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Precipitation Events, Soil Type, and Vineyard Management Practices Influence Soil Carbon Dynamics in a Mediterranean Climate (Lodi, California)

To characterize the effect of precipitation events, management practices, and soil type on vineyard carbon (C) dynamics, we monitored CO₂ emissions and labile C pools from nine vineyards in Lodi Wine Grape District, California, from April 2011 to December 2012. These commercial vineyards are replicates of three soil series (Redding, San Joaquin, and Tokay), representing a spectrum of soil texture and degree of soil development. We hypothesized that soil characteristics would influence the magnitude of CO₂ efflux occurring in response to precipitation and management events in a Mediterranean climate. During each field visit—bimonthly (April–October) and monthly (November–March)—we measured CO₂, soil temperature, and gravimetric water content (GWC) from vine and intervine (alleys) rows. Monthly, we collected soil samples for dissolved organic C (DOC), which tended to be greater in the alleys of San Joaquin and Redding than Tokay in summer but decreased after the onset of precipitation. In mid-May and mid-October 2012, CO₂ efflux was higher in Tokay than in San Joaquin or Redding. Carbon dioxide efflux across all soils increased as a result of seasonal management practices (i.e., tillage and mowing of cover crops). Management practices distinguished soil DOC between vine rows and alleys from June to October 2012. Soil type or clay content influenced CO₂ efflux across these vineyards, as did GWC and soil temperature. This 20-mo study indicated that CO₂ efflux responded to soil disturbance from management practices, precipitation, and irrigation.

Abbreviations: DOC, dissolved organic carbon; GHG, greenhouse gas; GWC, gravimetric water content; SOM, soil organic matter.

The capacity for agriculture and working lands to store carbon (C) to mitigate greenhouse gas (GHG) emissions is important to address climate change (Aguilera et al., 2013; Culman et al., 2014; Suddick et al., 2010, 2011). California represents the US vanguard with respect to implementation of policies and practices to mitigate GHG emissions. The Assembly Bill 32—California Global Warming Solutions Act of 2006 requires industries in California to reduce GHG emissions to 1990 levels by 2020. More recently, Senate

Core Ideas

- Vineyard management practices create spatial heterogeneity in CO₂ efflux and SOM content.

- Soil C dynamics are influenced by water availability rather than temperature in comparatively warm Mediterranean climates.

- Soil tillage, organic amendments, cover crops, irrigation and precipitation stimulate CO₂ efflux.
Bill 32 mandates reductions in GHG emissions to 40% below 1990 emissions levels by 2030. As such, empirical data that portray how soil types and agricultural practices affect C dynamics of woody perennial crops like wine grapes are needed to inform biogeochemical models and tools that assess potential C storage and thus GHG offsets (e.g., COMET-Farm, COMET-Planner; Whittaker et al., 2013). Although California provides at least 90% of the nation’s wine grape production, there are still relatively few multi-year assessments of soil C dynamics and CO2 emissions as compared with annual crop counterparts (i.e., Calleja-Cervantes et al., 2015; Carlisle et al., 2006; Steenwerth and Belina, 2008; Steenwerth et al., 2010; Wolff et al., 2018).

Wine grapes thrive in California’s Mediterranean climate, which is characterized by warm, dry summers and cool, wet winters (Aschmann, 1973). Typical of this climate are the repeated wet–dry cycles from either precipitation or irrigation, which elicit spikes in CO2 efflux and dynamic responses in soil C pools (Lundquist et al., 1999; Steenwerth et al., 2005). Wet–dry cycles in soil due to irrigation and precipitation increase the availability of labile C substrates, including those attributed to microbial cell lysis in response to stress from changes in microbial osmotic potential (Kieft et al., 1987; Van Gestel et al., 1993). Increases in C substrate availability result in increased microbial respiration (Lundquist et al., 1999; Steenwerth et al., 2005). Soil rewetting also causes physical displacement of CO2 in soil pores (Calderón and Jackson, 2002). Carbon dioxide emissions from vineyards, oak woodlands, and grasslands in this climate are limited typically by soil water availability rather than temperature (Rey et al., 2002; Steenwerth et al., 2010).

Management practices, like tillage, cover crops, and compost, in combination with fluctuations in soil water content from precipitation and irrigation, strongly influence soil C dynamics in vineyards and annual crop systems (Calderón and Jackson, 2002; Calleja-Cervantes et al., 2015; Jackson et al., 2003; Steenwerth and Belina, 2008). Tillage causes physical release of CO2 from the soil and disrupts protected C in soil aggregates, increasing its availability for soil microorganisms to respire (Reicosky, 1997). Root respiration and C deposition from cover crop and grape biomass and root exudation also contribute to soil CO2 emissions, and compost can increase labile C and soil organic matter (SOM) content (Calleja-Cervantes et al., 2015).

The spatial and temporal separation of these aforementioned management practices and their impacts on organic C availability within vineyard zones (i.e., vine rows and alleys) complicate the assessment of soil C dynamics in vineyards and underscore the imperative to examine both zones. For example, soil rewetting from drip irrigation occurs in the vine row for California’s wine grape production during the warm, dry summers (Di Castri, 1991), and mineral nitrogen fertilizers are delivered through the drip system. Herbaceous plant growth in the vine row is deterred through tillage or herbicide application under the vines, decreasing direct organic matter inputs in the vine row (Steenwerth and Belina, 2010). Alleys (i.e., the area between vine rows) are unfertilized and minimally disturbed until the wet winter, when resident vegetation or seeded cover crops are grown. This vegetation in the alleys is mown and mulched or tilled into the upper 15 to 25 cm in the spring, depending on competition between the alley vegetation and vines for soil resources and water, vegetation’s influence on weed management and establishment, the risk of frost damage, and the need to improve soil structure and reduce erosion (Guerra and Steenwerth, 2012). Compost, a source of organic C to build SOM, is applied typically every 4 yr and is broadcast across the vineyard, but some operations have more directed applications under the vine (A. Walker, personal communication, 2017).

Few studies have examined C dynamics in both vineyard zones (alley and vine row), multiple sites, and soil types within the same time period. Soil type, distinguished by parent material, mineralogy, and texture, influences protection of SOM, aggregate formation, and regulation of soil water content, all of which have been shown to influence soil C dynamics (Berhe et al., 2012; Denef et al., 2002; Six et al., 2004). Thus, we focus on the interactions of management practice and precipitation events across three major soil types in the Lodi wine grape production region to determine their effects on C dynamics and CO2 emissions from vineyards. This study captured the spatial heterogeneity of emissions from two vineyard zones (i.e., the vine row and alley) for nearly 2 yr from one of California’s major wine grape production regions. We hypothesized (i) that CO2 emissions from a given soil would correspond to fluctuations in soil resource pools in response to precipitation events and management practices in vine and alley rows and (ii) that efflux would vary with respect to soil type.

**MATERIALS AND METHODS**

**Site Description and Experimental Design**

Details on methods are described in Yu et al. (2017), and they are presented briefly here. Nine commercial vineyards near Lodi (38°37′27″N, 121°16′43″W), San Joaquin County, California, were monitored from April 2011 to December 2012. The period from May through September defines the dry season, corresponding most closely to summer. October through April define the wet season, based on at least 100 yr of precipitation records. Precipitation and air temperature data were collected from the nearest California Irrigation Management Information System station (Lodi West #166) (see Fig. 1 and 2 in Yu et al., 2017). The selected soil types represent three major soil landscapes found across the eastern margin of the Central Valley of California. They reflected differences in landscape age, degree of development, and thus physical, mineralogical, and chemical characteristics. The three soil series were: San Joaquin (Fine, mixed, active, thermic Abruptic Durixeralfs), Tokay (Coarse-loamy, mixed, superactive, thermic Typic Haploxerolls), and Redding (Fine, mixed, active, thermic Abruptic Durixeralfs) (n = 3 replicate vineyards per soil series). At one of the replicate vineyards, 45% Corning (Fine, mixed, active, thermic Typic Paluxeralf) 40% Redding complex is prevalent, but Redding is used as the label because replicate vineyards are primarily Redding. The Redding series exists on steeply undulating high terraces consisting of early Pleistocene alluvium derived from metamorphic rocks. The San Joaquin series formed on low terraces.
from late Pleistocene granitic alluvium. The Tokay series exists on Holocene alluvial fans of granitic alluvium (O’Geen et al., 2008).

The experimental design is completely randomized. Sample events serve as repeated measures within soil treatment and vineyard zone. Vineyard zone (vine or alley row) is a nested factor (n = 2). Map unit heterogeneity is represented by five randomly selected subreplicates per vineyard zone. A sample event refers to one complete cycle of field visits (~1 wk) to all nine vineyards. Details about vineyard floor management, vine row spacing, and irrigation schedules are presented in Yu et al. (2017).

**Soil Characterization**

Field collection and analytical methods for characterization of these soils (0–5, 5–10, 10–30, 30–50, and 50–100 cm) are described in Yu et al. (2017). Soils were assessed for dissolved organic C (DOC), pH, particle size analysis, and gravimetric water content (GWC).

**Soil Gas Sampling**

Briefly, at each subreplicate (n = 5 for each vineyard zone), a static gas chamber, following the design outlined by the USDA–ARS Greenhouse gas Reduction through Agricultural Carbon Enhancement network (GRACEnet) protocol, was installed in the vine and alley rows during April and May 2011 (Parkin and Ventera 2010; Yu et al., 2017). Collars in the vine row were inserted to 9-cm depth under a drip irrigation emitter and remained in place for the experiment’s duration. Collars in the alley rows sat adjacent to those in the vine row, remaining in place except during management events (tillage and mowing).

Field sampling occurred between 10 AM and 1 PM every 2 wk from April to October and monthly from November to March. Gas sampling occurred at 20-min intervals (0, 20, 40, and 60 min). Samples were stored in evacuated 12-mL glass vials with a rubber septum cap (Labco Limited, Ceredigion, UK). Air and soil temperature were measured simultaneously in the chamber at each sampling interval (54II Thermometer; Fluke Corporation, Everett, WA). Air samples collected during the sampling period served as ambient standards. Gas samples were analyzed on a gas chromatograph with a thermal conductivity detector (GC 2014; Shimadzu Corp., Columbia, MD). Fluxes were calculated according to a template from Ventera (2010) for four time points.

During each field visit, soil samples were randomly taken within a 2-m radius of the gas chamber for GWC. Samples were transported on ice to the laboratory and then measured for GWC and DOC (Jones and Willett, 2006). Only DOC was recorded monthly. See Yu et al. (2017) for methodological details.

**Statistical Analyses**

For each sampling date, data at the subreplicate level were averaged before subsequent analyses. For all analyses described here, data were transformed to meet the assumptions of normality and homogeneity of variance. Log_{10} transformation was used for soil temperature, DOC, and CO_{2} efflux. Gravimetric water content was square root transformed. All reported data in the text are mean and SE of raw data. Back-transformed least squares means and 95% confidence intervals for CO_{2} are in provided in Supplemental Table S1 (see Yu et al. [2017] for all other variables). A mixed model repeated measures ANOVA was used in SAS (Proc Mixed, SAS Version 9.3; SAS Institute, Cary, NC). Soil, Vineyard Zone, and Sample Event and their interactions were fixed effects, in which the denominator degrees of freedom for F tests was estimated with the Kenward–Roger’s method. Vineyard nested within soil was considered as a random effect because each vineyard had management practices that were not under experimental control. The interaction of Vineyard Zone × Vineyard (Soil) was determined to be a random effect, in which the ARMA function was used to account for the first order, moving average covariance structure for the repeated measurements. Significant interactions of fixed factors and sample events were revealed with multiple comparisons. Simple effects of significant Soil × Sample Event and Vineyard Zone × Sample Event interactions were assessed with the slice function. Post hoc pairwise comparisons using Tukey’s adjustment were conducted using the diff option. These pairwise comparisons were conducted based on a priori hypotheses that sample events in May and October would have greater variability in CO_{2} efflux and soil pools due to precipitation events. Value ranges are provided, but see Yu et al. (2017) for a graphical depiction of changes GWC, soil temperature, and DOC.

Path analyses were conducted with the Proc Calis procedure in SAS after review of mixed model results to identify the contribution of soil type, vineyard zone, soil temperature, and GWC on CO_{2} efflux (Mitchell, 1993). We hypothesized that (i) vineyard zone or alley and vine row, (ii) the large percentage of gravel in Redding, and (iii) the low percentage of clay in Tokay (i.e., high percentage of clay in Redding and San Joaquin) would influence the endogenous variables CO_{2} efflux, soil temperature, and GWC. Dissolved organic C could not be included because it only was collected monthly. Exogenous, categorical vineyard zone, and soil effects were recoded into dummy variables based on the a priori hypotheses. Data were converted into covariance matrices before path analysis with the Proc Calis procedure.

**RESULTS**

**Soil Characteristics**

Soil types differed by soil texture, total C and N content, and bulk density, but soil pH (6.04–6.81) was similar among soils and depths (0–30 cm). Gravel content was greatest in Redding (43.2–57.0%); Tokay and San Joaquin contained <1% gravel (Yu et al., 2017). Sand content was greatest in Tokay (64.6–66.6%), followed by Redding (53.6–54.2%) and San Joaquin (34.5–35.5%). Conversely, clay content was greatest in San Joaquin (19.5–20.1%) and Redding (14.1–15.7%) and lowest in Tokay (8.4–9.3%). In the alleles, percent total C and N (g C or N g^{-1} soil; 0–10 cm) tended to be greater in Redding (C: 1.14–1.32%, N: 0.06–0.07%) and Tokay (C: 0.82–0.91%, N: 0.10–0.12%), and San Joaquin (C: 1.42–1.64%, N: 0.10–0.12%) and San Joaquin (C: 1.42–1.64%, N: 0.13–0.14%) than in Tokay (C: 0.82–0.91%, N: 0.06–0.07%). In the vine rows, Redding had relatively higher total C (0–10 cm; 0.96–1.17%) than San Joaquin (0.67–1.04%) and Tokay (0.69–0.91%).
but no difference in total N. Among all soil types, total C and N (0–30 cm) tended to be lower in vine rows than in alleys.

### Soil Water Content and Temperature
Gravimetric water content closely tracked precipitation patterns of a Mediterranean climate. There were two dry seasons and one complete wet season in this study. Gravimetric water content was two to three times higher in the vine rows (0.10–0.19 g H$_2$O g$^{-1}$) than in the alleys (0.01–0.02 g H$_2$O g$^{-1}$) for sample events in the dry season when drip irrigation occurred (mid-July to September 2011 and from late May to October 2012; vineyard zone × sample event, F = 5.2, $p < 0.001$). No effect of soil type or vineyard zone on GWC occurred in the wet season (October 2011 to May 2012), but values tended to range from 0.05 g H$_2$O g$^{-1}$ when no rainfall occurred to 0.24 g H$_2$O g$^{-1}$ just after rainfall

During the dry season, soil temperatures varied by vineyard zone and by soil type (soil × sample event, F = 2.4, $p < 0.001$; vineyard zone × sample event, F = 3.6, $p < 0.001$). Soil temperature was a net 10 to 15°C lower in vine rows than in alleys in summer (June–August 2011 and May–August 2012). The soil temperatures in vine rows ranged from 22 to 32°C during the irrigation period but were as high as 48°C after cessation of irrigation late in the summer/early fall. The temperature in the alleys in summer tended to range from 42 to 46°C, when alleys also had comparatively low GWC. Soil temperatures in the wet, winter season were similar between vineyard zones across soil types (~10–28°C). In other periods, the vineyard zones showed distinctions by soil type, but there was no consistent relative ranking in soil temperatures among the three soil types.

### Dissolved Organic C
Dissolved organic C differed between vineyard zones, and it was highest in the alleys at sample events during the dry season (vineyard zone × sample event, F = 5.7, $p < 0.001$). Dissolved organic C was at least 1.5- to 4-fold higher in the alleys than in vine rows among all soils in 2011 and 2012 (July–September; $p < 0.05$). When soils had comparatively higher GWC after the onset of precipitation, DOC decreased and was similar between vineyard zones (October 2011 to April 2012 and after October 2012). Generally, DOC was lowest during the wet season (~30–80 mg DOC kg$^{-1}$ in vine row; 40–130 mg DOC kg$^{-1}$ in alley) compared with the dry season, with more marked differences between seasons in the alley than in the row (~30–100 mg DOC kg$^{-1}$ in vine row; 90–190 mg DOC kg$^{-1}$ in alley). When vegetation growth and compost application occurred in the alleys, DOC concentrations were nearly twice that of vine rows in December 2011 and January 2012 ($p < 0.01$). Dissolved organic C in the alleys from San Joaquin (110–240 mg DOC kg$^{-1}$) tended to be greater than Redding-Corning and Tokay (40–170 mg DOC kg$^{-1}$) during summer 2011, and again, San Joaquin and Redding-Corning tended to be greater than Tokay at some dates in summer 2012 (i.e., net difference of ~20–50 mg DOC kg$^{-1}$).

### CO$_2$ Efflux
Carbon dioxide efflux varied among the three soil types by sample event (soil × sample event, F = 1.4, $p < 0.03$) (Fig. 1). Specifically, CO$_2$ efflux differed among soil types on three sample events: one in 2011 and two in 2012. In early May 2011, Tokay had almost twice the CO$_2$ efflux as San Joaquin (Tokay: 13.6 ± 1.5 kg CO$_2$–C ha$^{-1}$, n = 30; San Joaquin: 7.7 ± 1.4 kg CO$_2$–C ha$^{-1}$, n = 20). In 2012, differences among the three soils occurred at the beginning and end of the dry season (mid-May and mid-October 2012; $p < 0.05$). Carbon dioxide efflux also increased in association with management events like tillage and compost application.

Carbon dioxide efflux from vineyard zones differed by sample event (vineyard zone × sample event, F = 2.5, $p < 0.001$) (Fig. 1). From February to early May and in December 2012, CO$_2$ efflux was higher from alleys than from vine rows ($p <
In both years, sample events in the dry season (August to mid-October) had higher CO₂ efflux from vine rows than alleys, corresponding to drip irrigation \((p < 0.05)\). After the first precipitation event in October 2011, peak CO₂ efflux from the alleys was greatest from San Joaquin, followed by Redding and Tokay \((p < 0.05)\). In contrast, CO₂ efflux from the vine row at this time was greatest in Tokay compared with San Joaquin and Redding \((p < 0.05)\). No other significant effects were detected.

Path analyses were used to examine the role of gravel or clay contents and vineyard zone on CO₂ emissions (Fig. 2; Table 1). The analysis reveals that gravel content had no direct or indirect effect on CO₂ efflux. Gravimetric water content was the major contributor to covariance in CO₂ efflux with respect to vineyard zone, indicated by standardized significant path coefficients, and soil temperature was directly moderated by GWC, especially during the irrigation season. Clay content had significant total, direct, and indirect effects on CO₂ emissions (Fig. 2). Soils with higher clay content had a significant direct, negative effect on CO₂ efflux and significant direct, positive effects on soil temperature and gravimetric water content. In path analyses comparing gravel or clay effect, vineyard zone had significant direct and indirect effects on CO₂ efflux (Fig. 2). Significant, indirect effects of clay content and vineyard zone, as mediated by GWC and soil temperature, were also indicated by the significant standardized path coefficients.

**DISCUSSION**

**Influence of Precipitation and Irrigation Events on CO₂ Efflux**

We hypothesized that soil type, precipitation events, and vineyard management practices would differentiate the magnitude of CO₂ efflux. In general, our findings are consistent with other studies on vineyards in Mediterranean climates (Carlisle et al., 2006; Steenwerth and Belina, 2008; Steenwerth et al., 2010; Wolff et al., 2018). We provide similar evidence that shows that precipitation and irrigation events increased CO₂ efflux and that the influence of soil was mediated through indirect effect of texture on GWC and soil temperature (Fig. 1–2). Soil CO₂ emissions were constrained by low soil water content in the dry summer, except in response to irrigation events, but also by low soil temperature in winter even though soil water content was sufficient to support microbial activity (Carlisle et al., 2006; Maestre and Cortina, 2003; Rey et al., 2002; Steenwerth et al., 2010). Observations in vineyards and oak woodlands in Mediterranean climates indicate that CO₂ efflux can be limited by soil temperature if GWC is \(\geq 20\%\), whereas in dry conditions in summer, CO₂ efflux is limited by soil water content (Rey et al., 2002; Steenwerth et al., 2010). Among soils in either vineyard zone GWC rarely reached 20\%, suggesting that this threshold found by others is site or soil specific. The significant direct and indirect effect of GWC on CO₂ efflux in path analysis and the absence of an effect of soil temperature underscore that water availability is more often the driver of CO₂ emissions in a...
Mediterranean climate in the relatively warm regions of the Central Valley in California (Fig. 2) (Carlisle et al., 2006; Steenwerth et al., 2010). Root respiration from vines corresponding to phenology in summer and alley vegetation in winter also were potential sources of CO₂ efflux (Hernández-Montes et al., 2017).

Carbon dioxide efflux increased in response to the first precipitation event of the wet season in October 2011. Gravimetric water content had a strong role in CO₂ efflux, especially because precipitation event of the wet season in October 2011. Gravimetric water contents and C availability, the diffusion of gases could vary. Second, macroaggregate disruption and slaking in response to increases in soil water content releases trapped gases and occluded SOM (Denef et al., 2002). In this scenario, the recently exposed SOM provides C for microbial mineralization, which likely varies by soil type in this study (i.e., DOC; Fig. 3 in Yu et al., 2017) (Harrison-Kirk et al., 2013). Third, rapidly rewetting soil also leads to increases in available labile C pools and can enhance lysis of soil microorganisms as the soil water potential increases, creating an additional labile C source for mineralization (Denef et al., 2002; Kieft et al., 1987).

Role of Vineyard Zone and Management Practices on CO₂ Efflux: Tillage, Cover Crops, and Compost

Distinctions in soil management within the vine and alley give rise to higher total soil C, DOC, and CO₂ efflux from alleys than from vine rows. These differences in soil C pools partly reflect C inputs from cover crops and compost. It is well known that cover crops contribute to labile organic C pools that increase SOM and support microbial respiration and C mineralization in vineyards and other crops in Mediterranean systems (Aguii et al., 2013; Belmonte et al., 2018; Steenwerth and Belina, 2008). In the current study, soil C content was greater in the surface (0–20 cm) as compared with lower depths (20–100 cm) due to the relatively greater distribution of roots in 0 to 10 cm from annual grasses, forbs, and the cover crops used in California vineyards (Belmonte et al., 2018; Steenwerth and Belina, 2008; Steenwerth et al., 2010; Yu et al., 2017). Cover crops, as well as tillage, can lead to a wide range of CO₂ emissions by influencing placement and deposition of organic C inputs via above- and belowground biomass, nutrient availability, soil structure, and organic matter content (Guerra and Steenwerth, 2012).

High CO₂ efflux immediately after tillage has been attributed to soil degassing from physical disturbance (i.e., "champagne effect") (Calderón and Jackson, 2002; Jackson et al., 2003; Reicosky, 1997). This physical disturbance disrupts soil aggregates and leads to microbial mineralization of labile and protected SOM (Calderón and Jackson, 2002; Jackson et al., 2003). Elevated CO₂ efflux can last from hours to days after tillage, depending on soil conditions (Jackson et al., 2003), as reflected in the increases in CO₂ after tillage in this study (Fig. 1). Yu (2015) simulated tillage in these same soil types and measured their C dynamics over 5 d. This strong increase in CO₂ efflux (from ~7–10 kg CO₂-C ha⁻¹ d⁻¹ to ~35–40 kg CO₂-C ha⁻¹ d⁻¹) also occurred in the first 3 to 6 h after simulated tillage in these soil types (one vineyard per soil type) (Yu, 2015). Tokay sustained comparatively higher rates of CO₂ emissions over the 5-d period after simulated tillage, just after precipitation (March 2012) (Yu, 2015). Tokay’s physical attributes likely influenced CO₂ effluxes; its coarse texture can facilitate enhanced drainage compared with the finer-textured Redding and San Joaquin soils, thus minimizing the limiting effect of soil water content on gaseous diffusion. Soil respiration increases after incorporation of cover crops (i.e., labile C) by tillage (Steenwerth et al., 2010), which led to the highest CO₂ efflux from Tokay in May 2012 (Yu et al., 2017).

Compost applications can have large, positive effects on increases in soil DOC, soil C content, and CO₂ emissions in vineyards and in other crop systems in Mediterranean climates (Aguiu et al., 2013; Calleja-Cervantes et al., 2015; Zhu et al., 2013). In these vineyards, growers applied compost as an organic nutrient amendment in combination with subsequent tillage and cover crop planting. These activities led to observable increases in CO₂ efflux from November to December 2012 for San Joaquin and Tokay. All three vineyards on Tokay received compost, whereas two vineyards on San Joaquin received compost. Just one vineyard in Redding received compost, suggesting that any possible effect from compost was undetected. The lack of a notable CO₂ efflux just after compost application (mid-October to early November) may be attributed to the low soil water content. Immediate correspondence between management events and GHG fluxes sometimes cannot be made or is not apparent due to lag times. A long-term study on the use of compost in Spanish vineyards demonstrated that CO₂ efflux from compost did not start to increase until about 60 d after application, with maximum CO₂ efflux 120 d later (Calleja-Cervantes et al., 2015). In the California vineyards studied here, this lag time overlaps with cultivation and spring warming, complicating the interpretation of the effect of compost on CO₂ efflux (Fig. 1).
A detailed discussion of limitations of this study’s approach can be found in Yu et al. (2017). Briefly, examination of several soil types was prioritized in this study, limiting measurement frequency. Therefore, any lag time between specific events in the vineyard and in-field flux measurements may have caused missed emissions within the first 24 to 48 h, leading to underestimations of CO₂ efflux associated with management events. This is attributed partly to CO₂ efflux’s ready responsiveness to physical disturbance from management practices like tillage and displacement by water from irrigation and precipitation (Calderón and Jackson, 2002; Reicosky 1997). Still, studies have shown that soil CO₂ emissions can continue 5 to 7 d after precipitation and tillage (Calderón et al., 2001; Steenwerth et al., 2005). The duration of this study and the lack of distinction between heterotrophic and autotrophic respiration also limited the detection of changes in soil C content and discernment of pathways related to C storage among vineyard zones and soil types over time (Aguilera et al., 2013; Hernández-Montes et al., 2017).

CONCLUSION

This work has demonstrated that vineyard floor management practices (i.e., irrigation, cover crops, compost, and tillage) and precipitation can lead to increases in soil C availability that, in turn, lead to CO₂ efflux (Steenwerth and Belina, 2008; Steenwerth et al., 2010). Spatial heterogeneity in soil attributes like total C, DOC, and GWC underpins observed distinctions in seasonal and event-based CO₂ efflux between vine rows and alleys. Soil type, at least as indicated here by clay content, influenced CO₂ efflux. Findings also suggest that C dynamics are limited by water availability rather than temperature in these vineyards. The CO₂ emissions from these vineyards, in part, are associated with practices like compost application and cover crops that build “soil health,” leading to improved soil structure, SOM content, infiltration, nitrogen availability and retention, and biological activity (Steenwerth and Belina, 2008; Yu et al., 2017). These attributes support productive agricultural systems and may increase SOM content to offset GHG emissions (Wolff et al., 2018; Yu et al., 2017). Optimization of practices that lead to such outcomes in vineyard systems is increasingly important to reduce their global warming potential and to contribute empirical data for GHG emissions model development to support quantification tools (Belmonte et al., 2018; Culman et al., 2014; Suddick et al., 2010, 2011; Yu et al., 2017; Wolff et al., 2018).

SUPPLEMENTAL MATERIAL

Least squares means and confidence intervals of back-transformed variables for 2011-2012 carbon dioxide flux data are provided in Supplemental Table S1.

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