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Impact of organic matter amendments on soil and tree water status in a California orchard

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ABSTRACT

Permanent crops like almond (*Prunus dulcis*) require significant water inputs for economic yields and long-term productivity. This demand creates a challenge in drought-prone regions like California. Use of organic matter amendments (OMA) can improve water use efficiency by conserving soil moisture and reducing tree water stress. The majority of almond orchards in California are no-till with irrigation targeted on a narrow tree berm where OMA is applied as surface mulch. We examined the effects of composted dairy manure (CM) and the timing of its application on soil moisture, soil water retention and tree water status in a young orchard planted in 2014. Treatments including Fall-applied CM (October 2015 and 2016), Spring-applied CM (April 2016 and 2017) and an unamended control were monitored during the 2016 and 2017 growing seasons. Fall-applied CM was more readily incorporated in soil organic matter of the 0–60 cm rooting zone as evidenced by significantly greater soil organic carbon (SOC) for Fall versus Spring-applied CM in 2016 ($p < 0.05$). Fall-applied CM significantly increased soil volumetric water content (VWC) by 22% from 0 to 150 cm depth during the driest period of year one and tended to make midday stem water potential (SWP) less negative relative to the control. Fall-applied CM tended to increase VWC in 2017, but treatment differences were no longer significant. Differences in VWC and SWP between Fall-applied CM and the control were most apparent at low VWC (< 10%). Two years of Fall-applied CM increased soil water retention between 0 to ˜100 kPa at 0–10 cm depth by 13% compared to the control. These results demonstrate Fall-applied CM was more effective at enhancing soil moisture retention and reducing tree water stress compared to Spring-applied CM. We also conclude OMA use may buffer against periods of limited water supply for young trees.

1. Introduction

Sustainable water use in permanent crops is a priority in regions of high-water demand like California. California's Central Valley hosts the world's largest region of permanent crops where orchards and vineyards comprise 13% of agricultural acreage, and produces 80% of almonds worldwide (CDFA, 2017; USDA, 2016). Irrigated tree crops account for 34% of agricultural water use in California. After dairy farming, nut crops are the highest net water users, defined as water applied minus runoff and leaching (Johnson and Cody, 2015). Climate change increases the likelihood of more frequent and high-intensity droughts (Swain et al., 2018), and given the high dependency of permanent crops on water resources, it is critical to increase water conservation and water use efficiency, particularly for intensively grown crops such as almond. Management practices to improve soil water storage and increase water availability during critical growth periods may lead to irrigation water savings, and increase orchard resilience during drought events.

Use of organic matter amendments (OMA) such as composted manure (CM) in orchards is a promising strategy to enhance water use efficiency (Lordan et al., 2015; Reganold et al., 2001). California is the number one dairy-producing state with over 1300 registered dairies (CDFA, 2017). Manure produced by dairies is an abundant OMA source available to growers in California's Central Valley. In a survey of OMA practices, 40% of OMA users identified soil water holding capacity as a primary or secondary benefit of OMA use (Khalsa and Brown, 2017). In California, almond orchards are predominantly no-till and equipped with microirrigation, where water is applied on a narrow tree berm allowing for targeted wetting of soil with tree roots (Smart et al., 2011; Tindula et al., 2013). As a result, OMA application is often as a surface mulch placed in the same wetted area in order to facilitate decomposition. The effect of OMA on soil moisture and tree water status in no-

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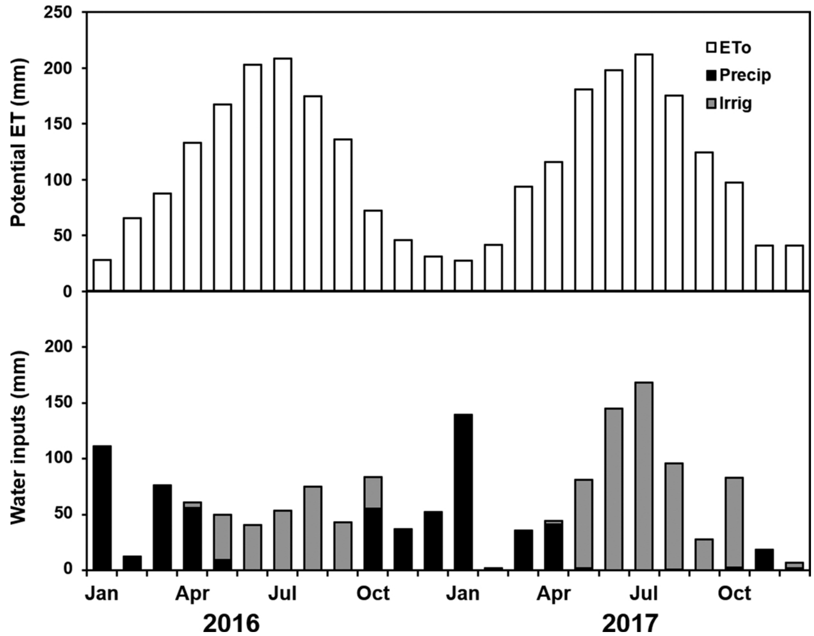


Fig. 1. Monthly potential evapotranspiration (ET_o) and water inputs including irrigation (Irrig) and precipitation (Precip) from Jan 2016 to Dec 2017.

till, partially wetted orchards is uncertain, and even less is known about how timing OMA application alters water use. It is widely observed that OMA increases soil organic matter (SOM) in orchards (Hannam et al., 2016; Lopez et al., 2014; Peck et al., 2011), which is a key indicator of soil quality (Dexter, 1988; Karlen et al., 1997). In conventional bare-floor orchards, soil is kept weed-free to facilitate harvest and SOM tends to be low due to minimal C inputs, compaction, and breakdown of physical structure (Deurer et al., 2008; Haynes, 1981). In California orchards, OMA is applied during tree dormancy to maximize the exclusion period between OMA application and harvest as a means to minimize food safety risk (Khalsa and Brown, 2017). Timing OMA application could alter decomposition, SOM accumulation and orchard water use.

SOM contributes to improved soil structure (Six et al., 2000; Tisdall and Oades, 1982), which in turn governs the movement and storage of soil water. SOM indirectly influences infiltration and retention of soil water, though its effects on soil available water capacity (AWC) are less understood (Celik et al., 2004; Minasny and McBratney, 2018a; Rawls et al., 2003). Soil AWC is an important link between soil moisture and tree water status. Increased SOM at shallow soil depths has been shown to enhance water infiltration (Dexter et al., 2008; Haynes, 1981; Merwin et al., 1994), water retention, and AWC of sandy soils (Foley and Cooperband, 2002; Gulser and Candemir, 2015; Jordan et al., 2010). However, the magnitude of this effect on AWC has a wide range of 1–10% for every 1% increase in soil organic carbon (SOC) (Eden et al., 2017; Minasny and McBratney, 2018a, 2018b). Yet one of the few permanent crop studies conducted in apple (*Malus spp.*) in a temperate climate reported no effect of OMA on soil AWC (Deurer et al., 2008). More research is needed on the complex effects of OMA and its management, including timing application, on soil water availability. This need is particularly urgent in permanent crops, where stress from limited soil moisture can impact orchard productivity for years beyond stress events (De la Rosa et al., 2016; Shackel et al., 1998).

Tree water status measured by midday stem water potential (SWP) is one of several factors that determines growth, productivity, and water use of orchards. Reduced photosynthesis, canopy development, and fruit growth are tree physiological responses to water stress (Lampinen et al., 2001; Shackel et al., 2000). There is strong evidence that water stress in the early stages of tree growth is detrimental to orchard productivity (Girona et al., 1997; Goldhamer et al., 1999; Shackel et al., 1998). Few studies have monitored SWP response in trees treated with OMA (Lordan et al., 2015). It is reasonable to ascertain that management practices such as OMA use that increase soil moisture retention will also reduce tree water stress, and ultimately improve tree growth and long-term orchard productivity.

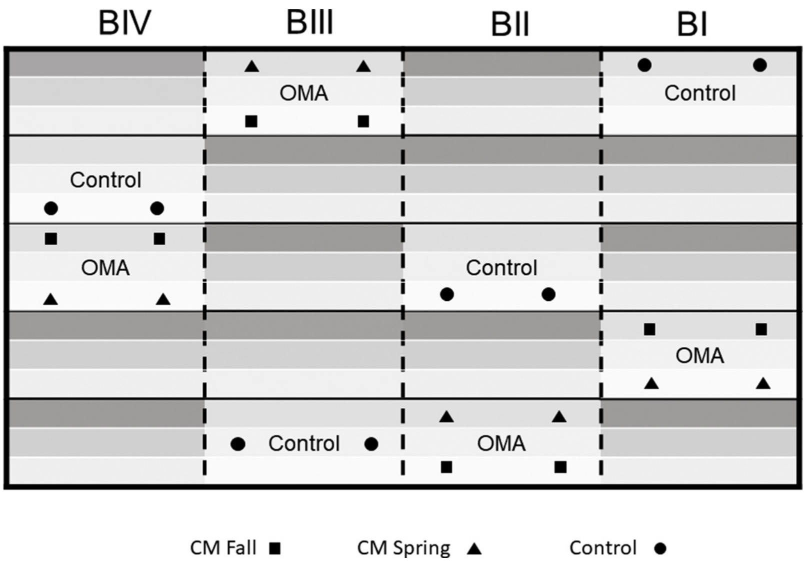
This study examines the impact of OMA and application timing on soil and tree water status under conditions where OMA is applied as mulch and wetted by irrigation during the growing season. The aim of this research was to quantify the impact of Fall-applied and Spring-applied composted dairy manure (CM) on volumetric water content (VWC), soil water retention and tree water status compared to an unamended control. We hypothesize SOM accumulation during OMA decomposition will enhance VWC and soil water retention with subsequent impacts on tree water status. We also predict higher VWC and tree SWP with Fall-applied CM compared to Spring-applied CM due to greater C incorporation into SOM during the winter months prior to the growing season.

2. Materials and methods

2.1. Study site

The experimental site was a 3rd and 4th leaf almond (*Prunus dulcis)* orchard during 2016 and 2017 in San Joaquin County, California (37° 49′ 33″ N 121° 6′ 46″ W) on Manteca fine sandy loam (mixed, thermic, Typic Durixeroll). The region has a Mediterranean climate with an average annual temperature of 17 °C and average annual rainfall 450 mm with most precipitation occurring between October and April. The orchard was planted in 2014 at a density of 272 tree ha^{-1} with 5.5 m tree and 6.7 m row spacings of the cultivar 'Nonpareil' and alternating rows of the cultivars 'Aldridge' and 'Carmel'. All trees were grafted on 'Hanson' rootstock. A native duripan soil layer observed at 120–150 cm depth was ripped prior to planting. The trees were irrigated using one microsprinkler per tree, each with a 3 m radius and a flow rate of 47 L hr^{-1}. The grower managed the orchard using standard irrigation, nutrient, pest and weed control practices for California almond orchards (Duncan et al., 2016).The trees were first harvested in 2017 during the second year of our trial.

The grower-managed orchard received 47% more water inputs in the 2017 growing season from April to October than in 2016 growing



Map 1. Experimental design in a 20 ha almond orchard trial (San Joaquin County, CA U.S.A.). Dashed lines denote four blocks (BI – BIV) and solid black lines denote plots randomly assigned an OMA treatment of composted manure (CM) or unamended control. White lines denote row separations of sub-plots (every 2 rows of "Nonpareil" variety trees) which were randomly assigned an application timing of Fall-applied or Spring-applied CM. Duplication locations denoted by solid shapes within each subplot were randomly selected for data collection.

season (Fig. 1). Low VWC in September 2017 was a result of deficit irrigation to dry down the orchard floor prior to harvest operations. Historical climate data were acquired from the CIMIS (California Irrigation Management Information System) station located 9.8 km from our field study site in Manteca, CA (CIMIS, 2018). Cumulative monthly reference evapotranspiration (ET_o) from May 1st to October 1st was similar in 2016 and 2017 (Fig. 1), with the highest ET_o measured in June and July in both years.

The experimental design was a randomized, complete split block design with four blocks and two main plot treatments. Main plots received OMA treatments applied with CM or an unamended control; and subplots were timing of OMA as either Fall-applied in October 2015 and 2016 prior to the subsequent growing season or Spring-applied in April 2016 and 2017 during the growing season, for a total of 12 plots (Map 1). Duplicate samples were taken at two locations per plot, which were randomly selected from a row length of 660 m. CM with a C to N ratio (C:N) of 11:1 was applied annually at the equivalent rate of 9 Mg ha^{-1} at 30% moisture as a surface mulch on the tree berm. The control was managed using synthetic fertilizer injected in split applications through the microsprinkler irrigation system. All plots received the same rate of water and fertilizer.

2.2. Field measurements

Aluminum neutron probe access tubes were installed to 1.5 m depth to monitor soil moisture during the growing season from April to October. Soil moisture was measured using a CPN 503TDR Hydroprobe (Instrotek Inc. Concord, CA). Hydroprobe counts measured soil moisture of a 20–30 cm radius sphere, and measurements were taken at 30 cm increments from 30 to 150 cm depth. Measurements were collected at 2-week intervals between 1 to 3 days before irrigation events to represent drier periods in the growing season and to minimize the variation due to irrigation. Missing data from October 2017 were the result of conflicting field operations. During installation of access tubes, soil samples were collected using a Madera sampler to determine bulk density and VWC for Hydroprobe calibration. The Hydroprobe count ratio was fitted to a linear calibration equation ($R^2 = 0.83$) to convert the count ratio to VWC (Dickey et al., 1993). Irrigation emitter flow rate was measured in all plots and equaled 41.5 L hr^{-1} ± 0.41 in 2016 and 36.4 L hr^{-1} ± 1.16 in 2017. Distribution uniformity (DU) was calculated using the ratio of average flow rate of lowest ¼ of the orchard and average flow rate of the whole orchard and equaled 92.7% in 2016 and 80.6% in 2017.

Tree midday stem water potential (SWP) was measured on trees within the same plots where access tubes were installed using a model 3000 pressure chamber (Soil moisture Equipment Corp, Goleta, CA). Readings were taken midday between 1:00 to 3:00 pm on the same day as soil moisture measurements. A leaf from a shaded position near the trunk was selected and bagged for a minimum of 10 min prior to recording the SWP measurement. SWP was measured from May to September when mature, healthy leaves were available. Baseline SWP (SWP for a fully-irrigated almond tree) was determined using the relative humidity and temperature measured at the field site on each day SWP measurements were performed, and calculated following McCutchan and Shackel (1992). SWP values are reported as the difference from the baseline.

A modified litter bag technique, referred to here as litter rings, was utilized to estimate decomposition of CM on tree berms as total mass loss of CM during the study period. Pre-weighed amendments were contained in a PVC pipe (30 cm diameter by 2.54 cm high) with coarse-mesh netting (0.08 cm openings) attached to the PVC pipe bottom and pinned on top of the soil. In August 2016 and 2017, litter rings were collected and weighed to estimate CM decomposition. During October 2016 and 2017, soil beneath litter rings from 0 to 60 cm depth were sampled, ground, de-carbonated, and analyzed for total soil organic carbon (SOC) (Harris et al., 2001). Brown and Sanden (*unpublished data*) estimated the active rooting zone for almond trees under micro-irrigation to be between 20–60 cm depth and Vrugt et al. (2001) determined almond tree water uptake under microirrigation occurred from 0 to 40 cm depth. Uniformity of soil texture was confirmed between experimental plots to 1.5 m depth by the rapid sieving technique (Kettler et al., 2001).

2.3. Water retention curves

Water retention curves were constructed using the Simplified Evaporation Method (Peters and Durner, 2008). Undisturbed soil samples were collected from Fall-applied CM and control plots in January 2018 from the 0–10 cm soil layer using 250 mL stainless steel rings at 30 cm from neutron probe access tubes. Samples were covered with plastic caps, stored at 4 °C, and processed within approximately 10 weeks of collection. Samples were saturated in a pan of water via capillary action, after which two precision tensiometers housed in a cylindrical pressure-sensing unit (HYPROP®, UMS GmbH, Munich, Germany) were inserted into each. Samples with sensor units were placed on a digital balance and left to dry gradually via evaporation at room temperature (28 °C) while water potential, pressure head, and sample mass were continuously recorded in the HYPROP-FIT® software v.3.5.1.13951 (Pertassek et al., 2015). Water retention curves were fit using the modified Van Genuchten model for soil hydraulic properties (Van Genuchten, 1980), given in Eq. 1 below:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \quad (1)$$

where θ is volumetric water content ($mm^3\,mm^{-3}$), θ_r is residual volumetric water content, θ_s is saturated volumetric water content, h is soil water potential (kPa), α is a scaling parameter inversely proportional to the mean pore diameter (cm^{-1}), and n and m are shaping parameters.

2.4. Statistical analyses

Soil moisture and midday SWP analyses were conducted using a mixed effects model structured for repeated measures on log-transformed data and SOC and OMA decomposition analyses were conducted by ANOVA and a Tukey test using SAS 9.4 (SAS Institute Cary, NC). VWC measurements below 150 cm depth were erratic, perhaps due to remnants of a duripan layer, and therefore eliminated from statistical analyses. We averaged VWC across depth in the root zone as the depth by treatment interaction was not significant ($p > 0.05$).

Optimal shaping and scaling parameters for Van Genuchten soil water retention curves were determined using PORT routines in the "stats" package of R (Gay, 1990) to minimize root-mean-square error. A lag element was included in the statistical model to account for residual autocorrelation and non-independence across time. The response variable was normalized by overall mean to account for different initial saturated water contents among samples. A linear model with the optimized Van Genuchten model and the lag element as explanatory variables was run for pooled (both treatments combined as fixed effect) and grouped (treatment as fixed effect) data. Comparative model fit between the two structures was evaluated using the Akaike Information Criterion (AIC) and Mallow's Cp metrics to test whether the Van Genuchten model parameters were significantly different between treatments, i.e., whether the model grouped by treatment was any more informative than the pooled model.

3. Results and discussion

3.1. Soil moisture

3.1.1. Seasonal soil moisture patterns

Soil moisture from 0 to 150 cm depth averaged across treatments and years decreased by 47% over the duration of the growing season (Fig. 2). In 2016 the VWC dropped 38% from April to June, and we observed relatively dry soil conditions with an average of 0.09 $cm^3\,cm^{-3}$ from July to October. In 2017 VWC decreased uniformly from April to September. These results are expected because almond trees deplete soil water reserves by mid-to-late summer, and high ET during June to August drives water loss from soil and leaf surfaces (Shackel et al. 1997). The overall average VWC was 20% less in 2016 than the average VWC in 2017 and the average monthly VWC ranged from 12% to 20% lower in 2016 compared to 2017, except in September when soil was similarly dry. These differences can be attributed to differing water management in a non-harvest (2016) and harvest (2017) year.

3.1.2. Effects of composted manure

Soil moisture from 0 to 150 cm depth was 8.2%–22% higher with CM relative to the control when averaged by month and treatment (Fig. 2). Fall-applied CM showed the highest mean VWC in all months except April 2016, and was significantly greater than the control from July to October 2016. We measured the largest significant difference between treatments in July 2016, with 24% higher VWC in Fall-applied CM compared to the control. The Fall and Spring timing treatments were not significantly different at $p < 0.05$. Soil moisture in 2017 exhibited similar trends as 2016, but treatment differences were smaller and no longer significant (Fig. 2). Soil SOC was significantly higher in the Fall-applied CM compared to Spring in 2016, but we observed no differences in 2017 (Table 1). The lack of a significant difference in 2017 for VWC may be related to increased irrigation, or it could be due to lower DU of irrigated water in 2017 compared to 2016 which was 80.6% and 92.7%, respectively.

Greater SOC for Fall-applied CM likely played a role in the observed significant differences in VWC between Fall-applied CM and the control (Fig. 2, Table 1). An increase in SOM as well as improved soil structure (Mays et al., 2015; Oliveira and Merwin, 2001) following OMA has also been observed in a variety of cropping systems, including permanent crops (Hannam et al., 2016; Lopez et al., 2014; Peck et al., 2011).

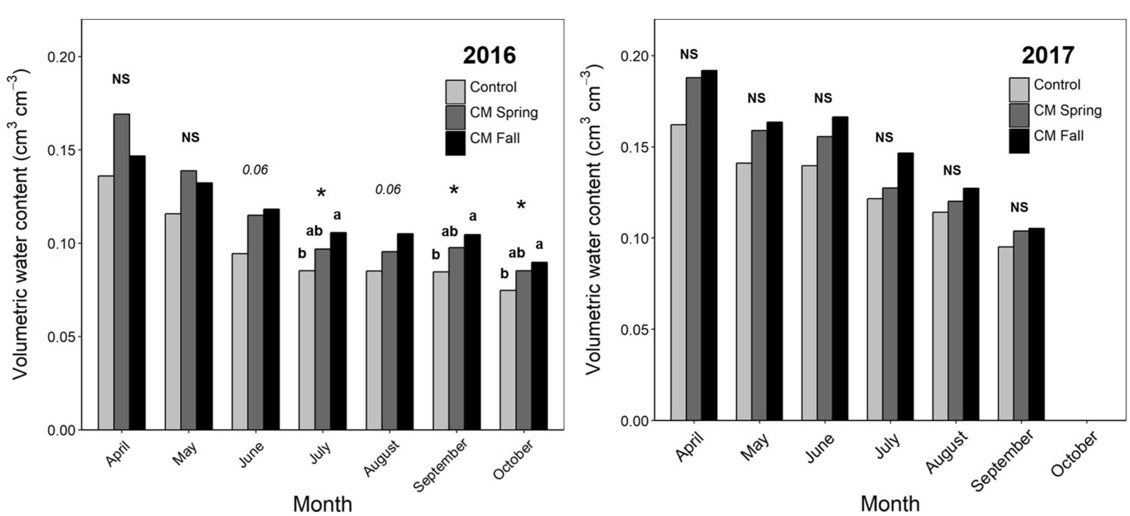


Fig. 2. Soil moisture represented by monthly averages during the growing season from April to October 2016 and 2017. Treatments are composted manure (CM) applied annually either in Fall (October 2015 and 2016) or Spring (April 2016 and 2017). Soil moisture is the volumetric water content ($cm^3\,cm^{-3}$) of soil to a depth of 150 cm. Bars are LS means with asterisks (*) representing significant differences between treatments and NS indicates no significant difference at α = 0.05; p-values close to α = 0.05 are given in italics. Monthly values with different letters are significantly different by Tukey comparisons.

Table 1
Total soil organic carbon (g C kg^{-1} soil) from 0 to 60 cm sampled in October 2016 and 2017. Treatments include Fall (October 2015 and 2016) and Spring-applied (April 2016 and 2017) composted manure (CM) at a rate of 9 Mg ha^{-1}. Values are means with significant ($p < 0.05$) differences *in italics* with different letters between treatments using a Tukey test.

	Total soil organic carbon	
	g C kg⁻¹ soil	
	2016	*2017*
Control	4.70 b	4.24 a
Spring-applied CM	4.79 b	4.60 a
Fall-applied CM	5.50 a	4.66 a
p value	*0.04*	0.81

Higher SOM from OMA in orchards also correlated with higher soil water infiltration and hydraulic conductivity (Goh et al., 2001; Lordan et al., 2015; Merwin et al., 1994). Studies with permanent crops support the observed increase in VWC in Fall-applied CM being the result of SOM accumulation improving soil structure leading to greater water infiltration and soil water retention.

The findings of this study are well aligned with the majority of permanent crop studies demonstrating enhanced soil moisture from OMA use, yet the magnitude of the effect may depend on the OMA source. There is strong evidence that OMA with a C:N ratio greater than 30:1 significantly increase soil water infiltration and reduce surface evaporation in orchards (Goh et al., 2001; Lordan et al., 2015; Zribi et al., 2015). The C:N ratio of CM from this trial (11:1) was lower than other organic mulches such as straw (75:1) and bark (200:1) (Bernal et al., 2017; Gale et al., 2006). Apples orchards treated with bark had higher VWC than untreated orchards (Granatstein and Mullinix, 2008) while straw mulch increased (Walsh et al., 1996) or had no effect on VWC (Oliveira and Merwin, 2001). There is less evidence for increased soil moisture with OMA sources with C:N less than 30:1 (Hannam et al., 2016). Studies in apple (Walsh et al., 1996) and California winegrape (Bound, 2014) report significantly higher soil water content with straw and bark mulch compared to a control, but no difference with CM. OMA with C:N greater than 30:1 is more resistant to microbial decomposition and provides physical protection to the soil surface, thereby reducing surface evaporation and improving water infiltration. The effects of OMA sources with C:N less than 30:1 are likely related to SOM accumulation rather than physical protection of the soil surface and tend to be observed in low SOM soils (Du et al., 2015; Mays et al., 2015) like many orchard soils in California.

Our results demonstrate that the effect of OMA timing on soil moisture alters soil and tree response as evidenced by Fall-applied CM increasing soil moisture more significantly than Spring-applied CM (Table 1). Overwintering and greater decomposition of Fall-applied CM compared to Spring-applied CM in 2016 and significantly greater decomposition of Fall-applied CM in 2017 (Table 2) likely resulted in greater C stabilization in SOM. Multiple studies showed cool temperatures reduce the rate of C mineralization of OMA (Ding et al., 2007; Nicolardot et al., 1994; Qi et al., 2016), whereas warm soil temperatures and adequate moisture accelerated microbial mineralization of SOC (Blanke, 1997; Lomander et al., 1998). As OMA undergoes decomposition, a fraction of labile C is transformed into more complex, less degradable C forms (Curtin et al., 1998; Grandy and Neff, 2008; Prescott, 2010). Decomposition under cooler temperatures may enhance C stabilization derived from CM and increase resistance to mineralization during subsequent growing seasons. Fall-applied CM increased SOM compared to Spring-applied CM, and hence may be more effective in enhancing infiltration and soil moisture retention.

Table 2
Composted manure decomposition from mass loss sampled in August 2016 and 2017. Treatments include composted manure with application in Fall (October 2015 and 2016) or Spring (April 2016 and 2017) at a rate of 9 Mg ha^{-1}. Values are means with significant ($p < 0.05$) differences *in italics* with different letters between treatments using a Tukey test.

	Composted manure decomposition	
	Mg ha⁻¹	
	2016	*2017*
Spring	4.22 a	2.97 b
Fall	4.56 a	4.13 a
p value	0.22	*0.04*

Significant differences ($p < 0.05$) in VWC between Fall-applied CM and the control were observed in 2016 when orchard soils were drier and in months with maximum soil water depletion (Fig. 2). Similarly, Fall-applied CM had greater SOM compared to Spring-applied CM in a dry year (2016), but not in a wetter year (2017) due to more intensive irrigation. Together, these findings suggest that CM has a greater effect on VWC in drier years, and that this effect is due to lower soil C mineralization in drier years. Current literature suggests OMA has a stronger effect on soil moisture in dry climates and during periods of high tree water uptake (Granatstein and Mullinix, 2008; Merwin et al., 1994; Walsh et al., 1996). In orchards in an arid and semi-arid climate, higher soil moisture (Du et al., 2015) and AWC (Li et al., 2017) was observed in plots with OMA. Potential water retention with OMA in dry soils has clear implications for orchard resilience to drought and suggests the greater benefit from OMA use may be during years when irrigation supply is limited.

3.2. Soil water retention

The Fall-applied CM treatment maintained an average of 13% more VWC between 50–150 kPa (in the plant available range) than the control (Fig. 3). The best linear model for water retention showed a significant increase in VWC with Fall-applied CM across all measured matric potentials, i.e., from saturation to slightly beyond field capacity ($t = 3.84$, $p < 0.001$). Model fit showed improvement with the inclusion of a grouped treatment effect and a lag element to account for auto-correlation of sequential measurements, indicating that coefficients for the Van Genuchten function differed for curves between Fall-applied CM and the control. Thus, although our equipment could not measure water content at the permanent wilting point, we suspect the curves would differ enough between field capacity and permanent wilting point to create differences in AWC between Fall-applied CM and the control.

Fall-applied CM had a significant effect on soil water retention in the topsoil (0–10 cm depth), and retained higher VWC than the control at matric potentials between 0 and ˜100 kPa (Fig. 3). Numerous studies found OMA significantly increased soil water retention at saturation and field capacity (Carter, 2007; Logsdon and Malone, 2015; Weber et al., 2007), water potentials at which SOM most strongly influences soil moisture (Hudson, 1994; Minasny and McBratney, 2018a; Rawls et al., 2003). A clay loam soil amended with CM had higher soil water retention at field capacity, which also correlated with lower bulk density and higher porosity, compared to an unamended control (Miller et al., 2015). At field capacity, soil water is retained in structural macropores (> 30 microns), and improvement in water retention with Fall-applied CM at field capacity can likely be attributed to macroaggregate formation and stabilization associated with the 10% increase in SOC relative to the control in 2017 (Eden et al., 2017; Rabot et al., 2018).

Climate, soil texture, and management factors strongly influence SOM dynamics, and OMA effects on soil water retention vary across environmental and agronomic conditions. Use of OMA tends to have the greatest effect on soil water retention of course-textured, sandy soils with a low initial SOM content (Foley and Cooperband, 2002; Gulser and Candemir, 2015; Weber et al., 2007) similar to the soil type in this study. A loamy sand in field crop rotation retained significantly greater

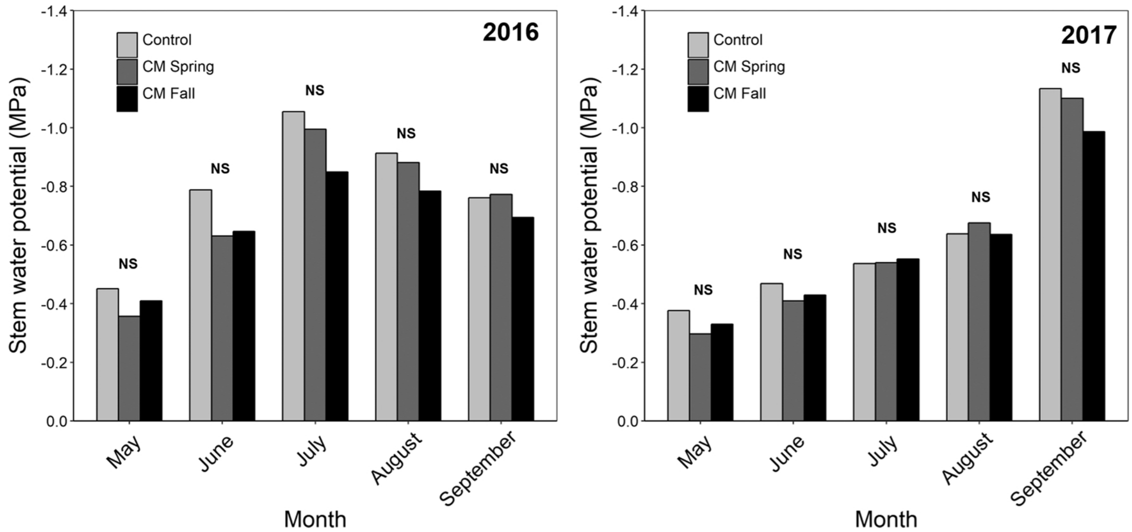


Fig. 3. Soil water retention curves for composted manure applied in Fall (CM Fall, solid line) and control (dashed line) treatments, measured with the Simplified Evaporation Method (gray points) and fitted with Van Genuchten soil hydraulic property functions optimized for each treatment group. Fitted lines represent the model grouped by treatment, which was the better model according the Cp and AIC metrics.

VWC after the second application of OMA and AWC increase as much as 45% with some OMA sources (Foley and Cooperband, 2002). Few studies have examined soil water retention as a function of OMA in permanent crops. Despite the lack of significant differences in VWC and SOC during 2017, we observed significantly higher soil water retention with Fall-applied CM after the 2017 growing season. Our findings are well-supported by studies that find OMA improves soil water retention and AWC in dry climates (Di Prima et al., 2018; Eden et al., 2017; Li et al., 2017), and small increases in SOM can have a marked effect on AWC in course-textured soils (Foley and Cooperband, 2002; Gulser and Candemir, 2015; Weber et al., 2007).

Greater soil water retention at the 0–10 cm depth combined with higher VWC at 0–150 cm depth observed in Fall-applied CM suggests enhanced water retention in the topsoil may lead to higher VWC in the subsoil. OMA applied as mulch in no-till systems tends to have the greatest effect on soil physical properties in the topsoil (Mays et al., 2014; Oliveira and Merwin, 2001). Maintaining adequate soil moisture in topsoil benefits microbial communities, which improves soil structure, nutrient cycling, and plant stress resilience (Six et al., 2004; Timmusk et al., 2014) and is important for fine root production, which facilitates nutrient and water uptake. Maximum water uptake by almond trees occurs at 20–30 cm depth (Koumanov et al., 2006; Vrugt et al., 2001), implying the greatest root activity is in topsoil. Enhanced water retention in the topsoil may lead to higher VWC in the subsoil, which can mitigate water stress in permanent crops (Li et al., 2017).

Soil AWC generally improves with OMA use, but the magnitude of these effects depends on climate and soil types. Hudson (1994) demonstrated soils with higher SOC had significantly greater AWC and estimated an increase of 2.2 to 3.7% with every 1% increase in SOC (Eden et al., 2017). Results from OMA studies vary widely; some report increases up to 86% in AWC on marginal or sandy soils (Celik et al., 2004; Foley and Cooperband, 2002), and others report an increase in VWC at field capacity, but no difference in AWC (Carter, 2007; Gulser and Candemir, 2015; Miller et al., 2015). Long-term annual application of manure over greater than 7 years resulted in a 2% increase in AWC for every 10 Mg C ha^{-1} applied with a persistent impact for 2 years after the last application (Bhogal et al., 2011). Other studies report short-term increases in AWC with OMA (Jordan et al., 2010; Weber et al., 2007) while others showed no effect of OMA on AWC (Deurer et al., 2008). Water retention in the Fall-applied CM and control treatments differed enough to suggest higher AWC with Fall-applied CM, as evidenced by higher VWC and SWP from Fall-applied CM during periods of low soil moisture. Improved AWC with OMA could help sustain tree growth in drought years and during periods of moisture deficit, and potentially delay or reduce the need for irrigation, thereby reducing orchard water use.

3.3. Tree water status

3.3.1. Seasonal SWP patterns

The seasonal pattern in SWP differed between 2016 and 2017 in the treatments and control (Fig. 4). Average monthly SWP was 0.07 to 0.25 MPa more negative from May to August 2016 compared to the same period in 2017 ($p =$ 0.01). In 2016, SWP peaked in July 2016 at -0.97 MPa below baseline. In 2017, SWP was less than −0.70 MPa below baseline for most of the growing season, and most negative (−1.07 MPa) in September 2017.

Patterns in soil moisture were reflected in measurements of SWP where increases and decreases in VWC equated with lower and higher tree water stress, respectively. SWP was 32% less negative in 2016 compared with 2017. High water stress of −1.1 MPa average SWP below baseline in September 2017 coincided with deficit irrigation to dry the orchard floor prior to harvest. SWP of −1.0 MPa below baseline is thought to be the threshold for onset of growth-limiting water stress in almonds (Espadafor et al., 2017), though Shackel et al. (1998) report a 50% reduction in tree circumference at −0.85 MPa SWP below baseline. Moderate water deficit has been shown to reduce growth of *Prunus spp.* (De la Rosa et al., 2016; Perez-Pastor et al., 2014) which could reduce future productivity (Forey et al., 2016; Shackel et al., 1998). Maximum vegetative growth is important during orchard establishment to hasten onset of yield in young trees (Goldhamer et al., 1999). Our findings suggest OMA use in young orchards could have a long-term impact on future orchard productivity due to a reduction in water stress at a critical point in tree life.

3.3.2. Effects of composted manure

Monthly average SWP was 0.03 to 0.15 MPa less negative from CM compared to the control during the majority of 2016 and 2017, but the effects were not significant in any month ($p > 0.05$) (Fig. 4). Fall-applied CM had the lowest water stress from June to September 2016, which averaged 0.13 MPa less than the control. Monthly average SWP was similar for all treatments from May to August 2017, with no apparent trends among treatments. In September 2017, when deficit irrigation was applied to facilitate harvest, overall water stress levels

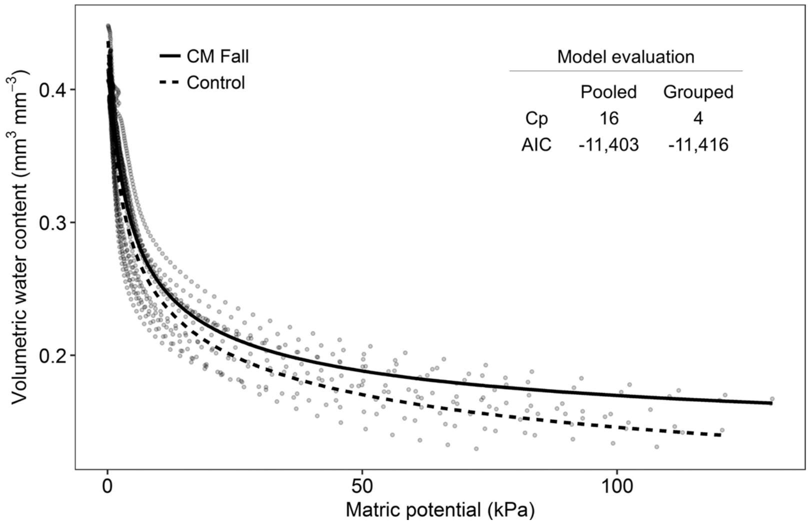


Fig. 4. Midday stem water potential difference from baseline (MPa) during the growing season from May to September 2016 and 2017 represented by monthly averages. Treatments are composted manure (CM) applied annually either in Fall (October 2015 and 2016) or Spring (April 2016 and 2017). Bars represent LS means, and NS indicates no significant difference at α = 0.05.

increased sharply yet Fall-applied CM trees were the least stressed.

The consistent pattern of lower tree stress observed in Fall-applied CM trees in 2016 correlates with the pattern of treatment effects on VWC (Fig. 2; Fig. 4). Measures of tree water status reflect interrelationships among soil, climate, and crop factors (Gomez-del-Campo, 2013). As a result, changes in soil moisture from OMA may not be detected by a SWP response. However, Lordan et al. (2015) reported less water stress in peach trees mulched with compost with greater differences in year two of the trial. The trends observed in SWP indicate OMA application in Fall could reduce tree water stress more than Spring application, and the correlation of increasing VWC and decreasing SWP from Fall-applied CM relative to the control suggests increased AWC from CM facilitated greater tree water uptake.

In Fall-applied CM trees, water stress trended lowest and SWP was 14% higher than the control in months when the mean VWC was less than 10%, whereas there was no trend in months when the mean VWC was greater than 10%. These differences could be related to greater soil water retention with Fall-applied CM, which increased soil water availability when moisture was limiting. This observation supports our conclusion that OMA use could increase drought resilience of permanent crops.

4. Conclusion

Efficient use of water resources from irrigation and precipitation is important for the long-term productivity of permanent crops in drought-prone regions like California. OMA enhanced VWC and soil water retention in the tree rooting zone, increased SOC, and decreased tree water stress, especially when applied in Fall. Fall application of OMA, which led to more complete decomposition and greater C stabilization during winter months, could contribute to higher SOM accumulation and VWC compared to Spring application. The strongest effects of OMA were observed in drier soils and during periods of high-water demand. Therefore, OMA use during orchard establishment or when water supply is limited can increase tree resilience, leading to greater assurance of productivity over the long-term.

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References

Bernal, M.P., Sommer, S.G., Chadwick, D., Qing, C., Li, G.X., Michel, F.C., 2017. lCurrent approaches and future trends in compost quality criteria for agronomic, environmental, and human health benefits. Adv. Agron. 144, 143–233. https://doi.org/10.1016/bs.agron.2017.03.002.

Bhogal, A., Nicholson, F.A., Young, I., Sturrock, C., Whitmore, A.P., Chambers, B.J., 2011. Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality. Eur. J. Soil Sci. 62, 174–181. https://doi.org/10.1111/j.1365-2389.2010.01319.x.

Blanke, M.M., 1997. Contribution of soil respiration to the carbon balance of an apple orchard. In: Barritt, B.H., Kappel, F. (Eds.), International Symposium on Integrating Canopy, Rootstocks and Environmental Physiology in Orchard Systems, Proceedings - Vols 1 and 2, Acta Horticulturae, pp. 337–344. https://doi.org/10.17660/ActaHortic.1997.451.39.

Bound, S.A., 2014. Mulch application in hops, grapes and olives. I Int. Symp. Org. Matter Manag. Compost Use Hortic. 1018, 361–368.

Carter, M.R., 2007. Long-term influence of compost on available water capacity of a fine sandy loam in a potato rotation. Can. J. Soil Sci. 87, 535–539. https://doi.org/10.4141/cjss06042.

CDFA, 2017. California Agricultural Statistics Review 2016-2017. Sacramento.

Celik, I., Ortas, I., Kilic, S., 2004. Effects of compost, mycorrhiza, manure and fertilizer on some physical properties of a Chromoxerert soil. Soil Tillage Res. 78, 59–67. https://doi.org/10.1016/j.still.2004.02.012.

CIMIS, 2018. California Irrigation Management Information System [WWW Document]. (accessed 12.8.18). https://cimis.water.ca.gov/Default.aspx.

Curtin, D., Selles, F., Wang, H., Campbell, C.A., Biederbeck, V.O., 1998. Carbon dioxide emissions and transformation of soil carbon and nitrogen during wheat straw decomposition. Soil Sci. Soc. Am. J. 62, 1035–1041. https://doi.org/10.2136/sssaj1998.03615995006200040026x.

De la Rosa, J.M., Conesa, M.R., Domingo, R., Aguayo, E., Falagan, N., Perez-Pastor, A., 2016. Combined effects of deficit irrigation and crop level on early nectarine trees. Agric. Water Manag. 170, 120–132. https://doi.org/10.1016/j.agwat.2016.01.012.

Deurer, M., Sivakumaran, S., Ralle, S., Vogeler, I., McLvor, I., Clothier, B., Green, S., Bachmann, J., 2008. A new method to quantify the impact of soil carbon management on biophysical soil properties: the example of two apple orchard systems in New Zealand. J. Environ. Qual. 37, 915–924. https://doi.org/10.2134/jeq2007.0508.

Dexter, A.R., 1988. Advances in characterization of soil structure. Soil Tillage Res. 11, 199–238. https://doi.org/10.1016/0167-1987(88)90002-5.

Dexter, A.R., Richard, G., Arrouays, D., Czyz, E.A., Jolivet, C., Duval, O., 2008. Complexed organic matter controls soil physical properties. Geoderma 144, 620–627. https://doi.org/10.1016/j.geoderma.2008.01.022.

Di Prima, S., Rodrigo-Comino, J., Novara, A., Iovino, M., Pirastru, M., Keesstra, S., Cerda, A., 2018. Soil physical quality of Citrus orchards under tillage, herbicide, and organic managements. Pedosphere 28, 463–477. https://doi.org/10.1016/s1002-0160(18)60025-6.

Dickey, G.L., Richard, A., Wright, J.L., Murray, N.R., Stone, J.F., Hunsaker, D.J., 1993. Soil bulk density sampling for neutron guage calibration. Irrigation and Drainage Systems. pp. 1103–1111.

Ding, W.X., Meng, L., Yin, Y.F., Cai, Z.C., Zheng, X.H., 2007. CO2 emission in an intensively cultivated loam as affected by long-term application of organic manure and nitrogen fertilizer. Soil Biol. Biochem. 39, 669–679. https://doi.org/10.1016/j.soilbio.2006.09.024.

Du, S.N., Bai, G.S., Yu, J., 2015. Soil properties and apricot growth under intercropping and mulching with erect milk vetch in the loess hilly-gully region. Plant Soil 390, 431–442. https://doi.org/10.1007/s11104-014-2363-7.

Duncan, R.A., Holtz, B.A., Doll, D.A., Klonsky, K.M., Sumner, D.A., Gutierrez, C.A., Stewart, D.E., 2016. Sample Costs for to Establish and Orchard and Produce Almonds. San Joaquin Valley North, University of California Cooperative Extension and UC Agricultural Issues Center.

Eden, M., Gerke, H.H., Houot, S., 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. Agron. Sustain. Dev. 37. https://doi.org/10.1007/s13593-017-0419-9.

Espadafor, M., Orgaz, F., Testi, L., Lorite, I.J., Gonzalez-Dugo, V., Fereres, E., 2017. Responses of transpiration and transpiration efficiency of almond trees to moderate water deficits. Sci. Hortic. (Amsterdam). 225, 6–14. https://doi.org/10.1016/j.scienta.2017.06.028.

Foley, B.J., Cooperband, L.R., 2002. Paper mill residuals and compost effects on soil carbon and physical properties. J. Environ. Qual. 31, 2086–2095.

Forey, O., Metay, A., Wery, J., 2016. Differential effect of regulated deficit irrigation on growth and photosynthesis in young peach trees intercropped with grass. Eur. J. Agron. 81, 106–116. https://doi.org/10.1016/j.eja.2016.09.006.

Gale, E.S., Sullivan, D.M., Cogger, C.G., Bary, A.I., Hemphill, D.D., Myhre, E.A., 2006. Estimating plant-available nitrogen release from manures, composts, and specialty products. J. Environ. Qual. 35, 2321–2332. https://doi.org/10.2134/jeq2006.0062.

Gay, D.M., 1990. Usage Summary for Selected Optimization Routines. (No. 153), Computing Science Technical Report. Murray Hill.

Girona, J., Marsal, J., Mata, M., Arbones, A., Miravete, C., 1997. Evaluation of almond (Amygdalus communis L.) seasonal sensitivity to water stress. Physiological and yield responses. Second Int. Symp. Irrig. Hortic. Crop. 1 (2), 489–496. https://doi.org/10.17660/ActaHortic.1997.449.68.

Goh, K.M., Pearson, D.R., Daly, M.J., 2001. Effects of apple orchard production systems on some important soil physical, chemical and biological quality parameters. Biol. Agric. Hortic. 18, 269–292.

Goldhamer, D.A., Fereres, E., Mata, M., Girona, J., Cohen, M., 1999. Sensitivity of continuous and discrete plant and soil water status monitoring in peach trees subjected to deficit irrigation. J. Am. Soc. Hortic. Sci. 124, 437–444.

Gomez-del-Campo, M., 2013. Summer deficit irrigation in a hedgerow olive orchard cv. Arbequina: relationship between soil and tree water status, and growth and yield components. Span. J. Agric. Res. 11, 547–557. https://doi.org/10.5424/sjar/2013112-3360.

Granatstein, D., Mullinix, K., 2008. Mulching options for northwest organic and conventional orchards. Hortscience 43, 45–50.

Grandy, A.S., Neff, J.C., 2008. Molecular C dynamics downstream: the biochemical decomposition sequence and its impact on soil organic matter structure and function. Sci. Total Environ. 404, 297–307. https://doi.org/10.1016/j.scitotenv.2007.11.013.

Gulser, C., Candemir, F., 2015. Effects of agricultural wastes on the hydraulic properties of a loamy sand cropland in Turkey. Soil Sci. Plant Nutr. 61, 384–391. https://doi.org/10.1080/00380768.2014.992042.

Hannam, K.D., Neilsen, G.H., Forge, T.A., Neilsen, D., Losso, I., Jones, M.D., Nichol, C., Fentabil, M.M., 2016. Irrigation practices, nutrient applications, and mulches affect soil nutrient dynamics in a young Merlot (Vitis vinifera L.) vineyard. Can. J. Soil Sci. 96, 23–36. https://doi.org/10.1139/cjss-2014-0118.

Harris, D., Horwath, W.R., van Kessel, C., 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. Soil Sci. Soc. Am. J. 65, 1853–1856. https://doi.org/10.2136/sssaj2001.1853.

Haynes, R.J., 1981. Effects of soil-management practices on soil physical-properties, earthworm population and tree root distribution in a commercial apple orchard. Soil Tillage Res. 1, 269–280. https://doi.org/10.1016/0167-1987(80)90029-x.

Hudson, B.D., 1994. Soil organic-matter and available water capacity. J. Soil Water Conserv. 49, 189–194.

Johnson, E., Cody, B.A., 2015. California Agricultural Production and Irrigated Water Use.

Jordan, A., Zavala, L.M., Gil, J., 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. Catena 81, 77–85. https://doi.org/10.1016/j.catena.2010.01.007.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61, 4–10.

Kettler, T.A., Doran, J.W., Gilbert, T.L., 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Sci. Soc. Am. J. 65, 849–852. https://doi.org/10.2136/sssaj2001.653849x.

Khalsa, S.D.S., Brown, P.H., 2017. Grower analysis of organic matter amendments in California orchards. J. Environ. Qual. 46, 649–658. https://doi.org/10.2134/jeq2016.11.0456.

Koumanov, K.S., Hopmans, J.W., Schwankl, L.W., 2006. Spatial and temporal distribution of root water uptake of an almond tree under microsprinkler irrigation. Irrig. Sci. 24, 267–278. https://doi.org/10.1007/s00271-005-0027-3.

Lampinen, B.D., Shackel, K.A., Southwick, S.M., Olson, W.H., 2001. Deficit irrigation strategies using midday stem water potential in prune. Irrig. Sci. 20, 47–54. https://doi.org/10.1007/s002710000028.

Li, Z.H., Wang, M., Yang, Y., Zhao, S.X., Zhang, Y.L., Wang, X.D., 2017. Effect of composted manure plus chemical fertilizer application on aridity response and productivity of apple trees on the loess plateau. China. Arid L. Res. Manag. 31, 388–403. https://doi.org/10.1080/15324982.2017.1344332.

Logsdon, S.D., Malone, R.W., 2015. Surface compost effect on hydrology: in-situ and soil cores. Compost Sci. Util. 23, 30–36. https://doi.org/10.1080/1065657x.2014.949909.

Lomander, A., Katterer, T., Andren, O., 1998. Carbon dioxide evolution from top- and subsoil as affected by moisture and constant and fluctuating temperature. Soil Biol. Biochem. 30, 2017–2022. https://doi.org/10.1016/s0038-0717(98)00076-5.

Lopez, R., Burgos, P., Hermoso, J.M., Hormaza, J.I., Gonzalez-Fernandez, J.J., 2014. Long term changes in soil properties and enzyme activities after almond shell mulching in avocado organic production. Soil Tillage Res. 143, 155–163. https://doi.org/10.1016/j.still.2014.06.004.

Lordan, J., Pascual, M., Villar, J.M., Fonseca, F., Papio, J., Montilla, V., Rufat, J., 2015. Use of organic mulch to enhance water-use efficiency and peach production under limiting soil conditions in a three-year-old orchard. Span. J. Agric. Res. 13. https://doi.org/10.5424/sjar/2015134-6694.

Mays, N., Brye, K.R., Rom, C.R., Savin, M., Garcia, M.E., 2014. Groundcover management and nutrient source effects on soil carbon and nitrogen sequestration in an organically managed apple orchard in the Ozark Highlands. Hortscience 49, 637–644.

Mays, N., Rom, C.R., Brye, K.R., Savin, M.C., Garcia, M.E., 2015. Groundcover management system and nutrient source impacts on soil quality indicators in an organically managed apple (Malus X domestica borkh.) orchard in the Ozark Highlands. Hortscience 50, 295–303.

McCutchan, H., Shackel, K.A., 1992. Stem-water potential as a sensitive indicator of water-stress in prune trees (prunus-domestica l cv french). J. Am. Soc. Hortic. Sci. 117, 607–611.

Merwin, I.A., Stiles, W.C., Vanes, H.M., 1994. Orchard groundcover management impacts on soil physical-properties. J. Am. Soc. Hortic. Sci. 119, 216–222.

Miller, J.J., Beasley, B.W., Drury, C.F., Larney, F.J., Hao, X., 2015. Influence of long-term (9 yr) composted and stockpiled feedlot manure application on selected soil physical properties of a clay loam soil in Southern Alberta. Compost Sci. Util. 23, 1–10. https://doi.org/10.1080/1065657x.2014.963741.

Minasny, B., McBratney, A.B., 2018a. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 69, 39–47. https://doi.org/10.1111/ejss.12475.

Minasny, B., McBratney, A.B., 2018b. Rejoinder to the comment on: B. Minasny & AB McBratney. 2018. Limited effect of organic matter on soil available water capacity. Eur. J. Soil Sci. 69, 155–157. https://doi.org/10.1111/ejss.12526.

Nicolardot, B., Fauvet, G., Cheneby, D., 1994. Carbon and nitrogen cycling through soil microbial biomass at various temperatures. Soil Biol. Biochem. 26, 253–261. https://doi.org/10.1016/0038-0717(94)90165-1.

Oliveira, M.T., Merwin, I.A., 2001. Soil physical conditions in a New York orchard after eight years under different groundcover management systems. Plant Soil 234, 233–237. https://doi.org/10.1023/a:1017992810626.

Peck, G.M., Merwin, I.A., Thies, J.E., Schindelbeck, R.R., Brown, M.G., 2011. Soil properties change during the transition to integrated and organic apple production in a New York orchard. Appl. Soil Ecol. 48, 18–30. https://doi.org/10.1016/j.apsoil.2011.02.008.

Perez-Pastor, A., Ruiz-Sanchez, M.C., Domingo, R., 2014. Effects of timing and intensity of deficit irrigation on vegetative and fruit growth of apricot trees. Agric. Water Manag. 134, 110–118. https://doi.org/10.1016/j.agwat.2013.12.007.

Pertassek, T., Peters, A., Durner, W., 2015. HYPROP-FIT Software User's Manual, V.3.0.

Peters, A., Durner, W., 2008. Simplified evaporation method for determining soil hydraulic properties. J. Hydrol. 356, 147–162. https://doi.org/10.1016/j.jhydrol.2008.04.016.

Prescott, C.E., 2010. Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? Biogeochemistry 101, 133–149. https://doi.org/10.1007/s10533-010-9439-0.

Qi, R.M., Li, J., Lin, Z.A., Li, Z.J., Li, Y.T., Yang, X.D., Zhang, J.J., Zhao, B.Q., 2016. Temperature effects on soil organic carbon, soil labile organic carbon fractions, and soil enzyme activities under long-term fertilization regimes. Appl. Soil Ecol. 102, 36–45. https://doi.org/10.1016/j.apsoil.2016.02.004.

Rabot, E., Wiesmeier, M., Schluter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137. https://doi.org/10.1016/j.geoderma.2017.11.009.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/s0016-7061(03)00094-6.

Reganold, J.P., Glover, J.D., Andrews, P.K., Hinman, H.R., 2001. Sustainability of three apple production systems. Nature 410, 926–930. https://doi.org/10.1038/35073574.

Shackel, K., Gurusinghe, S., Kester, D., Micke, W., Kester, D., 1998. Water stress responses of almond Prunus dulcis (Mill.) Webb. Trees under field conditions. In: Ferguson, L. (Ed.), Second International Symposium on Pistachios and Almonds, Acta Horticulturae, pp. 309–316.

Shackel, K., Lampinen, B., Sibbett, S., Olson, W., 2000. The relation of midday stem water potential to the growth and physiology of fruit trees under water limited conditions. Proc. Third Int. Symp. Irrig. Hortic. Crop. Vols 1 (2), 425–430. https://doi.org/10.17660/ActaHortic.2000.537.50.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79, 7–31. https://doi.org/10.1016/j.still.2004.03.008.

Six, J., Paustian, K., Elliott, E.T., Combrink, C., 2000. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. Soil Sci. Soc. Am. J. 64, 681–689.

Smart, D.R., Alsina, M.M., Wolff, M.W., Matiasek, M.G., Schellenberg, D.L., Edstrom, J.P., Brown, P.H., Scow, K.M., 2011. N2O emissions and Water management in California perennial crops. In: Guo, L., Gunasekara, A.S., McConnell, L.L. (Eds.), Understanding Greenhouse Gas Emissions from Agricultural Management, ACS Symposium Series. pp. 227–255 Amer Chemical Soc, [Smart, David R. Alsina, M. Mar Wolff, Michael W. Schellenberg, Daniel L.] Univ Calif Davis, Dept Viticulture & Enol, Robert Mondavi Inst N, Davis, CA 95616 USA. [Matiasek, Michael G. Scow, Kate M.] Univ Calif Davis, Dept Land Air & Water Resources, Davis.

Swain, D.L., Langenbrunner, B., Neelin, J.D., Hall, A., 2018. Increasing precipitation volatility in twenty-first-century California. Nat. Clim. Chang. 8, 427. https://doi.org/10.1038/s41558-018-0140-y. −+.

Timmusk, S., Abd El-Daim, I.A., Copolovici, L., Tanilas, T., Kannaste, A., Behers, L., Nevo, E., Seisenbaeva, G., Stenstrom, E., Niinemets, U., 2014. Drought-Tolerance of Wheat Improved by Rhizosphere Bacteria from Harsh Environments: Enhanced Biomass Production and Reduced Emissions of Stress Volatiles. PLoS One 9, 13. https://doi.org/10.1371/journal.pone.0096086.

Tindula, G.N., Orang, M.N., Snyder, R.L., 2013. Survey of irrigation methods in California in 2010. J. Irrig. Drain. Eng. 139, 233–238. https://doi.org/10.1061/(asce)ir.1943-4774.0000538.

Tisdall, J.M., Oades, J.M., 1982. Organic-matter and water-stable aggregates in soils. J. Soil Sci. (33), 141–163.

USDA, 2016. National Agricultural Statistics Service [WWW Document]. (accessed 12.8.18). https://quickstats.nass.usda.gov/.

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Vrugt, J.A., Hopmans, J.W., Simunek, J., 2001. Calibration of a two-dimensional root water uptake model. Soil Sci. Soc. Am. J. 65, 1027–1037. https://doi.org/10.2136/sssaj2001.6541027x.

Walsh, B.D., Salmins, S., Buszard, D.J., MacKenzie, A.F., 1996. Impact of soil management systems on organic dwarf apple orchards and soil aggregate stability, bulk density, temperature and water content. Can. J. Soil Sci. 76, 203–209.

Weber, J., Karczewska, A., Drozd, J., Licznar, M., Licznar, S., Jamroz, E., Kocowicz, A., 2007. Agricultural and ecological aspects of a sandy soil as affected by the application of municipal solid waste composts. Soil Biol. Biochem. 39, 1294–1302. https://doi.org/10.1016/j.soilbio.2006.12.005.

Zribi, W., Aragues, R., Medina, E., Faci, J.M., 2015. Efficiency of inorganic and organic mulching materials for soil evaporation control. Soil Tillage Res. 148, 40–45. https://doi.org/10.1016/j.still.2014.12.003.