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Effect of Organic Amendment Application Rate on Nitrous Oxide, Methane, and Carbon  
Dioxide Emissions: Field Study and Regional Farmer Survey

A Thesis submitted in partial satisfaction of the  
requirements for the degree Master of Arts  
in Geography

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June 2016

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June 2016

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Remember the expectations you have for yourself. Don't let people who see you as small diminish your spirit or determine your life's path. Be brave, be bold, and shine.

[This thesis was completed in Winter Quarter 2016 and filed in Spring Quarter 2016.]

## ABSTRACT

### Effect of Organic Amendment Application Rate on N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> Emissions: Field Study and Regional Farmer Survey

Michelle Oyewole

Application of organic amendments (OAs) has the potential to act as a greenhouse gas (GHG) emission mitigation strategy and increase soil carbon (C) storage in row crop agriculture. However, OA application may stimulate an increase in emissions of nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>), and carbon dioxide (CO<sub>2</sub>). To determine how compost application rate affects both GHG emissions and crop yield, a field study was conducted at an organic vegetable farm in Santa Barbara County (SBC), California. Additionally, a targeted survey of compost-using farmers ( $n = 14$ ) in SBC and adjacent counties was conducted to understand OA application practices of compost users in the region. In our field experiment, farm managers were asked to apply their normal, high compost (HC) treatment of 18.2 Mg ha<sup>-1</sup> and a low compost (LC) treatment of 9.1 Mg ha<sup>-1</sup> immediately prior to seeding of carrots (*Daucus carota* subsp. *sativus*). A commercial organic fertilizer (OF) was applied to beds of both HC and LC treatments 43 days after compost application (DAC) at the rate of 672 kg ha<sup>-1</sup>. N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions from static flux chambers, along with soil nitrate (NO<sub>3</sub><sup>-</sup>), soil ammonium (NH<sub>4</sub><sup>+</sup>), gravimetric soil moisture, and soil temperature in beds and furrows of each treatment, were measured approximately once weekly for the entire 95 day carrot growing season. Soil total C, total N, bulk density, organic matter, pH, plant tissue C and N, and crop yield were also measured during the

study. Seasonal N<sub>2</sub>O and CO<sub>2</sub> emissions were higher in HC than LC in beds ( $p < 0.001$  N<sub>2</sub>O,  $p = 0.035$  CO<sub>2</sub>); seasonal net uptake of CH<sub>4</sub> was not different in beds ( $p = 0.901$ ), but was significantly higher in LC than HC in furrows ( $p = 0.027$ ), though CH<sub>4</sub> fluxes were often highly variable. Significantly higher emissions of N<sub>2</sub>O and CO<sub>2</sub> in HC beds than LC beds were measured only after OF application (except CO<sub>2</sub> 5 DAC). Crop yield was higher in HC ( $2.82 \pm 0.21$  Mg ha<sup>-1</sup>) than LC ( $2.17 \pm 0.06$  Mg ha<sup>-1</sup>). Yield-scaled global warming potential (GWP), an indicator of agronomic efficiency, was not significantly different between treatments. CO<sub>2</sub> was not included in GWP due to its biogenic origin and an inability to accurately account for net soil C loss during this short time period. A higher amount of biochemically available organic matter and soil moisture in HC than LC may have led to higher decomposition and denitrification rates following OF application, suggesting that C storage benefits of OA application can be reduced by fertilizer addition. Because GWP per unit crop yield was not different between LC and HC, HC may better concurrently address concerns regarding atmospheric GHG emissions and global food demand. Our survey results indicate that average compost application rate in and around SBC ( $12.45 \pm 6.54$  Mg ha<sup>-1</sup>) was lower than HC in our study. While farmers understood the benefits of compost for long-term soil fertility and C storage, economic limitations to increasing compost application rate exist within this region of major crop production. To determine whether OA application affects decomposition of native soil organic matter for more accurate GWP calculation, future studies would benefit from including a control treatment and identifying origins of CO<sub>2</sub>-C emissions, potentially through use of isotopic labeling. New insights about the effects of OA application rate on GHG emissions can aid in assessment of OA use in agricultural C sequestration or GHG mitigation policies.

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## **I. Introduction**

### ***A. Problem Statement***

Agriculture contributes significantly to greenhouse gas (GHG) flux to the atmosphere, accounting for 52 and 84% of global anthropogenic methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions, respectively (Smith et al., 2008). The agricultural sector increases CO<sub>2</sub> emissions from the soil via losses of soil carbon during land conversion for agricultural production and through microbial decomposition stimulated by field management practices such as cultivation, fallowing, and N addition (Bol et al., 2003; Reicosky et al., 1997; Sperow et al., 2003; West et al., 2010). According to the Intergovernmental Panel on Climate Change (IPCC), global warming potentials (GWP) for N<sub>2</sub>O and CH<sub>4</sub> are 298 and 28 times that of CO<sub>2</sub> on a mass basis (100-year time horizon), which facilitates the synthesis of GWP into one number (Pachauri et al., 2014). Calculating yield-scaled GWP in row crop agriculture allows scientists to account for the often-dissociated concerns of global food demand and atmospheric GHG concentrations (Pittelkow et al., 2013; Van Groenigen et al., 2010).

In California, about half of the approximately 100 million acres of land are in agricultural production (Thompson, 2009), and over 25% are croplands, highlighting the opportunity for large-scale agricultural GHG mitigation from cropland within the state. Included in mitigation strategies are those that 1) reduce GHG emissions and 2) increase soil C storage (Smith et al., 2008). Application of organic amendments (OAs) to soils—including compost, manure, and other plant and animal byproducts—has the potential to do both by displacing emissions caused by production and application of conventional fertilizers and pesticides and increasing soil C inputs from crop residues and the OAs

themselves (Pachauri et al., 2014). However, OA application also increases availability of substrate for microbial GHG production, meaning OA application may increase agricultural GHG emissions (Thangarajan et al., 2013).

A widely used OA in organic agriculture is compost, which consists of organic matter such as plant or animal waste that has been decomposed, reaching high temperatures (but ideally no more than 60°C) through a process driven by the activity of thermophilic microbiota in compost piles (MacGregor et al., 1981). We found no published studies on the effects of compost application rate on N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> emissions and yield in row crop agriculture, which represents a gap in our understanding of an OA with high potential for climate change mitigation. Existing studies of compost application rate in row crop agriculture do not relate agronomic variables to GHG emissions. Some studies found diminishing yield returns but higher soil inorganic N concentrations with increasing compost application rates (Chang et al., 2007; Morra et al., 2010; Wong et al., 1999), suggesting an opportunity for improving N-use efficiency in compost application. Following OA application, management practices such as irrigation, tillage, and nutrient addition, may further affect GHG release. It is common for organic farmers to apply more than one OA to a field during a single growing season (Parr et al., 1989), so understanding the interaction of multiple OAs is important in improving projections of the GHG emission mitigation potential of OA application at any given rate.

## ***B. Objectives and Hypotheses***

At an organic vegetable farm in Santa Barbara County, CA, we measured N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> emissions, soil characteristics, and yield of two compost application rate treatments—a high compost application rate treatment (HC) of 18.2 Mg ha<sup>-1</sup> and a low compost application rate treatment (LC) of 9.1 Mg ha<sup>-1</sup>—in order to test the following hypotheses:

1. Differences in soil NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, soil moisture, and soil temperature, resulting from compost application rate treatments will be associated with differences in N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> fluxes between treatments.

Rationale: N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> production in soils are all driven primarily by microbial activity and can be limited by factors that affect microbial metabolism; namely, nutrient availability, moisture, and temperature. We did not measure other properties (e.g. soil C, pH, OM) with every flux measurement because they do not change as rapidly, and because moisture and nutrients are frequently limiting to biological activity in agricultural soils.

- a. NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup>: OAs are rich in nutrients such as N. Addition of OAs rich in inorganic N stimulates N transformation by providing substrate for nitrification and denitrification, which lead to N<sub>2</sub>O emission (Stark and Firestone, 1995). Nutrient addition also primes microbial decomposition that causes CO<sub>2</sub> release (Thangarajan et al., 2013). Addition of inorganic N has been frequently cited in agricultural studies as an inhibitor of methanotrophy (e.g. Hütsch, 1998).

- b. Moisture: OA application increases organic matter in the soil, which influences soil water-holding capacity by promoting soil aggregation and water storage in soil micropores (Oades, 1984). Water can limit microbial activity due to its roles in preventing cellular dehydration and transporting substrate necessary for metabolic and physiological functioning (Stark and Firestone, 1995). Because  $\text{N}_2\text{O}$  and  $\text{CH}_4$  production are both primarily driven by anaerobic conditions, we expect moisture content to be particularly important in predicting fluxes of these gases.
  - c. Temperature: We predicted that relative to LC, HC would result in higher soil moisture, which would reduce temperatures due to higher evaporative cooling (Dai et al., 1999). Because temperature controls rates of biological metabolism, we expected lower temperatures to reduce  $\text{N}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{CH}_4$  emissions; however, the influence of temperature on differences in gas fluxes between treatments was expected to be minimal compared to the effects of  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , or moisture, in part because we perceived the rates of compost application as not high enough to significantly change environmental conditions.
2. GWP ( $\text{N}_2\text{O}$  +  $\text{CH}_4$ ), yield-scaled GWP, and  $\text{CO}_2$  emissions will increase with compost application rate.

Rationale:

- a. GWP: GWP was expected to increase with higher compost application primarily due to the addition of more inorganic N, which increases  $\text{N}_2\text{O}$  emissions. Additionally, we expected that higher soil moisture due to higher

organic matter content would also lead to increased N<sub>2</sub>O and CH<sub>4</sub> emissions in the high compost treatment. CH<sub>4</sub> emission is often negligible in well-aerated soils, and in fact upland soils are typically a methane sink, so we expect the contribution of CH<sub>4</sub> to GWP to be minimal compared to N<sub>2</sub>O. However, higher soil moisture, and higher inorganic N, which inhibits CH<sub>4</sub> oxidation, could reduce the strength of the soil CH<sub>4</sub> sink to a higher degree in HC.

- b. Yield-scaled GWP: Some studies have documented diminished increases in yield with increasing OA application rates (Chang et al., 2007; Morra et al., 2010; Wong et al., 1999). Similarly, we predict that yield will not be significantly different between treatments and thus, with higher GWP in the high compost treatment, yield-scaled GWP (yield/GWP) will be higher as well.
- c. CO<sub>2</sub>: Decomposition of SOM is primed by nutrient addition (as reviewed by Thangarajan et al., 2013). Additionally, compost contains organic C compounds that can be decomposed and released as CO<sub>2</sub>. We predict that higher decomposition will lead to higher CO<sub>2</sub> emissions in HC.

- 3. Organic fertilizer (OF) applied at a single rate to both treatments mid-season will lead to higher N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions in both treatments.

Rationale: While not part of our original experimental design, farmers informed us before the start of the growing season that they would apply an organic fertilizer to our field site mid-season (at equal rates in both treatments). We predicted that nutrient application would stimulate decomposition and denitrification at higher rates in HC, due in part to



higher amounts of C from more added compost. We also predicted that addition of inorganic N at equal rates would inhibit CH<sub>4</sub> oxidation equally in both treatments.

In our farmer survey, we interviewed compost-using vegetable growers in the Tri-County area (Santa Barbara, San Luis Obispo, and Ventura Counties). Our objective was to provide context for compost application rates and practices within a region of major fruit and vegetable production in Southern California.

### ***C. Scope of Study***

#### **1. Overall**

Throughout the document we discuss OA application in annual vegetable and fruit crops. Relatively little will be said about perennial crops or flooded agricultural systems, and we will not discuss animal agriculture, so we do not necessarily expect results from this study to relate to these other systems.

#### **2. Field Study**

The field study was conducted at an organic farm that grows fruits, vegetables, and herbs in the eastern Goleta valley, CA (in Santa Barbara County) during the summer of 2014. This region experiences a Mediterranean climate. The field study was conducted on a field of carrots (*Daucus carota* subsp. *sativus*), grown on a Mollisol soil during a single growing season. Compost prepared on-site and a commercially available organic fertilizer (True 8-5-1 ©, True Organic Products Inc., Spreckels, CA) were applied to the soil. We acknowledge that there are many different types of OAs, and that chemical, physical, and biological characteristics of OAs should be assessed before comparison with other studies or broader

generalization (compost characterization is provided in following chapter). Temporal resolution of GHG flux and accompanying soil measurements are coarse, due in part to methodology used (i.e. static flux chambers). Results from this study can potentially be generalized to fields with similar climate, soils, and crops with similar life history strategies as carrots (e.g. potatoes, celery).

### 3. Survey

Annual crop farmers in Santa Barbara County and adjacent coastal counties (referred to as the Tri-County area: Santa Barbara, Ventura, and San Luis Obispo Counties) who use compost were surveyed ( $n = 14$ ). Farmers surveyed use a wide variety of OAs; this was dependent on factors such as availability, price, and access. Additionally, the farmers who were surveyed represented a wide range of farm sizes, self-reported soil types, and crops grown.

## ***D. Literature Review***

### 1. Organic Amendment Use in U.S. Agriculture

Since the creation of the United States Department of Agriculture (USDA) in 1862, agricultural research conducted in the United States has extensively documented the effectiveness of organic amendments (OAs) such as composts, manures, and crop residues in maintaining fertility and productivity of agricultural soils (Parr and Hornick, 1992). Discovery of ammonia synthesis by Fritz Haber in 1909 led to large-scale production of ammonia by 1913, which facilitated dramatic increases in the use of synthetic nitrogen fertilizers in the U.S. during the 20<sup>th</sup> century.

Farms that are certified organic through USDA-approved agencies are prohibited from using most synthetic materials, including fertilizers and pesticides. While some non-organic farms (i.e. “conventional,” biodynamic, etc.) use OAs, the vast majority of organic crop farms depend on OAs to maintain productivity. Organic agriculture has increased in popularity due to growing public concerns about the environment and health effects of pesticides, genetically-modified organisms, and food safety within conventional agriculture (Hughner et al., 2007). The share of certified organic croplands producing major vegetables in the U.S. has increased during the past two decades, from 1.62%, 3.69%, and 5.80% of tomato, lettuce, and carrot production in 2005, to 2.52%, 11.56%, and 14.35%, respectively, in 2011 (USDA ERS, 2013). The trend of increased land in organic crop production reinforces the need for better information about the environmental effects of organic management practices.

Organic farms vary dramatically in the rates and types of OAs used, dependent on factors such as crop type, soil type, environmental conditions, cost, labor, and access to machinery (Ouédraogo et al., 2001). Physical, chemical, and biological characteristics of OAs affect crop growth and can result in a wide range of environmental benefits or consequences (Thangarajan et al., 2013). Indeed, while OAs are typically viewed as an “environmentally-friendly” alternative to synthetic fertilizers, application of some OAs can lead to higher GHG emissions per unit-area than application of similar rates of synthetic fertilizer (Dambreville et al., 2006; Rochette et al., 2004). Accordingly, there is a need to quantify OA application rates that optimize the balance between minimizing GHG emissions and maximizing crop yield.

## 2. Influence of Organic Amendments on GHG Emissions

Addition of OAs to agricultural soils alters physical, chemical, and biological characteristics by adding organic matter containing C, nutrients, and other substances; increasing plant growth; altering environmental conditions such as temperature and moisture; and introducing or priming microbial communities. Below we discuss some of the main drivers of GHG emissions in response to OA application. Some effects of OA addition, such as increases in soil moisture or inorganic N, affect N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> production in different directions, as we will discuss in more detail. The microbiological nature of GHG production, including microbial responses to different environmental drivers, makes prediction of the net global warming effects of a given rate of OA application complex. For this reason, using the GWP values of different gases is useful in determining whether certain OA application rates cause a net positive or negative change in GWP.

### a. N<sub>2</sub>O Emissions

Agriculture is the largest sectoral emitter of N<sub>2</sub>O (Mosier and Kroeze, 2000). Many OAs provide nitrogen (N) and other nutrients (Eghball, 2002). It is estimated that only 20-55% of N applied to soils as OAs is used by plants (Eghball, 2000; Hasegawa et al., 2005; Xu et al., 2008), meaning excess N is available for leaching, run-off, or gaseous emission, though this varies widely by OA type and cropping system. N<sub>2</sub>O emissions are increased by OA application when inorganic N (NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>) and organic N that may be subsequently mineralized are made available to nitrifying and denitrifying microorganisms (Cabrera et al., 2005). N mineralization rate is therefore controlled by the chemical composition of the added organic residues (Whitmore, 1996), soil temperature and moisture (Kätterer et al.,

1998), drying and rewetting events (Fierer and Schimel, 2002; Kruse et al., 2004), and physical and chemical characteristics of the soil (Thomsen and Olesen, 2000; Van Veen et al., 1985) (as reviewed by Cabrera et al., 2005), all of which influence the ability of microorganisms to metabolize available N. In general, when OA application leads to increased available C, higher soil moisture, and/or increased activity of nitrifying and/or denitrifying microbial communities (Akiyama et al., 2004; Okano et al., 2004), we may expect an increase in N<sub>2</sub>O emissions. Application of OAs may also increase soil porosity (i.e. decrease bulk density) (Mbagwu, 1989), thereby increasing the availability of oxygen that can be used as a terminal electron acceptor in microbial metabolic processes, and decreasing the likelihood of N<sub>2</sub>O production. OAs such as compost and lime are often applied to increase pH. N<sub>2</sub>O production is optimal at slightly acid to alkaline pH (6 to 8), so increasing soil pH (in acidic to mildly acidic soils) can increase N<sub>2</sub>O emissions (Pathak, 1999).

#### b. CH<sub>4</sub> Emissions

Because methanogenesis is an anaerobic process upland soils tend to be methane sinks, oxidizing CH<sub>4</sub> from the atmosphere (Le Mer and Roger, 2001). However, CH<sub>4</sub> emissions can be either increased or decreased by OA application. OAs may provide substrate for methanogenesis in the form of organic C (Chadwick et al., 2000). Additionally, applying certain OAs such as rice straw may increase reducing conditions within the soil by stimulating rapid microbial O<sub>2</sub> consumption (Rath et al., 1999). This creates conditions where CO<sub>2</sub> is utilized as an electron acceptor instead of oxygen, releasing CH<sub>4</sub>. OAs may release NH<sub>4</sub><sup>+</sup> and NH<sub>3</sub> as organic matter is decomposed, which occupy enzyme binding sites and thereby effectively “compete” with CH<sub>4</sub> for oxidation by methane monooxygenase

(MMO), resulting in reduced soil CH<sub>4</sub> consumption (Bédard and Knowles, 1989; Bender and Conrad, 1994; Hansen et al., 1993). N application can also cause long-term decreases in the population of methanotrophs within the soil, decreasing CH<sub>4</sub> oxidation (Adamsen and King, 1993; Hütsch, 2001).

Conversely, increases in soil porosity following OA application may lead to decreases in CH<sub>4</sub> emission due to higher oxidation of C to CO<sub>2</sub>. Additionally, OAs such as compost may affect microbial communities by inoculating the soil with methanotrophic bacteria that flourished in response to methanogenesis during the composting process (Hütsch, 1998), thus increasing soil CH<sub>4</sub> consumption.

### c. CO<sub>2</sub> Emissions

Because soil CO<sub>2</sub> emissions are generated from C captured by photosynthesis, biogenic CO<sub>2</sub> emissions from soils are usually not included in the calculation of GWP (Wolf et al., 2015). However, OA addition may enhance decomposition of native SOM and result in net loss of native C by priming microbial activity (Kuzyakov and Bol, 2006; Thangarajan et al., 2013), which is a net loss that should be included in GWP calculations. Addition of readily available organic C promotes soil microbial activity and growth soon after application, and emissions of CO<sub>2</sub> increase as a result of preferential utilization of the new substrate, activation of microbial growth, and subsequent decomposition of less-utilizable substrates (De Nobili et al., 2001; Kuzyakov and Bol, 2006; as reviewed by Thangarajan et al., 2013). CO<sub>2</sub> emissions are also closely tied to plant growth, which may increase as a result of higher soil fertility following OA application, supplying organic residues to decomposers (Schlesinger and Andrews, 2000). Increases in CO<sub>2</sub> emissions can also be attributed to

higher plant respiration, due to improved soil fertility and access to nutrients resulting from OA application (Andruschkewitsch et al., 2013; Hodge et al., 1999). However, CO<sub>2</sub> emissions from plant respiration are not counted toward GHG emissions resulting from OM application, and indeed, plant respiration is excluded from measurement in many chamber based GHG flux studies (including this study). Addition of organic C tends to increase soil water retention (Rawls et al., 2003), which may increase decomposition rates in water-limited environments (Chapin et al., 2011). Increased soil porosity increases O<sub>2</sub> availability and gas diffusion, which has the potential to increase soil CO<sub>2</sub> emission. OA application may influence soil temperature, which is another critical control on microbial activity and decomposition (Thangarajan et al., 2013; Zhang et al., 2009).

### 3. Interaction with Other Management Practices

The effect of OA application rate on GHG emissions may be influenced by soil management practices. Because organic farmers employ a variety of OA application rates and types, irrigation regimes, tillage methods, and pest management strategies, it is important to consider how OA application interacts with other management practices when measuring biogeochemical processes such as soil GHG emissions. For example, in fields where multiple OAs are applied (e.g. compost for soil physical improvement and chicken manure to increase available nitrogen [Miyasaka et al., 2001]), their interaction may stimulate higher C loss and N<sub>2</sub>O release due to a priming effect. Accounting for other management practices occurring on the same field as OA application is an important step before comparing studies or making broader extrapolations.

#### 4. Additional Metrics for Reporting GHG Emissions

##### a. Global Warming Potential and Yield-Scaled Emissions

The Intergovernmental Panel on Climate Change (IPCC) has defined the global warming potential (GWP) of various greenhouse gases compared to CO<sub>2</sub> based on their radiative forcing and atmospheric lifetime. This enables reporting of N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> emissions as one value. In the IPCC Fifth Assessment Report, GWP of N<sub>2</sub>O and CH<sub>4</sub> are 298 and 28 times that of CO<sub>2</sub> on a mass basis (100-year time horizon) (Pachauri et al., 2014). Scaling GWP by yield in crop agriculture allows scientists to account for the often-dissociated concerns of global food demand and atmospheric GHG concentrations (Pittelkow et al., 2013; Van Groenigen et al., 2010). Yield-scaled N<sub>2</sub>O emissions may be considered a proxy for plant N-use efficiency when comparing N application rates.

##### b. Emission Factors

The current IPCC emission factor (EF) for N<sub>2</sub>O-N from N applied in agricultural soils is 1%, regardless of the form of N applied. This number tends to overestimate N<sub>2</sub>O depending on the form of N applied (Skiba et al., 2012), and therefore may not represent all farms under organic management. Emission factors are not as widely used for CH<sub>4</sub> or CO<sub>2</sub> in amendment application, presumably because of relatively negligible emissions from aerated agricultural soils for CH<sub>4</sub>, and the biogenic origin and plant-soil biocycling that characterizes the flux of CO<sub>2</sub>. We use them in this study to provide an estimate of the ratio of C added to C lost as CO<sub>2</sub>.



## 5. C Sequestration and GHG Policy

### a. Soil C Stabilization

OA application has been proposed as a soil C sequestration strategy (Lal, 2004; Paustian et al., 1997; Smith et al., 2008). In addition to offsetting GHG emissions from production and use of synthetic fertilizers, application of certain OAs may promote stabilization of C from the OA itself, and it may increase C storage resulting from deposition of plant residues due to improved soil fertility (Eghball and Power, 1999; Lal, 2004; Smith et al., 2008). OAs increase soil water-holding capacity, reduce bulk density, release N, and improve soil fertility, which increases plant net primary productivity (Ryals et al., 2014). C storage through agricultural soil management has also been studied in the context of conservation tillage, crop intensification, synthetic fertilization, and residue incorporation (Lal, 2004; Paustian et al., 1997; Smith et al., 2008). Added C can be stabilized in physically-protected, mineral-associated, or biochemically recalcitrant forms (Six et al., 2002). However, the amount of C stabilized depends on a number of factors, including the rate of OA application, environmental conditions, and subsequent management practices.

### b. OAs in Climate Change Mitigation Policy

OA application is increasingly supported as a strategy to aid in compliance with GHG mitigation policies (Owen et al., 2015; Ryals et al., 2014; Smith et al., 2008). Policies may provide monetary incentives for farmers using recommended management practices (RMP) including OA application, as well as no-till farming, cover cropping, and other sustainable management strategies (Lal, 2004). In California, incentives for farmers could be included within the existing *Global Warming Solutions Act of 2006* (Assembly Bill [A.B.] 32) and

related legislation, providing credits to farmers through the cap-and-trade program for increasing soil C storage. In 2015, at least two bills proposed in the California state legislature were aimed at increasing soil C sequestration as a GHG emission mitigation mechanism: A.B. 761 (Carbon sequestration: working lands) and Senate Bill (S.B.) 367 (Agricultural lands: greenhouse gases). If approved, these bills would amend current law (Cannella Environmental Farming Act of 1995) and enable farmers to apply for grants, loans, research funding, and technical assistance for management practices that reduce GHG emissions or increase C storage and protect ecosystem health. Such policies could help farmers in need of economic resources (e.g. low-income, small-scale, organic farmers) while reducing the environmental impact of California agriculture. However, because OA application also *causes* GHG emissions, understanding GHG emissions resulting from different OA application rates will enable implementation of policies that meet their intended goals.

## II. Journal Manuscript

### Effect of Organic Amendment Application Rate on N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> Emissions: Field Study and Regional Farmer Survey

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#### Abstract

Organic amendment (OA) application has the potential to increase soil carbon (C) storage as a climate change mitigation strategy, but can also lead to net greenhouse gas (GHG) emissions. A field study was conducted at an organic vegetable farm in Santa Barbara County (SBC), California to determine how compost application rate affects GHG emissions and crop yield. A survey of compost-using farmers ( $n = 14$ ) was also conducted to compare OA application practices within the region. In our field experiment, farm managers applied high (HC) and low compost (LC) treatments of 18.2 and 9.1 Mg ha<sup>-1</sup>, respectively. Organic fertilizer (OF) was applied 43 days after compost application (DAC) to all field beds at a single rate (672 kg ha<sup>-1</sup>). Application of OF led to significantly higher N<sub>2</sub>O (41%) and CO<sub>2</sub> (13%) emissions in HC than LC. CH<sub>4</sub> oxidation did not differ between treatments in beds, but was 95% higher in HC than LC in furrows ( $p = 0.027$ ). Crop yield was 1.3x higher in HC than LC, and as a result yield-scaled GWP did not differ between treatments, suggesting that HC better concurrently addresses concerns regarding atmospheric GHG emissions and global food demand. Higher amounts of biochemically available organic matter and soil moisture in HC than LC likely led to higher decomposition and denitrification rates following OF application. Survey results indicate that economic constraints limit compost application rate in this region (mean application rate, 12.45±6.54

Mg ha<sup>-1</sup>). New insights from this study can aid in assessing and improving the efficacy of OA application in agricultural GHG mitigation policies.

## **1. Introduction**

Agriculture accounts for 52 and 84% of global anthropogenic methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions, respectively (Smith et al., 2008). The sector also promotes losses of soil carbon (C) as CO<sub>2</sub> during land conversion and subsequent microbial decomposition stimulated by field management (e.g. cultivation, fallowing, and N addition) (Bol et al., 2003; Reicosky et al., 1997; Sperow et al., 2003; West et al., 2010). Global warming potentials (GWP) for N<sub>2</sub>O and CH<sub>4</sub> are 298 and 28 times that of CO<sub>2</sub> on a mass basis (100-year time horizon), which facilitates the synthesis of GWP into one number (Pachauri et al., 2014). Calculating yield-scaled GWP in row crop agriculture merges the oft-dissociated concerns of global food demand and atmospheric GHG concentrations (Pittelkow et al., 2013; Van Groenigen et al., 2010).

The magnitude of GHG emissions from the agricultural sector suggests the need for implementation of large-scale mitigation strategies. This includes strategies that 1) reduce GHG emissions and 2) increase soil C storage (Smith et al., 2008). Application of organic amendments (OAs) to soils—including compost, manure, and other plant and animal byproducts—has the potential to do both, by displacing emissions caused by production and application of conventional fertilizers and pesticides, and by increasing soil C inputs from crop residues and the OAs themselves (Pachauri et al., 2014). However, OA application rate also affects the soil environment and availability of substrate for microbial GHG production, which may increase GHG emissions (Thangarajan et al., 2013).

OA application practices vary significantly at the scale of the individual farm (Watson et al., 2002), and use of specific OAs may be affected by factors such as cost, labor, and machinery (Ouédraogo et al., 2001). Empirical data regarding the drivers of farmers' decisions can contribute to development of feasible and economical GHG reduction policies. In California, legislative opportunities exist for including OA application management in climate change mitigation strategies, such as in California's *Global Warming Solutions Act of 2006* (Assembly Bill [A.B.] 32). In 2015, California state legislators authored at least two bills promoting soil C sequestration on agricultural soils—A.B. 761, Levine (Carbon sequestration: working lands) and Senate Bill (S.B.) 367, Wolk (Agricultural lands: greenhouse gases), highlighting the need to understand GHG emissions resulting from OA applied at different rates and with different patterns.

For some OAs, the main benefits are the effects of organic matter (OM) on soil bulk density, water-holding capacity, and pH (Leroy et al., 2008; Odlare et al., 2008; Zhao et al., 2009). Added C can be stabilized in physically-protected, mineral-associated, or biochemically recalcitrant forms (Six et al., 2002), but it can also be released by practices that enhance OM decomposition. OA application also influences methane (CH<sub>4</sub>) emissions, though these emissions are often low in well-aerated soils (Le Mer and Roger, 2001). OAs may provide substrate for methanogenesis and certain OAs promote soil anaerobiosis (Rath et al., 1999), which would increase CH<sub>4</sub> emissions. Addition of OAs high in NH<sub>4</sub><sup>+</sup> can also inhibit methanotrophy by competing with CH<sub>4</sub> for methane monooxygenase (MMO) (Bédard and Knowles, 1989; Bender and Conrad, 1994; Hansen et al., 1993). On the other hand, compost addition may inoculate the soil with methanotrophic bacteria (Hütsch, 2001).

Many OAs also provide nitrogen (N) and other nutrients (Eghball, 2002). It is estimated that approximately 20-55% of N applied to soils as OAs is used by plants (Eghball, 2000; Hasegawa et al., 2005; Xu et al., 2008), meaning that excess N is available for leaching, runoff, or gaseous emission, though this varies widely by OA type and cropping system. Application of OAs may increase available C, soil moisture, and activity of nitrifying and denitrifying microbial communities (Akiyama et al., 2004; Okano et al., 2004) which would increase N<sub>2</sub>O emissions and may offset GHG emission mitigation efforts when N availability significantly exceeds plant demand. In fields where multiple OAs are applied (e.g. compost for soil physical improvement and chicken manure to increase available nitrogen [Miyasaka et al., 2001]), their interaction may stimulate higher C loss and N<sub>2</sub>O release. In addition to measuring emissions on an area basis, yield-scaled N<sub>2</sub>O emissions can be considered a proxy for plant N-use efficiency when comparing N application rates in different OA application treatments.

A widely used OA in organic agriculture is compost, which consists of organic matter such as plant litter or animal waste that has been decomposed, normally reaching high temperatures (but ideally no more than 60°C) through a thermophilic process driven by the activity of microbiota in compost piles (MacGregor et al., 1981). We found no published studies on the effects of compost application rate on N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> emissions and yield in row crop agriculture, which represents a gap in our understanding of an OA with high potential in climate change mitigation (Ryals et al., 2014). Existing studies of compost application rate in row crop agriculture do not relate agronomic variables to GHG emissions. Some studies found diminishing yield returns but higher soil inorganic N with increasing compost application rates (Chang et al., 2007; Morra et al., 2010; Wong et al., 1999),

suggesting an opportunity for improving N-use efficiency in compost application. Because many organic farmers use more than one OA during the same growing season, measuring the effects of multiple OAs on GHG emissions is critical in improving projections of the GHG emission mitigation potential of OA application.

At an organic vegetable farm in Santa Barbara County, CA, we measured  $N_2O$ ,  $CH_4$ , and  $CO_2$  emissions, soil characteristics, and yield of two compost application rate treatments in order to test the following hypotheses: 1) Differences in soil  $NO_3^-$ ,  $NH_4^+$ , soil moisture, and soil temperature, resulting from compost application rate treatments, will be associated with differences in  $N_2O$ ,  $CO_2$ , and  $CH_4$  fluxes between treatments, 2) GWP ( $N_2O + CH_4$ ), yield-scaled GWP, and  $CO_2$  emissions will increase with compost application rate, and 3) Organic fertilizer (OF) applied at a single rate to both treatments mid-season will lead to higher  $N_2O$ ,  $CO_2$ , and  $CH_4$  emissions in both treatments.

The third hypothesis was not an explicit part of our design, but we were informed before the season began that OF was to be applied to the field mid-season (at equal rates in both treatments). In our accompanying farmer survey, our objective was to provide context for compost application rates and practices within a region of major fruit and vegetable production in Southern California.

## **2. Materials and methods**

### **2.1 Site description and study design**

The field study was conducted on an organic vegetable farm in the eastern Goleta valley, in Santa Barbara County (SBC), CA ( $34^{\circ}25'N$ ,  $119^{\circ}48' W$ ) from July to October 2014. This region has a mild Mediterranean climate where most of the precipitation falls as rain

between October and April, and summers (the period of this experiment) are typically warm and dry. During the course of the experiment, total precipitation was 0.3 mm, and average daily minimum and maximum air temperatures were 15.1°C and 25.6°C, respectively. The farm has been used for organic food production under the same management for approximately 30 years. We dug a soil pit in the center of the field to 100 cm and described the soil profile. We classified the clay-rich soil as a fine, mixed, superactive, thermic, Calcic Haploxeroll (USDA NRCS, 1999). Our description included horizon designations, matrix color, texture, structure, rock fragments, roots, pores, consistence, effervescence, and pH (of these, pH was measured only in the top 20 cm; the rest were measured throughout the soil profile). Measurement of base saturation was not performed, so we used the USDA Web Soil Survey's description of soil types on the farm to differentiate when deciding between a Mollisol or Inceptisol classification. We designated the uppermost soil horizons as plow layers (Ap<sub>1</sub> 0-20 cm & Ap<sub>2</sub> 20-31 cm), which is consistent with our inability to easily sample deeply into the soil with push probes.

Compost was applied on July 16, 2014 with a spreader tractor and disced into the soil to ca. 20 cm in a single ca. 0.25 ha field. Beds were then formed to a height of ca. 15 cm relative to the furrows, seeded with carrot (*Daucus carota* subsp. *sativus*) using tractors, and irrigated uniformly using sprinklers. Compost is manufactured by the farm on-site via open-air thermophilic composting (4-7 months). Compost is composed of yard waste from a local waste management company (Marborg Industries, Santa Barbara, CA), horse manure, horse bedding, vegetable waste, straw, soil, chicken manure, other plant residues, and other organic wastes. Compost is mixed with gypsum (CaSO<sub>4</sub>.H<sub>2</sub>O) and sulfate of potash (K<sub>2</sub>SO<sub>4</sub>) immediately prior to application. Compost was 5.92 (±0.08)% C and 0.43 (±0.02)% N with



a C to N ratio (C:N) of 13.74. Additional compost characterization data are presented in Table 1.

The field was divided in half, and compost was applied at rates of 18.2 and 9.1 Mg ha<sup>-1</sup> in the high (HC) and low (LC) compost treatments which were on either half of the field, respectively. HC is the typical rate of application at this farm, applied once at the beginning of the season for most crops. Gas and soil measurements for each treatment took place in two positions, bed and furrow, occupying 46% and 54% of the field, respectively. Soil and gas flux measurements were taken in plots (15.5 x 0.4 m) established along field rows, containing one chamber in the bed and one chamber in the furrow. A block contained one plot in each LC and HC ( $n = 6$  blocks; 24 chambers total). Fields were irrigated with sprinklers on the same day as compost application and roughly once a week thereafter for 4 hours per session. In some weeks irrigation was done by treatment (i.e. on either half of the field) one day apart. The field was flame-weeded with a tractor 6 days after compost application (DAC). Tractor cultivation occurred 20 and 47 DAC. Hoeing occurred 27 DAC. Hand weeding began 70 DAC and lasted two weeks. Gas and soil sampling began on July 15, 2014 (one day before compost application) and ended with the beginning of harvest on October 19, 2014 (95 DAC). True 8-5-1 © (True Organic Products Inc., Spreckels, CA), a dry pelleted commercial organic fertilizer (OF), was applied to the subsurface, of beds only, at a rate of 672 kg ha<sup>-1</sup> with a precision applicator tractor (Clampco Products, Wadsworth, OH) at 43 DAC. The fertilizer was composed of meat and bone meal, poultry manure, and feather meal. It contained 8% total N (1.46% water-soluble organic N and 6.54% water insoluble organic N), 5% P as plant-available phosphate (P<sub>2</sub>O<sub>5</sub>), and 1% K as soluble potash (K<sub>2</sub>O).

## 2.2 N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> flux measurements

N<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> fluxes were measured once every 7-10 days throughout the growing season. Gas fluxes were measured and soils were sampled in a paired block design within a single round of flux measurements (i.e. one block per round). Wet field conditions limited access to chambers immediately following irrigation events. Gas sampling was typically conducted from early morning to early afternoon using the closed chamber method (Parkin and Venterea, 2010). Chamber bases were constructed of aluminum with lengths and widths of 27.5 cm and heights of 15-20 cm. They were inserted into the ground to depths of ca. 7-12 cm. Heights of chamber bases above the soil surface were measured immediately after placement and periodically thereafter to calculate headspace volume and account for changes in headspace volume due to soil settling. Chamber bases remained in the same position between most sampling events but were occasionally moved due to field machine operations. In that case, bases were replaced within 1 m of their original position, and were allowed to equilibrate for a minimum of 24 h before sampling. Chamber lids were constructed of aluminum with volumes of 4.4, 12.5, or 12.8 L. Water troughs sealing the chamber lids to chamber bases were used to isolate flux chambers from atmospheric conditions.

Air samples were taken from the chamber headspace through a rubber septum using a 30 ml airtight syringe at 0, 10, 20, and 40 minutes after closure of the chamber. Preliminary tests under field conditions showed that CO<sub>2</sub> concentrations were linear for the first 20 minutes following chamber deployment, so CO<sub>2</sub> flux was calculated using the first three time points. CH<sub>4</sub> flux was more linear using the 10-, 20- and 40- minute samples, presumably due to equilibration following headspace closure, so the first time point was

omitted. Fluxes were calculated using linear regression of gas concentrations versus chamber closure time and enclosed chamber volume. All gas fluxes were tested for linearity and reviewed to assess accuracy in instances when  $R^2 < 0.99$ . Fluxes were corrected to mass basis using the Ideal Gas Law. Cumulative emissions over the growing season were calculated using linear trapezoidal integration. Ambient air samples were taken from the field at 1.5 m above the soil surface at the beginning of sampling each block. All air samples were analyzed as soon as possible after collection (within 24 h) by gas chromatography.

Gas analysis was performed using a Shimadzu GC-14A gas chromatograph (Nakagyo-ku, Japan) equipped with a  $^{63}\text{Ni}$  electron capture detector (ECD), a thermal conductivity detector (TCD), and a flame ionization detector (FID) for measurement of  $\text{N}_2\text{O}$ ,  $\text{CO}_2$ , and  $\text{CH}_4$ , respectively. Four steel columns (length 0.75-3 m) containing 80/100 mesh Porapak<sup>TM</sup> N (Waters Corp, Milford, MA) within the column oven were used to separate the gas sample into components of interest and allow the gas sample to pass through the detectors for analysis. Carrier gases were  $\text{N}_2$  for the ECD and helium (He) for the FID and TCD. A gas mixture of 95% Ar and 5%  $\text{CH}_4$  was the makeup gas for the ECD. Helium was also used as a reference gas in the TCD. Hydrogen and air were the fuel source for the flame used in the FID. The detector temperatures were: ECD, 300°C; TCD, 110°C, FID, 150°C; and column oven, 55°C. Average retention times of analytes were 1.15 minutes for  $\text{CO}_2$ , 0.5 minutes for  $\text{CH}_4$ , and 2.97 minutes for  $\text{N}_2\text{O}$ , and the total time to analyze a sample was set to 3.5 minutes. Replicates (3-5) of three standards capturing the range of concentrations for each analyte were injected at the beginning, middle, and end of sample runs and used for calibration. Accuracy for all standards was within 5% (Air Liquide America Specialty

Gases, LLC, Plumsteadville, PA), and GC precision averaged 1.44%, 1.65%, and 5.85% for N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>, respectively.

### 2.3 Soil analysis, compost characterization, and plant analysis

We performed an initial soil description one day prior to compost application to assess the degree of spatial homogeneity by sampling soil to 25 cm every 10 m in vertical and horizontal transects, and analyzing soils for organic matter content and moisture. During the growing season, soil samples were collected at each chamber on all flux measurement dates. Compaction prevented deeper sampling in the furrows, so three replicate soil samples were taken to a depth of 20 cm in the beds and only to 10 cm in the furrows within 2 m of each chamber using a 3 cm diameter soil push probe. Samples were combined for each chamber on each date for determination of NO<sub>3</sub><sup>-</sup> and NH<sub>4</sub><sup>+</sup> concentrations and soil moisture. Soil temperature at 10 cm depth was measured at each chamber, typically between the interval of the 20- and 40-minute gas flux samples. Air temperature was measured 1.5 m above the soil surface. Soil moisture content was determined gravimetrically by drying a subsample for 48 h at 105°C.

Exchangeable NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> was determined by sieving subsamples to 2 mm, shaking 3 g soil in 32 ml 2 M KCl solution for 1 h on a gyratory spinner, then vacuum filtering through a glass fiber filter (Pall Gelmann Type A/E 1.0 um, Pall Gelman, Ann Arbor, MI), and freezing samples until analysis. Extracts were analyzed for NH<sub>4</sub><sup>+</sup> using diffusion and for NO<sub>3</sub><sup>-</sup> using cadmium (Cd) reduction followed by Griess-Ilovsay reaction using a Lachat Quickchem 8500 flow injection analyzer (Lachat Instruments, Loveland, CO). Five standards per analyte were prepared volumetrically with pipettes (Thermo Fisher Scientific, Bremen, Germany), using dissolved solutions of both KNO<sub>3</sub> and NH<sub>4</sub>Cl in 2 M KCl,

immediately prior to sampling. Standards were measured at the beginning of sample runs; check standards were run every 10 samples to monitor instrument precision.

Soil samples from 5, 49, and 95 DAC (corresponding to the beginning, middle, and end of the study) were dried at 105°C, ground, and analyzed for total C and total N using an elemental analyzer (Carlo Erba/Fisons NA 1500 Series, Fisons Instruments, Dearborn, MI). Soil pH was measured at the end of the season by shaking 10 g wet soil with deionized water (Milli-Q, Millipore Corp., Billerica, MA) in 1:1 slurries and analyzing slurries on a pH meter with a single junction combination pH electrode and Ag/AgCl reference (Accumet © basic AB15, Fisher Scientific, Pittsburgh, PA). Soil bulk density was determined on 9 and 95 DAC as oven dry weight divided by soil core volume of samples taken from the surface (3.3 cm depth) using brass coring rings. Three samples of ca. 25 g of compost were sampled at the time of compost application and analyzed for  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , total C, total N, pH, and bulk density using the same methods as described above for soil samples.

At the end of the growing season, marketable crop yield, non-marketable crop residue, and weeds were carefully harvested by hand and trowel and weighed separately from three replicate 7.5 m<sup>2</sup> plots total in each treatment 95 and 101 DAC. Marketable and non-marketable crop residues were combined to avoid human subjectivity in harvest measurement technique, and will henceforth be referred to as crop yield. Weed biomass is separate from carrot biomass and is not discussed. Aboveground and belowground biomass were separated and dried at 60°C. Plant subsamples were dried at 60°C, ground, and analyzed for total C and N as described above.

## 2.4 Statistical analysis

Repeated-measures analysis of variance (ANOVA) was performed on gas fluxes, inorganic N concentrations, soil moisture, and soil temperature using RANOVA in MATLAB® Version 2015a. One-way ANOVAs were performed using ANOVA1 in MATLAB for soil total C and N, plant C and N, soil pH, yield, OM, and pH. Additionally, one-way ANOVAs were performed for cumulative N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions. For each model, compost was designated as a fixed effect, and comparisons were made separately for each position (bed and furrow). Linear regression analyses showed a significant effect of fertilization on N<sub>2</sub>O and CO<sub>2</sub> emissions in both treatments (data not shown). Thus, separate pre- and post-fertilization ANOVAs for GHG emissions were completed in addition to ANOVAs for the entire season. The 0.05 confidence interval (p-value) was used to determine statistical significance.

## 2.5 GWP and emission factors

Total GWP was calculated as CO<sub>2</sub> equivalents over a 100-year time horizon using radiative forcing potential of 298 for N<sub>2</sub>O and 28 for CH<sub>4</sub> in kg CO<sub>2</sub> equivalents (Myhre et al., 2013). CO<sub>2</sub> was not included in the GWP calculation because we assumed it to be of biogenic origin (see Wolf et al., 2015). N<sub>2</sub>O emission factors (EFs) were calculated as percentage of N<sub>2</sub>O-N released during the growing season of compost- plus fertilizer-N applied, by treatment and position. CH<sub>4</sub> EFs were calculated as percentage of CH<sub>4</sub>-C released during the growing season of compost-C applied. CO<sub>2</sub> EFs were calculated in the same way—this infrequently used measure is provided as a comparison between treatments,

and along with yield-scaled CO<sub>2</sub>, provides an estimate of the ratio of C added to C lost as CO<sub>2</sub>.

## 2.6 Compost survey

We identified commercial farmers using compost in the Tri-County area (Ventura, San Luis Obispo, and Santa Barbara counties) by speaking with vendors from all stands that sold annual crops at three farmers markets in SBC during multiple visits (Goleta, Santa Barbara, and University of California, Santa Barbara [UCSB] markets). Farmers identified peers who also used compost. Many farmers in our preliminary outreach only used non-compost OAs (est. 30-50%), such as manures, crop residues, and compost tea, and they were not included in the survey. Of those ( $n = 16$ ) who stated that they use compost at their farm, we were unable to survey two. We surveyed only farmers growing annual fruits and vegetables to enable comparison with our field study, though some respondents grew both annual and perennial crops. To conduct surveys we submitted an application for, and were granted, exemption from human subjects protocol review through the Human Subjects Committee at the UCSB Office of Research. The first author administered all surveys, either via telephone or at farmers' markets, and coded all responses. Respondents ( $n = 14$ ) were asked 15 questions, including information about soil types and crops at the farms, rate of compost applied, factors contributing to variations in application rate, compost composition and source(s), reasons for application, and additional OAs used. When a range of compost application rates was given, the average was used for analysis. Average compost bulk density of 950 lb/yd<sup>3</sup> (0.564 g/cm<sup>3</sup>) was used to convert any compost application rates given on volumetric basis to mass basis (US Composting Council, 2001). Manually transcribed

survey data were entered into Excel (Microsoft Corporation, Redmond, WA), within which all statistical analyses for survey data were performed.

### **3. Results**

#### 3.1 Soil and plant data

##### 3.1.1 Soil moisture and temperature

Gravimetric soil moisture ranged from 7.0 to 16.4%, reaching its lowest values following weeks without irrigation, immediately prior to fertilization (43 DAC) (Figs. 1a, b). Prior to fertilization, furrow soil moisture was significantly higher in the low compost treatment (LC) than in the high compost treatment (HC) ( $p = 0.029$ ), and bed soil moisture was significantly higher in LC than in HC ( $p = 0.026$ ). However after fertilization, soil moisture was significantly higher in HC than in LC in both positions ( $p < 0.0001$ , both positions).

During the growing season for this crop of carrots (July to October), soil temperatures tended to decrease overall (Figs. 1c, d), ranging from 17.1 to 27.4 °C. There was no significant difference in soil temperature between LC and HC within either position for the entire season ( $p = 0.994$ , bed;  $p = 0.990$ , furrow), before fertilization, or after fertilization (Figs. 1c, d).

##### 3.1.2 Soil $\text{NH}_4^+$ and $\text{NO}_3^-$

Soil  $\text{NH}_4^+$  concentrations in the beds remained low until fertilization and increased steadily for two weeks following fertilization (Fig. 1e). After fertilization, bed  $\text{NH}_4^+$  concentration was significantly higher in LC than HC for 56-70 DAC, but this difference is



not statistically significant for the entire post-fertilization period ( $p = 0.167$ ).  $\text{NH}_4^+$  concentrations in the beds returned to baseline by 81 DAC. High variation in  $\text{NH}_4^+$  concentrations in the furrows at 49 DAC suggests inconsistent spillage or leaching of fertilizer from the beds (Fig. 1f), and there was no significant difference in furrow soil  $\text{NH}_4^+$  between treatments after fertilization ( $p = 0.841$ ). There was also no significant difference in soil  $\text{NH}_4^+$  between LC and HC in either position for the entire season ( $p = 0.062$ , bed;  $p = 0.954$ , furrow) or prior to fertilization ( $p = 0.087$ , bed;  $p = 0.540$ , furrow).

Similar to  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  concentrations in beds increased significantly after fertilization (Fig. 2g). Higher  $\text{NO}_3^-$  concentrations in the beds were observed as  $\text{NH}_4^+$  concentrations decreased (56-95 DAC). After fertilization, bed soil  $\text{NO}_3^-$  was higher in LC than HC (Fig. 1g), but this difference was not statistically significant ( $p = 0.077$ ), and there was no difference in furrows ( $p = 0.097$ ). Prior to fertilization, soil  $\text{NO}_3^-$  was significantly higher in HC than LC in furrows ( $p = 0.007$ ), but not statistically different in the beds ( $p = 0.843$ ).

### 3.1.3 Total C and N

Soil C was not significantly different between treatments within either position at the beginning (5 DAC), middle (49 DAC, after fertilization), or end (95 DAC, after first harvest) of the growing season (data not shown). From the middle to end of season, however, soil C concentrations increased from 1.08 to 1.22% ( $p = 0.096$ , one-way ANOVA) in LC bed, and from 1.07 to 1.30% in HC bed ( $p = 0.184$ ). Soil C increased in LC furrow from 0.959 to 1.14% ( $p = 0.07$ ) and in HC furrow from 0.888 to 1.12% ( $p = 0.10$ ) from the beginning to end of the season. None of these increases were significant. Interestingly, HC furrow C increased significantly from the beginning to middle of the season ( $p = 0.040$ ). All other differences between dates were not statistically significant.

Similarly, soil N at each measurement date was not significantly different between treatments, but changed within certain positions over time. For example, from the middle to end of the season, bed total N increased from 0.11 to 0.14% in LC ( $p = 0.023$ ) and from 0.10 to 0.13% in HC ( $p = 0.097$ ).

#### 3.1.4 Soil organic matter, bulk density, and pH

Soil organic matter (SOM) was slightly higher in LC than HC plots prior to compost application ( $p = 0.035$ ). However, 5 DAC, SOM was not significantly different between treatments ( $p = 0.648$ ) (Table 2). Differences in bulk density by compost treatment were varying and sometimes contrary to expectations. On day 9 (9 DAC), bed bulk density was significantly higher in HC than LC ( $1.33 \pm 0.04$  and  $1.25 \pm 0.05$  units, respectively) ( $p = 0.011$ ), and furrow bulk density was significantly higher in LC than HC ( $1.47 \pm 0.08$  and  $1.33 \pm 0.08$  g cm<sup>-3</sup>, respectively) ( $p = 0.009$ ). At the end of the season (96 DAC), bed bulk density was still higher in HC than LC, but the difference was no longer significant ( $1.19 \pm 0.08$  and  $1.11 \pm 0.02$  g cm<sup>-3</sup>, respectively) ( $p = 0.149$ ). Furrow bulk density was higher in HC than LC ( $1.36 \pm 0.03$  and  $1.25 \pm 0.04$  units, respectively) ( $p = 0.019$ ). Bulk density decreased significantly in all treatments and positions except HC furrow from the beginning to end of season. On both measurement dates, bulk density was significantly higher in furrows than beds ( $p = 0.004$ , 9 DAC;  $p = 0.003$ , 96 DAC). Soil pH was significantly higher in HC than LC in beds ( $7.89 \pm 0.11$  and  $7.67 \pm 0.21$ , respectively) ( $p = 0.038$ ), but not furrows ( $8.10 \pm 0.18$  and  $8.08 \pm 0.04$ , respectively) ( $p = 0.790$ ).

### 3.1.5 Crop harvest and tissue C and N

Carrot yield was 30.3% higher in HC than LC, with averages of 2.82 and 2.17 Mg (dry wt.) ha<sup>-1</sup>, respectively (p = 0.050). Wet weight yield of 33.3 and 22.6 Mg ha<sup>-1</sup> in HC and LC is similar to fresh market carrot yield in California (Nuñez, 2008). The schedule of farm management prevented extensive temporal replication of the yield measurement (measured on two of six harvest dates) (Table 3).

Carrot above- and below-ground biomass N ranged from 1.63 to 3.21%, and C ranged from 35.64 to 41.25%. There was no significant difference in plant C and N between LC and HC for either aboveground (p = 0.922, carbon; p = 0.838, nitrogen) or belowground biomass (p = 0.383, carbon; p = 0.850, nitrogen).

## 3.2 Gaseous emissions

### 3.2.1 N<sub>2</sub>O emissions

Hourly N<sub>2</sub>O flux ranged from 0.453 to 10.3 µg N m<sup>-2</sup> h<sup>-1</sup> in furrow LC, 0.772 to 46.1 µg N m<sup>-2</sup> h<sup>-1</sup> in furrow HC, -0.248 to 222 µg N m<sup>-2</sup> h<sup>-1</sup> in bed LC, and 0.709 to 284 µg N m<sup>-2</sup> h<sup>-1</sup> in bed HC (Fig. 2a). Rank of cumulative seasonal N<sub>2</sub>O emissions from low to high was furrow LC, furrow HC, bed LC, and bed HC (Fig. 2b). Seasonal N<sub>2</sub>O flux determined by repeated measures ANOVA was significantly higher in HC than LC in beds, but not statistically different in furrows (p = < 0.001, beds; p = 0.135, furrows) (Fig. 2b). Post-fertilization N<sub>2</sub>O fluxes were significantly higher in HC than LC in beds, but not in furrows (p = 0.039, bed; p = 0.192, furrow). Post-fertilization cumulative N<sub>2</sub>O emissions were significantly higher in both treatments and positions than pre-fertilization emissions (p < 0.0001, bed HC and bed LC; p = 0.008, furrow HC; p = 0.0118, furrow LC) (Fig. 3). There

was no significant difference in N<sub>2</sub>O emissions factors (EFs) or yield-scaled N<sub>2</sub>O emissions between treatments (Table 3).

### 3.2.2 CO<sub>2</sub> emissions

Hourly CO<sub>2</sub> flux ranged from 50.8 to 405 mg C m<sup>-2</sup> h<sup>-1</sup> in furrow LC, 84.6 to 460 mg C m<sup>-2</sup> h<sup>-1</sup> in furrow HC, 89.8 to 801 mg C m<sup>-2</sup> h<sup>-1</sup> in bed LC, and 77.0 to 858 mg C m<sup>-2</sup> h<sup>-1</sup> in bed HC (Fig. 4a). Rank of cumulative seasonal CO<sub>2</sub> emission from low to high was the same as for N<sub>2</sub>O (Fig. 4b). Seasonal CO<sub>2</sub> emission determined by repeated measures ANOVA was significantly higher in HC than LC in both positions ( $p = 0.035$ , beds;  $p = 0.043$ , furrows) (Fig. 4b). Similar to N<sub>2</sub>O, bed CO<sub>2</sub> emissions were significantly increased by mid-season fertilization. Post-fertilization, CO<sub>2</sub> fluxes were significantly higher in HC than LC in beds, but not significantly different in furrows ( $p = 0.042$ , beds;  $p = 0.985$ , furrows). Unlike N<sub>2</sub>O, cumulative CO<sub>2</sub> emissions in furrows were higher in the first half of the season in both treatments ( $p = 0.0004$ , furrow HC;  $p=0.09$ , furrow LC), but bed CO<sub>2</sub> emissions were similarly much higher after fertilization ( $p = 0.009$ , HC;  $p=0.070$ , LC) (Fig. 5). EFs and yield-scaled CO<sub>2</sub> emissions were calculated to compare treatments, and both were significantly higher in LC than HC (Table 3). EFs above 100% suggest that more C was decomposed (respired as CO<sub>2</sub>) than was added as compost in both treatments.

### 3.2.3 CH<sub>4</sub> emissions

There was high variability in CH<sub>4</sub> measurement due to difficulty in detecting such small and variable fluxes, and therefore data should be interpreted with caution (Fig. 6a). In all treatments and positions, the overall pattern in CH<sub>4</sub> was net oxidation rather than efflux (Fig. 6b). Standard errors for cumulative seasonal CH<sub>4</sub> fluxes were very high in all treatments and

positions (69-1124% of the mean). Hourly CH<sub>4</sub> flux ranged from -96.9 to 28.4 μg C m<sup>-2</sup> h<sup>-1</sup> in furrow HC, -42.3 to 119 μg C m<sup>-2</sup> h<sup>-1</sup> in bed HC, -69.6 to 47.8 μg C m<sup>-2</sup> h<sup>-1</sup> in bed LC, and -68.9 to 114 μg C m<sup>-2</sup> h<sup>-1</sup> in furrow LC. Seasonal CH<sub>4</sub> flux determined by repeated measures ANOVA was significantly lower (more negative) in HC than LC in furrows, but not statistically different in beds ( $p = 0.027$ , furrow;  $p = 0.901$ , bed) (Fig. 6b). Post-fertilizer CH<sub>4</sub> flux was not significantly different between treatments in either position ( $p = 0.070$ , furrow;  $p = 0.873$ , bed). Post-fertilizer emissions were significantly higher than pre-fertilizer emissions in Furrow LC ( $p = 0.003$ ), but were not statistically different in bed HC, bed LC, or furrow HC ( $p = 0.332$ ,  $p = 0.850$ , and  $p = 0.246$ , respectively). EFs and yield-scaled CH<sub>4</sub> emissions were not significantly different between treatments (Table 3).

#### 3.2.4 GWP and yield-scaled GWP

Contribution of N<sub>2</sub>O to total GWP was much greater than CH<sub>4</sub> in both treatments and positions (>99%); contribution of CH<sub>4</sub> to GWP was negative. Accordingly, rank of GWP from low to high was the same as for N<sub>2</sub>O emissions: furrow LC, furrow HC, bed LC, and bed HC. Yield-scaled GWP was not statistically different between treatments (Table 3).

#### 3.3 Compost survey

Compost application rates and OA management varied widely amongst farmers surveyed ( $n = 14$ ). Farm size ranged from 0.5 to 80 acres with a mean size of 29.17 ( $\pm 26.98$ ) acres and a median size of 26.5 acres. Self-reported soil texture ranged from “quite sandy” to “very clayey.” Over half (57%, 8 of 14) of farmers applied compost on a per crop basis, while the rest applied compost on a semi-regular or annual basis. Average compost application rate by crop was 12.25 ( $\pm 6.54$ ) Mg ha<sup>-1</sup> ( $n = 8$ ). The average application rate

including farmers who apply semi-regularly (100% of respondents) calculated using an average crop intensity of 3 crops/year was  $8.96 (\pm 6.84) \text{ Mg ha}^{-1}$ . However, 93% of farmers (13 of 14) said their application rate varies depending on factors such as crop type (57%, 8 of 14) and soil type (14%, 2 of 14). Application rate was usually chosen through “personal experience or trial-and-error” (53.9%, 7 of 13), while “recommendations from other farmers” and “use of soil testing” were the next most cited decision methods (15.4% each, 2 of 13). Of surveyed farmers, 23.1% (3 of 13) stated that cost was a limiting factor in compost application rate, and some farmers suggested limitation by other factors, such as machinery (15.4% each, 2 of 13). Primary reasons for compost application included soil fertility or benefits from OM (38.5%, 5 of 13), other physical benefits including water holding-capacity, drought-tolerance, and soil tilth (30.8%, 4 of 13), nitrogen and other nutrients (15.4%, 2 of 13), and additions of beneficial microbial communities (15.4%, 2 of 13) (Table 4).

In our aim to provide context for compost application rates and practices in the region, we found that farmers had various sources for their compost, and most used additional OAs. Six of the 14 surveyed farmers (42.9%) primarily made compost on-site, and the same number (42.9%) primarily obtained compost from local sources, while two (14.3%) primarily obtained compost from non-local sources (i.e. > 50 miles away). In total 64.2% (9 of 14) obtained at least a portion of their compost from off-site. Half of surveyed farmers added amendments to their compost before application. Of those, the most often cited compost amendment was gypsum (57%, 8 of 14). The majority of farmers who apply compost use other OAs as well (85.7%, 12 of 14). In total, 18 distinct OAs were used in addition to compost at all of the farms, the most cited of which were an organic fertilizer

called Biotic Organic 4-4-4 AZOMITE® (Perfect Blend LLC, Bellevue, WA) (23.1%, 3 of 13), feather meal (23.1%, 3 of 13), gypsum (23.1%, 3 of 13), fish byproducts or fish emulsion, kelp extract or seaweed, blood meal, horse manure, boron, and chicken manure (15.1%, 2 of 13, used each OA) (Table 4).

#### 4. Discussion

##### 4.1 Soil and plant data

##### 4.1.1 Soil $\text{NH}_4^+$ , $\text{NO}_3^-$ , and total N

In agreement with our first hypothesis, soil  $\text{NH}_4^+$  and  $\text{NO}_3^-$  were useful in explaining treatment differences in  $\text{CO}_2$  and  $\text{N}_2\text{O}$  flux; however, they did not appear to determine  $\text{CH}_4$  flux. Despite equal fertilization rate in both treatments, soil inorganic and total N were higher in LC than HC after fertilization in beds (Figs. 1e, g). Nitrification and denitrification rates were likely higher in HC than LC, presumably due to the effects of higher compost application on availability and metabolism of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  (Bengtsson et al., 2003; Flavel and Murphy, 2006). Furthermore, the likely presence of more available C in HC (from compost and crops) may have facilitated higher rates of denitrification. Low soil moisture levels limit denitrification by facilitating microbial oxidation and limit nitrification by reducing the diffusional supply of  $\text{NH}_4^+$  due to thin soil water films (Firestone and Davidson, 1989). Thus, higher moisture in bed HC at the end of the growing season may also explain greater N metabolism.

#### 4.1.2 Other soil properties and crop yield

In disagreement with our first hypothesis, soil moisture did not directly predict GHG emissions between compost application rates, but plant growth likely contributed to treatment differences in soil moisture at the end of the growing season. Soil fertility increases with compost application (Garcia-Gil et al., 2000) and root contributions to OM may partially account for higher end-of-season soil moisture in bed HC (Gregorich et al., 1996; Singh and Gupta, 1977). Indeed, crop yield, which is predominantly belowground biomass for carrots, is higher in HC (Table 3). At the beginning of the season, higher native SOM content in LC may have led to greater formation of water-stable aggregates in LC than in HC (Oades, 1984), leading to higher soil moisture, and partially minimizing the effects of compost application rate on soil moisture. Occasional differences in irrigation timing make it impossible to completely separate the effects of field conditions or management practices from the effects of OA addition on soil water-holding capacity. However, end-of-season soil moisture was significantly higher in bed HC than LC ( $p < 0.0001$ ) despite bed HC occasionally being watered further in time from soil sampling dates, suggesting that OM content was likely an important contributor to observed moisture differences. Prolonged effects of OAs on soil moisture are positively associated with application rate (Weber et al., 2007), which may also explain higher soil moisture in HC than LC at the end of the season.

Higher cumulative CO<sub>2</sub> and N<sub>2</sub>O emissions in HC despite insignificant differences in total soil C indicate that C quality (chemical or physical availability of C) was likely relatively more important than quantity in providing substrate and energy for decomposition and denitrification. Our study could have been improved by separating labile and recalcitrant SOM fractions, which provides a more sensitive indicator for the effects of management on



SOM dynamics (McLauchlan and Hobbie, 2004; Ren et al., 2014), since changes in SOM in response to agricultural management are difficult to detect in the short term (Blair et al., 1995; Ren et al., 2014; Six et al., 2002). Higher compost application rate led to higher pH in the beds of HC than LC ( $p = 0.038$ ), which may have improved conditions for nitrification (Goodroad and Keeney, 1984) and may have increased substrate available for denitrification.

#### 4.1.3 Nutrient requirements of carrots

There have been a number of studies demonstrating that carrots require little added N to maximize yield (Gutezeit, 1999; Sanderson and Ivany, 1997; Westerveld et al., 2006; Westerveld et al., 2006, but see Chen et al., 2004), that mineral fertilizer provides little benefit after high rates of OA have been applied (Haworth et al., 1966), and that late-season fertilization does not increase crop yield in carrots (Smoleń and Sady, 2009; Westerveld et al., 2006). These observations call into question the efficacy of the midseason fertilizer application that occurred during our study. However, the specific contexts of these studies must be considered when comparing them with ours. In our study, high  $N_2O$  loss following fertilization suggests opportunities for improving plant N-use efficiency. Mid-season organic fertilization also provided phosphorus (P) and potassium (K), which are elements that have been observed to limit carrot yield (Dechassa et al., 2003; Haworth et al., 1966; Orphanos and Krentos, 1988). The implication is that applying more P, K, or other limiting nutrients, and relatively less N, can provide significant yield benefits for carrot growth, though we did not explicitly measure this. Farmers often cited a belief that OA applications today will improve soils over the long term, which may be used to justify high organic fertilizer application rates. While this may be accurate for some properties of the soil, it is

clear that N losses are higher than necessary in many systems and that N losses could be more economically and environmentally efficient with improved rates, and likely timing, of application.

## 4.2 Gaseous emissions

### 4.2.1 N<sub>2</sub>O emissions

N<sub>2</sub>O emissions were not significantly higher in bed HC than LC *until after mid-season application of organic fertilizer* (OF [NPK ratio 8:5:1]) (Figs. 2b, 3), which is in disagreement with our second hypothesis predicting higher GHG emissions with higher compost application, but consistent with our third. OF likely provided substrate for denitrification and nitrification (Firestone and Davidson, 1989; Okano et al., 2004) and provided additional nutrients typically limiting to microbial growth and respiration (Amador and Jones, 1993). Higher N<sub>2</sub>O emission in HC was likely driven by denitrification in response to labile C availability, derived from higher plant growth (Table 3) and higher compost application (18.2 vs. 9.1 Mg ha<sup>-1</sup>) (Gregorich et al., 1996; Weier et al., 1993). Although there were no significant differences in measured total soil C at the end of the season, higher chemically available C from higher compost addition and higher plant growth in HC was likely important in stimulating microbial activity. Because addition of OM promotes macroaggregation within the soil, there may have been more moist or nutrient-rich microsites (Fig. 1) in HC than LC (Andruschkewitsch et al., 2013; Loecke and Robertson, 2009; Oades, 1984). Soil temperature is typically an important control on N<sub>2</sub>O emissions due to its influence on SOC mineralization and inorganic N availability (Davidson et al., 1998), but temperature did not differ significantly between treatments (Figs. 1c, d).

Cumulative N<sub>2</sub>O emissions were similar to other studies when combining emissions from both positions to scale to the entire field (Alluvione et al., 2010; Ding et al., 2013; Kontopoulou et al., 2015; Suddick and Six, 2013). For example, within a vegetable crop rotation in Davis, CA, Suddick and Six (2013) measured emissions ranging from 0.91 to 1.12 kg N<sub>2</sub>O-N ha<sup>-1</sup> y<sup>-1</sup> after application of 10 t ha<sup>-1</sup> of compost, biochar, or a combination. Those emissions are less than half of the N<sub>2</sub>O emissions in the beds of both LC and HC in this study, but similar to combined bed (46%) and furrow (54%) emissions of 1.25 and 1.80 kg N<sub>2</sub>O-N ha<sup>-1</sup> y<sup>-1</sup> in LC and HC, respectively (Table 4). Additionally, Ding et al. (2013) observed a three-fold increase in N<sub>2</sub>O emissions after compost application, resulting in a value similar to the range found within Suddick and Six (2013) (1.18 kg N<sub>2</sub>O-N ha<sup>-1</sup> y<sup>-1</sup> in Ding et al. 2013), for a wheat-rice rotation after compost application at a rate of 150 kg N ha<sup>-1</sup>. N<sub>2</sub>O emissions are likely underestimated because of our inability to measure fluxes until a few days after management events (irrigation).

#### 4.2.2 Yield-scaled N<sub>2</sub>O emissions and N<sub>2</sub>O emission factors

Linking GHG emissions to yield enables determination of N application rates that address atmospheric trace gas concentrations, consider global food demand, and optimize economic profit (Mosier et al., 2006; Van Groenigen et al., 2010). In disagreement with our second hypothesis, we found that yield-scaled N<sub>2</sub>O emissions were not significantly different between treatments, which suggests that crop nutrient-use efficiency (NUE) did not change with increasing compost application rate (Table 3). Thus, under similar conditions farmers may be able to increase the rate of pre-plant compost application to a certain point for carrots and similar crops (e.g. potatoes, celery), and maintain similar yield-scaled emissions.

N<sub>2</sub>O emission factors (EFs) were not statistically different between treatments and were smaller than those reported in other studies measuring N<sub>2</sub>O emissions from OA application (e.g. Angst et al., 2014; Velthof and Mosquera, 2011). Differences in cumulative N<sub>2</sub>O emissions and EFs may be due to lower N application rate or due to underestimation of N<sub>2</sub>O fluxes in our study (Velthof and Mosquera, 2011). We agree with authors who have stated that the default IPCC emission factor of 1% for N<sub>2</sub>O emissions is high when considering compost (e.g. Alluvione et al., 2010), and should be modified for use in GHG prediction. Better quantification of N<sub>2</sub>O EFs of different types of OAs, along with a method of quantifying EF that considers the form(s) of N applied and other biologically relevant management practices at the site, would improve large-scale estimates of N<sub>2</sub>O emissions.

#### 4.2.3 CH<sub>4</sub> emissions

CH<sub>4</sub> emissions contributed very minimally to GWP in our study (<0.01%) (Table 3). In contradiction to our second hypothesis, statistically significant net soil uptake of CH<sub>4</sub> (i.e. means are below *and* statistically different from zero) was measured in HC and not in LC (both positions) (Fig. 6b). However, increased CH<sub>4</sub> oxidation that is positively correlated with OA application (Hütsch, 1998) and higher OA application rates is consistent with other studies (e.g. Angst et al., 2014). This pattern has been attributed to increased aeration within the soil (Ball et al., 1997). While significant differences in bulk density between treatments were not measured, it is possible that this was due to our sampling method (i.e. at the soil surface as opposed to deeper in the soil profile). As NH<sub>4</sub><sup>+</sup> and NO<sub>2</sub><sup>-</sup> (nitrite) have been observed to inhibit CH<sub>4</sub> oxidation (Dubey et al., 2002; Hütsch, 1998), higher inorganic N in LC may have limited CH<sub>4</sub> oxidation (Figs. 1e-h). It is also possible that compost inoculated the soil with methanotrophic bacteria (Bender and Conrad, 1995; Hütsch, 1998), an effect

that was higher with higher compost application rate. In contradiction to our third hypothesis, CH<sub>4</sub> flux was unaffected by fertilization (Fig. 6b), meaning NH<sub>4</sub><sup>+</sup> addition did not inhibit CH<sub>4</sub> consumption. Soil moisture measurements do not explain treatment differences in CH<sub>4</sub> oxidation, which may be due to relatively low moisture overall within the system (Fig. 2).

#### 4.2.4 CO<sub>2</sub> emissions

For certain periods during the growing season, CO<sub>2</sub> emissions showed a response that was in agreement with our second hypothesis, but the patterns were not consistent. Cumulative CO<sub>2</sub> emission is higher in HC than LC prior to fertilization (43 DAC), but only in the furrows. However, consistent with our third hypothesis, fertilization in the beds led to increased CO<sub>2</sub> emissions that were higher in HC than LC, likely by accelerating OM turnover due to increased microbial activity or biomass, through the well established “priming effect” (González-Ubierna et al., 2015; Kuzyakov, 2010; Marinari et al., 2000; Wong et al., 1999). Higher cumulative seasonal CO<sub>2</sub> emission in HC in both positions suggests higher decomposition of OM, likely from both OAs and plant matter (Fig. 4).

In general, compost application increases aggregate stability, inorganic N and micronutrient concentrations, water retention, and soil microbial and enzymatic activity (Ferrerias et al., 2006; Morra et al., 2010; Mylavarapu and Zinati, 2009; Pagliai et al., 1981; Tisdall and Oades, 1982), all of which may have contributed to higher plant growth (Table 3), higher litterfall, and higher rhizodeposition in HC compared to LC. Additionally, OM is a strong sorbent of molecules and ions (Pignatello, 2012), which may have maintained a greater concentration of plant-available ions in the surface soil of HC. Large post-fertilization CO<sub>2</sub> pulses followed a nearly 2-week period without irrigation, suggesting that

irrigation may have contributed to SOC mineralization due to soil rewetting (Fierer and Schimel, 2002; Jabro et al., 2008) (Fig. 4b).

Short-term studies reporting CO<sub>2</sub> emissions in the context of yield or inputs can signal practices that may promote C stabilization (e.g. Lu et al., 2015), which may partially offset GHG emissions from field management and synthetic fertilizer production (Lal, 2004; Smith et al., 2008). In our study, the ratio of C added to C lost as CO<sub>2</sub>, as measured by CO<sub>2</sub> EFs and yield-scaled CO<sub>2</sub> emissions, decreased with compost application. This suggests that long-term soil C stabilization may increase with higher compost addition (Kong et al., 2005; Rasmussen et al., 1998; Tisdall and Oades, 1982). Indeed, the increase in total soil C was also higher in HC than LC, but this difference was not statistically significant and might have been more interpretable had we separated C into fractions based on degree of microbial accessibility. Application of finished compost increases the likelihood of C stabilization through occlusion within organo-mineral complexes and physical protection within the interior of aggregates (Verchot et al., 2011), partially because the compost has been “predigested” during decomposition in compost piles, and therefore contains OM that is less susceptible to immediate decomposition than some other OAs (Eshetu et al., 2013; Fabrizio et al., 2009; Pascual et al., 1999; Ryals et al., 2014). With any attempts to use OAs to increase soil C, however, it is especially important to consider how subsequent management practices (e.g. fertilization, irrigation, tillage, periods of fallow) (Ginting et al., 2003), climate, compost composition, soil type, and crop type may affect measured changes in soil C. In both treatments, CO<sub>2</sub> EFs were higher than 100%, which supports the idea that OF addition may have primed decomposition of native organic matter, but these values may also reflect decomposition of plant residues.

### 4.3 Compost survey

A clear opportunity for increased compost use is amongst farmers for whom cost is prohibitive to higher application rates (Table 4), which could occur through monetary incentives for compost use, provision or subsidization of compost, or technical assistance, by government agencies and policies. In California, two bills proposed in 2015 would provide such assistance to farmers. Administrative agencies and local governments may aid in this effort by publicizing and streamlining these opportunities to farmers, particularly those who are in greater need of financial assistance, and by making the data from monitoring efforts readily accessible to scientists. Additionally, however, it could be useful to provide training to ensure that farmers do not inadvertently increase GHG emissions through misguided practices.

As we expected, the level of compost application in the high compost treatment (HC) in our field study was higher than the average compost application rate in our target area ( $12.25 \text{ Mg ha}^{-1}$ ), likely due in part to the relatively large size of the farm where we conducted our field study which facilitated on-site compost production. Another clear result of our survey was the large diversity in OA application rates and types, which may be partially attributed to the large variety of crops cultivable in the warm microclimate characterizing this Tri-County area. Many farmers applied compost on a semi-regular basis to the soil instead of to specific crops (42.9%), which highlights the role of compost as a soil amendment, as opposed to a fertilizer. Indeed, the most frequently cited reason for compost application was physical benefit to the soil (Table 4), and most farmers applied OAs that provided macronutrients such as N and P *in addition to* the compost (Table 4). Farmers applying compost for soil physical improvement may want to consider effects of OA

application that potentially reduce soil fertility, including increased decomposition of native SOM. That said, farmers tend to have a practical understanding of the effects of their practices on crop yield and sustainability (Soleri and Cleveland, 2005), which is perhaps supported by observation at our field site of higher yields with the farm's typical rate of compost application of 18.1 Mg ha<sup>-1</sup> (HC).

## **5. Conclusion**

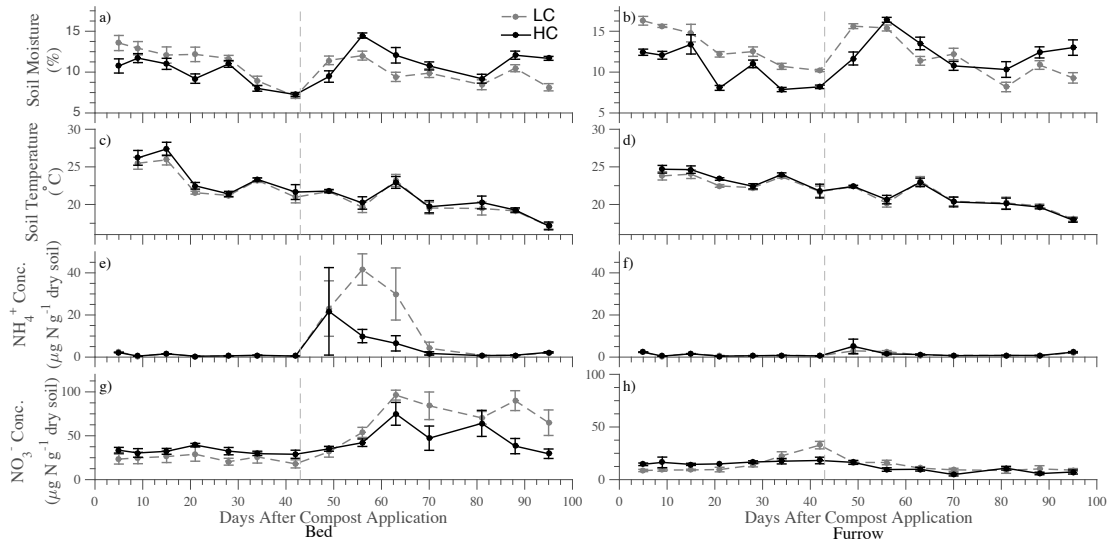
In order to implement effective GHG mitigation policies for agricultural soils, it is important to quantify how OA application rate affects both GHG emissions and crop growth. In our field study, we measured how compost application rate and how the interaction of two OAs affect GHG emissions from a carrot crop. Mid-season fertilization led to differences in GHG emissions between treatments, due to an interaction between compost treatments and organic fertilizer. N<sub>2</sub>O was the dominant contributor to GWP (N<sub>2</sub>O + CH<sub>4</sub>) in both treatments, and CH<sub>4</sub> contribution to GWP was negligible. Crop yield increased with compost application rate, but yield-scaled emissions were not significantly different between treatments. Due to relatively low N requirement of carrot crops in general, greater addition of compost relative to fertilizer could maintain or possibly increase crop growth and soil C while decreasing yield-scaled GWP.

Future studies should separate soil C into fractions based on availability for decomposition and could employ isotopic C labeling to measure net loss of native soil C. Replicating this study with different OAs and crop types would enable generalization to other agricultural systems. Specifically measuring microbiological parameters may improve interpretation of emissions (e.g. activity of nitrifying vs. denitrifying communities). Our survey results indicate that farmers understand the benefits of high rates of compost on soil

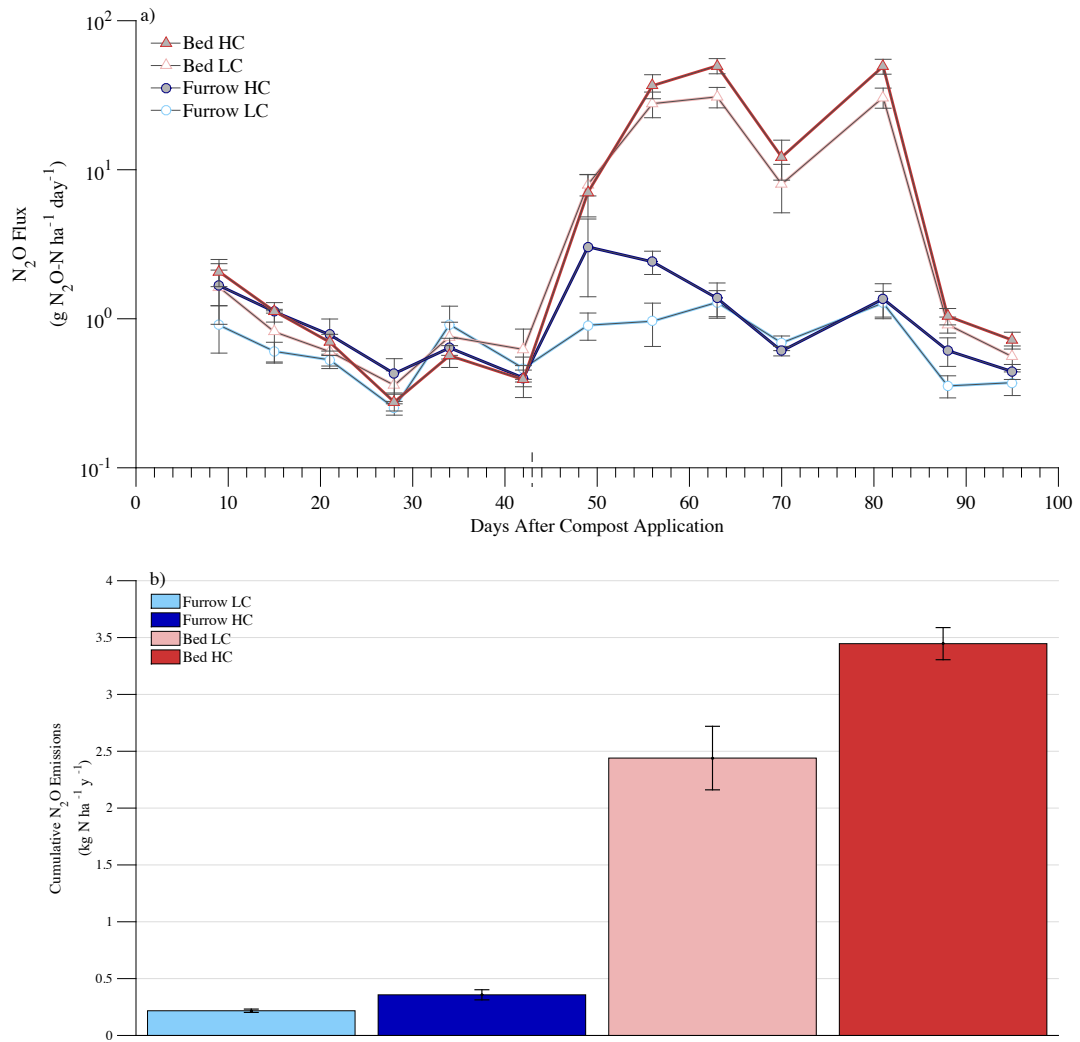


fertility and that there are opportunities to increase compost application at farms limited by cost and machinery, such as through incentive-based government programs. Our results demonstrate that application of compost at half the standard rate on one farm had an insignificant effect on GHG emissions until later management practices exaggerated the differences, which gives farm managers and government agencies a better understanding of some of the factors influencing GHG emission when using OAs. Together, our survey results and GHG estimates could contribute to development of policy recommendations that consider constraints faced by actual farmers and the resultant effects on climate change mitigation.

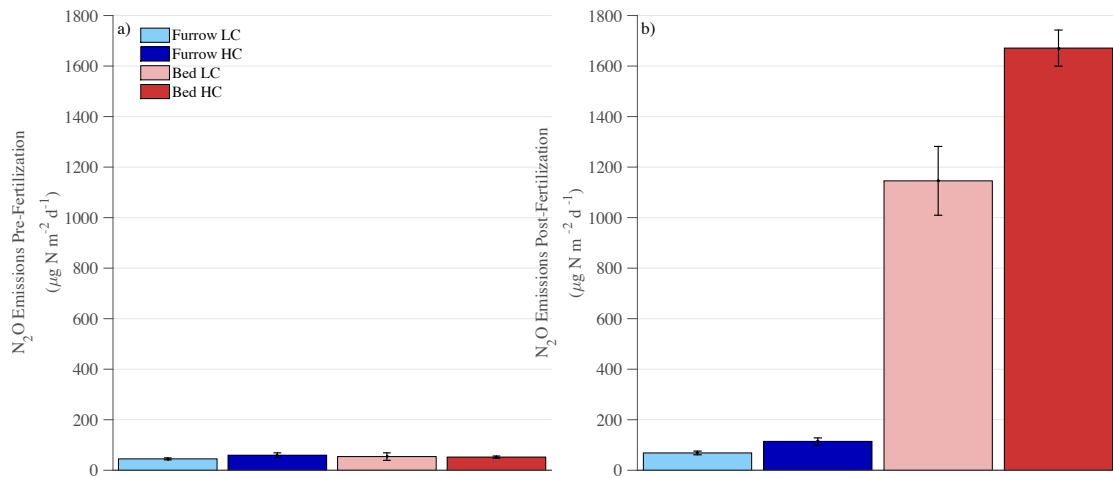
## 6. Figures



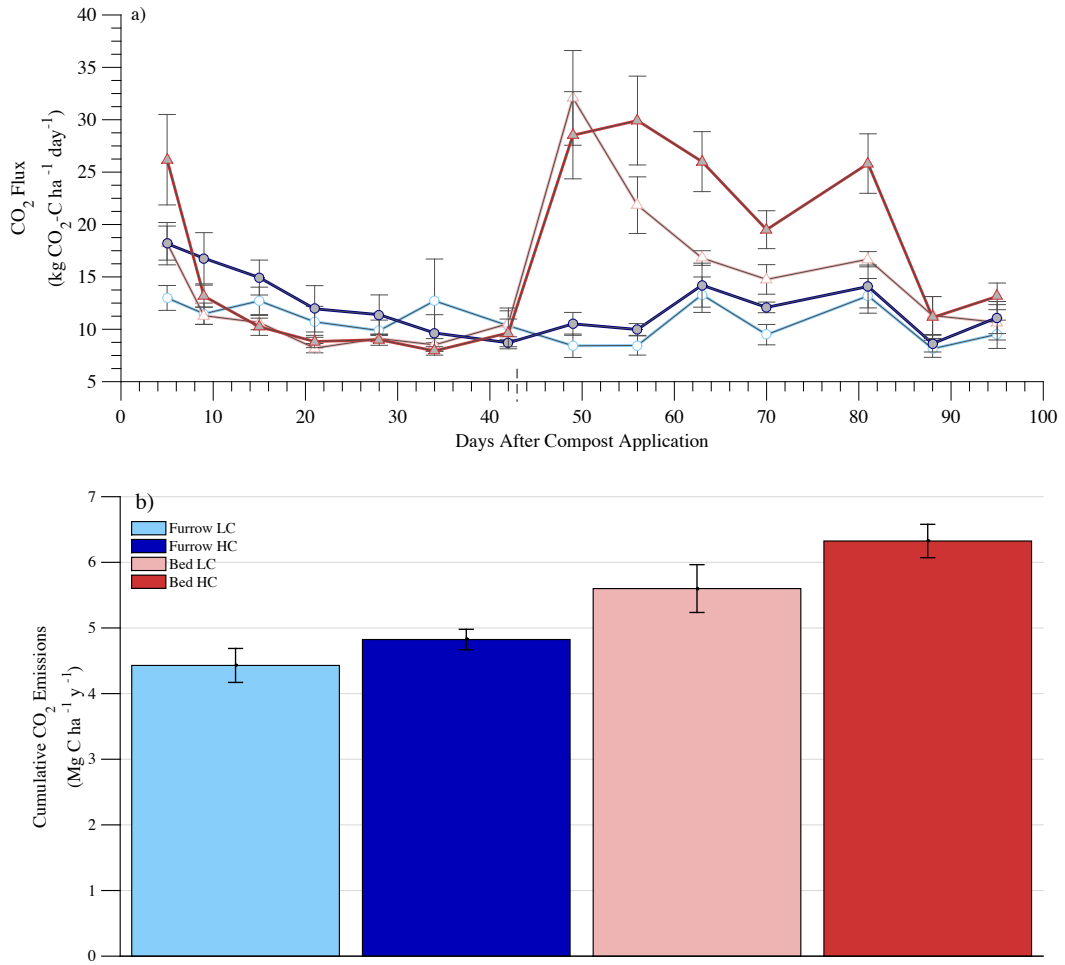
**Figure 1.** Gravimetric soil moisture, temperature, NH<sub>4</sub><sup>+</sup>-N, and NO<sub>3</sub><sup>-</sup>-N concentrations for LC and HC treatments, measured in beds and furrows, means and standard errors ( $n = 6$ ). Compost application rates were 9.1 and 18.2 Mg ha<sup>-1</sup> in LC and HC. Both treatments received organic fertilizer (OF) at a rate of 672 kg ha<sup>-1</sup> 43 DAC (dashed vertical line).



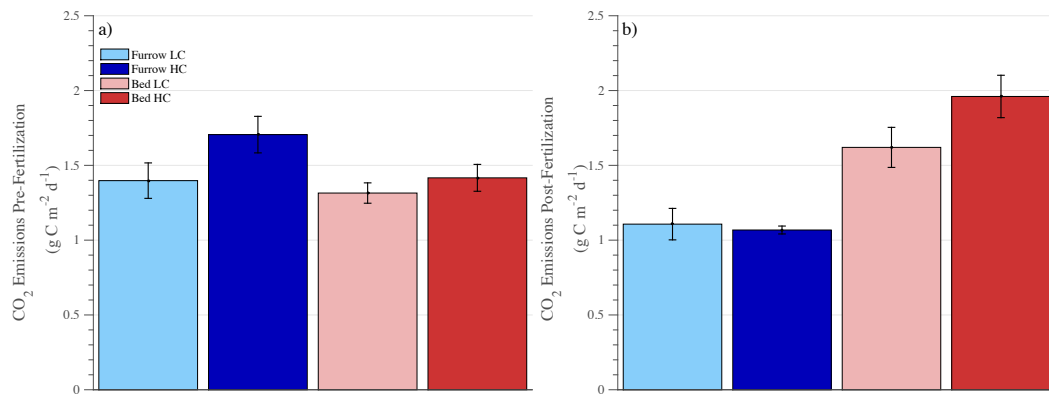
**Figure 2.** a) Seasonal  $N_2O$  flux, in beds and furrows, and b) cumulative (average) seasonal  $N_2O$  emission extrapolated to one year, means and standard errors ( $n = 6$ ). Y-axis in  $N_2O$  scatterplot is log-scaled. Compost application rates were 9.1 and 18.2  $Mg$   $ha^{-1}$  in LC and HC. Both treatments received organic fertilizer (OF) at a rate of 672  $kg$   $ha^{-1}$  43 DAC (dashed vertical line in 2a).



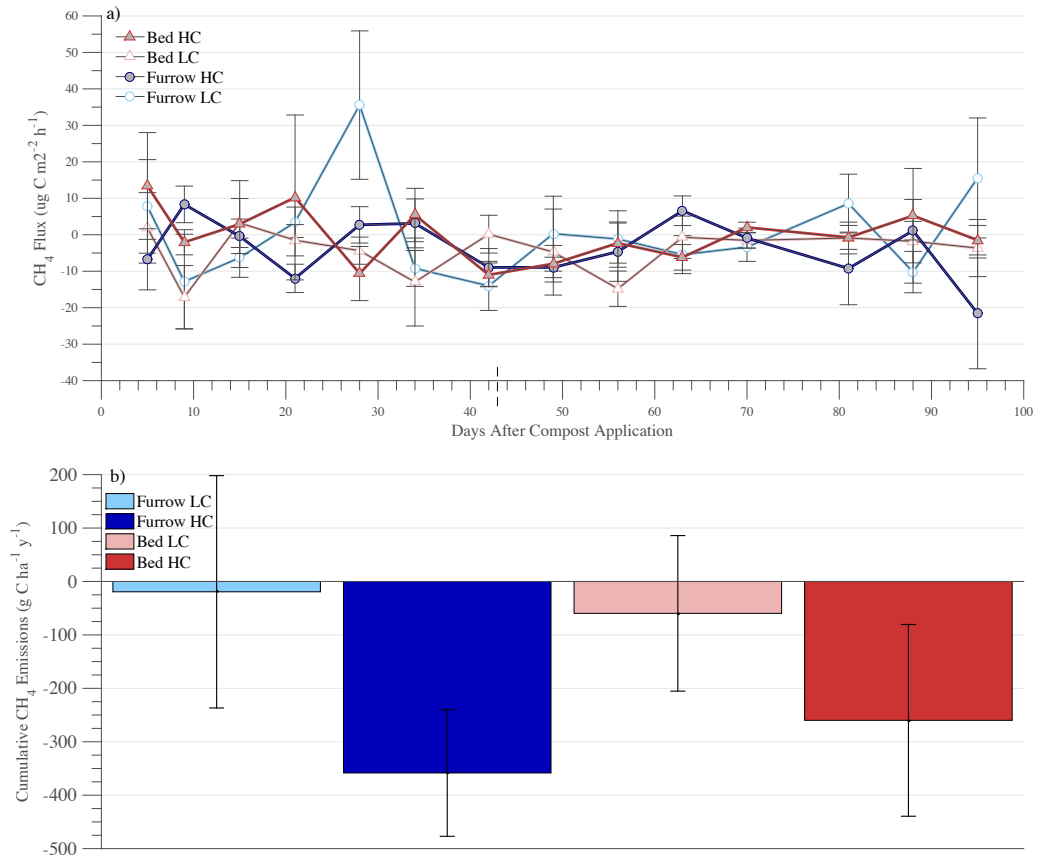
**Figure 3.** Average N<sub>2</sub>O emission pre- and post-fertilization, means and standard errors ( $n = 6$ ). Pre-fertilization emissions were standardized by 33 days and post-fertilization period were standardized by 46 days.



**Figure 4.** a) Seasonal CO<sub>2</sub> flux, and b) cumulative (average) seasonal CO<sub>2</sub> emissions in beds and furrows extrapolated to one year, means and standard errors ( $n = 6$ ). Compost application rates were 9.1 and 18.2 Mg ha<sup>-1</sup> in LC and HC. Both treatments received organic fertilizer (OF) at a rate of 672 kg ha<sup>-1</sup> 43 DAC (dashed vertical line in 4a).



**Figure 5.** Average CO<sub>2</sub> emission pre- and post-fertilization, means and standard errors ( $n = 6$ ). Pre-fertilization emissions were standardized by 37 days and post-fertilization period were standardized by 46 days.



**Figure 6.** a) Seasonal CH<sub>4</sub> flux and b) cumulative (average) seasonal CH<sub>4</sub> emissions in beds and furrows extrapolated to one year, means and standard errors ( $n = 6$ ). Compost application rates were 9.1 and 18.2  $\text{Mg ha}^{-1}$  in LC and HC. Both treatments received organic fertilizer (OF) at a rate of 672  $\text{kg ha}^{-1}$  43 DAC (dashed vertical line in 6a).

## 7. Tables

**Table 1**

Compost characterization data.

	Compost
pH	8
Bulk density (g cm <sup>3</sup> )	0.69(.02)
NO <sub>3</sub> <sup>-</sup> conc. (μg N g <sup>-1</sup> dry soil)	95.78 (1.89)
NH <sub>4</sub> <sup>+</sup> conc. (μg N g <sup>-1</sup> dry soil)	12.29(0.52)
Total N (%)	0.43 (0.02)
Total C (%)	5.92 (0.08)
C:N	13.74

Numbers in parentheses indicate standard error from three replicates for all but Total C and Total N which are from two replicates.

**Table 2**

Surface soil organic matter percentage before ( $n = 2$ ) and after ( $n = 6$ ) compost application, means and standard deviations. Soils were sampled to 25 cm before beds were shaped; after compost application, soils were sampled to 20 cm in beds and only to 10 cm in furrows due to compaction. Values determined by loss-on-ignition.

	Before Compost (%)	After Compost (%)	
		Bed	Furrow
High compost (HC)	1.94 (.01)	2.69 (0.24)	2.40 (0.27)
Low compost (LC)	2.42 (.13)	2.74 (0.22)	2.20 (0.57)



**Table 3**

Cumulative emissions, yield-scaled emissions, and emission factors (EFs) of N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>, yield, global warming potential (GWP), and yield-scaled GWP. Means and standard errors ( $n = 6$ ). GWP calculated using IPCC 5th Assessment Report Values for CO<sub>2</sub> equivalents of N<sub>2</sub>O and CH<sub>4</sub> of 298 and 28 based on a 100-year time horizon, but not including CO<sub>2</sub> due to its biogenic origin.

Cumulative emissions	N <sub>2</sub> O (kg ha <sup>-1</sup> y <sup>-1</sup> )	CO <sub>2</sub> (Mg ha <sup>-1</sup> y <sup>-1</sup> )	CH <sub>4</sub> (g-C ha <sup>-1</sup> y <sup>-1</sup> )	GWP (kg CO <sub>2</sub> eq ha <sup>-1</sup> )
LC Furrow	0.217 (0.015)	4.43 (0.26)	-20 (229)	57.0 (7.52)
HC Furrow	0.358 (0.045)	4.82 (0.16)	-378 (125)	84.2 (12.3)
LC Bed	2.44 (0.279)	5.60 (0.36)	-63 (154)	645 (74.2)
HC Bed	3.45 (0.141)	6.32 (0.25)	-274 (189)	906 (37.8)

Yield-scaled emissions	N <sub>2</sub> O (kg-N Mg <sup>-1</sup> )	CO <sub>2</sub> (Mg-C Mg <sup>-1</sup> )	CH <sub>4</sub> (g-C Mg <sup>-1</sup> )	Yield-scaled GWP (kg CO <sub>2</sub> eq ha <sup>-1</sup> )
LC Bed	1.1 (0.13)	2.581 (0.18)	-29.0 (70.8)	297 (35.1)
HC Bed	1.2 (0.10)	2.243 (0.19)	-97.3 (67.6)	321 (27.4)

Emission factors (EFs)	N <sub>2</sub> O (%)	CO <sub>2</sub> (%)	CH <sub>4</sub> (%)	Crop yield (Mg dry wt. ha <sup>-1</sup> )
LC Bed	0.691 (0.08)	268.274 (17.45)	-0.003 (0.01)	2.17 (0.06)
HC Bed	0.690 (0.03)	151.491 (6.08)	-0.007 (0.00)	2.82 (0.21)

**Table 4**Selected survey response data ( $n = 14$ ).

<i>Questions</i>	<i>Response (% of respondents)</i>		
<b>1. Reasons for variation in application rate?</b>	<i>Crop type</i> (57.1)	<i>Soil type</i> (14.3)	<i>Price, soil tests, other, OR none</i> (7.1)
<b>2. Cost limiting to application rate?</b>	<i>Yes</i> (23.1)	<i>No</i> (61.5)	<i>No; technology is a limiting factor</i> (15.4)
<b>3. Main compost source?</b>	<i>On farm</i> (42.9)	<i>Local supplier</i> (42.9)	<i>Distant supplier</i> (14.3)
<b>4. Which other organic amendments added to same fields?</b>	<i>Perfect Blend (4:4:4)<sup>TM</sup>, feather meal, OR gypsum</i> (23.1)	<i>Fish byproducts, kelp extract or seaweed, blood meal, horse manure, boron, OR chicken manure</i> (15.4)	<i>Wood ash, calcium, humic acid, crab shell, microbes, compost tea, bat guano, 10:10:25, bone meal, OR none</i> (7.7)

### III. Conclusions and Future Work

#### *A. Conclusions*

OA application rates within managed agricultural soils affect both GHG emissions and crop yields. Importantly, the effects of OA application on GHG emissions do not stand alone, but depend in part on interactions with other management practices. In our field study, we observed that two rates of compost application initially resulted in insignificant differences in emissions of  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  during the growing season of a carrot crop. However, this changed when organic fertilizer was applied in the middle of the growing season (43 DAC), which increased  $\text{N}_2\text{O}$  and  $\text{CO}_2$  release to higher rates in the high compost treatment. This suggests a need for holistic soil management in any effort to mitigate GHG emission or increase soil C sequestration with OA application, because subsequent management practices may offset benefits of application. In addition to measuring  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ , and  $\text{CO}_2$  emissions, we measured soil total C, which was not a sensitive enough indicator for detecting differences in C between treatments. Soil  $\text{NO}_3^-$  and soil  $\text{NH}_4^+$  were useful in explaining  $\text{N}_2\text{O}$  and  $\text{CO}_2$  emissions, but did not seem to influence  $\text{CH}_4$  emissions.

Crop yield was also higher in the high compost treatment, which is consistent with documented information regarding the benefits of OA application to agricultural soils, including increased porosity and water-holding capacity, slow release of nitrogen and other nutrients, and increased soil fertility. Yield-scaled GWP was not statistically different between treatments, indicating that the GHG efficiency of crop production did not change with increasing compost application. Thus, higher rates of compost application may better concurrently address concerns regarding atmospheric GHG emissions and global food

demand. Furthermore, higher OA application rates may improve efforts to sustainably increase cropping intensity, which could reduce land-clearing for agriculture.

Our survey results indicate that there are financial limitations to increasing the rate of compost applied at many organic farms in the Tri-County area. Here, farmers obtain compost from a variety of independent sources, but efforts to provide OAs through government programs may alleviate some financial and logistical pressures that these farmers face, while improving the sustainability of agricultural soil management. In 2015, the County of Santa Barbara included in the County Plan its intention to support legislation proposed in California that aims to increase soil C sequestration in agricultural lands (A.B. 761, Wolk and S.B. 367, Levine). If passed, these policies would provide monetary incentive for farmers that engage in practices that either reduce GHG emissions or increase C sequestration. It could be beneficial for the County to publicize these opportunities and to partner with researchers who can monitor the long-term effects on soils. The IPCC estimates that increasing C sequestered in agricultural soils has the potential to restore about 50% of the 80 Pg of C that have been lost from soils since 1850 (Kroodsma and Field, 2006), which makes such policies increasingly important in mitigating climate change.

### ***B. Future Work***

In future studies, more precise measurement of soil C over time for different starting conditions is recommended, in order to determine to what extent CO<sub>2</sub> emissions are due to loss of native soil organic matter. This may include using isotope labeling, or measuring soil C in different fractions (e.g. mineral associated, biochemically recalcitrant, biochemically labile). These efforts would enable inclusion of CO<sub>2</sub> emissions in calculation

of GWP. Additionally, for a realistic estimate of the effect of OA application on GWP, pre-field components of a broader life-cycle assessment should be included, such as emissions during the composting process and the manufacture of organic fertilizer (OF).

Our field study, one growing season of a carrot crop at one organic farm, is limited in scope and duration. Future research may experiment with different soil or crop types which may respond differently to OA application. Future research could also compare other OAs with documented C sequestration potential, such as biochar or manure. Longer studies should be implemented to determine whether there are legacy effects of compost application at different rates. Because our study was conducted on an organic farm under a demanding production schedule, we were unable to include a control (i.e. no compost), which would have increased the robustness of our results. Additionally, we recommend that more OA application rates are studied to determine whether there are rates of compost application that optimize the balance between crop yield and GHG emissions within different agricultural systems.

Our survey specifically targeted farmers who use compost, but future studies might expand the scope because organic farmers use a large variety of OAs depending on factors such as cost, availability, labor, and machinery. Future surveys should ask farmers specifically about what knowledge, if any, they have about government programs available for them to participate in, and their attitudes toward participation. Such programs are likely to be helpful to small-scale organic farmers that have recently established a commercial enterprise and could use additional funding. With the aim of incorporating as many farms as possible in C sequestration or GHG mitigation efforts, follow-up surveys can be expanded to rangelands and growers of perennial crops.

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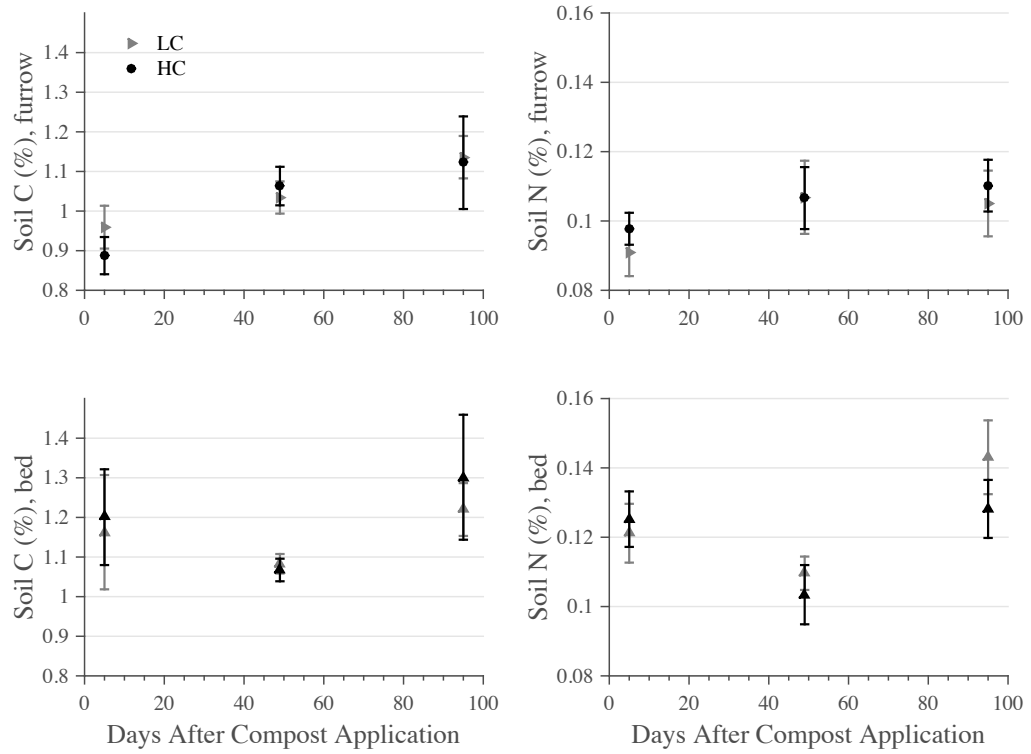
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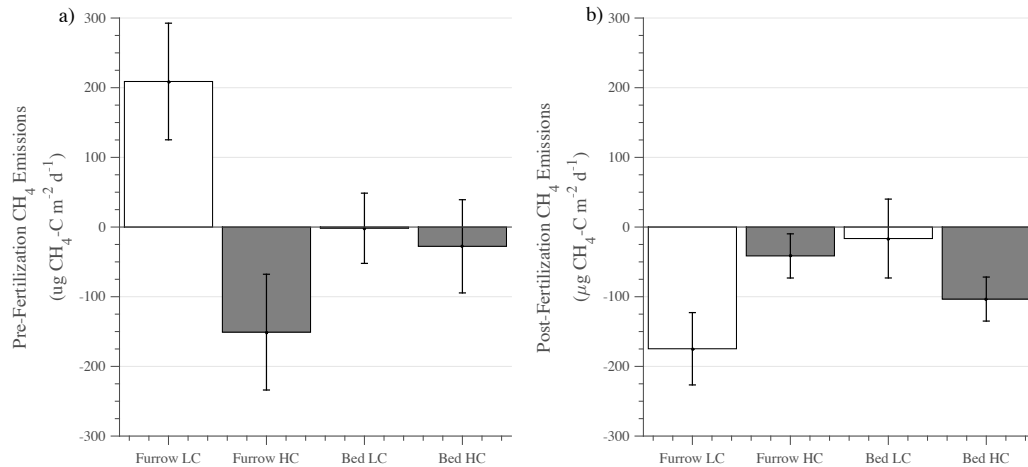
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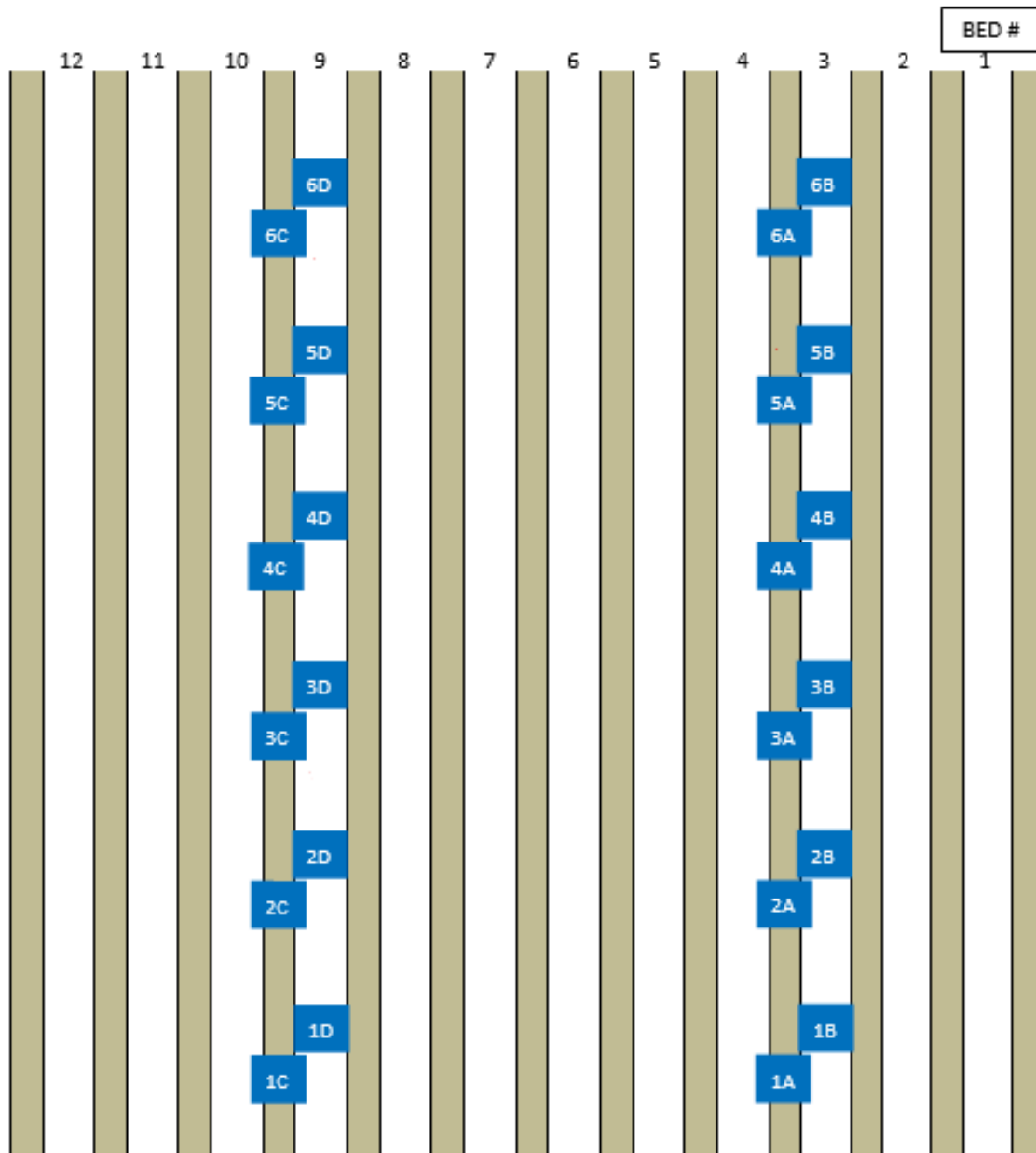
## V. Appendix



**Figure A1.** Soil carbon and nitrogen percentages in beds (0-20 cm) and furrows (0-10 cm), 5, 49, and 95 DAC, means and standard errors ( $n = 6$ ).



**Figure A2.** Cumulative (average)  $CH_4$  emission pre- and post-fertilization, means and standard errors ( $n = 6$ ). Pre-fertilization period was standardized by 37 days and post-fertilization period was standardized by 46 days.



**Figure A3.** Diagram of field site with flux chambers (not to scale). Blue boxes represent flux chambers. White numbered columns represent beds and tan columns represent furrows. Each number (1 - 6) designates a block (6 blocks total). Chambers A and B are in the low compost treatment (LC) and chambers C and D are in the high compost treatment (HC). One set of 2 chambers within a block (i.e. either A and B or C and D) comprises a plot.

**Table A1**

Farm management practices on the carrot field during the growing season.

Date	Days after Compost Application	Flux and Soil Sampling	LC Irrigation	HC Irrigation	Management Event
7/15/14	-1	X			
7/16/14	0		x	x	Compost applied, field disked, bed shaped, carrots seeded
7/16/14	3		x	x	
7/21/14	5	X			
7/22/14	6				Flame weeding
7/22/14	6		x		
7/23/14	7			x	
7/25/14	9	X			
7/25/14	9				
7/28/14	12		x	x	
7/31/14	15	X			
8/5/14	20				Cultivation in beds
8/6/14	21	X		x	
8/7/14	22		x		
8/12/14	27				Hoeing in beds
8/13/14	28	X			
8/19/14	34	X			
8/21/14	36		x	x	
8/27/14	42	X			
8/28/14	43				Organic fertilization in beds
9/1/14	47			x	Cultivation
9/2/14	48		x		
9/3/14	49	X			
9/9/14	55		x	x	
9/10/14	56	X			
9/15/14	61			x	
9/16/14	62		x		
9/17/14	63	X			
9/22/14	68			x	
9/23/14	69		x		
9/24/14	70	X			Hand weeding commences (knives used)
9/29/14	75			x	
9/30/14	76		x		
10/5/14	81	X			
10/6/14	82			x	
10/7/14	83		x		
10/12/14	88	X			
10/16/14	82			x	
10/17/14	93		x		
10/18/14	94				Harvest commences
10/19/14	95	X			
11/8/14	115				Harvest ends and field cultivation

Black “x” indicates irrigation date that is certain; grey “x” indicates irrigation date that is probable but not confirmed.

**Table A2.**  
Compost survey questions

1.	What are the main crops grown on your farm?
2.	What soil types exist on your farm?
3.	How much compost do you apply to your fields per unit area?
4.	How did you decide upon this rate of compost application (e.g. soil lab test results, recommendations from other farmers, recommendations from agricultural agencies, crop or soil type, weather/season, personal experience, etc.)?
5.	A. Do your application rates ever vary depending on soil type, crop type, soil lab test results, time of year, price, or any other factors?
	B. [If yes] Briefly explain how.
6.	Does the cost of producing or buying compost prevent you from adding as much as you would like to?
7.	Where does your compost come from? Please estimate the proportion in an average year obtained from each source.
8.	A. What types of organic matter and other ingredients is your compost made of?
	B. If you purchase compost, do you add any other amendments to the compost before you apply it? What are they?
9.	What are the main reasons you apply compost?
10.	What amendments do you apply to the same fields and crops that you apply compost to?
11.	Is there anything else, unique or otherwise, that you would like us to know about your compost application or management practices?
12.	*How many acres of farmland do you have?

\*Question 12 was not initially included and was added after completing two surveys.

**Table A3** Soil classification datasheet. Classification protocol, codes, and abbreviation meanings located within (Schoeneberger, 2002).

Horizon	Matrix Color	Texture	Struct.	Rock Frag.	Roots	Pores	Consistence (RR, St, Pl <sup>†</sup> )	Reaction	
Sym- bol	Depth (cm)	Dry Moist	Clay (%)	Tex Mod/ Texture	Gr, Si, Ty*	% Rnd <sup>‡</sup>	Qu, Si, Lo <sup>§</sup>	Moist	Effer- vescence
Ap1	0-20	10 YR 4/3 10 YR 3/3	50	Silty Clay (10-40-50)	2, M, SBK	1-5% SR	1, VF, TU 3, F/M, TU	MH SS, FR, SP	NE
Ap2	20-31	10 YR 4/3 10 YR 3/3	55	Clay (15-30-55)	2, M, ABK	1-5% SR	1, VF, TU 2, VF, T	SH VFR, SS, VP	NE
Bw1	31-41	2.5 Y 4/2 7.5 YR 3/1	55	Clay 15-30-55)	2, M, ABK	1-5% SR	1, VF, TU 2, VF, T	H ER, SS, SP	NE
Bw2	41-48	2.5 Y 4/2 7.5 YR 3/1	50	Silty Clay (10-40-50)	3, M, ABK	0%	1, VF, TU 1, VF, T	MH FR, SS, MP	VS
Bk1	48-64	2.5 Y 5/3 10 YR 3/3	55	Clay (5-40-55)	2, M, ABK	0%	3, F, TU 1, VF, T	MH FI, SS, MP	VS
Bk2	64-91	10 YR 5/4 10 YR 4/3	55	Silty Clay (10-35-55)	2, M, SBK	0%	3, F, TU 1, VF, T	SH VFR, SS, SP	SL
Bk3	91+	2.5 Y 5/4 10 YR 4/3	50	Silty Clay (5-45-50)	2, M, SBK	1-5% WR	1, VF, TU 1, VF, T	SH FR, MS, MP	SL

\*Gr, Si, Ty = Grain, Size, Type

‡Rnd = Roundness

<sup>§</sup>Qu, Si, Lo = Quantity, Size, Location

§Qu, Si, Sh = Quantity, Size, Shape

†RR, St, Pl = Rupture resistance, Stickiness, Plasticity

**Table A4.** Gas flux data and soil temperatures, air temperatures, and soil moisture data.

ID	Date	Rate	Pos.	A.T. (°C)	S.T. (°C)	S.M. (%)	NH <sub>4</sub> <sup>+</sup> conc.	NO <sub>3</sub> <sup>-</sup> conc.	CH <sub>4</sub> flux	CO <sub>2</sub> flux	N <sub>2</sub> O flux
1A	7/21/14	Low	Furrow	25.3	24.5	14.9	2.7	10.7	-8.9	264.7	*
1B	7/21/14	Low	Bed	25.3	24.5	14.6	2.6	7.7	-17.6	265.6	*
1C	7/21/14	High	Furrow	25.3	24.5	12.7	2.5	16.3	-24.4	230.4	*
1D	7/21/14	High	Bed	25.3	24.5	13.0	2.1	30.3	80.7	581.4	*
2A	7/21/14	Low	Furrow	25.3	24.5	16.0	1.6	4.7	70.2	215.3	*
2B	7/21/14	Low	Bed	25.3	24.5	15.1	3.0	7.3	24.7	374.9	*
2C	7/21/14	High	Furrow	25.3	24.5	13.2	2.3	10.4	5.4	199.0	*
2D	7/21/14	High	Bed	25.3	24.5	12.6	2.0	36.2	-13.5	589.0	*
3A	7/21/14	Low	Furrow	25.3	24.5	16.9	2.4	7.3	8.2	159.8	*
3B	7/21/14	Low	Bed	25.3	24.5	14.4	2.2	28.7	-11.5	288.4	*
3C	7/21/14	High	Furrow	25.3	24.5	12.8	2.7	12.2	-7.3	239.4	*
3D	7/21/14	High	Bed	25.3	24.5	9.9	2.2	31.5	17.0	282.6	*
4A	7/21/14	Low	Furrow	25.3	24.5	14.7	1.9	12.3	-13.1	153.0	*
4B	7/21/14	Low	Bed	25.3	24.5	9.1	2.4	42.5	37.7	213.8	*
4C	7/21/14	High	Furrow	25.3	24.5	13.3	2.3	18.7	21.3	412.7	*
4D	7/21/14	High	Bed	25.3	24.5	8.6	2.4	46.5	0.1	214.9	*
5A	7/21/14	Low	Furrow	25.3	24.5	17.9	2.4	9.2	-5.5	227.5	*
5B	7/21/14	Low	Bed	25.3	24.5	13.4	2.2	31.3	-3.6	217.5	*
5C	7/21/14	High	Furrow	25.3	24.5	11.0	2.5	15.7	-35.3	294.2	*
5D	7/21/14	High	Bed	25.3	24.5	8.2	1.9	34.5	-18.1	290.4	*
6A	7/21/14	Low	Furrow	25.3	24.5	17.3	2.8	8.0	-4.3	170.5	*
6B	7/21/14	Low	Bed	25.3	24.5	14.7	2.2	23.1	-18.4	310.5	*
6C	7/21/14	High	Furrow	25.3	24.5	11.6	2.0	14.2	0.0	289.9	*
6D	7/21/14	High	Bed	25.3	24.5	12.3	2.3	22.3	14.2	442.1	*
1A	7/25/14	Low	Furrow	23.3	21.7	15.0	0.4	6.7	-0.3	150.2	1.5
1B	7/25/14	Low	Bed	23.3	22.4	14.7	0.4	7.9	-22.7	157.2	3.7
1C	7/25/14	High	Furrow	23.3	23.1	13.1	0.8	8.0	9.5	233.1	2.7
1D	7/25/14	High	Bed	23.3	24.5	13.8	0.5	24.8	-11.8	274.0	17.1
2A	7/25/14	Low	Furrow	24	23.9	15.7	0.3	9.1	-9.8	213.2	2.1
2B	7/25/14	Low	Bed	24	26.3	14.4	0.5	8.0	-14.4	226.5	21.6
2C	7/25/14	High	Furrow	24	25	13.0	0.3	11.2	28.4	229.4	6.7
2D	7/25/14	High	Bed	24	24.1	12.9	0.5	30.6	-11.6	183.0	4.8
3A	7/25/14	Low	Furrow	24.4	24.1	16.3	0.5	12.5	-68.9	230.8	5.0
3B	7/25/14	Low	Bed	24.4	26.3	13.9	0.5	21.9	3.8	156.6	4.0
3C	7/25/14	High	Furrow	24.4	24.6	12.0	0.4	13.2	-9.5	411.5	2.9
3D	7/25/14	High	Bed	24.4	28.1	11.0	0.5	43.2	1.2	188.0	6.7
4A	7/25/14	Low	Furrow	22.1	23.2	15.4	0.5	7.3	-21.8	132.7	2.7
4B	7/25/14	Low	Bed	22.1	25	9.3	0.6	51.4	-51.9	143.3	4.1
4C	7/25/14	High	Furrow	22.1	23.5	12.2	0.5	13.1	2.8	295.7	13.5
4D	7/25/14	High	Bed	22.1	23.6	10.7	0.5	44.8	-1.2	160.9	8.7
5A	7/25/14	Low	Furrow	32.1	24.1	15.7	0.4	12.4	26.7	159.6	1.5
5B	7/25/14	Low	Bed	32.1	24.7	12.5	0.4	30.5	6.0	160.6	3.3
5C	7/25/14	High	Furrow	32.1	25.4	9.8	0.4	41.2	10.1	136.6	4.4
5D	7/25/14	High	Bed	32.1	27.7	10.4	0.5	13.2	10.2	187.2	7.9
6A	7/25/14	Low	Furrow	23.4	25.8	15.8	0.4	6.6	-2.9	165.8	9.9
6B	7/25/14	Low	Bed	23.4	28.2	12.8	0.3	29.2	-23.4	191.6	4.0
6C	7/25/14	High	Furrow	23.4	26.5	12.2	0.5	11.5	8.8	231.8	11.6
6D	7/25/14	High	Bed	23.4	29.2	11.5	0.4	26.0	1.0	213.1	6.5
1A	7/31/14	Low	Furrow	25.1	21.9	14.1	1.8	11.7	-9.0	161.5	1.7

1B	7/31/14	Low	Bed	25.1	23.4	14.5	1.4	11.1	-19.8	134.1	2.3
1C	7/31/14	High	Furrow	25.1	23.2	12.3	1.6	14.3	8.7	282.5	3.0
1D	7/31/14	High	Bed	25.1	24.2	12.6	1.6	30.3	-21.8	166.3	4.6
2A	7/31/14	Low	Furrow	24	24.1	14.5	1.9	7.4	-9.1	255.2	3.2
2B	7/31/14	Low	Bed	24	25.9	13.9	1.7	10.7	2.4	191.2	9.4
2C	7/31/14	High	Furrow	24	24.8	12.6	1.6	12.3	-7.8	232.2	4.9
2D	7/31/14	High	Bed	24	27.7	12.8	1.6	25.5	-11.2	118.2	4.3
3A	7/31/14	Low	Furrow	23.3	25.7	19.7	1.7	10.2	-10.7	256.0	3.9
3B	7/31/14	Low	Bed	23.3	27.9	12.8	1.7	33.2	-13.0	156.3	3.2
3C	7/31/14	High	Furrow	23.3	25.4	12.7	1.5	18.2	-16.3	294.9	4.7
3D	7/31/14	High	Bed	23.3	30.3	8.6	1.5	31.8	31.2	175.1	4.7
4A	7/31/14	Low	Furrow	25.3	22.9	12.2	1.5	9.2	12.9	151.6	1.7
4B	7/31/14	Low	Bed	25.3	24.9	9.9	1.5	54.5	20.0	194.3	0.2
4C	7/31/14	High	Furrow	25.3	23.4	12.2	1.6	16.8	5.0	246.1	3.3
4D	7/31/14	High	Bed	25.3	25.7	10.0	1.5	45.6	44.3	135.9	5.3
5A	7/31/14	Low	Furrow	24.9	24.4	15.0	1.5	9.2	-25.5	155.0	1.9
5B	7/31/14	Low	Bed	24.9	26	8.4	1.5	29.6	14.3	138.7	2.4
5C	7/31/14	High	Furrow	24.9	24.6	11.3	1.7	12.3	-6.3	129.2	4.2
5D	7/31/14	High	Bed	24.9	27.6	10.4	1.5	37.2	-27.6	140.4	4.6
6A	7/31/14	Low	Furrow	25.6	25.2	13.1	1.6	7.6	3.6	185.9	2.8
6B	7/31/14	Low	Bed	25.6	27.5	13.1	1.4	18.7	15.5	161.0	3.4
6C	7/31/14	High	Furrow	25.6	26.4	19.2	1.5	13.1	14.2	184.4	7.8
6D	7/31/14	High	Bed	25.6	28.8	11.7	1.6	23.3	2.7	202.7	4.7
1A	8/6/14	Low	Furrow	20	23.2	12.3	1.4	0.1	0.0	180.0	2.8
1B	8/6/14	Low	Bed	20	22.1	13.6	0.4	13.9	-5.6	137.3	1.9
1C	8/6/14	High	Furrow	20	24	7.7	0.4	24.2	-9.6	311.5	1.6
1D	8/6/14	High	Bed	20	23.5	10.3	0.3	38.3	-3.9	150.6	2.8
2A	8/6/14	Low	Furrow	18.8	22.2	13.2	0.5	8.9	-0.3	247.4	2.3
2B	8/6/14	Low	Bed	18.8	21.4	15.6	0.3	14.1	17.1	152.8	5.3
2C	8/6/14	High	Furrow	18.8	23.4	7.1	0.6	12.6	-12.9	214.6	2.1
2D	8/6/14	High	Bed	18.8	21.6	11.4	0.4	36.8	-4.7	129.0	3.2
3A	8/6/14	Low	Furrow	18.3	22.5	12.0	0.5	15.3	-4.8	181.0	2.7
3B	8/6/14	Low	Bed	18.3	21.3	11.4	0.3	31.9	-7.7	109.3	1.5
3C	8/6/14	High	Furrow	18.3	23.6	9.3	0.5	*	-3.1	132.7	1.4
3D	8/6/14	High	Bed	18.3	21.6	9.2	0.5	46.4	118.8	119.3	2.5
4A	8/6/14	Low	Furrow	20.3	22.7	10.7	0.3	13.6	-1.9	79.4	1.9
4B	8/6/14	Low	Bed	20.3	22.2	9.3	0.3	64.8	0.8	122.0	2.1
4C	8/6/14	High	Furrow	20.3	23.4	8.0	0.4	10.2	-7.9	226.9	6.8
4D	8/6/14	High	Bed	20.3	23.4	8.3	0.5	42.5	-42.3	153.3	4.5
5A	8/6/14	Low	Furrow	19	22.2	12.4	0.6	10.6	23.4	148.9	1.9
5B	8/6/14	Low	Bed	19	21.4	11.2	0.3	31.5	-13.5	116.1	1.9
5C	8/6/14	High	Furrow	19	23.1	8.1	0.3	13.5	-30.3	96.6	2.5
5D	8/6/14	High	Bed	19	23.5	8.4	0.3	39.1	-3.8	101.5	1.7
6A	8/6/14	Low	Furrow	18.8	22	12.3	0.5	9.0	4.2	145.1	1.6
6B	8/6/14	Low	Bed	18.8	21	12.0	0.4	17.4	-0.1	113.9	2.4
6C	8/6/14	High	Furrow	18.8	22.8	8.2	0.6	14.3	-8.0	113.3	5.1
6D	8/6/14	High	Bed	18.8	21.3	7.6	0.5	33.3	-2.7	156.0	2.7
1A	8/13/14	Low	Furrow	20.4	21.5	12.5	0.7	12.5	-2.8	151.0	1.1
1B	8/13/14	Low	Bed	20.4	20.8	12.5	0.5	19.3	8.4	129.6	0.9
1C	8/13/14	High	Furrow	20.4	21.5	10.4	0.8	17.5	5.8	157.9	1.2
1D	8/13/14	High	Bed	20.4	20.3	10.7	0.9	31.7	-7.4	140.0	0.9
2A	8/13/14	Low	Furrow	22.1	22	10.4	0.6	8.0	4.4	170.2	1.1
2B	8/13/14	Low	Bed	22.1	21.4	11.2	0.5	12.1	-10.2	151.9	3.2
2C	8/13/14	High	Furrow	22.1	22.3	12.2	0.9	13.7	21.7	314.4	1.6
2D	8/13/14	High	Bed	22.1	21.3	11.9	0.5	15.6	7.5	142.1	1.0
3A	8/13/14	Low	Furrow	24.6	23.2	14.1	0.7	19.9	80.9	209.4	1.1

3B	8/13/14	Low	Bed	24.6	22	12.7	1.1	15.2	-16.0	147.3	1.0
3C	8/13/14	High	Furrow	24.6	23.8	11.2	0.3	20.0	4.4	143.9	0.9
3D	8/13/14	High	Bed	24.6	22.8	12.2	0.7	47.0	4.9	137.8	1.2
4A	8/13/14	Low	Furrow	20.1	21.8	11.4	0.3	14.4	-5.1	96.7	0.6
4B	8/13/14	Low	Bed	20.1	20.6	10.4	0.3	15.0	-4.8	134.1	1.0
4C	8/13/14	High	Furrow	20.1	21.8	12.3	0.7	15.0	-12.3	150.0	3.9
4D	8/13/14	High	Bed	20.1	20.9	11.4	0.7	34.7	-24.2	129.3	1.4
5A	8/13/14	Low	Furrow	21.6	22	13.8	0.4	14.8	22.3	138.8	1.5
5B	8/13/14	Low	Bed	21.6	20.7	11.2	0.4	22.6	4.2	147.6	1.8
5C	8/13/14	High	Furrow	21.6	22.1	10.6	0.5	14.3	-9.1	116.5	0.9
5D	8/13/14	High	Bed	21.6	21.3	9.6	0.4	36.1	-4.8	107.3	0.7
6A	8/13/14	Low	Furrow	22.6	22.9	12.8	0.6	12.6	113.7	138.9	1.0
6B	8/13/14	Low	Bed	22.6	21.7	12.1	0.7	38.5	-7.8	125.0	1.1
6C	8/13/14	High	Furrow	22.6	23	9.4	0.8	19.8	5.9	161.7	2.2
6D	8/13/14	High	Bed	22.6	21.8	10.2	0.5	29.9	-39.9	169.1	1.7
1A	8/19/14	Low	Furrow	20.8	24	10.3	0.9	17.6	-27.8	266.1	5.4
1B	8/19/14	Low	Bed	20.8	23.4	8.8	0.8	11.3	-11.1	152.1	1.8
1C	8/19/14	High	Furrow	20.8	24.2	7.7	0.7	21.9	22.6	210.9	3.9
1D	8/19/14	High	Bed	20.8	23.8	8.1	0.9	35.0	2.1	134.1	2.7
2A	8/19/14	Low	Furrow	21.2	23.5	11.6	0.9	13.7	-21.1	300.7	5.7
2B	8/19/14	Low	Bed	21.2	23.2	8.6	0.7	12.7	-69.6	147.9	6.9
2C	8/19/14	High	Furrow	21.2	24	8.8	0.9	13.0	-14.3	223.6	3.9
2D	8/19/14	High	Bed	21.2	23.5	8.0	0.8	28.0	-2.3	115.7	2.0
3A	8/19/14	Low	Furrow	22.7	23.2	11.1	0.8	39.4	-2.0	404.8	8.2
3B	8/19/14	Low	Bed	22.7	22.3	8.7	1.0	37.7	5.4	126.2	1.7
3C	8/19/14	High	Furrow	22.7	23.5	8.1	0.7	11.1	22.2	182.5	2.2
3D	8/19/14	High	Bed	22.7	23	6.7	0.8	28.4	-8.2	130.5	1.6
4A	8/19/14	Low	Furrow	20.8	24.3	9.1	0.9	27.8	-3.5	50.8	0.5
4B	8/19/14	Low	Bed	20.8	24	7.6	0.7	55.2	-6.9	90.0	3.6
4C	8/19/14	High	Furrow	20.8	24.6	7.4	0.8	19.1	-13.7	84.6	1.8
4D	8/19/14	High	Bed	20.8	23.8	9.3	1.0	22.1	1.7	121.2	3.1
5A	8/19/14	Low	Furrow	21.6	23.8	11.1	1.0	20.6	0.9	72.5	1.3
5B	8/19/14	Low	Bed	21.6	23.9	8.4	0.9	22.0	-10.3	126.5	2.3
5C	8/19/14	High	Furrow	21.6	24.4	7.0	0.9	12.8	3.2	93.3	1.5
5D	8/19/14	High	Bed	21.6	23.4	7.7	0.7	27.9	41.2	93.9	1.1
6A	8/19/14	Low	Furrow	22.6	23.3	11.1	0.7	16.3	-1.8	70.7	1.8
6B	8/19/14	Low	Bed	22.6	22.5	11.6	0.7	16.7	14.8	137.6	2.8
6C	8/19/14	High	Furrow	22.6	23.2	8.3	0.6	27.3	-1.3	89.5	2.6
6D	8/19/14	High	Bed	22.6	22.5	8.1	0.9	36.1	-1.9	132.1	3.7
1A	8/27/14	Low	Furrow	28.5	24.5	10.0	0.9	20.5	-41.0	205.5	1.6
1B	8/27/14	Low	Bed	28.5	23.8	6.2	0.6	5.3	-10.4	248.0	1.7
1C	8/27/14	High	Furrow	28.5	25.2	8.9	0.7	16.1	15.5	158.0	2.0
1D	8/27/14	High	Bed	28.5	24.9	7.1	0.4	16.7	-4.3	230.0	3.5
2A	8/27/14	Low	Furrow	24.4	23.2	10.4	0.7	39.4	-6.6	166.3	2.6
2B	8/27/14	Low	Bed	24.4	22.2	7.2	0.4	10.7	2.8	213.7	7.4
2C	8/27/14	High	Furrow	24.4	23.2	8.3	0.5	13.2	-16.2	145.3	2.0
2D	8/27/14	High	Bed	24.4	23.7	8.2	0.5	37.6	-2.0	151.9	1.5
3A	8/27/14	Low	Furrow	24.7	21.8	10.4	0.6	39.0	1.2	232.9	3.5
3B	8/27/14	Low	Bed	24.7	21.3	7.0	0.5	23.2	21.4	126.0	1.6
3C	8/27/14	High	Furrow	24.7	22.2	8.6	0.4	15.9	-6.2	108.8	0.8
3D	8/27/14	High	Bed	24.7	22.4	7.1	0.5	37.2	-7.3	171.1	1.6
4A	8/27/14	Low	Furrow	24.7	20.6	9.6	0.6	33.7	-1.1	133.5	1.2
4B	8/27/14	Low	Bed	24.7	20.3	7.9	0.4	37.4	-5.7	140.0	1.9
4C	8/27/14	High	Furrow	24.7	21	7.4	0.5	28.8	-17.3	122.1	1.6
4D	8/27/14	High	Bed	24.7	20.7	7.4	0.4	39.1	-12.0	118.2	1.4
5A	8/27/14	Low	Furrow	22.8	20.2	10.5	0.5	40.5	-26.6	104.9	1.1



5B	8/27/14	Low	Bed	22.8	19	6.9	0.5	13.2	-12.8	125.9	1.6
5C	8/27/14	High	Furrow	22.8	19	8.0	0.8	9.1	-16.6	152.5	1.4
5D	8/27/14	High	Bed	22.8	19.1	6.3	0.6	13.3	-18.4	125.3	1.0
6A	8/27/14	Low	Furrow	19.8	20	10.2	0.6	23.6	-10.0	104.6	1.6
6B	8/27/14	Low	Bed	19.8	19.2	6.9	0.6	18.0	5.8	112.0	1.4
6C	8/27/14	High	Furrow	19.8	20.1	8.0	0.5	26.1	-12.9	111.8	2.2
6D	8/27/14	High	Bed	19.8	19.1	7.3	0.6	29.6	-22.1	88.5	0.8
1A	9/3/14	Low	Furrow	19.7	21.9	15.5	1.9	17.2	-10.2	131.9	4.1
1B	9/3/14	Low	Bed	19.7	21.1	10.1	1.4	12.4	2.2	801.0	24.9
1C	9/3/14	High	Furrow	19.7	22.1	14.8	0.8	14.1	-2.3	194.8	46.1
1D	9/3/14	High	Bed	19.7	21.2	11.6	0.9	35.8	-5.5	429.1	68.1
2A	9/3/14	Low	Furrow	19.4	22	15.1	2.1	24.0	42.1	84.4	2.0
2B	9/3/14	Low	Bed	19.4	21.5	11.3	66.2	33.7	-25.7	398.0	23.0
2C	9/3/14	High	Furrow	19.4	22.1	9.0	0.5	24.0	-7.4	181.2	12.0
2D	9/3/14	High	Bed	19.4	21.3	7.9	0.9	46.4	-6.5	632.5	39.6
3A	9/3/14	Low	Furrow	19.9	22.3	16.9	10.8	13.8	-30.8	101.9	2.0
3B	9/3/14	Low	Bed	19.9	21.7	13.5	63.1	40.3	-1.3	425.9	31.4
3C	9/3/14	High	Furrow	19.9	22.3	10.5	22.1	17.8	-8.3	128.2	3.1
3D	9/3/14	High	Bed	19.9	21.6	11.5	1.0	30.3	-3.3	180.4	6.1
4A	9/3/14	Low	Furrow	20.4	22.4	15.5	1.1	14.6	-4.3	121.6	2.6
4B	9/3/14	Low	Bed	20.4	21.6	12.2	2.4	54.9	-43.0	308.5	32.5
4C	9/3/14	High	Furrow	20.4	22.3	12.4	1.9	17.5	-4.7	98.2	5.7
4D	9/3/14	High	Bed	20.4	21.9	8.0	1.3	33.6	0.6	520.0	24.2
5A	9/3/14	Low	Furrow	20.2	22.7	15.9	1.0	13.5	15.0	206.3	5.2
5B	9/3/14	Low	Bed	20.2	22.1	11.3	2.9	25.2	42.3	488.0	28.3
5C	9/3/14	High	Furrow	20.2	22.6	11.2	1.6	14.5	-22.0	158.5	5.0
5D	9/3/14	High	Bed	20.2	22.2	8.3	0.7	37.6	-0.5	355.3	8.6
6A	9/3/14	Low	Furrow	21	22.9	14.8	0.9	15.0	-9.9	126.3	6.7
6B	9/3/14	Low	Bed	21	22.4	10.2	2.2	23.7	-2.9	519.9	59.1
6C	9/3/14	High	Furrow	21	23	12.1	3.7	10.6	-9.1	203.1	4.1
6D	9/3/14	High	Bed	21	22.5	9.5	125.6	27.0	-32.4	497.0	30.0
1A	9/10/14	Low	Furrow	23.7	22.3	14.8	3.7	15.5	-5.0	157.7	3.0
1B	9/10/14	Low	Bed	23.7	22.2	11.3	30.7	45.0	-20.8	465.7	166.5
1C	9/10/14	High	Furrow	23.7	22.7	16.9	1.6	12.1	-0.4	141.5	12.5
1D	9/10/14	High	Bed	23.7	23	15.1	3.3	40.1	-11.6	445.7	249.2
2A	9/10/14	Low	Furrow	21.4	20.9	16.5	3.6	25.5	-6.6	131.0	1.8
2B	9/10/14	Low	Bed	21.4	21.3	14.0	41.2	69.1	-11.8	452.7	202.6
2C	9/10/14	High	Furrow	21.4	21.8	15.5	0.9	11.6	-33.8	189.0	15.5
2D	9/10/14	High	Bed	21.4	21.3	13.4	3.7	40.0	-17.4	621.0	185.4
3A	9/10/14	Low	Furrow	21.8	19.8	16.3	1.7	13.0	-22.6	134.5	2.1
3B	9/10/14	Low	Bed	21.8	19.3	10.9	42.6	43.8	-30.4	315.6	68.2
3C	9/10/14	High	Furrow	21.8	20.7	17.5	1.3	6.6	4.4	157.6	11.6
3D	9/10/14	High	Bed	21.8	21.4	14.7	18.4	46.0	-8.6	668.0	63.2
4A	9/10/14	Low	Furrow	21.4	19.9	14.2	2.3	18.5	-3.3	137.0	4.8
4B	9/10/14	Low	Bed	21.4	18.5	10.6	21.8	67.4	-18.5	283.4	73.9
4C	9/10/14	High	Furrow	21.4	20	16.2	3.2	13.7	-3.5	139.1	4.1
4D	9/10/14	High	Bed	21.4	18.9	13.6	4.3	52.0	19.1	418.7	109.7
5A	9/10/14	Low	Furrow	20.4	19.3	15.5	1.2	10.7	34.6	152.2	10.1
5B	9/10/14	Low	Bed	20.4	18.6	12.2	37.8	35.8	5.1	247.0	98.3
5C	9/10/14	High	Furrow	20.4	19.6	15.9	1.1	2.9	-18.7	157.9	11.2
5D	9/10/14	High	Bed	20.4	19	14.9	9.8	23.5	7.3	299.7	195.7
6A	9/10/14	Low	Furrow	19.1	18.8	15.1	3.4	14.7	-4.1	62.4	2.2
6B	9/10/14	Low	Bed	19.1	17.9	13.2	75.3	62.1	-12.5	238.2	84.8
6C	9/10/14	High	Furrow	19.1	19.1	16.4	1.0	10.7	24.3	129.7	5.5
6D	9/10/14	High	Bed	19.1	17.6	15.1	20.5	50.9	-2.4	289.8	114.0
1A	9/17/14	Low	Furrow	24.5	21.5	12.9	1.0	9.2	-0.5	130.3	3.9

1B	9/17/14	Low	Bed	24.5	21.1	12.0	19.6	105.4	0.7	304.5	104.4
1C	9/17/14	High	Furrow	24.5	21.4	16.6	2.3	6.8	3.3	143.8	2.7
1D	9/17/14	High	Bed	24.5	20.6	16.6	22.7	127.6	-5.6	349.4	114.8
2A	9/17/14	Low	Furrow	26.2	21.7	10.1	1.0	8.7	-12.9	193.9	3.6
2B	9/17/14	Low	Bed	26.2	21.5	9.4	89.0	96.9	-1.3	259.9	129.0
2C	9/17/14	High	Furrow	26.2	21.9	11.8	1.5	16.7	7.5	142.9	2.4
2D	9/17/14	High	Bed	26.2	21.5	9.9	1.1	70.1	-20.0	310.7	182.6
3A	9/17/14	Low	Furrow	26	22.2	11.3	1.1	12.3	10.0	173.5	3.3
3B	9/17/14	Low	Bed	26	22.1	8.1	20.9	77.4	8.7	246.8	97.1
3C	9/17/14	High	Furrow	26	22.2	12.9	0.6	13.4	25.7	186.4	4.4
3D	9/17/14	High	Bed	26	22.2	11.0	1.4	57.3	1.6	582.8	252.4
4A	9/17/14	Low	Furrow	26.5	24.3	12.7	0.9	7.2	3.6	177.9	5.0
4B	9/17/14	Low	Bed	26.5	23.7	9.3	0.7	82.7	-14.0	226.8	85.5
4C	9/17/14	High	Furrow	26.5	23	13.8	0.9	8.0	4.7	232.4	4.0
4D	9/17/14	High	Bed	26.5	23	11.1	1.2	32.9	0.7	418.6	189.8
5A	9/17/14	Low	Furrow	25.8	23.9	9.7	0.7	11.2	-7.2	314.7	6.1
5B	9/17/14	Low	Bed	25.8	24.9	9.1	24.0	102.2	-18.3	257.0	133.3
5C	9/17/14	High	Furrow	25.8	24.1	11.6	0.9	7.3	-2.5	246.1	10.2
5D	9/17/14	High	Bed	25.8	24.6	11.7	1.4	89.1	-12.8	432.1	223.0
6A	9/17/14	Low	Furrow	29.2	25	11.6	0.9	16.9	-25.7	229.0	10.3
6B	9/17/14	Low	Bed	29.2	25.9	8.5	25.5	113.3	20.1	245.1	221.9
6C	9/17/14	High	Furrow	29.2	25	14.4	1.1	6.9	0.8	351.2	10.7
6D	9/17/14	High	Bed	29.2	25.7	12.1	11.5	73.0	-1.1	290.0	283.9
1A	9/24/14	Low	Furrow	22.7	22.6	13.9	1.2	5.9	3.7	121.0	2.2
1B	9/24/14	Low	Bed	22.7	22.2	11.1	2.7	86.1	-0.9	314.8	86.1
1C	9/24/14	High	Furrow	22.7	23	12.0	0.7	2.3	1.3	154.6	2.0
1D	9/24/14	High	Bed	22.7	22.2	11.7	0.8	17.0	-0.7	283.8	48.4
2A	9/24/14	Low	Furrow	23.1	21.6	13.8	0.7	13.9	0.9	165.4	2.2
2B	9/24/14	Low	Bed	23.1	21.1	10.2	0.9	41.8	-3.9	248.5	41.0
2C	9/24/14	High	Furrow	23.1	21.2	11.4	0.6	11.1	-1.1	198.0	2.4
2D	9/24/14	High	Bed	23.1	21.6	9.3	5.7	75.2	5.8	295.5	74.0
3A	9/24/14	Low	Furrow	22.5	20.1	9.2	0.7	11.3	2.0	168.7	4.1
3B	9/24/14	Low	Bed	22.5	19.9	7.9	0.5	77.9	6.1	211.9	35.6
3C	9/24/14	High	Furrow	22.5	20.2	9.2	0.6	4.5	-1.0	205.1	2.3
3D	9/24/14	High	Bed	22.5	20.4	9.3	1.0	19.0	3.9	427.3	112.3
4A	9/24/14	Low	Furrow	22.1	19.8	11.7	1.3	5.0	4.4	126.0	2.8
4B	9/24/14	Low	Bed	22.1	18.9	9.5	0.6	92.1	2.6	225.8	5.1
4C	9/24/14	High	Furrow	22.1	19.8	11.0	0.8	4.2	10.0	197.5	2.6
4D	9/24/14	High	Bed	22.1	18.6	10.7	1.7	16.3	0.4	280.9	36.2
5A	9/24/14	Low	Furrow	18	19.6	12.0	0.3	7.8	-16.4	192.8	3.5
5B	9/24/14	Low	Bed	18	18	9.2	1.8	54.6	-8.5	188.9	20.0
5C	9/24/14	High	Furrow	18	19.3	9.1	0.7	3.1	-4.3	175.8	3.3
5D	9/24/14	High	Bed	18	18	11.5	0.7	64.2	-2.6	274.1	16.7
6A	9/24/14	Low	Furrow	17.2	18.8	12.7	1.0	11.9	-14.9	95.8	2.5
6B	9/24/14	Low	Bed	17.2	17.1	11.4	18.6	152.3	-4.5	163.1	12.3
6C	9/24/14	High	Furrow	17.2	18.5	12.0	0.7	3.8	-10.2	177.1	2.6
6D	9/24/14	High	Bed	17.2	17.4	12.0	0.6	91.8	5.4	226.6	16.2
1A	10/5/14	Low	Furrow	23.8	17.9	10.5	0.5	10.5	2.7	130.6	3.9
1B	10/5/14	Low	Bed	23.8	17.2	10.0	1.3	87.1	3.8	305.2	104.7
1C	10/5/14	High	Furrow	23.8	18.3	14.8	1.0	17.1	2.2	144.2	2.7
1D	10/5/14	High	Bed	23.8	17.4	10.8	0.9	24.1	-9.9	350.3	115.1
2A	10/5/14	Low	Furrow	27.3	18.6	7.9	0.5	10.0	32.2	193.2	3.6
2B	10/5/14	Low	Bed	27.3	17.5	6.4	1.1	91.1	-9.2	259.0	128.5
2C	10/5/14	High	Furrow	27.3	18.3	8.1	0.5	14.8	-55.5	142.4	2.4
2D	10/5/14	High	Bed	27.3	18.4	6.9	0.7	100.8	2.4	309.5	182.0
3A	10/5/14	Low	Furrow	28.3	20.2	9.0	1.3	19.5	6.4	172.2	3.3

3B	10/5/14	Low	Bed	28.3	18.7	8.2	1.1	63.9	-12.0	244.9	96.4
3C	10/5/14	High	Furrow	28.3	19.5	9.3	0.9	9.9	-8.2	185.0	4.4
3D	10/5/14	High	Bed	28.3	20.6	9.4	0.9	26.1	-8.2	578.3	250.5
4A	10/5/14	Low	Furrow	28.5	20.1	6.4	1.0	2.8	-20.6	176.7	4.9
4B	10/5/14	Low	Bed	28.5	19.4	10.3	0.8	42.9	17.6	225.3	84.9
4C	10/5/14	High	Furrow	28.5	20	10.1	0.9	9.9	14.8	230.8	3.9
4D	10/5/14	High	Bed	28.5	20.4	9.2	0.6	49.8	12.2	415.8	188.5
5A	10/5/14	Low	Furrow	29.1	21.2	7.2	0.7	0.9	1.0	311.3	6.0
5B	10/5/14	Low	Bed	29.1	21.8	7.6	0.6	75.1	-5.0	254.2	131.9
5C	10/5/14	High	Furrow	29.1	21.7	9.1	0.6	7.5	1.7	243.4	10.1
5D	10/5/14	High	Bed	29.1	23	8.8	0.6	107.2	1.3	427.4	220.5
6A	10/5/14	Low	Furrow	34.2	23.2	8.0	0.6	8.6	29.6	225.2	10.1
6B	10/5/14	Low	Bed	34.2	22.2	8.3	0.5	62.2	-0.5	241.1	218.3
6C	10/5/14	High	Furrow	34.2	22.8	10.6	0.8	5.9	-10.4	345.5	10.5
6D	10/5/14	High	Bed	34.2	21.8	10.1	0.5	76.5	-2.0	285.2	279.3
1A	10/12/14	Low	Furrow	24.4	19.8	9.5	0.6	6.4	14.0	135.1	2.5
1B	10/12/14	Low	Bed	24.4	19.7	9.2	0.9	91.3	-39.5	295.0	5.4
1C	10/12/14	High	Furrow	24.4	20.2	13.7	0.7	3.5	-2.8	184.0	2.9
1D	10/12/14	High	Bed	24.4	20	13.1	0.8	15.7	-31.0	77.0	4.9
2A	10/12/14	Low	Furrow	24.5	20.8	13.0	0.8	24.2	-18.7	147.1	1.3
2B	10/12/14	Low	Bed	24.5	19.9	11.3	0.5	104.0	-6.3	181.4	4.3
2C	10/12/14	High	Furrow	24.5	20.4	11.9	0.8	4.8	-3.4	139.9	1.6
2D	10/12/14	High	Bed	24.5	20	11.5	0.5	70.6	-2.7	229.9	2.4
3A	10/12/14	Low	Furrow	22.8	19.7	10.6	0.8	10.6	-6.3	108.8	1.8
3B	10/12/14	Low	Bed	22.8	19.2	10.2	0.7	119.0	47.8	187.7	4.7
3C	10/12/14	High	Furrow	22.8	19.6	13.0	0.8	10.7	5.3	117.7	1.9
3D	10/12/14	High	Bed	22.8	19.3	13.4	0.8	18.6	-7.2	163.1	5.5
4A	10/12/14	Low	Furrow	24.2	19.9	9.9	0.7	10.9	-7.2	166.4	1.0
4B	10/12/14	Low	Bed	24.2	19.2	9.9	0.8	111.4	-5.1	140.1	2.8
4C	10/12/14	High	Furrow	24.2	19.6	12.4	0.8	6.0	-7.0	138.6	1.6
4D	10/12/14	High	Bed	24.2	19.4	12.5	1.8	31.4	64.3	281.6	5.2
5A	10/12/14	Low	Furrow	20.5	19.7	10.6	0.7	4.4	-24.7	106.2	1.2
5B	10/12/14	Low	Bed	20.5	18.8	10.2	0.7	47.1	-0.4	127.4	2.9
5C	10/12/14	High	Furrow	20.5	19.1	9.4	0.7	3.5	7.3	110.9	2.2
5D	10/12/14	High	Bed	20.5	18.5	10.1	0.7	54.8	2.5	153.6	5.0
6A	10/12/14	Low	Furrow	18.7	18.9	11.7	0.5	4.7	-18.6	82.6	1.0
6B	10/12/14	Low	Bed	18.7	18.1	12.1	0.7	67.4	-7.4	105.2	2.7
6C	10/12/14	High	Furrow	18.7	19	14.1	0.8	5.9	7.4	100.2	5.1
6D	10/12/14	High	Bed	18.7	18.4	11.7	0.9	38.2	5.6	114.7	2.9
1A	10/19/14	Low	Furrow	23.6	18.8	10.8	2.4	5.0	92.4	205.0	2.1
1B	10/19/14	Low	Bed	23.6	18.3	8.6	1.7	13.9	-36.3	266.4	3.1
1C	10/19/14	High	Furrow	23.6	19	16.4	2.7	16.1	-9.3	192.3	1.9
1D	10/19/14	High	Bed	23.6	19.2	11.7	2.2	28.2	-8.5	250.2	2.9
2A	10/19/14	Low	Furrow	21.4	18.4	7.6	2.2	11.6	13.6	207.2	2.3
2B	10/19/14	Low	Bed	21.4	17.6	7.6	3.1	107.6	13.2	191.5	2.7
2C	10/19/14	High	Furrow	21.4	18.1	11.9	2.0	5.2	-0.4	274.7	2.7
2D	10/19/14	High	Bed	21.4	17.5	12.1	1.5	54.5	-5.8	246.3	4.8
3A	10/19/14	Low	Furrow	20.3	17.1	9.7	1.4	12.9	-27.4	116.5	0.5
3B	10/19/14	Low	Bed	20.3	15.9	8.2	2.6	56.8	-8.1	178.8	2.4
3C	10/19/14	High	Furrow	20.3	17.5	14.6	3.2	6.1	-96.9	158.4	2.0
3D	10/19/14	High	Bed	20.3	15.9	12.4	2.0	30.0	-2.0	209.1	2.8
4A	10/19/14	Low	Furrow	23	18.6	10.2	2.9	8.4	9.2	148.3	1.1
4B	10/19/14	Low	Bed	23	18	7.5	1.4	45.0	17.2	124.8	1.5
4C	10/19/14	High	Furrow	23	18.3	13.6	2.2	7.6	-13.0	145.8	1.7
4D	10/19/14	High	Bed	23	17.8	11.5	3.5	17.7	5.9	212.2	2.8
5A	10/19/14	Low	Furrow	20.4	18.1	7.1	2.5	4.6	0.6	102.4	1.8

5B	10/19/14	Low	Bed	20.4	16.8	7.0	2.3	63.0	-8.2	89.8	0.7
5C	10/19/14	High	Furrow	20.4	17.3	10.2	2.7	6.1	-3.2	125.6	1.6
5D	10/19/14	High	Bed	20.4	16.5	10.7	1.6	27.5	-12.6	139.0	2.7
6A	10/19/14	Low	Furrow	19.1	17.3	10.4	1.4	11.8	5.1	93.2	1.6
6B	10/19/14	Low	Bed	19.1	16.2	10.0	1.8	103.0	0.4	126.3	3.5
6C	10/19/14	High	Furrow	19.1	17.3	11.3	1.1	2.3	-6.5	122.3	1.2
6D	10/19/14	High	Bed	19.1	16	11.7	2.7	19.3	14.1	148.0	1.9

\* = missing data

Legend: ID = Chamber ID; A.T. = air temperature, S.T. = soil temperature, S.M.= soil moisture,  $\text{NH}_4^+$  and  $\text{NO}_3^-$  conc. units =  $\mu\text{g N g}^{-1}$  dry soil,  $\text{CH}_4$  flux units =  $\mu\text{g C m}^{-2} \text{h}^{-1}$ ,  $\text{CO}_2$  flux units =  $\text{mg CO}_2 \text{m}^{-2} \text{h}^{-1}$ ,  $\text{N}_2\text{O}$  flux units =  $\mu\text{g N m}^{-2} \text{h}^{-1}$