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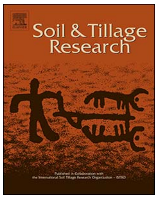

Minimum tillage of a cover crop lowers net GWP and sequesters soil carbon in a California vineyard

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ABSTRACT

The net global warming potential (GWP) of a cropping system describes net exchanges of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Greenhouse gas intensity (GHGI) relates net GWP to productivity. The use of a barley cover crop was tested in a California vineyard from 2003 to 2010 under two alternative tillage systems, along with a business-as-usual control treatment with incorporation of native weeds. The aim was a comprehensive assessment of barleý s potential to sequester carbon in the soil, and of related (tillage-derived) effects on the vineyarḿ s net GWP and GHGI. Measurements were made over two years (2009–2010) and included surface fluxes of N_2O and CH_4, differences in soil carbon, fuel consumption and yield. Above- and belowground net primary productivity (ANPP and BNPP) were also measured to enable further calculations of carbon input. Over 7 years yields and ANPP were lowered under minimum tillage, but soil carbon accumulation in this treatment produced a net GWP of approx. -873 kg CO_2-eq ha^{-1} yr^{-1}, which would remain negative over a timeframe of at least 31 years, allowing for removal of vines but not for deep tillage. Conventional-tilled alleys with and without cover crops had positive net GWP because their treatments caused little or no gain in soil carbon and their net GWPs could only be considered negative if wood accumulation was included. Fuel combustion contributed the most to net GWP, followed by soil carbon loss under twice-yearly tillage. Total N_2O emissions accounted for 63–76 kg CO_2–eq ha^{-1} yr^{-1}. In a vineyard where 8.4–16.8 kg N ha^{-1} yr^{-1} were applied, 90% of N_2O emissions occurred at least 4 months after fertigation, mainly following precipitation. Total CH_4 fluxes were negative and offset 5–10 kg CO_2–eq ha^{-1} yr^{-1}. A minimum-tilled system with cover crops offers potential for important GWP offsets in this climate and soil, if possible negative impacts on yields are acceptable.

1. Introduction

In terrestrial nutrient cycles, about half of the carbon (C) emitted to the atmosphere originates from heterotrophic respiration on or in surface soils (Trumbore, 2006), while nearly all of the nitrogen (N) emitted is derived from soil-based microbial processes near the soil surface (Gruber and Galloway, 2008). Edaphic changes caused by management can strongly affect this cycling. In particular, tillage management and the use of cover crops can alter the production and consumption of the three primary biogenic greenhouse gases (GHGs) that include C and N: carbon dioxide (CO_2) (Calderon et al., 2001), methane (CH_4) (Huetsch, 1998), and nitrous oxide (N_2O) (Malhi et al., 2006).

In order to explore options for mitigating agricultural emissions of these GHGs, it is useful to estimate the net production, consumption or fixation of all three, allowing a measurement of Net Global Warming Potential (net GWP) (Robertson et al., 2000). Since GHGs warm the Earth́s surface through the same mechanism, absorbing surface-emitted infrared radiation and re-emitting infrared radiation (IPCC, 2007a), the GWP of each gas can be calculated using its atmospheric lifetime and radiative efficiency (W m^{-2} ppm^{-1}). They are standardized into CO_2-equivalents (CO_2-eq), for which, because of CO_2's uncertain residence time in the atmosphere, a time horizon must be selected (most often 100 years) (IPCC, 2013a). Through assessments of net GWP and of GHGI, in which GWP is indexed by yield, the present study addresses several potential tradeoffs in attempts to diminish GHG sources.

The greatest and earliest impact of agriculture on net GWP typically comes from the loss of soil C, emitted as CO_2 following tillage. It is estimated that 1/3 of anthropogenic CO_2 emissions since 1750 have come from land use change, where tillage is typically involved (IPCC, 2007b). Nevertheless, it is hypothesized that if historical depletion can be reversed, these soils may sequester up to 50 ppm of atmospheric CO_2 over 50 years (Lal, 2003), which would effectively remove about 40% of the anthropogenic carbon currently in the atmosphere. Cover-cropping and reduced tillage are considered the major means available, and

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they may have great potential in the open areas of permanent cropping systems such as grapes. Permanent cropping systems have not received the same attention as have annuals, despite their high potential to sequester carbon into soil (Post and Kwon, 2000; Kroodsma and Field, 2006; Jastrow et al., 2007; DuPont et al., 2010; Morgan et al., 2010).

There has been an increase in debate over SOC effects of tillage. It is broadly expected that the reduction of tillage will raise SOC levels, but some researchers have argued that tillage redistributes SOC rather than lowering its overall content (Baker et al., 2007) when compared to zero tillage.

Cover crops may increase C input into soils and should thereby contribute to an increase in SOC over time in many Mediterranean systems (Kong et al., 2005). Vineyard studies have observed increases in the upper levels of soil under reduced tillage and cover crops (Peregrina et al., 2010; Ruiz-Colmenero et al., 2013). However, cover crops may not sequester enough carbon to offset accompanying changes, such as increased organic matter oxidation with the disruption of soil, if they are to be incorporated. They also usually entail additional fuel emissions, as when more tractor passes are required for seeding, mowing and incorporation.

Debate persists over whether tillage increases or decreases soil N_2O emissions. It is often assumed that tillage reduces N_2O emissions by diminishing anoxic conditions or microsites in soils (Soane et al., 2012), but some studies of N-fertilized grain crops have observed lower N_2O emissions with reduced or zero tillage (Malhi et al., 2006; Mutegi et al., 2010; Omonode et al., 2011; Drury et al., 2012). It should be noted that N_2O emission from N fertilizer use is the greatest contributor to net GWP in most cropping systems, after the initial loss of soil carbon with tillage (Robertson and Grace, 2004). But this may not be the case in some low-input permanent cropping systems, like most winegrape vineyards.

A debate also exists over tillage effects on methane emissions. Upland soils are typically methane sinks, and it is usually expected that tillage should lead to greater CH_4 oxidation (Liu et al., 2006), since negative correlations are seen with water-filled pore space while positive correlations have been reported with relative gas diffusivity (Ball, 2013). But a number of contrary results have been observed (Venterea et al., 2005; Patino-Zuniga et al., 2009; Sainju et al., 2012), possibly due to diminished or redistributed soil organic C (SOC) with tillage (Jacinthe and Lal, 2003; Bayer et al., 2012). Such results may also be due to the fact that methanotrophic populations, which tend to be highly specialized, are less diverse in disturbed soil, potentially reducing oxidation rates (Levine et al., 2011). Other factors like pH, soil structure, tillage timing and optimal levels of moisture remain to be studied (Huetsch, 2001; Lemke and Janzen, 2007). And it is difficult to predict whether drier soils that exist in the driveways between the trees and vines of orchards and vineyards (Alsina et al., 2013) may have more effect in boosting methane oxidation (consumption) or may lower soil C retention (Hartmann et al., 2011).

Finally, the use of cover crops may aid soil fertility but adversely affect crop yields, especially where the two compete for scarce water during the growing season. This would be particularly relevant in Mediterranean climates. When that is the case, the choice of soil management practices may be informed by framing net GWPs on a scale that accounts for yield. “Greenhouse gas intensity” (GHGI) per unit of production (Mosier et al., 2006) was the most relevant here because it includes changes in soil carbon.

Despite the general movement towards comprehensive net GWP and GHGI studies in many crops to address such questions, to our knowledge no study has assessed all three principal GHGs in a vineyard, nor have any vineyard carbon budgets been published that consider above- and belowground inputs to soil C. Researchers have studied vineyard management effects on emissions of CO_2 (Evrendilek et al., 2005; Carlisle et al., 2006; Steenwerth et al., 2010) and N_2O separately (Steenwerth and Belina, 2008; Garland et al., 2011; Smart et al., 2011), while one limited carbon balance study has been carried out (Sekikawa, 2005). We are unaware of any vineyard investigations that have considered CH_4 oxidation. Overall, tremendous uncertainty exists concerning the quantity of GHGs produced and consumed in vineyards (Carlisle, 2010).

For this study, the use of a barley cover crop was assessed in the 6th–8th years of establishment following two alternative tillage systems, minimum tillage and yearly incorporation. The control treatment continued the management of past decades, with no cover crop, although local weeds were allowed to grow over the winter, which were incorporated every spring. The present study provides a farm-gate estimate of three tillage/cover crop systemś net GWPs.

2. Materials and methods

2.1. Experimental design and maintenance

The test site consisted of a *V. vinifera* cv Cabernet Sauvignon vineyard in its 17th and 18th years of growth at the UC Davis Oakville Research Station in Napa Valley, California (latitude 38° 25′ 55″ N, longitude 122° 24′ 48″ W; elevation 46 m). The soil is a Bale loam, classified as a fine-loamy, mixed, thermic Cumulic Ultic Haploxeroll (Lambert and Kashiwagi, 1978), with an averaged texture of 33% sand, 42% silt, and 25% clay, a pH of 5.6. The Ap horizon extends to about 20 cm, with greater clay content below.

In 1991 the site was planted to three rootstocks in a randomized complete blocks design (RCBD). The driveways (alleys) were 180 cm (6 feet) wide, in addition to a 60 cm (2-foot) wide designated drip zone below the vine rows, which was kept clear of vegetation using glyphosate herbicide. In October 2003 three alley tillage/cover crop treatments were established, using three blocks in an RCBD. As a result of superimposition on the rootstock experiment, within each alley treatment-block combination there were 6 subplots divided among the 3 rootstocks, with 2 replications per rootstock. The subplots had 2 measured vines, so that a total of 108 data vines were monitored for pruning weights and harvest weights starting in Oct. 2003. Further biomass measurements and all gas emissions during the 6th to 8th years of the alley treatment experiment (all of 2009 and 2010) were carried out on a single rootstock (*V. riparia* x *V. rupestris* cv 101-14 Mgt), which represented intermediate vigor.

The alley treatments consisted of 1) a minimum-tilled dwarf barley (*Hordeum depressum* cv UC603) cover crop treatment disked to a depth of 2–3 cm every second fall to aid planting and establishment of the cover crop, and mowed but not tilled in spring, where the chopped residues of grapevine prunings and cover crops were left on the surface; 2) a barley cover crop under conventional tillage for which soil was disked to a depth of approximately 10 cm in the fall prior to planting the cover crop, and mowed and disked twice in the spring to incorporate residues; and 3) a conventional tillage treatment where resident annual weeds were mowed and disked twice to approximately 10 cm depth in the spring, which continued the soiĺs previous use. Investigation with a metal rod after disking showed no difference in Ap horizon depth between once-annual and twice-annual tillage. Directly below the Ap horizon repeated disking created a thin, high-density, corrugated soil layer. Cover crop roots rarely penetrated past 25 cm of depth. Floor management implements were those commonly used in regional winegrape vineyards, consisting of a tandem disk, a seed drill and a flail mower. Tillage dates were 4/1/09, 5/8/09, 10/26/09, 3/22/10, 5/11/10, and 10/21/10.

Once-yearly drip fertigations were applied on June 26, 2009 and July 8, 2010 at the rates of 8.4 kg N ha^{-1} and 16.8 kg N ha^{-1}, respectively. These were followed by 9 irrigations in 2009, and 7 in 2010, at intervals of 1–2 weeks.

2.2. Soil organic carbon

Soil organic carbon sequestration was assessed in each of the alley treatments under dry conditions. In August of 2010, bulk density was assessed at the centers of the alleys as well as the alley shoulders, 30 cm from the edges of alley vegetation, using brass rings of 8.3 cm internal diameter and 6 cm length. It was found that differing bulk densities had developed in the Ap horizons of tilled versus minimum-tilled alleys, so the principle of equivalent depth was followed in ensuing SOC tests (Ellert and Bettany, 1995; McCarty et al., 1998; Powlson et al., 2011). Samples were taken in August 2010 at 0–7.5 cm (Mosier et al., 2005) and 7.5–15 cm in minimum-tilled rows, and at equivalents of 0–8.6 cm and 8.6–16.3 cm in the conventional-tilled rows. Three parallel transects of the vineyard were made (top, middle and bottom), perpendicular across alley treatments, and reflecting consistent levels considering the vineyard's slight downward slope (2%) along the vine rows. Twelve cores were taken per plot at each depth: three at alley center and three at alley-shoulder, in each of the two outside alleys of each plot. Samples of each depth were pooled to describe each outside alley's C contents, but these two alleys were finally pooled as well to describe plots in statistical analysis. Samples were dried at 60 °C, sieved to < 2 mm, ball-milled, and analyzed by dynamic flash combustion coupled to a gas chromatograph (GC) equipped with a thermal conductivity detector (TCD) for CO_2. The soil contains no reported carbonates (Pierce, 2006), nor were any apparent during the study, consistent with the precipitation regime (Nordt, 2006).

2.3. Indices of annual net primary productivity

Annual net primary productivity (NPP) was measured directly. Cane production (prunings) and grape yields were monitored on all three rootstocks from 2006 to 2010. Grape yields were recorded on a fresh-weight basis. Weights of pruned canes were reported as dried biomass, based on field-weights adjusted for water content with oven-dried samples.

Other NPP measurements were taken on 101-14 rootstock, recorded as dry weights. Vine root and trunk-wood biomasses were assessed in the summer of 2009, with one sample per plot. Remaining NPP measured in 2009 and 2010 included sub-samples of leaf biomass, emerging shoots removed from vines for management (suckering or secondary pruning), alley vegetation biomass from quadrants of 324 cm^2, and alley vegetation roots from the area within the same sub-sample quadrants down to 20 cm depth. Cover crop roots considered for BNPP were those separable from soil with a root-washer (Gillison's Variety Fabrication, Inc., Benzonia, MI, USA). Grapevine woody root biomass data is taken from Alsina et al. (2014) in the same plots.

Grapevine water potentials were studied in the summers in response to the lowered cane prunings and yields which had been observed under minimum tillage. Midday leaf water potential (Ψ_{md}) was measured using a pressure chamber (Soil Moisture Inc., Santa Barbara, CA) with shaded leaves from mid-canopy positions in the summers of 2009 and 2010.

2.4. Measurement of GHG emissions

Calculation of vineyard net GWP included data for: 1) aboveground net primary productivity (ANPP) including yield; 2) belowground net primary productivity (BNPP); 3) differences in soil carbon after a 7-year period; 4) emissions of N_2O; 5) soil CH_4 fluxes; and 6) fossil fuel consumption. The values of CO_2 equivalents used were those of AR5 (IPCC, 2013b), where 1 kg N_2O = 265 kg CO_2, and 1 kg CH_4 = 28 kg CO_2.

The amount of CO_2 released from diesel fuel combustion during vineyard tractor operations was calculated for each year and each treatment based on: 1) type of tractor (Kubota M6030); 2) distance traveled; 3) speed; and 4) horsepower required for attached implements. Management included: 1) insecticide, fungicide, and herbicide applications; 2) tillage using a tandem disk; 3) mowing using a flail mower; and 4) cover crop seeding using a seed drill. Tractor-specific performance data was obtained from the Nebraska Tractor Tests (1986) and agreed with reports of fuel use per day by our tractor.

Emissions of CO_2 through soil respiration (R_s) were measured approximately once every 2 weeks in the alleys, and at least 3 times in a week for tillage events. 8-cm high PVC collars were inserted to 6 cm in the centers of alleys at maximum distance from vine trunks on 101-14 rootstock. Effluxes were measured between 14:30 and 16:00 using an infrared gas analyzer (LI-6400/09, LiCor Inc., Lincoln, NE). To describe emissions from the drip zone, monthly measurements were made during 2010. After each gas flux measurement, samples for gravimetric soil moisture were taken approximately 60 cm from the collar at 0–20 cm using a soil auger.

In this vineyard, temperature (Pierce, 2006) and seasonal temperature-moisture relationships (Steenwerth et al., 2010) were not found to be sufficient predictors of variation in R_s; and conclusions of both studies were ratified by our data. To adjust for diurnal variation we therefore followed an empirical approach, measuring predawn R_s several times in each season to find a proportion of daily maxima and minima by season, allowing an estimate of minimum emissions for each sampling date. We then used diurnal variation curves in soil CO_2 emissions observed in the same vineyard by Pierce (2006) and Steenwerth and co-workers (Steenwerth et al., 2010) over four seasons, in 72-h campaigns. Integrating the area under the curves, we arrived at a factor of 0.92 to be applied to the previously mentioned averages of maxima and minima. Thus estimated daily emissions were determined for every sampling date and collar, and yearlong totals were integrated from this data.

N_2O and CH_4 emissions were measured using static chambers positioned in the alley centers and drip zone centers at maximum distance from vine trunks. The chambers were generally in conformity with recommendations by Parkin et al. (2003) and consisted of 20.3 cm diameter PVC rings 11 cm high placed over 8 cm PVC collars with one beveled outer edge, inserted 5 cm into the soil. Chambers had manual mixing fans and a stretchable rubber sleeve that closed over the collars. They were covered with aluminum insulation to reflect radiation and to moderate temperature change inside the chamber.

Samples of gas taken from the chamber using a 20-mL syringe were injected and stored in 12-mL tubes (Exetainer®, Labco Limited, Buckinghamshire UK) with silicone sealant placed over the septum before evacuation down to 50 mTorr. Extensive testing revealed that positively pressurized Exetainers gave consistent GC readings in second-round testing, while limiting sample contamination after collection. The gas was analyzed for N_2O using a ^{63}Ni electron capture detector (ECD) and for CH_4 using a flame ionizing detector (FID), both on the same gas chromatograph (GC-2014, Shimadzu Inc., Kyoto, Japan). Using three gas samples taken over 30-min intervals, ambient temperatures reported for that hour by a CIMIS weather station adjacent to the vineyard, and an elevation of 50 m, generally at 100,725 Pa or 0.994 atm of pressure, the ideal gas law was used to determine the flux of gases from the soil, according to examples in the GRACENet Protocols (Parkin and Venterea, 2010).

According to the laboratory protocol, measurements to describe average daily emissions were taken around 14:00, lasting until 15:30. Subsequently, diurnal flux changes were studied on 6 occasions (4/2/2010, 4/23/2010, 5/7/2010, 9/15/2010, 10/18/2010, and 10/23/2010). These showed approximately sinusoidal patterns of N_2O emission, with minima at an average of 7:25 and maxima at an average of 21:17, confirming that the standard measurement time represented average fluxes. Methane (CH_4) flux showed very high variability, but where patterns were detectable, they followed diurnal variation similar to that of N_2O.

N_2O and CH_4 emissions were monitored over a minimum of one week with at least 3 sampling dates following 3 events: first fall rains, spring tillage in 2010, and N-fertigation. Similarly, 3 irrigations were studied for at least 2 days each in 2010. Fertigations were monitored with chambers at three distances from the dripper (Alsina et al., 2013). Outside those events, relevant fluxes generally were seen after precipitation. For this reason, measurements were taken for about 41% of the rain events (> 5 mm over three days) that occurred, focusing on the first, second and sometimes third days after rain. Ultimately, emissions data did not show high dependence upon the quantity of precipitation ($R^2 = 0.02$ for rainfall in previous 24 h; $R^2 = 0.14$ for rainfall over previous three days), nor upon water content of soil to 20 cm ($R^2 = 0.002$). Given that the estimation of total trace gas fluxes depended to an important degree on estimation of fluxes from unmeasured rain events, an empirical approach was therefore preferred, applying the average proportional rates of decline measured over 12 rain events, following the consistent peaking of N_2O fluxes 12–24 h after the cessation of rain (for CH_4, minimum oxidation rates). This rate of decline allowed the estimation of total emissions from each sampled position for those events when three daily measurements were not feasible. That estimate was multiplied to account for the fact that 59% of precipitation had not been monitored for trace gas emissions.

Measurements of gas fluxes not associated with management or precipitation events were evenly spaced throughout the year, at 2–3 week intervals, and were averaged to form treatment-specific baseline flux rates for both CH_4 and N_2O. Summation of management-related emissions, measured rain-induced emissions and baseline emissions yielded a net annual production or consumption of N_2O and CH_4 per plot and position (alley and drip zone).

2.5. Statistical analyses

Treatment differences were tested as an RCBD with PROC MIXED for ANOVA, with fixed effects of treatment (tillage), treatment per year, year, block, and block per year, and a random effect for block*treatment (plot effect) (SAS, Cary, NC). Despite abnormal distributions on the daily level, the annual data required no transformations. Tillage effects on SOC were analyzed using a similar model where the repeated measures were the three parallel transects taken in the summer of 2010, which like years were regarded as fixed effects.

Differences in pruning weights and grape harvests over 5 measured years included 3 varieties of rootstock and were tested using a split-plot (for rootstock and tillage) PROC MIXED for ANOVA, with degrees of freedom estimated using the Satterthwaite method (SAS, Cary, NC). The fixed effects were tillage, rootstock, and year, all of their interactions, Block, and Block by Year. The random effect was the interaction of tillage, rootstock and block (plot effect).

For these mixed models the default REML (restricted maximum likelihood) approach was preferred, testing for $*P \le 0.05$. Differences in annual NPP were analyzed by type of biomass on a per year basis using PROC GLM for ANOVA and Tukey's range test for pairwise comparison (SAS, Cary, NC), where significant differences were accepted when the probability of Type I error was at $*P \le 0.05$.

3. Results and discussion

3.1. Changes in soil organic carbon

Following treatment establishment in 2003, eight rounds of sample combustion measurements between June 2004 and July 2005 suggested that the minimum-tilled treatment had begun with lower levels of soil carbon than the conventional-tilled cover crop, but that it was accumulating carbon (Pierce, unpublished results). In August of 2010 treatment differences were seen between the minimum-tilled and the two conventional-tilled treatments ($p = 0.003$), using the equivalent depth approach (Ellert and Bettany, 1995; Powlson et al., 2011) (Table 1). In agreement with these results, row-cropping studies have found SOC increases in the upper 7.5 cm of the soil following conversion from conventional tillage to minimum-tilled cover crops (Doran, 1980; Mosier et al., 2005) including dry-farmed systems similar to many orchard and vineyard alleys (Halvorson et al., 2002).

Using the conventional tillage without cover crop treatment as a "business-as-usual" control (Robertson and Grace, 2004), soil C was seen to have increased by 3.07 t per ha (8.4% of total) in the upper 7.5 cm of the minimum tillage treatment, equivalent to the upper 8.6 cm of the conventional-tilled treatments, indicating soil C sequestration of 2.30 Mg C ha^{-1}in the vineyard as a whole, considering herbicide-treated drip zones to be unaffected by tillage treatment (Table 1). Twice-yearly tillage appeared to result in a slight soil C loss at this depth (384 kg ha^{-1} or $< -1\%$), but the difference was not significant. Mediterranean-climate studies in rainfed systems in Spain have generally supported the accumulation of SOC with reduced or no tillage down to 30–40 cm, although not all observed differences have been significant (Hernanz et al., 2002; Álvaro-Fuentes et al., 2008; López-Bellido et al., 2010; Plaza-Bonilla et al., 2010; López-Fando and Pardo, 2011).

Some researchers have cast doubt on SOC gains with reduced tillage, raising the possibilities that tillage may redistribute SOC below typical measured depths, or that crop roots may be deeper under conventional tillage (Baker et al., 2007). Here the redistribution hypothesis was addressed through carbon content sampling at 7.5–15 cm equivalent depth (8.6–16.3 cm in conventional-tilled rows). But these showed very similar, statistically indistinguishable levels of SOC.

Certain attributes of the system may have favored SOC accumulation under minimum tillage. Fall seed bed preparation in the minimum-tilled treatment had little persistent effect, since dry soil prevented disk penetration below 2–3 cm, an observation also made by Seddaiu et al. (2013). Fall rains, which induced high respiratory activity, fell on soil freshly broken in the tilled systems; rain followed tillage in the spring as well. Although 2009 saw higher vegetative biomass under minimum tillage, the tilled cover crop was higher in 2010, and incorporation of prunings was higher in the tilled cover crop, giving no reason to expect that aboveground C input to the soil accounted for differing SOC levels.

3.2. Patterns of soil respiration (R_s)

Total soil respiration (R_s) from the vineyard was estimated at 6.63 mt C ha^{-1} yr^{-1}. Per-treatment ANPP's and R_s had no evident relation, but estimating the sources of R_s remains a point of interest. In minimum-tilled alleys, R_s averaged 7.89 mt C (Table 2), and the annual increase in SOC was equivalent to 5.2% of R_s, which is a high rate of retention of cycling carbon. Given that all ANPP was directed into the alley soils, not the drip zone, the biomass input, including the measured cover crop roots, was about 3.59 mt Cha^{-1} yr^{-1} in minimum-tilled

Table 1
Soil carbon at equivalent depths by treatment, compared to the historically managed control (Till-NoCC). Standard errors of the mean are shown. Letters indicate REML differences ($*P < 0.05$).

Treatment	Depth Sampled	Avg C (% mass)	SE (% mass)	BD (g/cm^{-3})	C (Mg ha^{-2})	Difference
MinTill-CC	0–7.5 cm	2.46%	0.10%	1.28	23.616 a	3.072
Till-CC	0–8.6 cm	2.10%	0.04%	1.12	20.160 b	−0.384
Till-NoCC	0–8.6 cm	2.14%	0.05%	1.12	20.544 b	N/A
MinTill-CC	7.5–15.0 cm	1.64%	0.09%	1.45	17.835	−0.217
Till-CC	8.6–16.1 cm	1.64%	0.09%	1.45	17.835	−0.217
Till-NoCC	8.6–16.1 cm	1.66%	0.10%	1.45	18.053	N/A

Table 2
Annual emissions: CO_2, N_2O and CH_4 in drip zones and alley treatments. Standard errors of the mean are shown. Letters indicate differences according to REML testing both years of data together (*$P < 0.05$). Vineyard averages, used for Table 6, include the drip zone.

2009	**MinTill-CC**	**Till-CC**	**Till-NoCC**	**drip zone**
CO_2 (mt ha^{-1} yr^{-1})	19.04 ± 0.10	21.95 ± 1.54	19.95 ± 0.13	
N_2O (kg ha^{-1} yr^{-1})	0.22 ± 0.04	0.26 ± 0.02	0.21 ± 0.04	0.27 ± 0.03
CH_4 (kg ha^{-1} yr^{-1})	−0.27 ± 0.34 a	−0.54 ± 0.07 a	−0.45 ± 0.25 a	0.07 ± 0.01 b
2010	**MinTill-CC**	**Till-CC**	**Till-NoCC**	**drip zone**
CO_2 (mt ha^{-1} yr^{-1})	38.84 ± 1.54	29.43 ± 0.55	32.21 ± 0.72	16.05 ± 0.82
N_2O (kg ha^{-1} yr^{-1})	0.23 ± 0.07	0.32 ± 0.07	0.30 ± 0.07	0.27 ± 0.08
CH_4 (kg ha^{-1} yr^{-1})	−0.24 ± 0.46 a	−0.45 ± 0.91 a	−0.38 ± 0.49 a	0.0 ± 0.0 b
Vineyard Averages	**MinTill-CC**	**Till-CC**	**Till-NoCC**	
CO_2 (mt ha^{-1} yr^{-1})	25.72	23.28	23.57	
N_2O (kg ha^{-1} yr^{-1})	0.24	0.29	0.26	
CH_4 (kg ha^{-1} yr^{-1})	−0.18	−0.36	−0.30	

alleys (Table 4). That is 45% of alley R_s, leaving about 55% accounted for by root respiration, root turnover, and exudation from cover crop and grapevine roots. For an estimation of the contribution of grapevine vs. alley vegetation roots to these CO_2 emissions, one can note that drip zone R_s averaged 41% that of minimum-tilled alleys in 2010. If grapevine roots had the same presence in the alleys as in the drip zone, approximately 14% remained to be contributed by the exudation, respiration and in-year turnover of cover crop roots. Many simplifications are involved in these estimates, but they inform us to a degree about the cycling of carbon in this vineyard soil.

Measurements were frequent during the week after tillage events to capture the expected additional effluxes of CO_2 made possible by breakup of aggregates and metabolysis of formerly occluded substrates (Jackson et al., 2003). Dry fall tillage may have different effects on SOC and soil structure than does wet spring tillage (Maidl and Fischbeck, 1987). Momentary increases in R_s were seen with tillage in the spring, but it was not possible to describe long-term effects of particular tillage events. Among treatments, the twice-yearly-tilled treatment consistently saw the lowest CO_2 efflux at tillage, just as it had the lowest soil C, although differences from once-yearly tillage without cover crop were not significant. The planting of the cover crop, with a high measured biomass, evidently was not sufficient to offset the fact that this treatment underwent more tillage, probably impeding aggregation and the buildup of soil organic matter (Calderon et al., 2001).

Although R_s measurements showed high variability in time, R_s tends to peak during the late spring (Carlisle et al., 2006) and reaches its lowest level in late summer (Fig. 1). This is not only the result of high soil moisture and high temperatures in the spring, but also agrees with described rates of root growth in grapevines, as well as possibly in the cover crop. Between dormancy and bud break significant loss of C and N takes place from grapevine roots (Zapata et al., 2004). On the same research station where this study was carried out, Eissenstat et al. (2005) noted a "pulse of root growth in early spring prior to bloom" in the same rootstock we measured (101-14). The spikes we observed tended to occur later in spring, but that may reflect the time for roots to turn over or die back following a flush of growth, or the time needed for exudates to become available to the microbial community for respiration.

Overall alley R_s was 65% higher in 2010 than in 2009 (Table 2), a difference mainly ascribable to precipitation, since 2010 had 56% more rainfall (65 cm vs. 102 cm). This was reflected in measurements of water-filled pore space as well (Fig. 2).

3.3. Nitrous oxide emissions (N_2O)

Total N_2O emissions were low, averaging 0.26 kg N_2O ha^{-1} yr^{-1} (68.9 kg CO_2-eq ha^{-1} yr^{-1}). With high spatial variability of emissions within treatments, no treatment differences were found over the two-year period (Table 2). Among discrete events, rates of N_2O emissions (as well as of CH_4 emissions) were most strongly affected by the annual N fertigation and by the first fall rains, both coming after long dry periods. Remaining precipitations considered together emitted less N_2O than the first rains. Overall, temperature and soil moisture were not predictive of N_2O emissions.

Nitrous oxide emissions measured during the three days following rainfall events represented the majority overall. The greatest single

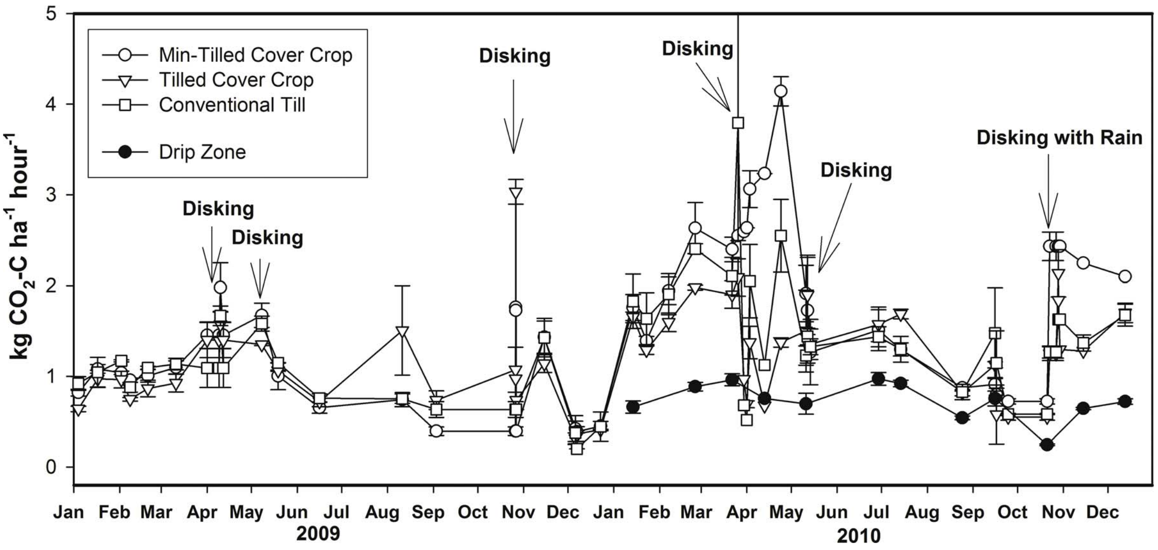

Fig. 1. Measured daily soil emissions of carbon dioxide by alley (n = 3), Jan. 2009-Dec. 2010, and in the drip zone in 2010 (n = 3). Standard errors of the mean are shown.

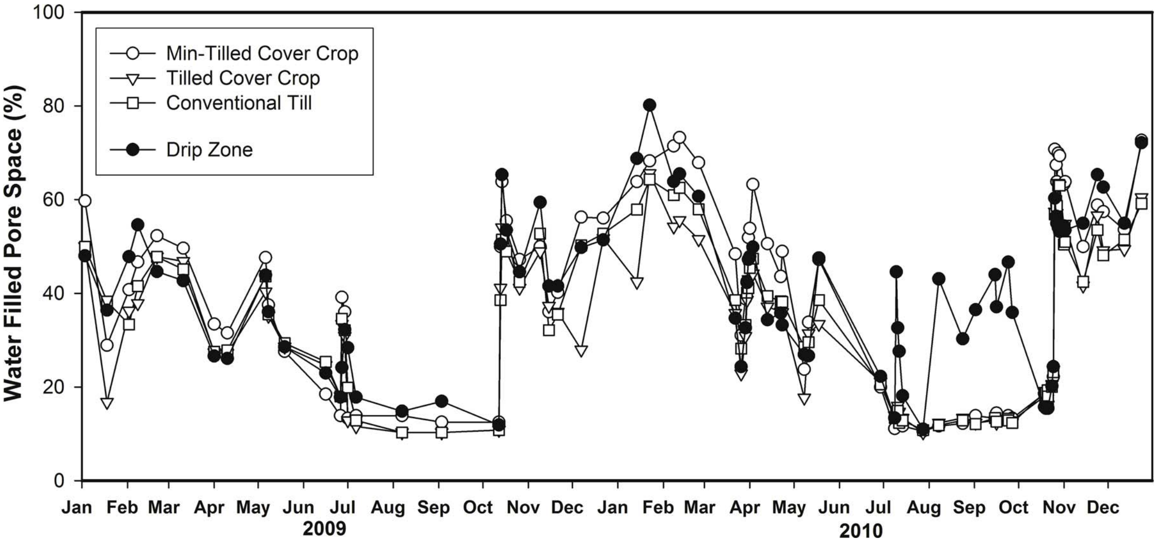

Fig. 2. Measured soil water contents expressed as water-filled pore space for the dates of soil gas emission measurements, by alley and drip zone (n = 3).

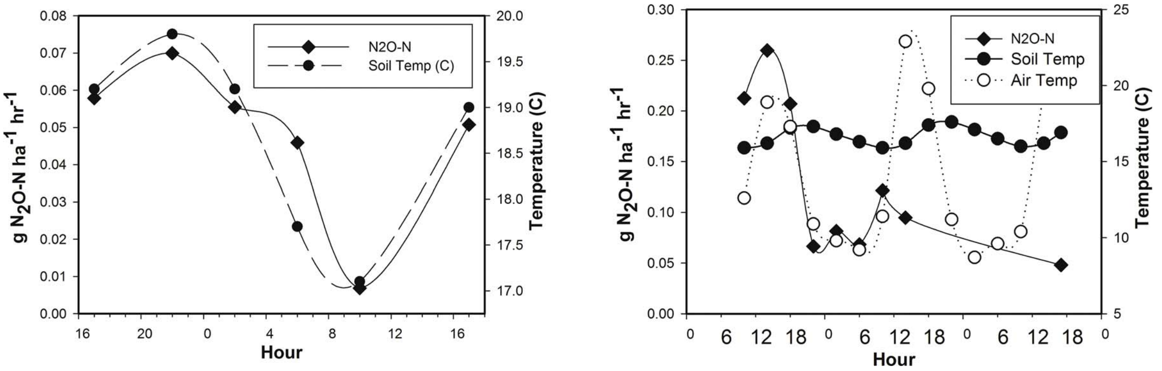

Fig. 3. Typical diurnal patterns of nitrous oxide emissions after irrigation (left, 9/15-16/2010) and after fall rains (right, 10/18-20/2010). Vineyard averages show the typical rates of decline after rain, as well as greater sensitivity to ambient temperature in the first days after rain.

yearly efflux of N_2O came from the alleys during the first fall rains (Table 4), which were heavy in both years (117 mm in 2009, 86 mm in 2010, both over three days). Instantaneous rates of emission following other precipitation events did not show high dependence upon the quantity of precipitation. However, consistent rates of decline were seen in the 3 days afterwards on 6 occasions (averaging: Day 2 = 57% ± 6% of Day 1, Day 3 = 38% ± 11% of Day 2) (example in Fig. 3).

Contrary to expectations, fertigations with KNO_3 in late June 2009 and early July 2010, which were followed by 4 warm dry months, only accounted for a small proportion (average 9%) of the N_2O emitted annually, equivalent to 6.1 kg CO_2 ha^{-1} yr^{-1} (Table 3). These emissions came almost exclusively from the herbicide-treated drip zone, as measured within the first 2 weeks after application, and were of similar magnitude in both years. Corresponding emission factors (fraction of fertilizer N emitted as N_2O) ranged between 0.2% from drip zones within the conventional-tilled cover crop and 0.6% of applied N within the minimum-tilled cover crop, possibly because of root intrusion imparting greater labile carbon under minimum tillage. Emissions from the 2nd and 3rd, 5th and 8th subsequent irrigations in 2010 were very low, so even with their inclusion the emission factors would differ strongly from the 0.9% estimated globally in a study based on diverse cropping systems (Bouwman et al., 2002).

Measured emissions were highest in the twice-yearly-tilled treatment in both years (Table 2). While tillage of dry soil showed no heightened N_2O emissions, rain after tillage in early April 2010 may have heightened N_2O emissions, as has been reported following tillage under high moisture conditions in the spring (Maidl and Fischbeck, 1987), also agreeing with increased denitrification and spikes in respiration observed after spring tillage (Calderon et al., 2001). However, two weeks later, the minimum tillage treatment had higher emissions following rain (Fig. 4), when its water filled pore space (WFPS) was 52% as opposed to 38% in the conventional-tilled treatments.

The higher overall emissions from the most frequently-tilled treatment may be due in part to an existing plow-pan. The tilled depth in disk ruts was within the upper 20 cm where heightened denitrification activity is expected (Smart et al., 2011), and the plow pan could have limited infiltration of water below those depths while establishing anoxic zones favoring denitrification. Times of minimum and maximum daily N_2O emissions typically corresponded to soil temperature at

Table 3
2-year averaged proportional contribution of events to annual N_2O emissions.

Yearly Event	%N_2O
First Rain	37%
Seasonal Rains	30%
Fertigation	9%
Irrigations	1%
First Tillage followed by Rain	8%
Second Tillage followed by Rain	2%
Baseline	13%

Table 4
Measurements of aboveground net primary production (ANPP) and belowground net primary production (BNPP) (Mg C ha^{-1} $year^{-1}$) in the vineyard under three tillage/cover crop systems. Values are means (n = 3) for each growing season. Means followed by different letters are significantly different using Tukey's range test (*$P < 0.05$). *Vine root and wood estimates for 2010 were based on 2009 data, which averaged growth over 18 years based on standing woody biomasses.

2009	vine					alley veg.				
Treatment	roots	wood	canes	leaves	grapes	roots	surface	total BNPP	total ANPP	total NPP
minimum till – CC	0.15	0.22	0.41	0.59	0.46	0.18 a	1.57	0.33	3.25	3.59
conventional till – CC	0.12	0.24	0.64	0.78	0.65	0.14 ab	1.54	0.26	3.85	4.14
conventional till – No CC	0.13	0.23	0.61	0.82	0.64	0.08 b	0.88	0.21	3.18	3.40
p-value	*0.50*	*0.97*	*0.06*	*0.18*	*0.29*	*0.02*	*0.06*	*0.15*	*0.11*	*0.08*

2010	vine					alley veg.				
Treatment	roots*	wood*	canes	leaves	grapes	roots	surface	total BNPP	total ANPP	total NPP
minimum till – CC	0.15	0.22	0.63 b	0.76	0.75	0.10 b	1.00 b	0.25 a	3.36 b	3.09 b
conventional till – CC	0.12	0.24	1.02 a	0.92	1.13	0.12 a	1.24 a	0.24 b	4.55 a	4.35 a
conventional till – No CC	0.13	0.23	0.92 a	0.82	1.04	0.10 b	0.99 b	0.23 b	4.00 ab	3.80 ab
p-value			*0.01*	*0.58*	*0.30*	*0.01*	*0.02*	*0.00*	*0.01*	*0.01*

15 cm, except on days immediately after rain, when emissions more closely tracked ambient temperatures (Fig. 3). Research on such tillage effects is lacking, but similar conditions have been reported for paddy soils (Koegel-Knabner et al., 2010). And the assumption that tillage reduces N_2O emissions by promoting aerated soil conditions has been questioned by many (Venterea et al., 2005; Malhi et al., 2006; Mutegi et al., 2010; Omonode et al., 2011; Drury et al., 2012). Some investigations that failed to show reduced N_2O emissions with tillage have found factors other than aeration to be important, such as soil carbon content (Jahangir et al., 2011; Yazaki et al., 2011), N fertilizer input (Pelster et al., 2011) or choice of crop (Smith et al., 2011).

3.4. Methane fluxes (CH_4)

In upland soils, CH_4 oxidation by methanotrophs generally outweighs methanogenesis. Alley treatments in this experiment were net sinks for CH_4, but the herbicide-treated drip zone may not have been (Table 2, Fig. 5). Precipitation caused a decline in CH_4 oxidation and sometimes resulted in net methanogenic CH_4 production, possibly linked to the finding that high soil moisture can limit CH_4 transport in soil, thus limiting oxidation (Hartmann et al., 2011). The minimum-tilled treatment appeared to have the lowest overall net CH_4 oxidation during both years, possibly due to its greater bulk density and higher water-filled pore space (WFPS). CH_4 oxidation was a small component of net GWP in all treatments (Table 6). As with N_2O, strong net effluxes of CH_4 were seen with annual N fertigation, with subsequent drip irrigations, and with the first fall rains. Remaining precipitations appeared to cause a slight initial suppression of CH_4 oxidation rates over the first two days relative to baseline (−8% ± 24%), but this was compensated by an increase on the third day (34% ± 302%).

No treatment differences were significant, although all alley treatments were different from the drip zone. High coefficients of variation were seen between yearly summed emissions from plots, of 102% in alleys and 81% in drip. There was no significant correlation of CH_4 flux with temperature at 15 cm, nor with WFPS in the upper 20 cm of soil; Huetsch (1998) has shown elevated consumption of CH_4 underneath the Ap horizon.

Observed net zero-to-positive emissions in the drip zone were the result of lower rates of CH_4 consumption during most of the year combined with large CH_4 effluxes soon after KNO_3 fertigations, which ranged up to 9.17 g CH_4 ha^{-1} h^{-1}. These effluxes were very consistent among treatments and years, and the rates were much greater than seen in even the heaviest rains (Fig. 5). It has been reported that ammonium (NH_4^+) amendments can inhibit CH_4 oxidation (Gulledge and Schimel,

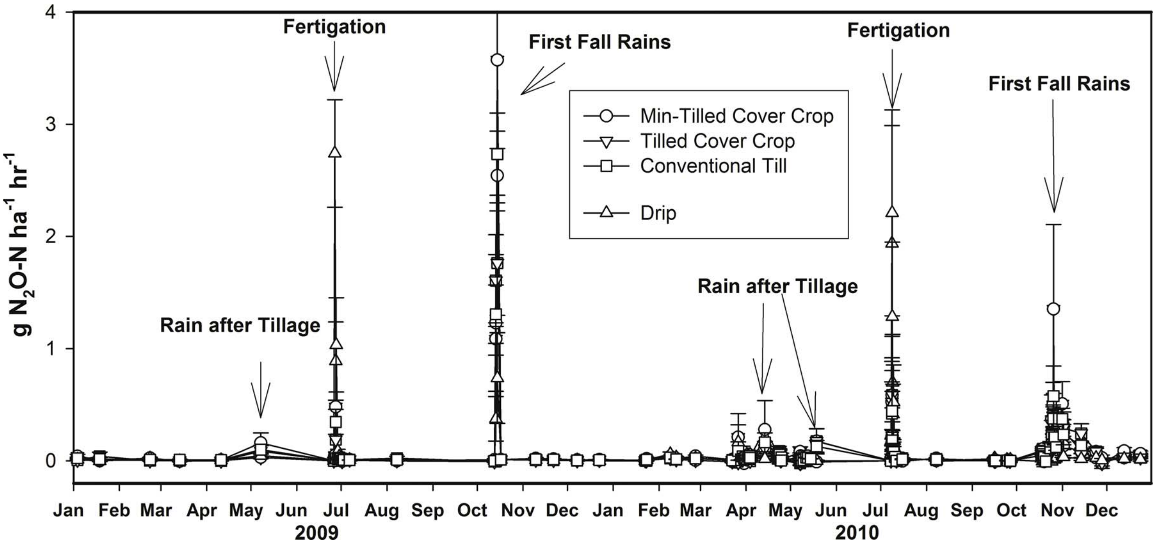

Fig. 4. Nitrous oxide fluxes in three alley treatments (n = 3) and drip-irrigated vine rows sectors (n = 9), Jan. 2009-Dec. 2010. Standard errors of the mean are shown.

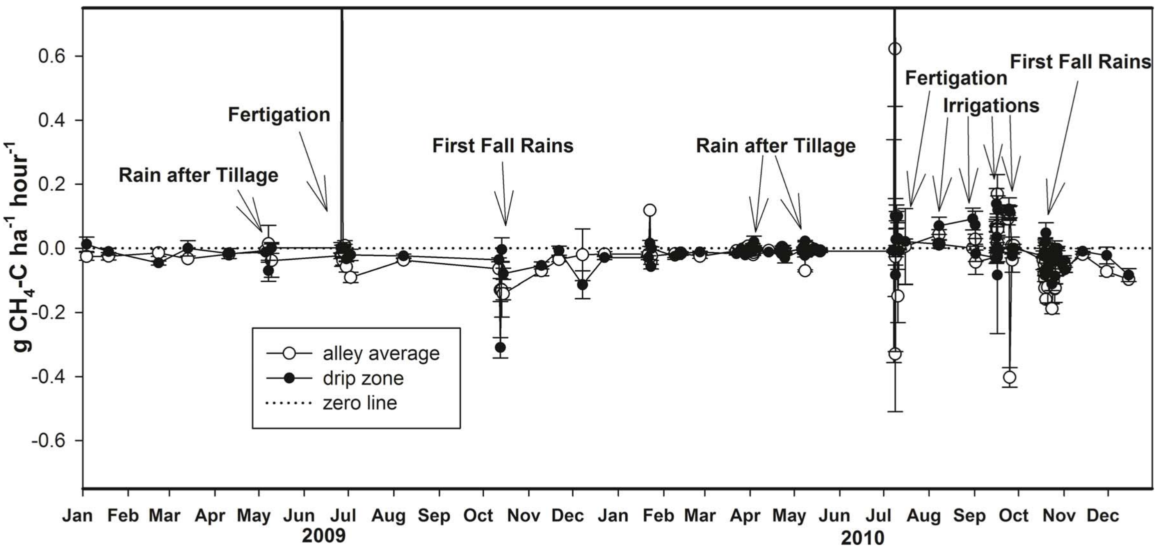

Fig. 5. Observed emissions of methane by alley (n = 9) and in the drip zone (n = 9). Tillage treatments were analyzed separately, but data showed no apparent patterns by treatment. On most dates fluxes were negative, except for some points following rain or fertigation. Effluxes after fertigations were far above the typical scale and are discussed in section 3.4.

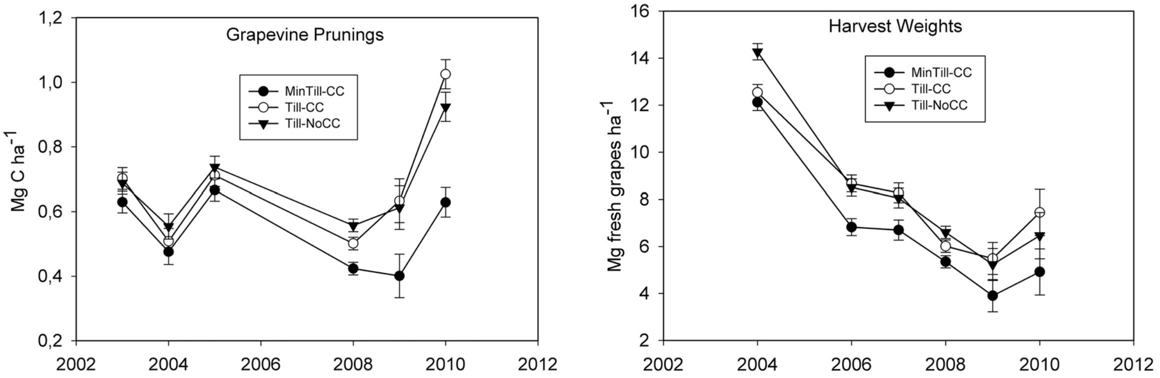

Fig. 6. Fresh weights and cane growth by cover crop/tillage treatment. Yearly cane growth was assessed through pruning weights in the following February. One harvest and two prunings were not assessed. Error bars describe standard error of the mean (n = 3).

1998), and that soil mineral-N is negatively correlated with total soil CH_4 oxidation (Chan and Parkin, 2001a, 2001b), but we know of no reports of an effect of nitrate (NO_3^-) application on methanogenesis, nor of potassium.

3.5. Yield and net primary productivity

The vineyard was in its 11th year of growth at the outset of the tillage experiment in 2003, and in its 18th year in 2010. Over a period of eight years (2003–2010) yields trended downwards in all treatments, in accord with the aging of the vines (Fig. 6). Comparing the three treatments, yields and cane production in the two conventional tillage treatments were not significantly different, but minimum tillage exhibited significantly lower yields ($p = 0.025$) and significantly lower cane production (pruning weights, $p = 0.019$) (Fig. 6). The yield effects of minimum tillage were immediate, but cane-wood effects were stronger in years 7 and 8. All measured components of grapevine ANPP in 2009 and 2010 were lower under minimum tillage than in the conventional-tilled treatments, although few year-by-year differences were found to be significant (Table 4).

The differences observed could be due to changes in grapevine water status under deficit irrigation, as well as possible competition for nutrients. After a winter of low rainfall in 2009, significantly greater water stress was observed in minimum-tilled vines from July 14 through September 12 (Table 5), commencing 2 months after the last spring rains. Gravimetric moisture was typically higher in minimum-tilled rows at 0–20 cm depth, so more water was available to cover crop transpiration. This may have restricted accumulation of soil water at greater depths where it would be available to vine roots in the summer. In these treatments it was observed in 2009 that minimum-tilled rows had greater root presence at 0–60 cm, while conventional-tilled vines appeared to have higher presence at 60–90 cm (Alsina, unpublished results). In summer 2010, after a winter of heavy rainfall, no treatment differences were found in vine water potentials, but in shoot growth and yield minimum-tilled vines maintained similar proportions relative to the conventional treatments. Overall, grapevine shoot growth is

Table 5
Mid-day vine water potential measurements in summer 2009 (after a relatively dry winter) and summer 2010 (after a wet winter). The two conventional-tilled treatments were pooled for analysis since there were no apparent differences between them.

Date	Min-Till Ψ_{md} (MPa)	Con-Till Ψ_{md} (MPa)	Significance RCB, $^*P < 0.05$
06-07-2009	−1.30	−1.24	NS
14-07-2009	−1.05	−0.94	S
28-07-2009	−1.03	−0.92	S
13-08-2009	−1.10	−1.06	S
29-08-2009	−1.28	−1.19	S
12-09-2009	−1.17	−1.09	S
28-07-2010	−0.90	−0.84	NS
25-08-2010	−1.11	−1.14	NS
13-09-2010	−0.04	−0.98	NS

Table 6
Net GWP by tillage treatment as the average yearly losses/gains of Soil C and of trace GHGs N_2O and CH_4 in CO_2 equivalents (factors of 265 and 28 respectively, applied to Table 1 values), not including the retention of wood in the trunks and cordons of vines. Negative values indicate consumption of GHGs. GHG Intensity represents GHGs emitted per mass of fresh grapes harvested (kg CO_2–eq kg^{-1}).

Net GWP	MinTill-CC	Till-CC	Till-NoCC
GHG Sources	Flux in kg CO_2-eq ha^{-1} yr^{-1}		
Change in SOC	−1123.57	172.86	N/A
N_2O	62.61	75.53	68.57
CH_4	−5.11	−10.15	−8.47
Fuel C	192.50	234.67	199.83
Net GWP	−873.57	472.91	259.93
Yield (grape fresh wt., kg ha^{-1})	4369.50	6477.00	6306.00
Yield-Indexed GWP (GHG Intensity)	−0.20	0.07	0.04

highly sensitive to water supply (Keller, 2005; Smart et al., 2006), and recovered more strongly than did yield. Yield can be less sensitive to water deficit because water-stressed vines put a higher fraction of photosynthate into fruit production (Williams et al., 1994; Poni et al., 2007).

3.6. Net GWP and GHG Intensity

Our application of net GWP follows the example reported by Robertson et al. (2000) by including tractor fuel, which was tied to tillage practice, as well as soil carbon. GHG Intensity (Mosier et al., 2006) indexes this net GWP by yield (Table 6); GHG Intensity differs from "yield-scaling" because it accounts for soil carbon changes (Van Groenigen et al., 2010; Linquist et al., 2012; Schellenberg et al., 2012). Net GWP and GHG Intensity were negative for the minimum tillage system due to its gain in soil carbon, and positive in the tilled treatments. Minimum tillage increased soil C content ($p = 0.003$) while decreasing fuel consumption and observed quantity of N_2O emitted. It can be estimated that it would take 31 years for cumulative N_2O, fuel combustion and CH_4 fluxes to equal the sequestration accomplished under minimum tillage management with a barley cover crop. In fact more sequestration will probably take place, past the 7 year point assessed here. But the rate of sequestration with minimum tillage will decrease as SOC approaches a new equilibrium (Stewart et al., 2007) and any tillage events outside the minimum regime could slow or reverse the process (Conant et al., 2007). Within conventional-tilled systems, lowered fuel use would offer the greatest point of leverage over net GWP.

The quantification of net GWP data, the analysis of different sources of N_2O, and of components of ANPP, BNPP, and soil respiration (R_s) together allow various uses of the data. For example, net GWP can be assessed with or without the retention of woody biomass. Data on the impacts of the tillage-cover crop treatments on vine productivity and R_s allow an improved perspective on the mechanisms and tradeoffs of vineyard soil carbon sequestration.

4. Conclusion

In this study, tillage management and fuel use were seen to be the major controls over vineyard GWP. Net GWP was negative where there was an increase in soil organic carbon with a minimum-tilled barley cover crop over 7 seasons, sequestering 1.50 metric tons of CO_2 per hectare per year in the alleys, or 1.12 metric tons in the whole vineyard including drip zones where no change is incurred. In this treatment oxidation of CH_4 contributed 0.5% more in net GWP mitigation. Meanwhile, emissions from fossil fuel use on-farm negated 17% of C sequestration per year and N_2O emissions negated 6%. Across treatments, once-yearly N-fertigations of 8.4 and 16.8 kg N ha^{-1} yr^{-1} only contributed 9% of total N_2O emissions, while emissions in the spring were apparently increased by tillage.

Yield-indexing of GWP studies allows comparison of varied production systems and may prove useful in management decisions. Under minimum tillage grape yields were lowered. The yield loss was probably due mainly to water competition from permanent cover crops, since vines in the treatment showed greater water stress following a winter with less rain.

On the other hand, tilling twice a year instead of once, in order to allow seeding of a barley cover crop, produced no evident effects on water status and only slightly higher yields. But it entailed the highest GHG Intensity, since more frequent tillage required more fuel while apparently restricting soil C-sequestration in the plow layer.

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