Soil & Tillage Research 175 (2018) 244–254

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

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

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ARTICLE INFO

Keywords:
Nitrous oxide
Soil respiration
Fertigation
Methane

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 barleýs potential to sequester carbon in the soil, and of related (tillage-derived) effects on the vineyarđs 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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http://dx.doi.org/10.1016/j.still.2017.06.003
Received 5 October 2015; Received in revised form 14 June 2017; Accepted 15 June 2017
Available online 30 September 2017

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 6^{th}–8^{th} 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