.00
July	0.00	0.00	0.00
August	0.00	0.00	0.25
September	0.00	6.10	0.25
Total	321.06	360.18	468.12

[a] Data collected by the California Irrigation Management Information System, San Joaquin Valley, Lodi west, station number 166.

[b] October, November, and December are in the preceding year. So, for "2008," these months are in 2007, as the water-year spans 1 Oct to 30 Sept.

X-sodium (Na): 0.02 cmolc/kg; X-calcium (Ca): 7.23 cmolc/kg; X-magnesium (Mg): 0.81 cmolc/kg; and cation exchange capacity: 10.59 cmolc/kg. Texture was 53.3% sand, 32.0% silt, and 14.7% clay (Steenwerth et al. 2013). The vine rows ran east to west and vines were trained to bilateral cordons and trellised with two-wire vertical shoot-positioning. Data vines were pruned to two buds per spur, with 12 to 14 spurs per vine. Vine rows (0.6 m width) were kept free of weed growth with herbicide applications. Nutrient, pest, and resident vegetation management were conducted according to current commercial practices. See Steenwerth et al. (2013) for a complete description of vineyard management practices.

Experimental design and treatment descriptions. The experimental design was a randomized complete block with four blocks, each consisting of two treatment replicates per block. Each block was ~400 m east to west, with 190 vines per row and 12 vine rows per block. Treatment replicates were composed of two adjacent alleys on either side of a vine row. Ten adjacent data vines per replicate were sampled for attributes described below (n = 8 total replicates per treatment). When the study was initiated, all treatments were disked (ca. 0 to 20 cm), rolled, and the respective cover crops were planted into these prepared seedbeds. Cover crops were planted by a drill seeder in early November each year (112 kg seed/ha). The reference treatment consisted of resident vegetation (RV) that was allowed to grow during the winter rainy season (RV + Till). Cover crop treatments were either 'Dusky' oats (*Avena sativa*) (Oats) or a mixture of 'Dusky' oats and legumes (Oats/Legumes: 37% oats, 28% Fava bean (*Vicia faba*), 10% common vetch (*Vicia sativa*), and 25% Magnus peas (*Pisum sativum*)). The cover crops were mown and tilled (Oats + Till, Oats/Legumes + Till) or just mown (Oats + NoTill, Oats/Legumes + NoTill) in the spring prior to budbreak (April). The tilled treatments were disked and rolled three times each summer according to the grower-cooperator's typical practices, and once each October prior to planting the cover crops.

Vines were deficit-irrigated by supplying 60 to 70% of vineyard evapotranspiration (ET_c) each season, following standard sustained deficit irrigation practices (Williams et al. 2010). Weekly ET_c values were calculated using crop coefficients (K_c) and daily reference evapotranspiration (ET_0), according to the following equation:

$$ET_c = K_c \times ET_0 \quad \text{Eq. 1}$$

Crop coefficients were estimated on a weekly basis from the relationship between percent shaded area measured beneath the canopy at solar noon (Williams and Ayars 2005). Daily values for reference evapotranspiration (ET_0), relative humidity, air vapor pressure, and precipitation were obtained from the nearest California Irrigation Management Information System weather station to the experimental site (Station LODI-01.P, Jahant Rd., San Joaquin County; lat. 38°12′N; long. 121°19′W). Vapor pressure deficit was calculated as the difference between saturated air vapor pressure and air vapor pressure. The sustained deficit irrigation strategy was coordinated with the vineyard manager. Stem water potentials (Ψ_{STEM}) were measured every two to three weeks in 2008 and every two weeks in 2009 to track the water stress of the vines and to determine any treatment contributions to vine water stress. Ψ_{STEM} was measured according to standard methods as described (Williams and Araujo 2002).

Soil analysis and plant community assessment. Plant species composition was assessed annually in April. Permanent transects (40 m) in the middle of the alleys were set up within each treatment replicate to measure the weed community. All sample collection and field measurements were taken from the middle of the alley. A 10 pin frame was used in a variant of the point intercept method to estimate the abundance of individual species. The frame was placed at four meter intervals in the middle of the alley and each pin was dropped vertically (i.e., 10 frames per transect). Plant species contacted by the pins were recorded, including bare soil if no plants were present (Table 2). To estimate percent plant cover in the alley in April, annually, a quadrat (1 m × 1 m, 36 intersecting points) was held parallel to the ground at one meter height and the proportion of intersecting points covering vegetation or bare ground was recorded. Subsequent measurements were not made as plant regrowth is typically minimal due to lack of precipitation.

Mean aboveground biomass was collected annually in April from three subreplicates (0.5 m × 0.25 m quadrats) along each transect (n = 4 replicates per treatment). Plant biomass of each subreplicate was sorted by oats, planted legumes, and weeds, then dried at 60°C for 72 hr. After weighing, total C and N concentrations of oats, legumes, and weeds were determined by combustion (Pella 1990). Species richness (S), diversity (Shannon's diversity index, H'), and evenness (E) were calculated from the frequency data collected in each treatment replicate (PCORD 6, Ludwig and Reynolds 1988; Table 3). The treatment with the highest value for H' has a higher S, has more species present in equal abundance than the other treatments, or both. Cover crops were not included so as not to alter E, S, or H' artificially.

Gravimetric water content (Θ_g), inorganic N pools (NH_4-N and NO_3-N), and potential net mineralizable N (PMN) were measured annually from each transect in April of 2008 to 2010. Soil cores from five locations along each transect were combined, mixed, and placed on ice in the field. For Θ_g, soil (100 g) was dried at 105°C for 48 hr. Potential net N mineralization, an assay of soil N availability, was measured by anaerobic incubation at 40°C for seven days (Waring and Bremner 1964, Soon et al. 2007). Soil NH_4-N and NO_3-N pools were extracted with 2 M KCl with a 5:1 ratio of KCl to soil. NH_4-N and NO_3-N were determined by colorimetric analysis (Kempers and Kok 1989, Miranda et al. 2001).

Vine and vine row measurements. Volumetric soil water content (Θ_v) was measured either weekly or biweekly during the growing season via frequency domain reflectometry (DIVINER 2000), and in most cases coincided with grapevine stem water potential measurements. Access tubes for the Diviner 2000 were placed in the data vine row adjacent to the permanent transects used to assess the vineyard floor plant community. They were placed midway between two vines and not directly underneath drip irrigation emitters (3.8 L/hr).

Measurements were only taken in 2008 and 2009 due to lack of personnel resources in 2010. Θ_v was obtained every 10 cm between 10 and 110 cm deep from two subreplicate tubes per treatment-replicate. Means from each subreplicate were calculated for each treatment-replicate for the depths 0 to 30 cm, 30 to 60 cm, and 60 to 110 cm (n = 8). Θ_v readings of the Diviner were calibrated against Θ_g, calculated from soil samples collected from corresponding depths in rows adjacent to the Diviner tubes and the 40 m transect (data not shown). Soils were combined by depth, mixed, and a 100 g subsample was dried (105°C, 48 hr) to determine Θ_g. Yields at harvest and pruning weights in the dormant season were collected from each of 10 data vines for each treatment replicate. However, because the commercial grower pruned the vines prior to data collection, no data for the baseline growth from 2007 growth season are available.

An earlier study (Steenwerth et al. 2013) examined the impacts of these same vineyard floor management practices on grapevine nutrition at this location and so these data are not formally presented here.

Statistical analysis. Canonical correspondence analysis (CCA) was used to evaluate treatment effects on weed community structure (ter Braak 1987, Baumgartner et al. 2007, Lepš and Šmilauer 2003). Treatments were treated as independent variables, species frequency as dependent variables, and years and blocks as covariables (Baumgartner et al. 2008). Analysis was based on weed species frequency present in >10% of samples. Cover crops were run as supplementary species (Lepš and Šmilauer 2003). Analyses were performed in CANOCO4.5 with axis scores centered to interspecies distances and biplot scaling (Lepš and Šmilauer 2003). Reduced model permutation testing was then used to determine the significance of the main effect of treatment. Automatic forward selection with Monte Carlo permutation tests was used to determine the significance of the treatments. Treatment centroids and canonical coefficients for the species are presented in biplots (Figure 1). Proximity of a species score to a treatment centroid signifies that the species had the highest relative abundance in that treatment and was important in distinguishing that treatment from other treatments.

Table 3 Shannon's diversity (H'), evenness, and richness indices of weed community by treatment (n = 8).

Treatment[a]	Richness	H´	Evenness
RV + Till	10.2 a[b]	1.8 a	0.77 a
O + Till	6.9 b	1.4 b	0.74 ab
O + NoTill	6.3 b	1.2 b	0.73 ab
O/L + Till	6.2 b	1.3 b	0.67 b
O/L + NoTill	6.5 b	1.2 b	0.67 b

[a] RV: Resident vegetation; O: Dusky oats; O/L: Oats and legumes.
[b] Letters indicate mean separation as determined by differences of least square means ($p < 0.05$).

Table 2 Plant species found among the vineyard floor treatments.

Common name	Bayer Code	Family	Form	Latin Name
'Dusky' oats[a]	AVESA	Poaceae	Graminoid	*Avena sativa*
Fava bean[a]	VICFA	Fabaceae	Forb	*Vicia faba*
Common vetch[a]	VICSA	Fabaceae	Forb	*Vicia sativa*
Pea[a]	PSSAT	Poaceae	Forb	*Pisum sativum*
Annual bluegrass	POAAN	Poaceae	Graminoid	*Poa annua* L.
Bermuda grass	CYNDA	Poaceae	Graminoid	*Cynodon dactylon* (L.) Pers.
Burclover	MEDPO	Fabaceae	Forb	*Medicago hispida* Gaertn. var. *apiculata* (Willd.) Urb.
Common fiddleneck	AMSME	Boraginaceae	Forb	*Amsinckia menziesii* (Lehm.) A. Nelson & J.F. Macbr. var. *intermedia* (Fisch. & C.A. Mey.) Ganders
Common chickweed	STEME	Caryophyllaceae	Forb	*Stellaria media* (L.) Vill.
Desert rock purslane	CLNCM	Portulacaceae	Forb	*Calandrinia ciliata* (Ruiz & Pav.) DC.
Hare barley	HORMC	Poaceae	Graminoid	*Hordeum murinum* L. ssp. *leporinum* (Link) Arcang.
Leafy spurge	EUPHES	Euphorbiaceae	Forb	*Euphorbia esula* L.
Miner's lettuce	MONPER	Portulacaceae	Forb	*Claytonia perfoliata* Donn ex Willd. ssp. *perfoliata*
Pannicle willowherb	EPIPC	Onagraceae	Forb	*Epilobium brachycarpum* C. Presl
Prickly lettuce	LACSE	Asteraceae	Forb	*Lactuca serriola* L.
Rattail fescue	VULMYU	Poaceae	Graminoid	*Vulpia myuros* (L.) C.C. Gmel.
Redstem filaree	EROCIC	Geraniaceae	Forb	*Erodium cicutarium* (L.) L'Hér.
Ripgut brome	BRODI	Poaceae	Graminoid	*Bromus diandrus* Roth ssp. *rigidus* (Roth) Lainz
Shepherd's purse	CAPBP	Brassicaceae	Forb	*Capsella bursa-pastoris* (L.) Medik.
Soft brome	BROMO	Poaceae	Graminoid	*Bromus hordeaceus* L.
Sowthistle	SONCSP	Asteraceae	Forb	*Sonchus* sp.
Toad rush	IUNBU	Juncaceae	Graminoid	*Juncus bufonius* L.
Wild oat	AVEFA	Poaceae	Graminoid	*Avena fatua* L.
Wild radish	RAPRA	Brassicaceae	Forb	*Raphanus raphanistrum* L.
Italian ryegrass	LOLMU	Poaceae	Graminoid	*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot
Bare soil	BARE	n.a.[b]	n.a.	n.a.

[a] Species planted as cover crops.
[b] n.a., not applicable.

Analysis of variance (ANOVA) was used to determine the effects of treatment and year on weed and cover-crop biomass; species richness; evenness and diversity; stem water potential; and Θ_v (SAS, v. 9.3). ANOVA also was used to analyze sample scores for treatment effects. ANOVAs were performed using the MIXED procedure with Kenward–Roger as the denominator degrees-of-freedom method (Littell et al. 1996). Year was considered a repeated measure, block and block interactions were random effects, and treatment, year, and treatment × year were fixed effects. To model variable correlation across year, the covariance structure was compound symmetry, chosen based on Akaike information criterion. Where interactions existed, multiple comparisons were made using differences of least square means.

Results and Discussion

Plant community composition. We hypothesized that shifts in weed communities could be related to the presence or absence of tillage and cover crops. Not surprisingly, weed community composition varied by vineyard floor treatment, yet only 26.5% of the variation in weed community composition among samples was represented by Axis 1 and 2 in the CCA (Figure 1, Table 2). This segregation pattern among vineyard floor treatments along Axis 1 indicates that plant communities in tillage treatments were distinct from mown treatments, regardless of cover crop type. The presence of a cover crop, regardless of whether it is a legume, also shifts the weed community composition, as indicated by the isolation of Till + RV from all other treatments along Axis 2.

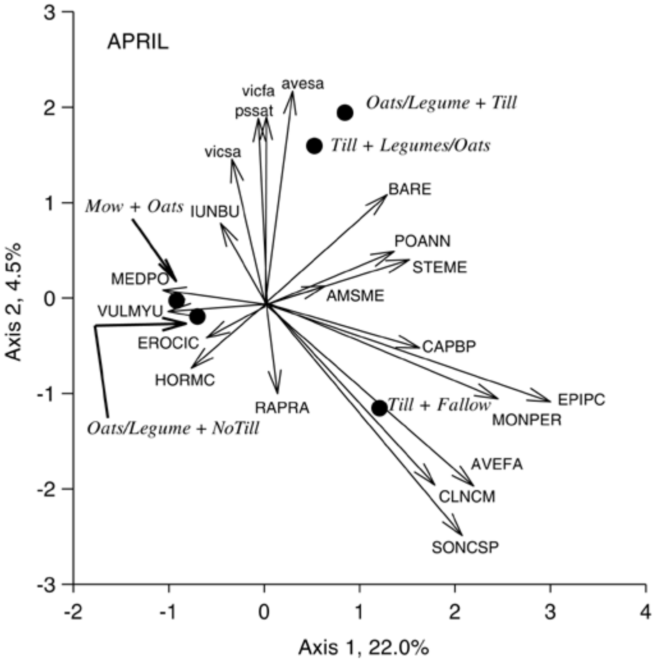

Figure 1 Canonical correspondence analysis of weed species frequency in April. Year and block served as covariables to determine effect of vineyard floor treatment on weed community composition. Cover crop species are written in lower case and were run as supplementary variables so as to remove their influence on the ordination of weed species. Refer to Table 2 for a key to the Bayer codes. Percentage of species variance represented by each axis is indicated by values next to labels Axis 1 and Axis 2.

Weed species that segregated to the side of Axis 1 with the three tilled treatment centroids or the two mown treatment centroids are in greater abundance in those respective treatments (Figure 1). Till + RV had greater abundance of wild oat (*Avena fatua* L.), miner's lettuce (*Claytonia perfoliata* Donn ex Willd. ssp. *perfoliata*), shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.), desert rock purselane (*Calandrinia ciliata* (Ruiz & Pav.) DC.), and panicle willowherb (*Epilobium brachycarpum* C. Presl.). Of these, panicle willowherb is of greatest concern as it can interfere with winegrape harvest activities due to its tall stature when mature and flowering (Baumgartner et al. 2007). Oats + Till and Oats/Legumes + Till were associated with greater abundance of common chickweed (*Stellaria media* (L.) Vill.), annual bluegrass (*Poa annua* L.) and bare soil (BARE). The abundance of burclover (*Medicago hispida* Gaertn. var. *apiculata* (Willd.) Urb.), rattail fescue (*Vulpia myuros* (L.) C.C. Gmel.), and redstem filaree (*Erodium cicutarium* (L.) L›Hér.) was consistently greater in the two no-till treatments, Oats + NoTill and Oats/Legumes + NoTill, than in the tilled treatments. Burclover is sensitive to tillage, preferring a no-till treatment in a Napa vineyard (Baumgartner et al. 2008), but growers often express concerns about burclover as it tends to wrap around tillage implements in vineyards (J. Roncoroni, personal communication).

Despite the lower intensity of tillage in the vineyard compared to annual cropping systems, tillage does influence the composition of weed communities, even after just three years of study. In part, this effect may be attributed to changes in the seedbank and germination environment. Tillage affects the depth of seedling recruitment by homogenizing their vertical distribution and increases temperature at greater depths (Anderson et al. 1998, Sosnoskie et al. 2006), whereas no-till systems have a more shallow depth of recruitment and seeds that remain on the surface are exposed to diverse conditions that decrease or increase germination, depending on the species (Chauhan et al. 2006, Soriano et al. 1968). Even after just three years, effects of cultivation versus herbicide application for weed control under the vine were evident in seed distribution in seedbanks from a vineyard in Napa, CA (Steenwerth et al. 2010), suggesting that the current study's three year duration would be sufficient to affect seedbank within mown or tilled treatments.

Shannon's diversity index (H'), evenness, and richness differed by treatment only ($p < 0.05$; Table 3). H' and richness were lower in all four treatments with cover crops than in Till + RV. Evenness in Till + RV was greater than in either Oats/Legumes + Till or Oats/Legumes + NoTill. The remaining two vineyard floor treatments planted to just oats did not differ from the other treatments. These findings suggest that the presence of cover crops can decrease weed community diversity, evenness, and richness, similar to observations by Smith et al. (2015), who suggest that cover crop types and relatively higher biomass production both facilitated changes in weed community structure and composition. While not examined in the current study, decreases in these indices are also implicated in diminished seed predation by beneficial arthropods in a vineyard within California's Central Coast

(Sanguankeo and León 2011), although the richness values in the current study are similar to the lowest values observed in the herbicide treatment in that study and 3-fold lower than their highest values in their cover crop treatment. The lack of tillage's consistent effect on these indices is distinct from previous studies, in which more intensively managed annual agricultural systems typically demonstrate decreased diversity compared to low-input, no-till counterparts (Barberí and Mazzoncini 2001, Hyvönen and Salonen 2002, Mas and Verdù 2003, Ngouajio and McGiffen 2002).

Vineyard floor biomass and vineyard N status. The observed shift in weed community composition and differences in diversity, evenness, and richness among treatments did not correspond to consistent effects of treatment on vineyard floor biomass and indicators of plant and soil N status. Total plant biomass and its individual components of oat, legume, and weed biomass varied by year and floor treatment (treatment × year, $p < 0.0001$). Plant biomass did not differ among cover crop treatments in 2008, but the tilled treatments typically were greater in 2009 and 2010 (Steenwerth et al. 2013). The one exception was in 2010, when RV + Till had 2- to 3-fold less plant biomass than the other tilled treatments. In some instances, percent cover differed among treatments, but was not consistent annually (data not shown). Annual differences in biomass production and cover can partly be attributed to differences in precipitation, which varied 1.5-fold from 2008 to 2010.

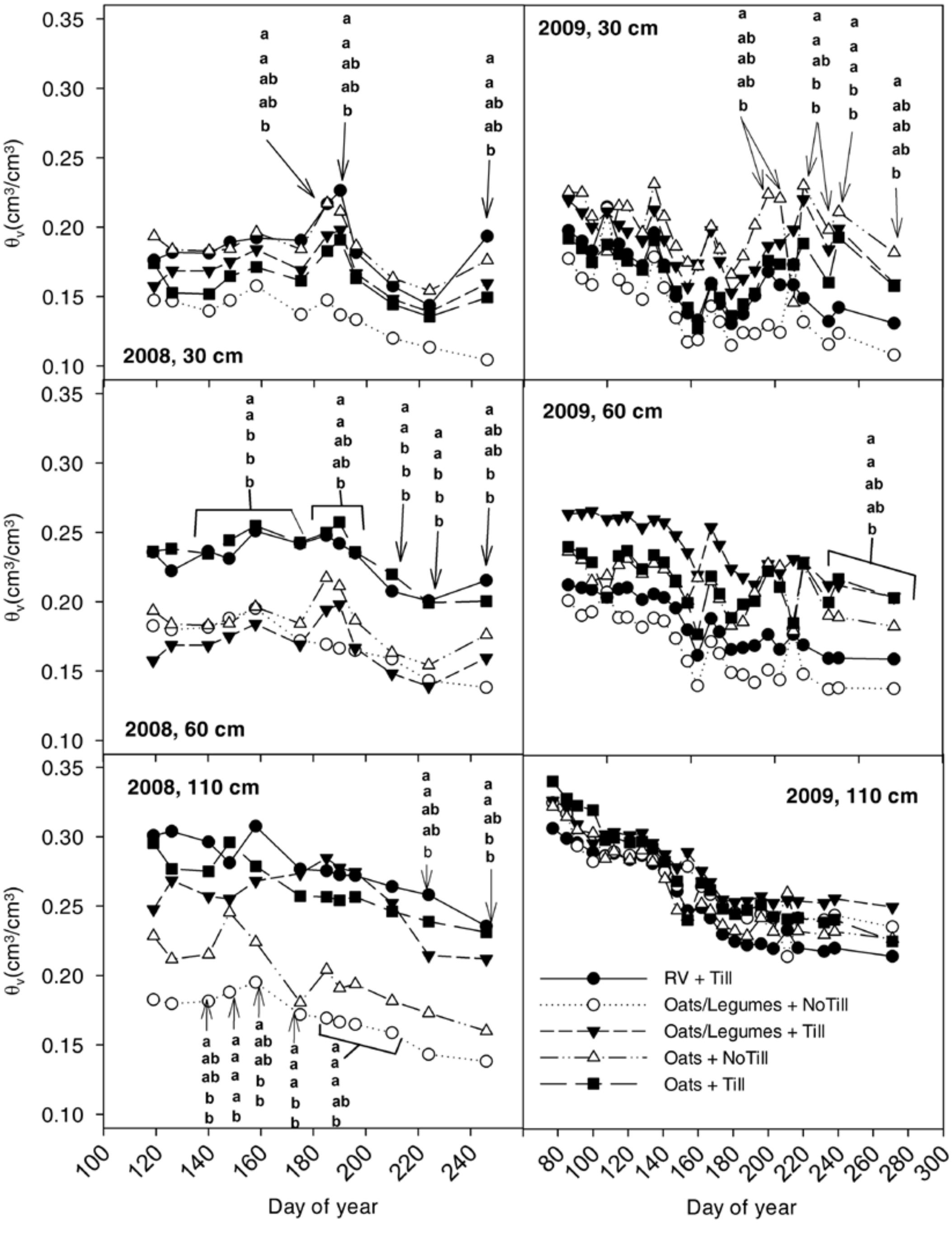

Figure 2 Seasonal pattern of soil water content (Θ_V) of plots subjected to vineyard floor management treatments in 2008 and 2009 from 0 to 30 cm, 30 to 60 cm, and 60 to 110 cm depth (n = 8). Letters indicate significance according to differences of least square means ($p < 0.05$). The descending order of the letters corresponds to the vertical placement of points for treatments on that date.

Mean total N in the aboveground biomass was greater in treatments with leguminous cover crops than in the other three treatments (total N in aboveground biomass, g N/m^2, x ± SE, n = 12; RV + Till: 9.30 ± 0.64; Oats + Till: 10.10 ± 0.60; Oats/Legumes + Till: 15.86 ± 0.87; Oats + NoTill: 12.46 ± 1.10; Oats/Legumes + NoTill: 14.99 ± 0.75; treatment $p < 0.05$). Of the individual components (oats, legumes, and weeds), only weed C:N ratios were distinguished by the presence or absence of tillage. C:N ratios in aboveground weed biomass varied among treatments ($p < 0.05$), such that RV + Till (24.53 ± 0.99), Oats + Till (24.33 ± 1.99), and Oats/Legumes + Till (21.73 ± 0.87) were greater than Oats + NoTill (18.00 ± 0.67) and Oats/Legumes + NoTill (19.85 ± 1.04), suggesting that returning fresh plant matter to the soil by tillage made N more readily available for uptake by the vineyard floor vegetation during the subsequent season. Surprisingly, soil inorganic N pools (NH_4-N and NO_3-N) and PMN did not differ among treatments and thus did not reflect these differences in aboveground N concentration or C:N ratios (data not shown). However, treatment effects on inorganic N pools would not necessarily be expected, as these pools turn over on a scale of hours to days (Burger and Jackson 2003). PMN only differed by year ($p < 0.05$ as μg NH_4-N/g/wk; in February: 26.88 to 32.68 in year 1, 33.28 to 39.57 in year 2, and 29.31 to 34.48 in year 3; in April: 44.62 to 50.97 in year 1, 23.68 to 26.71 in year 2, and 34.43 to 38.01 in year 3), suggesting that annual variation in climate and/or annual plant biomass production influenced PMN more than vineyard floor treatment in this study. Furthermore, soil N availability, or PMN, depends on soil organic N concentration, the accumulation of which can take longer than the three-year duration of this study (Steenwerth and Belina 2008a, 2008b). However, petiole NO_3-N differed by growth stage (bloom, veraison, harvest) among vineyard floor management treatments within years and its concentrations in the tilled treatments was twice that of no-till treatments, suggesting a possible temporal offset between soil N availability and plant uptake related to the vineyard floor management practices (Steenwerth et al. 2013). Although treatment differences in pruning weight were not detected in the current study, decreased nitrate uptake due to low soil water content could lead to low vegetative growth and petiole nitrate concentrations (Celette et al. 2009).

Soil and plant water status. Despite distinctions in vineyard floor plant community composition and diversity with or without tillage, the vineyard floor management treatments had inconsistent annual effects on the Θ_v across each growing season (Figure 2). Furthermore, Ψ_{STEM} decreased over the growing season in each year, but no distinctions among treatments occurred (Figure 3). Differences in Θ_v typically occurred toward the end of each growth season in 2008 and 2009 (Figure 2), although differences occurred more frequently in 2008 than 2009. Oats/Legumes + NoTill, Oats + NoTill, and Oats/Legumes + Till reduced Θ_v in at least one of three soil layers in 2008 and Oats/Legumes + NoTill in the two upper layers in 2009, but these differences had no consistent influence on plant water status. The temporal and spatial patterns of Θ_v may be attributed, in part, to the cessation of rainfall two months earlier in 2008 than in 2009 despite similar annual quantities (Table 1), leading to treatment differences both earlier in the season and at deeper soil depths. Of note, the Oats/Legumes + NoTill plots consistently exhibit the lowest Θ_v across all measured depths in 2008 and in the two upper

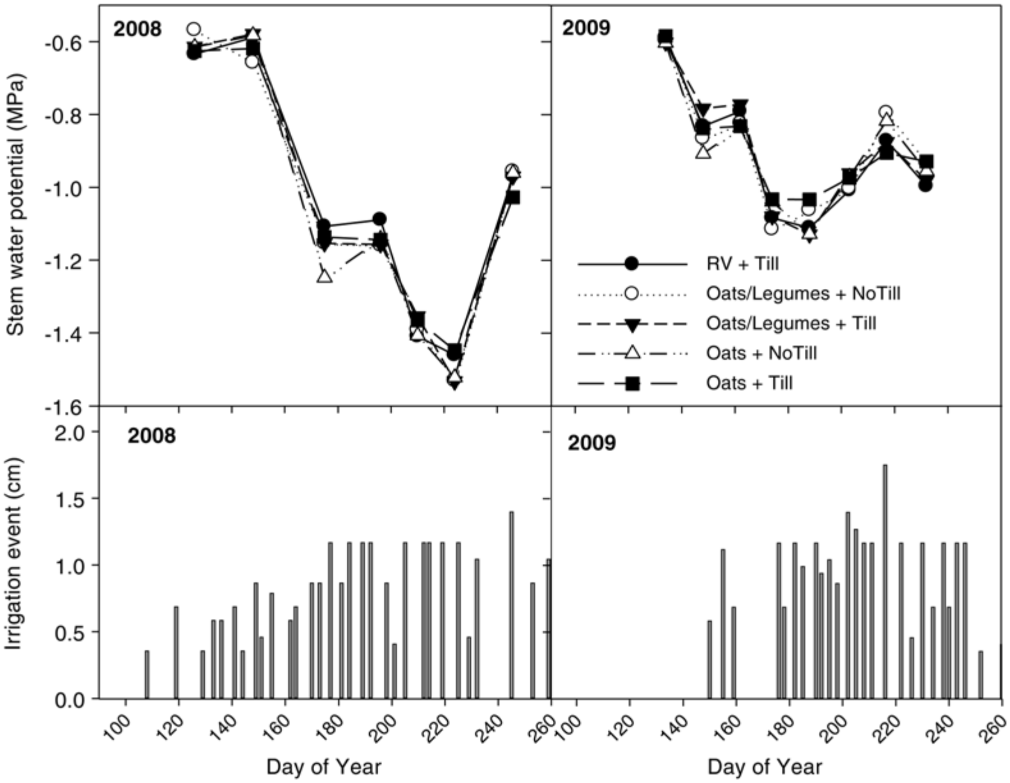

Figure 3 Midday stem water potential of vines from plots subjected to floor management treatments in 2008 and 2009. Each data point represents the mean of three leaves from each of eight replicated blocks (n = 8). The two lower panels indicate irrigation events in 2008 and 2009. In 2008, four irrigation events in the total amount of 2.66 cm occurred after Day of Year 260 (8 Sept and 8, 23, and 29 Oct). In 2009, six irrigation events in the total amount of 5.64 cm occurred after Day of Year 260 (20, 23, and 29 Sept and 7, 14, and 20 Oct).

depths in 2009. The 30 to 60 cm depth has been documented as a zone of high grapevine root biomass, and thus potentially an active zone of water uptake (Morlat and Jacquet 2003, Smart et al. 2006). In 2008, the no-till treatments had consistently lower Θ_v than the tilled treatments at nearly all depths ($p < 0.05$). This cannot be attributed to greater aboveground biomass: no differences occurred among treatments in 2008 and only Oats + Till had greater biomass than the other four treatments in 2009 (Steenwerth et al. 2013). Instead, we suggest observed regrowth of the cover crops in the no-till treatments (~20% cover) through May could have contributed to depleting soil moisture later in the season, but cover crops were senescent from June until after harvest.

Effects of vineyard floor treatments on Θ_v were not associated with significant effects on plant water status as measured by Ψ_{STEM} (Figure 3). A similar lack of influence of cover crops on vine water status was reported previously (Morlat and Jacquet 2003). The lack of a relationship between Θ_v and Ψ_{STEM} may indicate that the depths we measured for Θ_v do not reflect the depths from which the vines are accessing water or that water uptake by cover crops and vines occurred at different depths. In fact, grapevine roots can be spatially distinct from, or distributed below, roots of permanent cover crops (Van Huysteen 1988, Morlat and Jacquet 2003). Establishment of these vineyard floor treatments in a well-established and mature Merlot vineyard may also be expected to result in minimal water stress because a well-established grape root system can access Θ_v at greater depths than measured here (Figure 2, Singleton and Maudsley 1996). In 2008 and 2009, the soil water content at 110 cm also decreased significantly over the growth season (more drastically in 2009), but Ψ_{STEM} values stayed ≥-1.2MPa, suggesting that the vines may have compensated for diminished available water content in the two upper depths by using water at the lower depth, thereby masking any effect of vineyard floor treatment on stem water potential. Other reasons for lack of a strong effect of vineyard floor treatments on Θ_v include temporal and spatial complementarity between the vine and cover crop. Temporal complementarity can occur because the period of intense water uptake by the intercrop (winter-spring) often happens earlier than for the vine (spring-summer-to harvest) (Celette et al. 2008). Spatial complementarity can happen in arid climates and drip-irrigated vineyards, as fine roots tend to concentrate in the dripzone where water is easily accessible, while the surrounding dry soil may impede new root growth (Stevens and Douglas 1994). In this context, soil water content also may not reflect vine water uptake, as it was measured between vines and not directly in the dripzone.

Growth of plant tissues is often the first trait impacted by water stress and is associated with decreased cell turgor and expansion (Kramer and Boyer 1995, Hsiao 1973). Despite the absence of significant effects of the vineyard floor treatments on plant water status (Figure 3), yield and Ravaz index were impacted by vineyard floor treatment, but only in 2010 ($p < 0.05$, Table 4). Oats/Legumes + NoTill had the highest yield and Ravaz index, but overall, no consistent effect of cover crop or tillage practice on yield, Ravaz index, or mean cluster weight was evident among treatments (Steenwerth et al. 2013). Impacts of vineyard floor treatments on yield, Ravaz index, and mean cluster weight could have been delayed, as differences were only observed in 2010. Impacts of newly established vineyard floor practices on vine vegetative growth and yield in a dry-farmed vineyard were delayed from one to two years after establishment (Ripoche et al. 2011). These impacts on vegetative and fruit parameters were attributed to reduced soil and tissue N concentrations and a more negative predawn leaf water potential due to competition from summer perennial grass cover compared to bare soil. In the current study, no reductions in vegetative growth were detected by treatment, and yield did not correspond to treatment differences in Θ_v; petiole nitrate concentrations at bloom, veraison, and harvest; or soil N availability from the preceding year (Steenwerth et al. 2013).

Effects of the vineyard floor treatments on fruit characteristics like berry chemistry and size were not evident, varying by year only, except for titratable acidity in 2008 (Table 5). Changes in vegetative and fruit parameters in response to permanent cover crops were more apparent when vine water status indicated high water stress (Ripoche et al. 2011, Celette et al. 2008, 2009). In the current study, there was no effect of vineyard floor treatment on stem water potential, likely

Table 4 Mean values of pruning weight, pruning weight per row length and Ravaz index from plots subjected to vineyard floor management treatments from 2008 to 2010[a] (n = 8).

Year/ treatments[b]	Pruning weight/ row length (kg/m)[c]	Yield (kg/m)	Ravaz index (kg/kg)[d]
2008			
RV + Till	0.45	6.2	14.1
O + Till	0.38	5.9	15.3
O + NoTill	0.40	6.8	14.2
O/L + Till	0.40	6.1	16.2
O/L + NoTill	0.35	5.6	16.3
2009			
RV + Till[d]	0.35	8.8	26.1 a[e]
O + Till	0.29	9.2	33.1 b
O + NoTill	0.28	8.5	31.3 b
O/L + Till	0.31	9.0	30.0 b
O/L + NoTill	0.32	8.1	25.8 a
2010			
RV + Till[d]	0.52	5.1 a	9.9 a
O + Till	0.46	3.9 b	8.7 a
O + NoTill	0.48	4.9 a	10.1 a
O/L + Till	0.44	4.3 b	9.9 a
O/L + NoTill	0.46	6.0 c	13.6 b

[a] The grower-collaborator had pruned the vines before data collection could occur for the baseline measurement representing growth from 2007.

[b] RV: resident vegetation; O: dusky oats; O/L: oats and legumes.

[c] Pruning weight differed only by treatment by ANOVA, where RV + Till differed from all other treatments ($p < 0.05$). No differences among other treatments were detected by differences of least square means ($p < 0.05$).

[d] Ravaz index compares the mean yield from harvest to mean pruning weight of the subsequent dormant season.

[e] Letters indicate mean separation within year as determined by differences of least square means ($p < 0.05$).

because vines were irrigated regularly and typically maintained Ψ_{STEM} above -1.2MPa (except two dates in 2008, Figure 3), and because temporal and spatial complementarity can occur between vines and dormant-season cover crops as discussed earlier (Stevens and Douglas 1994, Celette et al. 2008, 2009).

Under these circumstances, preference should be given to treatments that promote soil conservation and optimal nutritional status of the vine. Ensuring senescence of the cover crop or multiple passes with the mower could alleviate any potential negative effects of cover crop regrowth on Θ_v, especially in the no-till management strategy. Cover crop regrowth can have a strong impact on water use of the vineyard system. In a two-year old Sangiovese vineyard, there was a 35 to 49% reduction in evapotranspiration immediately after mowing the cover crop of *Festuca arundinacea* var. *barfelix*, but this reduction in ET diminished with cover crop regrowth (Centinari et al. 2013).

A contributing factor to the lack of effect of vineyard floor management practices on the grapevine is that the vineyard was overcropped, especially in the second year, as indicated by the Ravaz index (Table 4; Steenwerth et al. 2013). This may have masked responses to these treatments. The high values for the yield and Ravaz index, especially in the second year, are indicative of this commercial vineyard's management goal of high yields per hectare. In this same growing region, yields between 17.7 and 30.2 kg/vine on six-year old irrigated Merlot on 5BB (2.1 m between vines) were reported in cover-cropped, disked vineyard floor treatments (Ingels et al. 2005). According to the Crush Report for 2014, ~21.7 metric tonnes per hectare were produced from vineyards in San Joaquin County, which includes Lodi, compared to 8.6 metric tonnes per hectare in Napa County (NASS 2014a, 2014b). This is a common practice in this winegrape production region, as the price per tonne can be a magnitude of order lower than in many other California regions (C. Storm, personal communication 2010, NASS 2014a, 2014b).

Table 5 Mean values for fruit characteristics for vines from plots subjected to five vineyard floor management treatments from 2008 to 2010 (n = 8).

Year/ treatment[a]	Brix[b] (°)	pH[b]	Titratable acidity (mg/L)	Berry wt/ 100 berries[b] (g)	Sugar/ 100 berries[b] (g)
2008					
RV + Till	24.8	3.57	6.83 a[c]	127.10	31.5
O + Till	24.5	3.53	5.93 b	124.51	30.5
O + NoTill	24.6	3.56	5.60 b	124.26	30.6
O/L + Till	24.5	3.57	5.74 b	125.10	30.6
O/L + NoTill	24.8	3.55	6.62 a	125.14	31.0
2009					
RV + Till	23.2	3.42	5.82	133.10	30.9
O + Till	23.2	3.39	5.51	134.61	31.2
O + NoTill	23.7	3.40	5.82	134.19	31.8
O/L + Till	23.4	3.43	5.66	133.37	31.2
O/L + NoTill	23.7	3.39	5.57	140.02	33.2
2010					
RV + Till	23.2	3.27	6.51	110.68	25.6
O + Till	22.9	3.29	6.34	113.23	26.0
O + NoTill	22.9	3.26	6.13	108.62	24.9
O/L + Till	23.0	3.27	6.43	107.46	24.7
O/L + NoTill	23.2	3.26	6.21	111.44	25.9

[a] RV: resident vegetation; O: dusky oats; O/L: oats and legumes.

[b] Brix, pH, and berry weight per 100 berries differed by year ($p < 0.05$). Sugar per berry differed by year and by treatment ($p < 0.05$). They did not have significant interaction for year by treatment, and so no delineation of significance is indicated.

[c] Letters indicate mean separation within year as determined by differences of least square means ($p < 0.05$).

Conclusion

The outcome of this study demonstrated that changes in weed community composition in response to tillage and cover cropping were not associated with increased competition with grapevines. This was evident through the lack of vine water stress, little to no effects on juice characteristics, nutrition parameters, or vine vegetative growth, and inconsistent effects on yield and Ravaz index, despite distinctions in soil water content among treatments. Nonetheless, tillage and use of cover crops both led to minor differentiation in the weed community composition of vineyard alleys despite relatively few tillage passes compared to annual cropping systems. In aggregate, the study's findings suggest that cover crops and no-till practices can be implemented with limited or no significant competitive effect in well-established, irrigated vineyards like the one studied here, providing a measure of support for their employment in reducing agricultural emissions of particulate matter (e.g., PM10) and building soil organic matter for greenhouse gas mitigation in the San Joaquin Valley.

Literature Cited

Anderson RL, DL Tanaka, AL Black and EE Schweizer. 1998. Weed community and species response to crop rotation, tillage, and nitrogen fertility. Weed Technol 12:531-536.

Baker JB, Southard RJ and Mitchell JP. 2005. Agricultural dust production in standard and conservation tillage systems in the San Joaquin Valley. J Environ Qual 34:1260-1269.

Bàrberi P and Mazzoncini M. 2001. Changes in weed community composition as influenced by cover crop and management system in continuous corn. Weed Sci 49:491-499.

Baumgartner K, Steenwerth KL and Veilleux L. 2007. Effects of organic and conventional practices on weed control in a perennial cropping system. Weed Sci 55:352-358.

Baumgartner K, Steenwerth KL and Veilleux L. 2008. Cover-crop systems affect weed communities in a California vineyard. Weed Sci 56:596-605.

Burger M and Jackson LE. 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biol Biochem 35:29-36.

Calderón FJ and Jackson LE. 2002. Rototillage, disking and subsequent irrigation: Effects on soil nitrogen dynamics, microbial biomass and carbon dioxide efflux. J Environ Qual 31:752-758.

Calderón FJ, Jackson LE, Scow KM and Rolston DE. 2001. Short-term dynamics of nitrogen, microbial activity, and phospholipid fatty acids after tillage. Soil Sci Soc Am J 65:118-126.

Celette F, Gaudin R and Gary C. 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. Eur J Agron 29:153-162.

Celette F, Findeling A and Gary C. 2009. Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. Eur J Agron 30:41-51.

Centinari M, Filippetti I, Bauerle T, Allegro G, Valentini G and Poni S. 2013. Cover crop water use in relation to vineyard floor management practices. Am J Enol Vitic 64:522-526.

Chauhan BS, Gill GS and Preston C. 2006. Tillage system effects on weed ecology, herbicide activity and persistence: A review. Aust J Exp Agr 46:1557-1570.

Guerra B and Steenwerth K. 2012. Influence of floor management technique on grapevine growth, disease pressure, and juice and wine composition: A review. Am J Enol Vitic 63:149-164.

Hsiao TC 1973. Plant responses to water stress. Ann Rev Plant Phys Plant Molec Biol 24:519-570.

Hyvönen T and Salonen J. 2002. Weed species diversity and community composition in cropping practices at two intensity levels—a six year experiment. Plant Ecol 154:73-81.

Ingels CA, Scow KM, Whisson DA and Drenovsky RE. 2005. Effects of cover crops on grapevines, yield, juice composition, soil microbial ecology, and gopher activity. Am J Enol Vitic 56:19-29.

Jackson LE 2000. Fates and losses of nitrogen from a nitrogen-15-labeled cover crop in an intensively managed vegetable system. Soil Sci Soc Am J 64:1404-1412.

Kempers AJ and Kok CJ. 1989. Re-examination of the determination of ammonium as the indophenol blue complex using salicylate. Anal Chim Acta 221:147-155.

Kramer PJ and Boyer JS. 1995. Water Relations of Plants and Soil. Academic Press, Inc., San Diego, CA

Lepš J and Šmilauer P. 2003. Multivariate Analysis of Ecological Data Using CANOCO. Cambridge University Press, Cambridge, UK.

Littell RC, Milliken GA, Stroup WW and Wolfinger RD. 1996. SAS System for Mixed Models. SAS Institute, Cary, NC.

Ludwig JA and Reynolds JF. 1988. Statistical Ecology, a Primer on Methods and Computing. Wiley and Sons, Inc., New York.

Mas MT and Verdù AMC. 2003. Tillage system effects on weed communities in a 4-year crop rotation under Mediterranean dryland conditions. Soil Till Res 74:15-24.

Miranda KM, Espey MG and Wink DA. 2001. A rapid, simple spectrophotometric method for simultaneous detection of nitrate and nitrite. Nitric Oxide-Biol Ch 5:62-71.

Morlat R and Jacquet A. 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am J Enol Vitic 54:1-7.

National Agricultural Statistics Service. 2014a. California Acreage Report, 2014 Crop. http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Acreage/ (accessed 9 Nov 2015).

National Agricultural Statistics Service. 2014b. Grape Crush Report, Final 2014. http://www.nass.usda.gov/Statistics_by_State/California/Publications/Grape_Crush/Final (accessed 9 Nov 2015).

Ngouajio M and McGiffen ME. 2002. Going organic changes weed population dynamics. HortTechnology 12:590-596.

Pella E. 1990. Elemental organic analysis 2. State of the Art Am Lab 22:28.

Ripoche A, Celette F, Cinna JP and Gary C. 2010. Design of intercrop management plans to fulfill production and environmental objectives in vineyards. Eur J Agron 32:30-39.

Ripoche A, Metay A, Celette F and Gary C. 2011. Changing the soil surface management in vineyards: Immediate and delayed effects on the growth and yield of grapevine. Plant Soil 339:259-271.

Sanguankeo PP and León RG. 2011. Weed management practices determine plant and arthropod diversity and seed predation in vineyards. Weed Res 51:404-412.

Singleton PL and Maudsley D. 1996. Patterns of water extraction by grapevines on two soils in the Waikato, New Zealand. N Zeal J Crop Hort 24:415-424.

Smart D, Schwass E, Lakso A and Morano L. 2006. Grapevine rooting patterns: A comprehensive analysis and a review. *In* Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium. LP Christensen and DR Smart (eds.), pp. 153-169. ASEV, Davis, CA.

Smith RG, Atwood LW, Pollnac FW and Warren ND. 2015. Cover-crop species as distinct biotic filters in weed community assembly. Weed Sci 63:282-295.

Soon YK, Haq A and Arshad MA. 2007. Sensitivity of nitrogen mineralization indicators to crop and soil management. Commun Soil Sci Plan 38:2029-2043.

Soriano A, Zeiger E, Servey E and Suero A. 1968. The effect of cultivation on the vertical distribution of seeds in the soil. J Appl Ecol 5:253-257.

Sosnoskie LM, Herms CP and Cardina J. 2006. Weed seedbank community composition in a 35-yr-old tillage and rotation experiment. Weed Sci 54:263-273.

Steenwerth K and Belina KM. 2008a. Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem. Appl Soil Ecol 40:359-369.

Steenwerth K and Belina KM. 2008b. Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Appl Soil Ecol 40:370-380.

Steenwerth K, Baumgartner K, Belina K and Veilleux L. 2010. Vineyard weed seedbank composition responds to glyphosate and cultivation after three years. Weed Sci 58:310-316.

Steenwerth KL, McElrone AJ, Calderón-Orellana A, Hanifin RC, Storm C, Collatz W and Manuck C. 2013. Cover crops and tillage in a mature Merlot vineyard show few effects on grapevines. Am J Enol Vitic 64:515-521.

Stevens RM and Douglas T. 1994. Distribution of grapevine roots and salt under drip and full-ground cover microjet irrigation systems. Irrigation Sci 15:147-152.

ter Braak CJF. 1987. Ordination. *In* Data Analysis in Community and Landscape Ecology. RH Jongman et al. (eds.), pp. 91-169. Center for Agricultural Publishing and Documentation, Wageningen, The Netherlands.

Tesic D, Keller M and Hutton RJ. 2007. Influence of vineyard floor management practices on grapevine vegetative growth, yield, and fruit composition. Am J Enol Vitic 58:1-11.

van Huyssteen L. 1988. Grapevine root growth in response to tillage and root pruning practices. *In* The Grapevine Root and Its Environment. JL Van Zyl (ed.), pp. 44-56. Department of Agriculture and Water Supply, Pretoria, South Africa.

van Huyssteen L. 1989. The effect of soil management and fertilization on grape composition and wine quality with special reference to South African Conditions. *In* Proceedings for the Seventh Australian Wine Industry Technical Conference. Adelaide, South Australia.

Waring SA and Bremner JM. 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability in forest soils. Nature 201:951-952.

Williams LE and Araujo FJ. 2002. Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera*. J Am Soc Hort Sci 127:448-454.

Williams LE and Ayars JE. 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agr Forest Meteorol 132:201-211.

Williams LE, Grimes DW and Phene CJ. 2010. The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines. Irrigation Sci 28:233-243.