Summer 2019

Seasonal soil carbon fluxes in transitioning agricultural soils in Central Washington State: Relations to land-use, environmental factors and soil carbon-nitrogen characteristics

Brandon Kautzman
Central Washington University, kautzmanb@outlook.com

SEASONAL SOIL CARBON FLUXES IN TRANSITIONING AGRICULTURAL SOILS IN CENTRAL WASHINGTON STATE: RELATIONS TO LAND-USE, ENVIRONMENTAL FACTORS AND SOIL CARBON-NITROGEN CHARACTERISTICS

A Thesis

Presented to

The Graduate Faculty

Central Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Geological Sciences

---

by

Brandon John Kautzman

July 2019

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

We hereby approve the thesis of

Brandon John Kautzman

Candidate for the degree of Master of Science

APPROVED FOR THE GRADUATE FACULTY

______________ ____
Dr. Carey Gazis, Committee Chair

______________ ____
Dr. Susan Kaspari

______________ ____
Dr. Karl Lillquist

______________ ____
Dean of Graduate Studies

ABSTRACT

SEASONAL SOIL CARBON FLUXES IN TRANSITIONING AGRICULTURAL SOIL IN CENTRAL WASHINGTON: RELATIONS TO LAND-USE, ENVIRONMENTAL FACTORS AND SOIL CARBON-NITROGEN CHARACTERISTICS

by

Brandon John Kautzman

July 2019

Changing agricultural land-use practices to increase soil carbon sequestration contributes to climate change mitigation and improved food security by moving CO_2 from the atmosphere into soil as soil organic carbon (SOC). In 2016, a farm in Thorp, Washington, Spoon Full Farm, began converting land historically farmed using conventional methods of tillage and synthetic fertilizers to conservation farming methods with direct seeding and organic soil amendments with a goal of sequestering carbon in the soil. This project evaluates relationships of soil CO_2 respiration and net ecological exchange (NEE) with land-use types, seasonal environmental factors (air temperature, relative humidity, soil temperature and soil moisture) and soil carbon and nitrogen properties (SOC, SON, $\delta^{13}C$, and $\delta^{15}N$) on that farm in order to inform land management decisions affecting soil carbon sequestration. Three farm land-use areas studied were: 1) no-till vegetable garden with regular organic matter amendments; 2) no-till hay fields; and 3) historically unfarmed areas. Soil CO_2 fluxes were measured on these three land-use areas in spring after snowmelt; summer, when garden and hay fields are irrigated and unfarmed areas are dry; and fall when soil and air temperatures are lower and moisture has returned to soils. Continuous soil CO_2 flux measurements of garden soils indicate primary environmental factors influencing soil CO_2 flux during summer are air and soil temperature, and

during fall are soil temperature and moisture. Garden beds have positive NEE during summer and spring days indicating net CO_2 losses from soil. Garden bed respiration is likely dominated by microbial decomposition of compost. Summer period soil CO_2 flux correlates with SOC for all land-use types individually, while vegetable garden SOC and SON correlate with CO_2 flux annually. This suggests SOC influences summer soil CO_2 flux regardless of land-use type, while annual CO_2 flux from composted garden soil depends on overall organic content from compost inputs. Hay field CO_2 flux during summer shows strong correlation with elevated surface SOC within the crop root zone.

ACKNOWLEDGMENTS

I would foremost like to acknowledge the support of the owners and all the farmers of Spoon Full Farm, without which this project could not have occurred. Specifically, I thank Lee and Mericos Rhodes, whose vision of clean sustainable farming in aid to communities and the environment helps keep the importance of projects like this clear. I would like to acknowledge my advisor, Carey Gazis, for her aid and instruction in all aspects of this research and my thesis committee members, Susan Kaspari and Karl Lillquist. Finally, I would like to acknowledge Angela Halfpenny and Breanne MacInnes for their instruction on various lab equipment used during the course of this research, and Peter Zencak for his help with the construction of many essential soil collars.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Soil carbon sequestration through changes in land-use practices has the potential to remove significant amounts of carbon dioxide from the atmosphere, which has risen significantly due to anthropogenic causes. Before the start of the Industrial Revolution, around 1750 A.D., the atmospheric carbon dioxide concentration was about 280 ppm, but has risen beyond 400 ppm, likely the highest concentration in the last 20 million years (Prentice et al., 2005). In September of 2016, the global level of carbon dioxide in the atmosphere reached 400 ppm, up 30% from about 200 years ago (Kahn, 2017; IPCC, 2001). Currently, carbon dioxide continues to increase by 2 ppm per year, with major implications for the global climate (e.g., Arce et al., 2014), such as higher global surface and ocean temperatures. This temperature increase affects many of Earth's climatic and hydrologic processes including storm incidence and intensity, melting of polar ice caps and glaciers, and global sea level rise. Most of the increase of atmospheric carbon dioxide is from the burning of fossil fuels, but it is estimated that 10-30% of the greenhouse gas (GHG) emissions since the 1980s is due to the conversion of natural ecosystems to agricultural uses (Janzen, 2004). This not only includes deforestation and burning of terrestrial biomass, but also soil disruption.

Globally, soil, including both deep and shallow soil profiles, is estimated to contain about 3000 Pg (Petagrams) of soil organic carbon (SOC). SOC in the top 1 m of soil is estimated at ~1325 Pg (Kochy et al., 2015). The active carbon pool in soil, which includes organic and inorganic carbon, is estimated between 1700 and 2500 Pg; this pool represents the largest active terrestrial carbon pool compared to 620 Pg of carbon in vegetation, and 780 Pg of carbon in the atmosphere (Lal, 2010).

There is now considerable international interest in researching methods for transferring atmospheric CO_2 into soils. There is a growing body of evidence supporting the idea that the organic carbon concentration pool in global agricultural soils could be increased by changes in land-use practices, primarily conservation tillage including no-till farming. No-till farming involves direct seeding of crops into a field with as little soil disturbance as possible. This is in contrast to what is often called “conventional farming” which involves plowing or tilling of the soil prior to seed spreading. Regularly disturbing the soil has negative impacts on overall soil health including reductions in SOC, and soil organic matter (SOM) in general, through disturbances to soil aggregates that protect SOC and mineralization of SOC to CO_2 through increased exposure with O in the atmosphere and increased rates of microbial decomposition. Conversion to conservation tillage practices can help reverse this loss of SOC globally on conventionally farmed agricultural land.

CHAPTER II

LITERATURE REVIEW

Soil Carbon Fundamentals

In an attempt to understand soil carbon dynamics, researchers employ a variety of techniques to determine soil carbon turnover rates.Soil carbon turnover rate is the length of time that it takes for carbon to cycle into and out of soils and is one of the primary aspects of soil carbon dynamics. It can be described by the equation:

$$\frac{\delta C}{\delta t} = I - kC$$

where t is time, k is decomposition rate, I is carbon input, and kC is carbon loss. This equation is relatively simple, but the actual processes underlying these values are complex.

Inputs to the soil carbon pool originate from atmospheric carbon. The transport of organic carbon from the atmosphere into the soil is controlled by biological processes. Through the process of photosynthesis in plants and microorganisms, carbon dioxide (CO_2) and water (H_2O) are converted into organic molecules such as glucose ($C_6H_{12}O_6$). These organic molecules are the matter that makes up the structure of the photosynthetic organisms and all other organisms that consume them. These organic molecules are then transported to the soil through the decomposition of organisms, or as exudates from the roots of plants.

When organic material in the form of plant or animal matter dies, it falls to the ground and then is decomposed by microorganisms. Much of this consumed carbon rich material is returned to the atmosphere as CO_2 through the cellular respiration of the microorganisms, but some is converted into a more persistent form of organic matter that is associated with fine minerals and thus called mineral associate organic carbon (MAOC). According to Dumale et al. (2009) this more persistent carbon pool is sometimes referred to as the particulate organic matter carbon (POMC), associated with particle sizes fall between 2 mm and 53 μm but also including particles that are 2 mm or larger. It is chemically composed of amino compounds, glycoproteins, POMC aggregates, and humic acids. Humus is considered the slow carbon pool due to resistance to decomposition with turn-over time of 20 to 50 years. MAOC includes silt and clay sized particles (<53 μm) and is made stable by chemical adsorption to mineral surfaces (Kaiser et al., 2007). It is considered the passive carbon pool due to being physically protected or chemically resistant with turn-over times ranging from 800 to 2000 years. Stable forms of carbon in soil are important for soil carbon sequestration because they have high residence times.

Residence times of carbon in the soil are directly related to soil carbon turn-over rates. If the turn-over rate (TR) can be thought of as the rate of carbon cycling in the soil pool per year, then the mean residence time (MRT) is inverse to TR and represents the mean time carbon stays in the soil pool. MRT is ultimately dependent on the stability of particular carbon pools and their associated CO_2 efflux process. Organic soils are generally a mixture of carbon pools that vary widely in residence times. Kuzyakov (2006) states that plant associated carbon (PAC) bears the shortest MRT ranging from minutes to hours for plant assimilation process and corresponding root respiration, and weeks to months for microbial decomposition of plant residues. SOM possesses the longest MRT with the SOM in the rhizosphere varying between months, years and decades depending on increased microbial activity from available C sources otherwise known as 'priming'. Root exudates or organic matter amendments prime the soil by increasing microbial activity resulting in elevated SOM decomposition. SOM in root-free soil has the highest MRT, decades to hundreds of years, with CO_2 efflux occurring through microbial soil respiration.

Varying MRT represents differing levels of carbon sequestration potential in soil. Carbon pools with high MRT correspond with high sequestration potential, while pools with short MRT corresponding to reduced potential. Short residence times of minutes to months from the plant associated carbon pools are of no value for soil carbon storage purposes. Only high carbon sequestration potential from SOM pools bearing MRT of decades to centuries can make meaningful reductions to atmospheric carbon (Kuzyakov, 2006).

Climate plays a primary role in the natural carbon content in soils. The primary factors are soil moisture levels which influence photosynthetic production, and temperature which influences decomposition rate and microbial respiration. Temperate regions with high moisture and periods of low temperature result in high levels of carbon accumulation due to increased organic production and low decomposition and respiration rates. Conversely, arid regions have low levels of soil carbon due to low organic production from low moisture. Tropical regions have soil carbon content that falls between temperate and arid regions due to high organic production countered by high decomposition and respiration from abundant moisture and high temperatures.

Soil carbon levels also change with depth in the soil profile, regardless of climate. Soil carbon concentrations are highest near the top of the profile and gradually decrease with depth. Although the upper 30 cm of global soils contain larger concentrations of carbon, the soil carbon concentration below 30 cm is estimated to be as much as 46-63% of total global soil carbon. Deeper soil carbon yields older radiocarbon ages compared to shallow soil carbon indicating that deep soil carbon is more stable than shallow soil carbon (Rumpel and Kogel-Knaber, 2010). This has implications for the importance of deeper soils ability to act as a sink for continuous storage of atmospheric carbon.

Land-Use Practices

Changing land-use practices, such as converting from tillage to no-till farming, and grazing management has the potential to store 0.4 – 1.2 GtC per year globally (Lal, 2004). This total estimate includes changes in managing range and grass land, irrigated soils, and restoring degraded soil, but the majority of increased storage capacity results from changing agricultural practices of cropland soils. Modern monoculture and yearly tillage farming practices prevents the sequestration of carbon into the soil. Soil disruption through tilling has also historically contributed to release of stored soil carbon as carbon dioxide into the atmosphere. Tilling the soil stimulates aerobic microbial respiration resulting in as much as a 50% loss of organic soil carbon (Lal, 2004). The switch to no-till or reduced tillage, cover crops and other practices that improve soil health could result in soil carbon sequestration of 0 – 150 kg C ha^{-1} y^{-1} in dry and warm regions, and 100 – 1000 kg C ha^{-1} y^{-1} in humid and cold regions (Lal, 2004). Implementing such changes in tilling practices could sequester ~10% of the global anthropogenic carbon emissions during the next 25 years (IAEA, 2017).

Many research studies have concluded that conservation tillage practices generally increase SOC and SOM in soils. Al-Kaisi et al. (2005) compared SOC after applications of no-till, strip-till and moldboard plowing on rotating corn and soybean fields over three years, and found that no-till and strip-till increased SOC by 14.7 and 11.4%, respectively, compared with moldboard plowing. Similarly, Schillinger et al. (2007) compared no-till with tillage-based winter wheat-summer fallow cropping and determined that after eight years the SOC in the top 5 cm of the no-till system was nearly as high as that of native undisturbed soil of the same region. West and Post (2002) conducted a global data analysis of 67 continuous agricultural experiments involving changes to SOC after converting from conventional tillage to no-till. They concluded that this switch results in sequestration of 57 +/- 14 g C m^{-2} y^{-1} on average. Clearly, there is substantial evidence that supports the idea that conversion from conventional to conservation (i.e., no-till) tillage practices increases carbon sequestration of agricultural soils.

There is also a growing body of research suggesting that applications of organic matter amendments when establishing conservation tillage plots is an effective way to facilitate the initiation of the soil carbon sequestration process. Owen et al. (2015) with the Marin Carbon Project (2018) concluded that from 1954 to 2011 manured fields on commercial dairies served as a sink for atmospheric CO_2 on the order of 74 +/- 73 g C removed m^{-2} yr^{-1}, while non-manured fields were essentially net zero. Ryals and Silver (2013) found that a single application of composted organic matter increased the net soil carbon storage by 25-75% over two years, without including carbon derived directly from the compost. Ryals et al. (2015) used collected data and the biogeochemical model DAYCENT to evaluate the effects of organic matter amendments under different application rates and determined that soil carbon sequestration rates increased for all treatment levels. Based on this research, it can be concluded that a combination of organic matter amendments and no-till farming will serve to significantly increase carbon sequestration rates in agricultural soils.

Conservation Tillage Conversion Benefits

One concern regarding the adoption of soil management practices which sequester carbon is that there is no apparent incentive for farmers to change their current practices. However, there are several potential benefits to these farmers. Increased organic carbon in soil is directly related to soil health, thus the productivity of the soil. Increasing the soil carbon in degraded cropland has been shown to increase yields of major agricultural crops such as wheat and corn (Johnston, 1986; Kanchikerimath and Singh, 2001). Converting soil management to increase SOC has also been shown to improve soil structure thus increase the available water capacity of soils. Alliaumea et al. (2013) showed an increase of water holding capacity in the upper 20 cm of soil by 8.4 mm for every 10 g SOC increase per kg of soil. Abawi and Widmer (2000) provided evidence suggesting that improved soil health reduces the damage caused by soil borne pathogens, nematodes, and root diseases. Clearly there are benefits to soil fertility, health, and water use efficiency when farming practices are adjusted to sequester additional carbon, but there are other potential economic incentives to farmers through a carbon credits system.

The state of California and European Union countries have begun a carbon credits system dubbed the cap-and-trade system which involves buying and selling of carbon credits. Credits are generated through the conversion of carbon from the atmosphere into stable solid forms. These credits are then sold to companies who have exceeded their maximum carbon emissions. Some currently accepted methods of carbon sequestration are through long-term forest, wetland restoration and even soil carbon sequestration through compost additions to grazed grasslands, but soil carbon sequestration through shifts in tillage practices has not yet been accepted as a viable strategy (Terra Global Capital, 2014). Advances in this regard are being made through efforts such as the Marin Carbon Project (2018) in California which focuses largely on documenting and validating alternate soil carbon sequestration techniques including conservation tillage. One of the challenges preventing soil carbon from being a part of the cap-and-trade system is the limitation on the ability to effectively and accurately measure changes in soil carbon stocks and an incomplete understanding of soil carbon turnover and stabilization.

Measuring Soil Carbon

Accurately measuring the flux of carbon stocks in soil over time can prove to be a challenge. Part of this challenge involves determining the changes in mass balance of soil carbon over relatively short periods of time. Accurately measuring mass balance to detect changes in the soil pool depends on accurate measurements of bulk density of the soil, which changes with time and land-use (IAEA, 2017). Determining mass balance is further complicated due to small annual changes in soil carbon relative to background soil carbon levels, and large heterogeneity of carbon content across landscapes.

Spatial variability and relatively high initial SOC content necessitates large sample numbers from large soil plots in order to achieve statistically significant results. One study by Garten and Wullschleger (1999) noted that in order to detect a net soil carbon change of 1 t C per ha (2-3% of initial SOC) at a statistical 90% confidence level required more than 100 samples. Another study by Smith (2006) required 16 samples to detect a 5 t C per ha (10-15% of initial SOC) increase in soil carbon with a 90% confidence level. Both studies highlight problems with such investigations since collecting and analyzing >100 samples may be prohibitive due to time and cost, and most land management practices cannot achieve an increase of 5 t C per ha within a reasonable study timeframe. Figure 1 shows the results of Don et al. (2007) on the spatial variability of SOC and bulk density in the top 60 cm of a soil profile along a transect line through their study area. The range of variances is a good example of the problems involved with achieving statistically significant results, as measured SOC stocks ranged between 57 and 136 t C per ha.

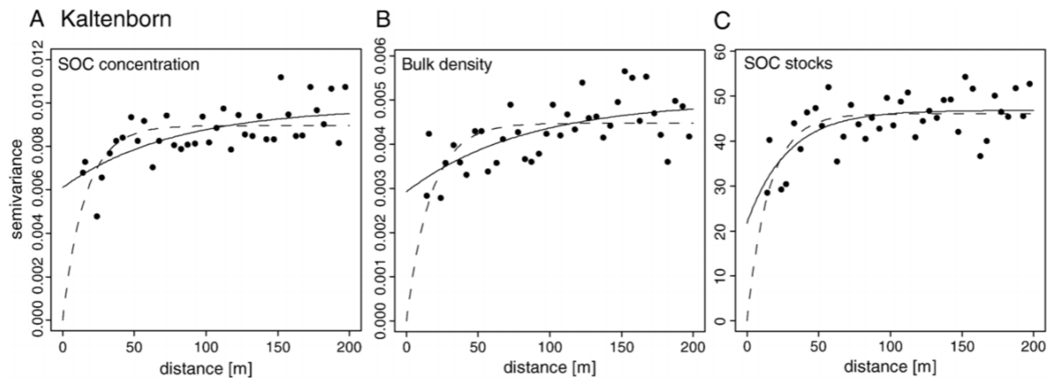

Figure 1 – Semivariograms of mean SOC concentration (A), mean bulk density (B) and SOC stock (t C ha-1) (C) for 0-60 cm soil depth along a transect line in a grassland. Horizontal axis indicates distances from start point on each transect, and vertical axis indicates the dissimilarity of observations as a function of distance (semivariance). Solid and dashed lines show fit to exponential model with and without nugget (dimension of variable) respectively (Don et al., 2007).

Research by Cambardella and Elliot (1992) measured changes in particulate organic matter (POM) using a series of relatively small plots. This method used plots with dimensions of 8.5 by 46.0 m with three tillage treatments and three replicates each. Soil cores were collected every 4.5 m along the 46.0 m length and oriented randomly along the width for a total of 10 cores per plot. Composite samples of each plot were formed from the 10 dried samples for that plot. This method provides an accurate analysis of POM for each plot which can then be generalized for surrounding land with identical land-use histories. SOC and SOM can also be accurately measured using this reduced area plot sampling technique. Other methods requiring fewer samples to get accurate SOC and SOM for larger plots involve carbon isotope analysis.

Carbon Isotopes and Soil Dynamics

The most common isotope of carbon is ^{12}C, which comprises 98.90% of all of the carbon on the planet. The majority of the remaining 1.10% is in the form of the carbon isotope ^{13}C, and a very small amount (<0.000001%) in the form of ^{14}C. All three of the carbon isotopes are distributed throughout the globe through the carbon cycle in various proportions. Carbon is transferred through a number of processes such as carbon fixation from the atmosphere through photosynthesis in plants, decomposition of organic matter in soil, respiration of plants and animals into the atmosphere, equilibrium between the ocean and atmosphere, and emissions by human activities. All of these processes influence the ratios of carbon isotopes in each system relative to each other. Relative isotope fractions can act as signatures which are used to track carbon cycle processes, including carbon soil dynamics.

Measuring carbon turnover rate in soil using the natural abundances of ^{13}C takes advantage of the natural fractionation of ^{13}C by different plant types. Fractionation of ^{13}C occurs during various photosynthetic processes which preferentially uptake the lighter isotope ^{12}C. This is due to the uptake of the lighter carbon isotope requiring less energy by the photosynthetic process. The result is that the ratio of ^{13}C to ^{12}C is lower in the resulting plant matter than in the atmosphere. The fractionation ratio of ^{13}C in plants also depends on which type of photosynthetic process it undergoes; C-3 or C-4. C-3 plants include beans, rice cotton and cool weather, year-long grasses; C-4 plants include sorghum, maize, and warm season grasses. Both processes use different enzymes in order to carry out photosynthesis which transforms CO_2 into a 3-carbon acid (3-phosphoglyceric acid) for C-3 plants, and a 4-carbon acid (oxaloatcetate) for C-4 plants.

The ratio of ^{13}C to ^{12}C is defined as $\delta^{13}C$ and is based on the equation:

$$\delta^{13}\text{C}\ ‰ = \frac{\frac{13C}{12C}\text{sample} - \frac{13C}{12C}\text{standard}}{\frac{13C}{12C}\text{standard}} \times \frac{1000}{1}$$

The standard that ^{13}C ratios are compared to is Pee Dee Belemnite which would have a $\delta^{13}C$ ‰ of 0. Fractionation of ^{13}C occurs differently for both plant types with $\delta^{13}C$ of approximately –27 ‰ for C-3 plants, and approximately –13 ‰ for C-4 plants.

Carbon isotope inputs in soils are directly associated with the plants that are growing in them so the $\delta^{13}C$ of plants will be transferred to the soil. This relationship is used by researchers to study the carbon turnover rate in soil based on the types of plants in a plot and the amount of time they are there. By planting either only C-3 plants in a plot and rotating to only C-4 plants after a fixed amount of time (or visa-versa) the change of $\delta^{13}C$ from the new to the old vegetation can be inferred. Clapp et al. (2000) began continuous planting of corn, a C-4 crop, in a field previously farmed under a rotation of oat and alfalfa, C-3 crops. After 13 years the $\delta^{13}C$ was measured to be less negative for each sample location and the amount gained was used to determine the loss of the original SOC with the C-3 crop label. This gives an indication of the rate of decomposition and turnover rate of the carbon in soil.

Natural abundances of ^{13}C in soil have also been used to reveal other soil processes. For example, SOC concentration decline with increased depth in the soil, as is expected, but $\delta^{13}C$ generally increases with increased depth in the soil. This indicates that soil carbon processes are active even when carbon concentrations are low (Feng, 1999). Some experiments have suggested that this increase in $\delta^{13}C$ with depth may be due to an increased component from microbial processes deeper in the soil profile (Van Dam et al., 1997; Bostrom et al., 2007). This phenomenon is poorly understood but may have a significant effect on global carbon dynamics considering that over half of the global estimated soil carbon is stored below the upper 30 cm of soil (Rumpel and Kogel-Knaber, 2010). Subsurface soil is also important for buffering atmospheric carbon since it is generally stable at longer timescales than near surface soil carbon (Paul et al., 1997). Deep soil has relatively low carbon concentrations suggesting a high potential for carbon storage.

Soil CO_2 Flux

Evaluating net changes in SOC storage over time requires assessment of inputs and outputs of SOC, and this is often done through measurements of soil CO_2 flux. As stated previously, carbon leaves and enters the soil in the form of CO_2 through the processes photosynthesis, and autotrophic and heterotrophic respiration of organisms associated with the soil. Autotrophic organisms produce their own food through photosynthesis which also fixes atmospheric CO_2, while heterotrophic organisms sustain themselves by consuming other organisms or SOM. Plant root respiration is an important autotrophic component of soil CO_2 flux, while heterotrophic components are primarily microbial respiration of decomposing organic residues (Kuzyakov, 2006).

Measurements of soil CO_2 flux include only the respiration of heterotrophic and autotrophic soil components, but net gains or losses of CO_2 from soil can be determined by measuring net ecological exchange (NEE). NEE is the difference between rates of soil CO_2 respiration and rates of soil CO_2 fixation through autotrophic photosynthesis. NEE is negative during periods when the rate of CO_2 fixation exceeds the rate of CO_2 respiration, and represents net removal of CO_2 from the atmosphere. The rate of CO_2 fixation, and respiration from both heterotrophic and autotrophic components in the soil are influenced by a variety of factors including air temperature, soil temperature, soil moisture, photosynthetic active radiation, plant density, organic matter content and more (Liu et al, 2010; Contasta et al., 2011; Fitter et al., 1998; Dai et al., 2017). Complex interactions among these factors determines the whether soils sequester more CO_2 than they release over time.

Total soil CO_2 flux is comprised of both heterotrophic and autotrophic components. Measuring the inputs and outputs of CO_2 from different components can provide an accounting of changing SOC stocks and help determine whether soil is acting as a net carbon source or sink. Analyzing how interactions between land-use, soil characteristics and environmental factors relate to magnitudes of soil CO_2 flux can inform land management decisions for optimizing soil carbon sequestration.

CHAPTER III

JOURNAL ARTICLE

Seasonal soil carbon fluxes in transitioning agricultural soils in Central Washington State: Relations to land-use, environmental factors and coil carbon-nitrogen characteristics

Introduction

Global atmospheric CO_2 reached 400 ppm in September 2016, up 30% from about 200 years ago (Kahn, 2017; IPCC, 2001). Atmospheric CO_2 continues to increase by 2 ppm per year, with major implications for global climate (e.g., Arce et al., 2014) such as higher global surface and ocean temperatures. Most of the increased atmospheric CO_2 is from the burning of fossil fuels, but it is estimated that 10-30% of the greenhouse gas (GHG) emissions since the 1980's are from converting natural ecosystems to agricultural uses (Janzen, 2014). Understanding how land management practices affect soil-atmosphere carbon cycling can inform practical approaches for increasing carbon storage in soils and increasing soil fertility.

The active carbon pool in soil, which includes organic and inorganic carbon, is estimated between 1700 and 2500 Pg; this pool represents the largest active terrestrial carbon pool compared to 620 Pg of carbon in vegetation, and 780 Pg of carbon in the atmosphere (Lal, 2010). Soil represents a large potential carbon source or sink dependent on management and climatic influences (Lal, 2004; Luo et al., 2017). Measuring net soil carbon budget balance requires accurate accounting of soil CO_2 flux.

Soil CO_2 flux comprises CO_2 respiration from floral cellular respiration, and decomposition of soil organic matter by heterotrophic microbial organisms. Rates of soil respiration are influenced by factors including: air temperature, soil temperature, soil moisture, photosynthetic active radiation, vegetation type/density, soil clay content, and soil nutrients and organic matter (Liu et al, 2010; Contasta et al., 2011; Fitter et al., 1998; Dai et al., 2017).

Numerous studies have documented the seasonal and interannual variability of soil CO_2 respiration and its relation to environmental factors including temperature and soil moisture. Air and soil temperature are closely linked; rises in each tend to increase soil CO_2 respiration by stimulating soil microbial activity, organic matter decomposition, plant-root activity, and oxidation (Boone et al., 1998; Yu et al., 2017). The influence of soil moisture on soil respiration is less clear, though generally higher moisture content enables plant and microbial activity acting to increase soil CO_2 respiration. Temperature and moisture interactions on soil respiration are often complicated, though studies have suggested that soil respiration is more sensitive to temperature fluctuations in soils with higher relative moisture content (Carlyle and Bathan, 1988; Harper et al., 2005).

Soil organic carbon (SOC) and soil organic nitrogen (SON) content has been shown to influence soil response to environmental factors and subsequent soil CO_2 flux variability (Zheng et al., 2009). Soils with higher SOC content are generally more sensitive to SOC decomposition with increasing temperatures (Zhou et al., 2009). In particular, carbon inputs to soils that already have relatively high SOC significantly increases soil CO_2 flux (Dai et al., 2017). SON has a strong influence on carbon cycling in soils because it is an important nutrient for plant growth (Lebauer and Treseder, 2008). Addition of nitrogen to soils has also been shown to increase carbon sequestration as well as stimulate soil respiration (Maaroufi et al., 2015; Chen et al., 2017).

This study examines seasonal soil CO_2 flux relationships between environmental factors, soil carbon-nitrogen characteristics, and land-use type in Kittitas Basin in central Washington State. In contrast to other studies that have examined these relationships, we use a holistic approach that examines how these relationships vary with season. Additionally, this study is unique in that it examines soil CO_2 flux relationships for multiple land-use types, including irrigated hay fields and vegetable gardens, in a semi-arid environment. Few if any soil CO_2 flux studies have been conducted in similar agricultural conditions. Thorough understanding of soil respiration response to variation in SOC and SON and environmental factors is important for predicting fluxes in soil carbon budgets. Management of SOC and SON through additives, tillage, irrigation and crop type can be optimized according to annual temperature and moisture patterns to achieve an ideal balance to maximize soil fertility and control soil CO_2 emissions to ensure a net uptake of carbon.

Materials and Methods

Study Area

Spoon Full Farm (47.1 ºN, 120.7 ºW) is located 520 m above sea level on flood plain alluvium of the Yakima River in Kittitas Valley, WA. Kittitas County is an important agricultural region ranked 39th of 3,079 United States counties in sale of agricultural products (USDA, 2012), and consists of a series of nested glacial outwash terraces, floodplains, alluvial fans and glacial moraines overlaying Columbia River Flood Basalts. According to US Soil Taxonomy Soil Survey Geographic Database (NRCS-SSURGO, 2019) Spoon Full Farm land consists of Weirman complex and Kayak-Weirman complex soils. Weirman soils are Torrifluventic Haploxerolls characterized by 0-2 % slopes and very gravelly-cobble sandy loam. Kayak soils are Aquandic Endoaqualls characterized 0-2 % slopes with ashy loam at the surface and increasingly gravelly and sandy with depth. Average annual precipitation is 22.6 cm rainfall and 53.6 cm snowfall, with most occurring from November to February. Annual average temperature is 8.9 ºC, with average high and low of 15.6 ºC and 2.2 ºC, respectively (NOAA, 2019). Irrigated farming of Timothy hay is the dominant agricultural practice in this valley. Spoon Full Farm has historically been farmed for Timothy hay using irrigation, synthetic fertilizers and occasional tilling for weed control. As of 2016, agricultural practices at the site were shifted, removing use of synthetic fertilizers and tilling, and adding rotational grazing of chickens, sheep and cattle. Additionally, a 3 ha section in the NW corner of the farm has been converted to no-till mixed vegetable garden with regular application of organic mint-hay compost, and organic N.

Sample Site Description

The study area is divided into three land-use types – vegetable garden (VG), hay fields (HF), and unfarmed (UF). Table 1 displays sample location descriptions and abbreviations for each sample site.

VG is a 3 ha area in the NW corner of the study area consisting of about 50 plots measuring 35 m x 13 m; each plot contains seven beds measuring 32 m x 0.75 m. Each bed is established by a single turning over of formerly hayed soil and an immediate application of 0.6 m^3 of organic mint hay compost (78 kg C m^{-3}, 9 kg N m^{-3}). Throughout the growing season, new beds receive one additional application of 0.3 m^3 while established beds receive two 0.3 m^3 applications, for a total annual compost application of 0.9 m^3 for new beds and 0.6 m^3 for established beds. Total annual VG compost amendments equate to a minimum of 19,400 kg C ha^{-1}, and 2,200 kg N ha^{-1}. Each bed also receives about 1.1 L of 12% organic N fertilizer annually totaling an additional 620 kg N ha^{-1}. During the growing season, plots receive daily scheduled drip or sprinkler irrigation dependent on vegetable type being grown.

HF represent 34 ha of Timothy hay fields that are divided into three separate sections;triangle field (TF), boot field (BF), and pivot field (PF). Each section is irrigated weekly throughout the growing season by sprinkler, while being managed to provide a series of rotational grazing and two rounds of harvesting through the growing season. Hay fields do not receive organic matter amendments.

UF is a 10 ha native shrub-steppe environment between the hay fields and the Yakima River on Weirman complex soils. It consists of native sage brush and grasses, and is rimmed by a stand of cottonwood trees. UF land has not historically been used for agricultural production, likely because its closer proximity to the Yakima River rendered the soil here was more gravelly and less fertile.

Table 1 – Sample location descriptions including land-use type, CO2 flux sample regime, max sample depth, basic site description and soil collar position details.

Sample Sites

Land Use	Sample Location		Flux Sample Type	Max Sample Depth (cm)	Description	Soil Collar Details
Vegetable Garden VG	**GMP-N**	Multiplexer North	Continous	30	Established composted bed	Bare soil near vegetation
	GMP-S	Multiplexer South	Continous	30	Established composted bed	Bare soil near vegetation
	GMP-G	Multiplexer Grass	Continous	30	Grassed garden path	Grass
	GMP-I	Multiplexer Interbed	Continous	N/A	Transition zone between bed and grass	Bare soil near grass and vegetation
	WN	West-North	Survey	40	Established composted bed	Bare soil near vegetation
	EM	East-Middle	Survey	30	New compsted bed	Bare soil near vegetation
	ES	East-South	Survey	30	New compsted bed	Bare soil near vegetation
Hay Field HF	**TF-N**	Triangle Field North	Survey	60	Timothy hay harvesting/grazing	Hay
	TF-S	Triangle Field South	Survey	40	Timothy hay harvesting/grazing	Hay
	BF-N	Boot Field North	Survey	60	Timothy hay harvesting/grazing	Hay
	BF-S	Boot Field South	Survey	60	Timothy hay harvesting/grazing	Hay
	PF-N	Pivot Field North	Survey	40	Timothy hay harvesting/grazing	Hay
	PF-M	Pivot Field Middle	Survey	40	Timothy hay harvesting/grazing	Hay
	PF-S	Pivot Field South	Survey	60	Timothy hay harvesting/grazing	Hay
Unfarmed UF	**E-SB**	East Sage Brush	Survey	40	Between native sage brush	Wild grass
	WN-SB	West-North Sage Brush	Survey	60	Between native sage brush	Wild grass
	WS-SB	West-South Sage Brush	Survey	40	Between native sage brush	Wild grass
	E-T	East Trees	Survey	40	Under cottonwood canopy	Wild grass and leaves

Soil Sampling and Analysis

Sample locations are shown in Figure 1A. Garden Multiplexer (GMP, Figure 1B) represents four sites in the vegetable garden where continuous CO2 flux measurements were made. Soil samples were collected during June and July of 2018. Each sample location consisted of a 10 m x 25 m plot with soil cores taken every 5m along the length, and oriented randomly along the width for a total of 5 soil cores per plot. VG soils were sampled at depth intervals 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm minimum, with depth 30-40 cm being reached when possible through the extremely gravely subsurface. HF and UF soils were sampled at depth intervals 0-10 cm, 10-20 cm, and 20-40 cm minimum, with depth 40-60 cm being reached when possible. Composite samples were formed from the 5 cores for each sample location at each depth interval to account for spatial heterogeneity of soil properties (method adapted from Cambardella and Elliot, 1992). SOC, SON, δ13C, and δ15N of each depth interval composite sample and mint compost applied to garden beds were analyzed with a Thermo Scientific Elemental Analyzer connected through a continuous flow system to Thermo Scientific Delta V Plus Isotope Ratio Mass Spectrometer (IRMS) in the Geological Science Department of CWU. Uncertainties based on standard deviation of acetanilide standard: SOC ± 0.53%, SON ± 0.06%, δ13C ± 0.19‰, δ15N ± 0.12‰.

Soil bulk density was determined by gathering one sample for each sample location at each depth interval, including material > 2 mm, with a fixed volume sampler. Particles > 2 mm were sieved and weighed, then converted to a volume based on the density of quartz (2.648 g cm^{-3}), since the majority of particles > 2 mm were dominantly felsic composition. Volume of particles > 2 mm was subtracted from total sample volume to find bulk density of remaining soil (particles < 2 mm). In some cases when soil and land-use were considered comparable, bulk

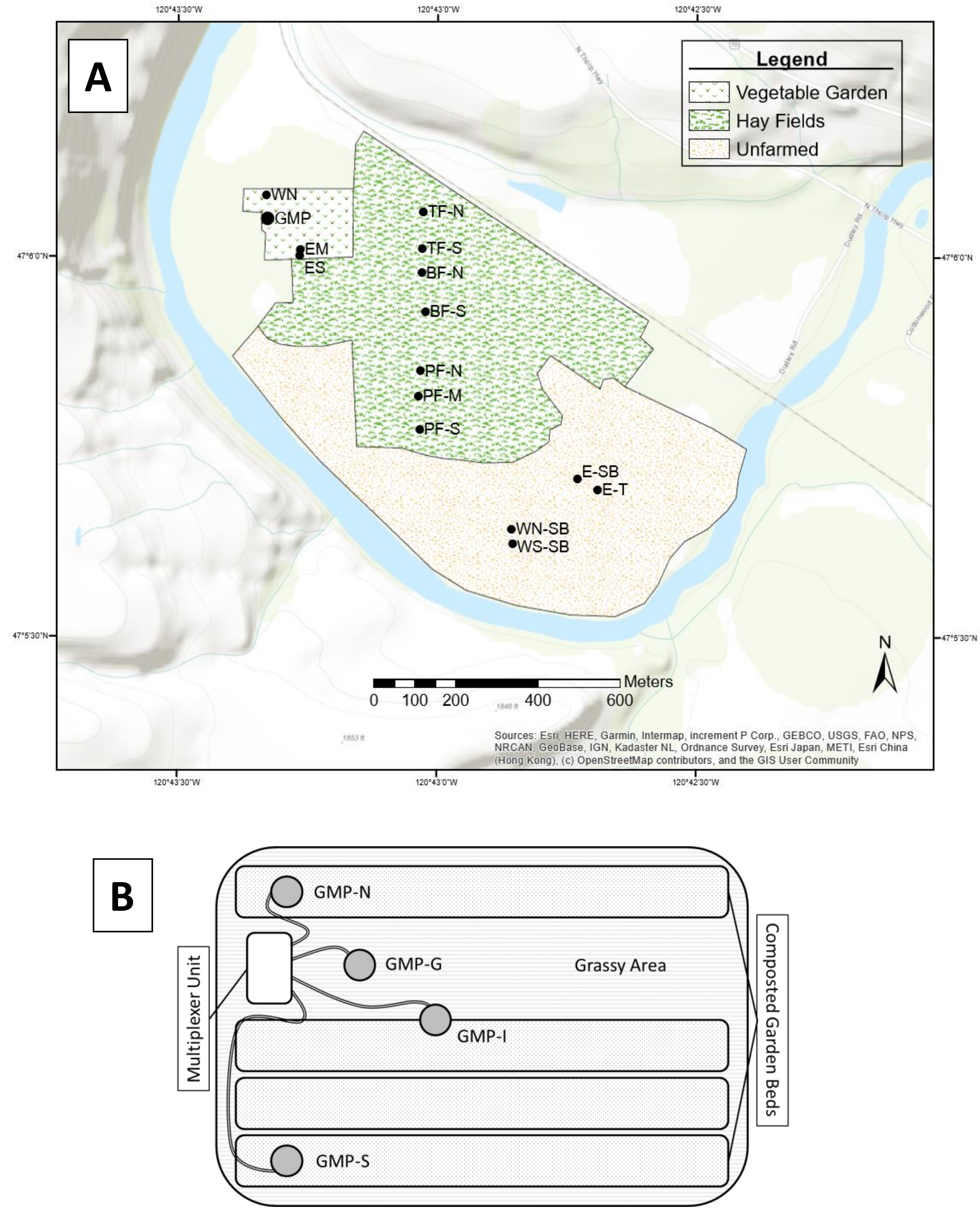

Figure 2 – (A) Map of Spoon Full Farm showing land-use areas and sample locations. (B) Inset of Garden Multiplexer (GMP) sample location showing configuration of continuous measurement sample locations connected through Licor Multiplexer Unit (not to scale).

densities at each depth were averaged to account for soil heterogeneity and sampling uncertainties. VG established-bed bulk densities comprise G-WN, GMP-N, and GMP-S, VG new-bed bulk densities comprise G-EM, and G-ES, and GMP-G bulk density is measured individually due to its unique soil type. Bulk density of all seven HF sample locations are averaged due to similar soil characteristics. Bulk density of UF sage brush locations are averaged while UF-ET is measured individually.

Grain size distribution of sample locations was determined through a series of sieving and laser particle measurement. Sieve fractions > 2 mm, and 1-2 mm were removed. Then 1.5-2.0 g of the <1 mm soil was mixed with 80 mL 9.0 mmol/L sodium hexametaphosphate ($Na_6P_6O_{18}$) solution to disaggregate clay particles over 24 hrs for analysis via Malvern Mastersizer 3000 with attached Hydro LV automated wet sample dispersion (Sperraza et al., 2009).

Soil Respiration

Surface soil CO_2 flux was measured at each sample location using a LI-8100A Automated Soil CO_2 Flux System (Licor Inc.), which determines CO_2 concentrations using an infrared gas analyzer. PVC collars (20 cm diameter) were pushed 6-8 cm into soil, leaving 3-5 cm of the upper collar exposed. Collars were allowed 24 hours before initial measurements to prevent errors from immediate soil disturbance, though it has been suggested that soil collars may continue to decrease root respiration with time by severing root networks (Heinemeyer et al., 2011). Sample sites GMP-N, GMP-S, GMP-G, and GMP-I were measured for soil CO_2 flux with 20 cm opaque, and for net ecological exchange (NEE) with transparent continuous chambers (LI-8100-104 and LI-8100-104C) fitted over soil collars and connected to the CO_2 analyzer through the LI-8150 Multiplexer unit to operate continuous CO_2 measurements. Due to electricity proximity limitations, all other sample site CO_2 flux was measured with a 20 cm respiration survey chamber (LI-8100-103) fitted over soil collars. LI sample chambers are designed with a pressure vent to prevent soil respiration sampling errors associated with wind and pressure gradients (Bain et al., 2005).

Table 2 – Start and end dates of representative soil CO_2 flux sample periods with relative climate attributes for each season. Measurements were not conducted during the winter due to heavy snowfall over soil. Average seasonal values based on 1981-2010 normals (NOAA, 2019).

Representative CO_2 Flux Sample Periods

Season	Start	End	Climate	High Temp. Avg. (°C)	Low Temp. Avg. (°C)	Avg. Precipitation (mm)
Summer	7/10/2018	9/9/2018	Hot and dry	27.3	10.9	9.7
Fall	11/18/2018	12/2/2018	Cool and wet	16.0	1.4	19.0
Winter	-	-	Cold and snowy	2.7	-5.9	33.7
Spring	3/25/2019	4/11/2019	Warm and wet	16.0	1.8	16.0

Continuous measurements were conducted consistently through seasonal periods (Table 2) at 2 hour intervals, rotating through the 4 GMP sample locations. During the summer and spring season periods collars of GMP-N, GMP-S and GMP-I were regularly cleared of plants and weeds leaving bare soil. Each continuous measurement consists of a 30 sec system pre-purge to prepare for 2 min CO_2 flux sampling, followed by a 30 sec system post-purge. Final measurement results are the average of 3 consecutive measurements. Temperature and relative humidity were measured in the chamber during measurements, while soil moisture and soil temperature were measured to 5 cm depth with a GS1 soil moisture probe (LI-8150-205) and soil temperature thermistor (LI-8150-203) connected to the continuous chambers. Probe readings are dependents on where they are placed, so their position must be consistent. Additionally, soil moisture probe readings compared with gravimetric measurements of soil moisture agree much better at lower % soil moisture. Continuous measurements were taken with an opaque chamber except during periods when the single available transparent chamber was rotated through the four sample sites. Each continuous sample location recorded transparent chamber measurements a minimum 2 days during each sampling period to estimate seasonal net carbon exchange or net ecological exchange (NEE).

Survey chamber measurements were conducted each season for all other sample locations. Two rounds of sampling were conducted during summer and one round in fall and spring. Measurements were taken between 11:00 AM and 5:00 PM in order to compare seasonal afternoon CO_2 flux for each land-use type. Vegetation within soil collars was not altered to preserve site conditions. Survey measurements consist of a 30 sec system pre-purge to prepare for 2 min CO_2 flux sampling, followed by a 30 sec system post-purge. Final measurement results are the average of 12 consecutive measurements. Temperature and relative humidity were measured in the chamber during measurements, while soil moisture was measured to 5 cm depth with a GS1 soil moisture probe (LI-8100-205) and soil temperature was measured to 15 cm depth with a soil temperature probe (6000-09TC Omega) connected to LI-8100A auxiliary sensor interface. All survey measurements were made with an opaque chamber.

Statistical Analysis

CO_2 flux variation from continuous sample locations was compared to chamber temperature, relative humidity, soil moisture and soil temperature by statistical analysis via Pearson correlation (two-tailed). Correlations were analyzed for each sampling season individually and annually. Correlation is considered significant if significance value (p) is below 0.05; a correlation is considered strong if correlation coefficient (r) is greater than 0.7, moderate between 0.7 and 0.3, and weak below 0.3.

Afternoon CO_2 flux variation from survey chamber sample locations, and daytime (11:00 AM – 5:00 PM) CO_2 flux variation from continuous measurements was compared with soil characteristics: SOC (g cm^{-3}), SON (g cm^{-3}), C:N, $\delta^{13}C$, and $\delta^{15}N$. Total weighted average of soil characteristics for two depths, 10 cm and 30 cm, was calculated for each land-use type and compared with seasonal and annual CO_2 flux via Pearson correlation (two-tailed). Correlation is considered significant if significance value is below 0.05, however significance values below 0.1 are also considered suggestive of a significant relationship due to small sample sizes under each land-use type, and warrant further study. To compute average annual CO_2 flux winter values were estimated at 50% fall season values due to low temperatures causing reduced CO_2 respiration (Lloyd, 1994). Annual CO_2 flux is considered the average of all seasons. Sample location GMP-G is excluded from VG correlation since it is grass and does not represent the composted garden bed land-use type. GMP-N $\delta^{13}C$ and $\delta^{15}N$ are excluded due to anomalously high values suggesting analysis error.

Results

Soil properties of land-use types

Soils of different land-use types show distinct carbon and nitrogen characteristics (Figure 2). Error bars represent one standard deviation of sample sites for each land-use type, and SOC-SON is reported as % by weight. VG soils have the greatest SOC and SON concentrations at all depths of the soil profile; averaging 8.2 % SOC and 0.9 % SON in the upper 5 cm, and about 1.0 % SOC and 0.1 % SON between 30 and 40 cm depth. HF and UF soils have similar SOC and SON concentrations with depth; averaging 2.0 % SOC and 0.16 % SON in the upper 10 cm, and 0.5 % SOC and 0.060 % SON between 40 and 60 cm depth. In contrast, VG has the lowest $\delta^{13}C$ with an average value of -26.7 ‰ in the upper 5 cm, and -25.7 ‰ between 30 and 40 cm depth. HF and UF share similar $\delta^{13}C$ profiles with average of -26.4 ‰ in the upper 10 cm, and -24.9 ‰ between 20 and 40 cm depth. For $\delta^{15}N$, the two farmed land uses, VG and HF, share similar profile concentrations and UF has the lowest $\delta^{15}N$ with 2.6 ‰ in the upper 10 cm, and 3.4 ‰ between 40 and 60 cm. Average of three analyzed compost samples resulted in 35 % SOC, 4.1 % SON, -26.5 ‰ $\delta^{13}C$, and -3.4 ‰ $\delta^{15}N$.

Seasonal continuous variation in CO_2 flux

Soil CO_2 flux and environmental factors measured with the LICOR continuous measurement system (multiplexer) displayed patterns that varied seasonally (Figure 3). During the summer period there was significant variation of average CO_2 flux over time and among the four sample location (Figure A). GMP-I consistently had the lowest flux through summer averaging 3.1 µmol m^{-2} s^{-1} followed by GMP-S (5.2 µmol m^{-2} s^{-1}), GMP-G (6.5 µmol m^{-2} s^{-1}), and GMP-N (7.9 µmol m^{-2} s^{-1}). Each sample location began with an increase in flux corresponding with concurrent increase in soil and air temperature and decreased relative humidity. Soil moisture stayed relatively consistent around 35% for sample locations excluding GMP-N which starts at about 23% and gradually declined to below 10% during the summer period. Sprinkler irrigation was not as direct at GMP-N compared with other GMP sample locations. CO_2 flux for sample locations, excluding GMP-N, peaks early in the sampling period (between Aug-6 and Aug-9) then gradually declined over the rest of the period concurrent with air and soil temperature peak and decline, and inversely correlated with relative humidity. GMP-N showed the largest summer variability starting below 4.0 µmol m^{-2} s^{-1} on Jul-31 and increasing, with some fluctuation, to peak at 12 µmol m^{-2} s^{-1} on Aug-21 then gradually declined to 6 µmol m^{-2} s^{-1} at the end of the summer sampling season on Sep-9.

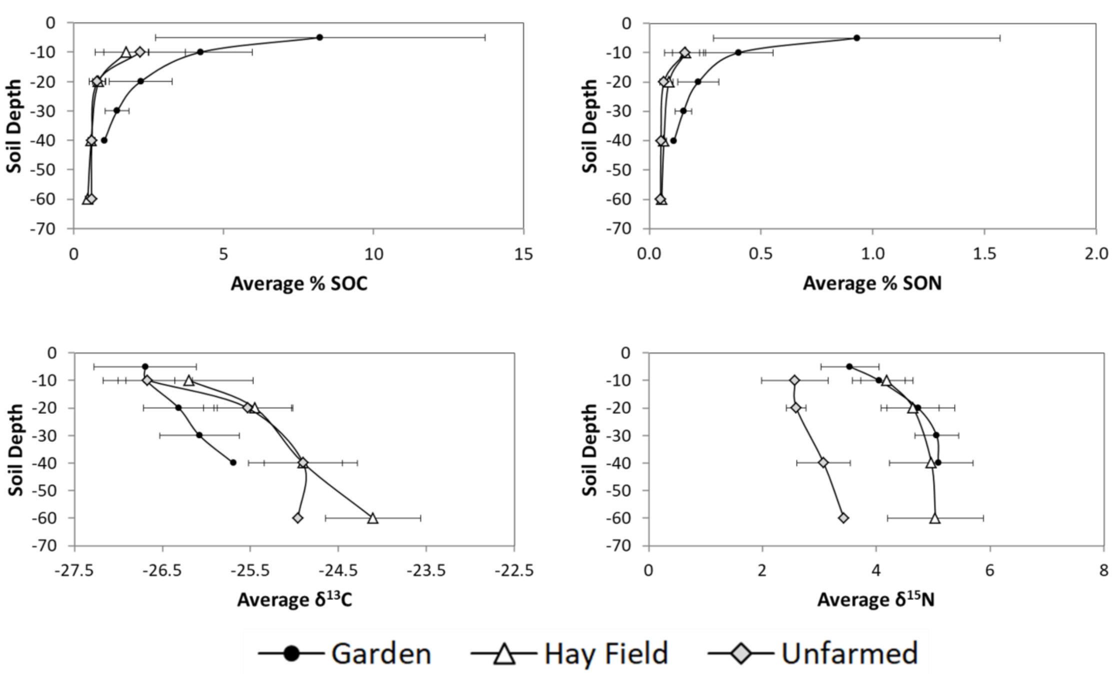

Figure 3 – Average soil characteristics (SOC, SON, $\delta^{13}C$, and $\delta^{15}N$) for land-use types (vegetable garden, hay field, and unfarmed) at measured depth intervals. Error bars represents one standard deviation of measured values for each depth interval of individual land-use types, and SOC-SON is % by weight.

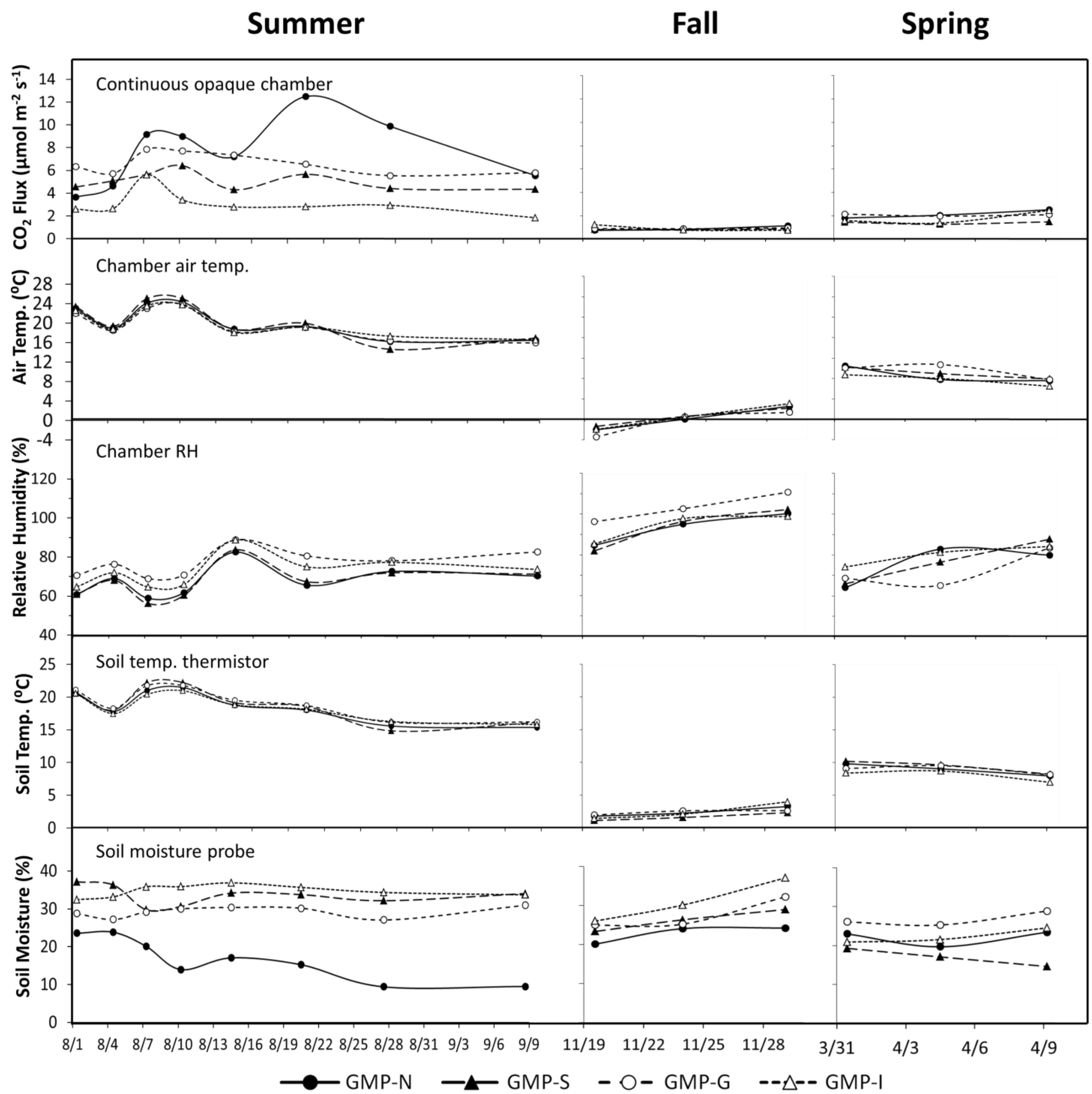

Figure 4 – Seasonal continuous measurement period CO_2 flux (μmol m^{-2} s^{-1}), air temperature (ºC), relative humidity (%), soil temperature (ºC), and soil moisture (%). Plotted points on smoothed lines represent averaged measurements over varying 3-10 day time periods (dependent on duration and continuity of measurements). Site names are garden multiplexer (GMP) north (N), south (S), grass (G) and interbed (I).

During the fall period CO_2 flux among all sample locations remained consistently low (average 0.9 µmol m^{-2} s^{-1}), with little continuous variation among them. All measured environmental factors gradually increased over the fall sampling period. Air and soil temperature among all sampling locations was very similar, relative humidity inversely mirrored air temperature, and SM varied the most among all locations, GMP-I being 5-10% greater than GMP-N with GMP-G and GMP-S intermediate.

During the spring period CO_2 flux among all sample location remained consistent at approximately twice the flux of the fall period (1.7 µmol m^{-2} s^{-1}), with slight continuous variation among them. Air temperature and soil temperature slightly decreased gradually over the course of the sampling period for all locations. There was a range of about 10% between SM of GMP-S and GMP-G at the beginning of the period which increased to a range of nearly 20% at the end of the period as GMP-S gradually decreased, while GMP-N and GMP-I remained intermediate.

Seasonal diurnal CO_2 flux pattern variation

Diurnal soil CO_2 flux showed distinctly different seasonal pattern both in magnitude and in daily fluctuations that correlated with variations in environmental factors (Figure 4). Highest diurnal flux variation was observed in the summer period with average variation for nighttime low and daily peak being between 4 µmol m^{-2} s^{-1} (GMP-I) and 8 µmol m^{-2} s^{-1} (GMP-N). Average summer peak for all sites was at around 14:00, matching the timing of the peak in air and soil temperature and low in relative humidity. Average daily air temperature, soil temperature and relative humidity was very similar for all sample locations; however, GMP-S and GMP-G average slightly higher soil temperature (2-4 ºC) during the afternoon hours (11:00-16:00). Sample locations GMP-N and GMP-I had more consistent shade cover from nearby

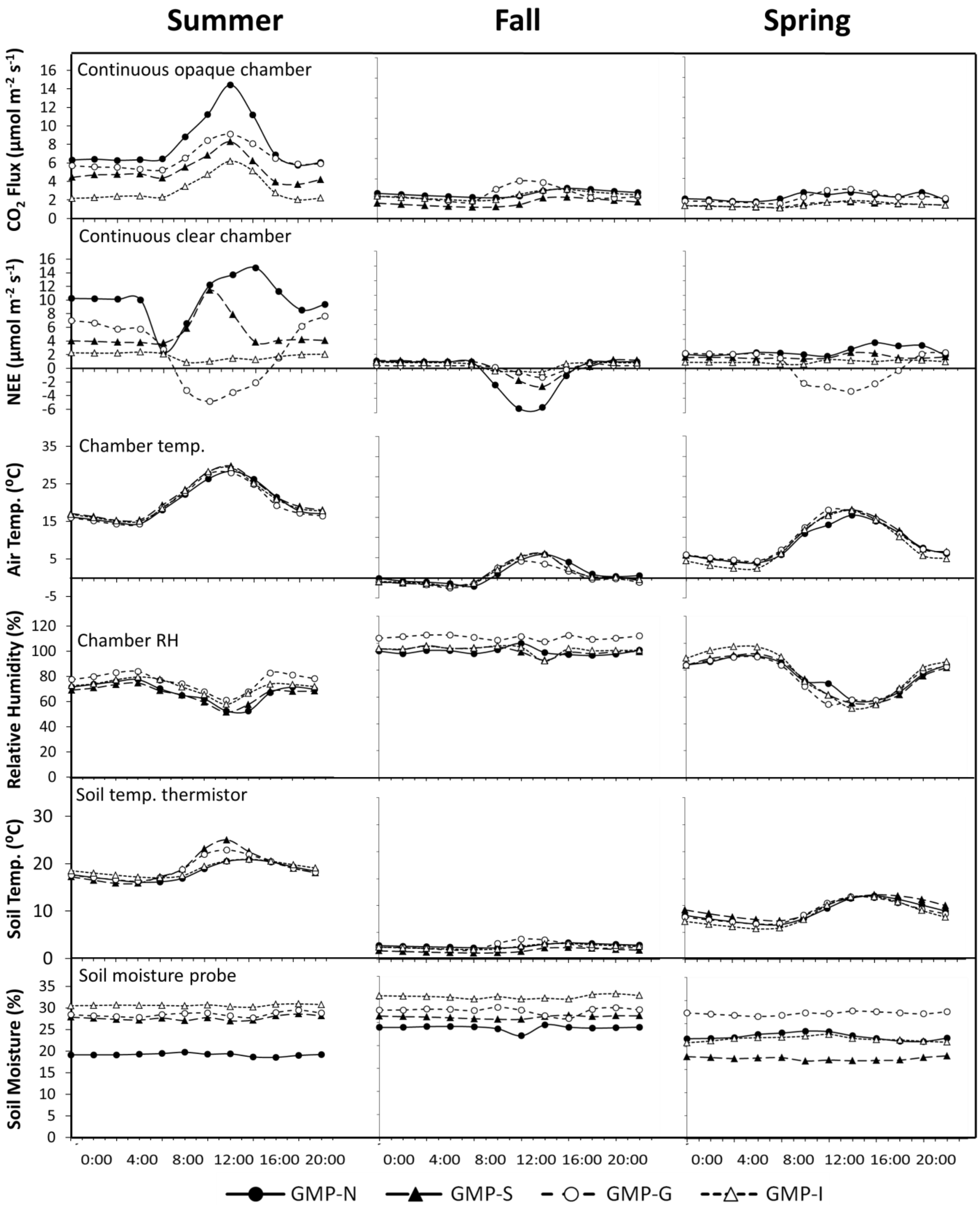

Figure 5 – Average seasonal diurnal patterns of CO_2 flux (µmol m^{-2} s^{-1}), NEE (µmol m^{-2} s^{-1}), air temperature (ºC), relative humidity (%), soil temperature (ºC), and soil moisture (%) for four multiplexer sites in the vegetable garden. Plotted points on smoothed lines are average seasonal measurements of 2 hr intervals.

vegetation. SM did not show any diurnal variation for any sample location, but daily average SM for GMP-N was 7-10% lower than other sample locations. Average diurnal net ecological exchange (NEE) of carbon varied greatly among sample locations based on the vegetation in and around soil collars. The period of observation of NEE in clear chambers was 2 days, significantly shorter than the soil CO_2 flux measurements using opaque chambers. The comparison of these fluxes showed relative CO_2 contributions of plant respiration between sample locations. GMP-G is the only location in which negative NEE was observed during the afternoon, indicating a period of net CO_2 uptake by soils and plants within the collar. All other sample locations maintained positive NEE, indicating net carbon flux out of the soil. GMP-N NEE was greatest throughout the night and daytime, reaching an afternoon peak similar to average diurnal CO_2 flux. GMP-S showed a similar CO_2 flux-NEE pattern which highlights the large contribution of SOC decomposition to overall soil CO_2 emission of these mostly vegetation-free zones. Unlike all other sample locations, GMP-I did not show diurnal NEE variation.

Very little variation in diurnal CO_2 flux was observed during the fall period. CO_2 flux rate remained around 2 µmol m^{-2} s^{-1} for all sample locations with a slight peak to nearly 4 µmol m^{-2} s^{-1} for GMP-G. During this period average diurnal soil temperature, soil moisture and relative humidity were similarly stable, while daily soil temperature increased in the afternoon concurrent with the daily GMP-G flux peak. Soil temperature, air temperature and relative humidity were similar for all sample location, while soil moisture ranged from about 25-31% with GMP-N being low and GMP-I high. Negative NEE in the afternoon was observed for all sample locations during this period. GMP-N and GMP-S soil chamber collars were not regularly cleared of vegetation during the fall period so low SOC decomposition rates and photosynthetic carbon fixation from vegetation buildup resulted in these locations acting as net carbon dioxide sinks during the fall afternoons reaching rate of -6.0 μmol m^{-2} s^{-1} for GMP-N around noon during this sampling period. All periods of lowest daily NEE for all sample locations occurred during peaks of daily average air temperature.

Diurnal CO_2 flux rates for the spring period were very similar to the fall period in both magnitude and lack of variation, despite relatively large differences in soil temperature, air temperature and relative humidity. Average spring soil and air temperatures are greater than 7 ºC higher than the fall, and relative humidity about 20% lower. These three environmental factors also show large daily variation similar to the summer period; however, unlike the summer period, there was no correlating daily variation in CO_2 flux. Relative percentage of soil moisture between sample locations shifted this season with highest values for GMP-G at about 27% to lowest at GMP-S low of about 16%, GMP-N and GMP-I both average about 21% soil moisture. Daily NEE variation did not differ from CO_2 flux for any location other than GMP-G which showed a daily decline to 4 μmol m^{-2} s^{-1} during the afternoon concurrent with average daily timing for soil and air temperature peaks and relative humidity low. During the spring period continuous sample locations, excluding GMP-G, have net CO_2 flux out of the soil.

Environmental factors correlation with CO_2 flux and NEE

Comparing CO_2 flux and NEE measured using the multiplexer and continuous chambers with environmental factors through correlation analysis shows significant relationships both seasonally and annually (Table 3).

GMP-G CO2 flux was significantly ($p < 0.01$) strongly ($r > 0.7$) correlated with air and soil temperature during the annual, summer and spring periods. However, this same correlation

Table 3 – Pearson correlation coefficients between continuous seasonal CO_2 flux and NEE observations, and concurrently measured environmental factors; air temperature (AT), relative humidity (RH), soil temperature (ST) to 15 cm depth, and soil moisture (SM) to 5 cm depth.

		Soil CO_2 Flux				NEE			
		AT (°C)	RH (%)	ST (°C) (15cm)	SM (%) (5cm)	AT (°C)	RH (%)	ST (°C) (15cm)	SM (%) (5cm)
Annual	GMP-N	0.679**	-0.520**	0.624**	-0.519**	0.722**	-0.378**	0.791**	-0.040
	GMP-S	0.806**	-0.555**	0.813**	0.492**	0.432**	-0.118	0.428**	0.226
	GMP-G	0.900**	-0.492**	0.948**	0.141**	-0.151	0.298**	0.170	0.041
	GMP-I	0.686**	-0.484**	0.588**	0.283**	0.447**	-0.528**	0.609**	-0.090
Summer	GMP-N	0.479**	-0.447**	0.230**	-0.309**	0.485*	-0.564**	0.580**	-0.230
	GMP-S	0.624**	-0.503**	0.550**	-0.492**	0.719**	-0.517**	0.502*	-0.396
	GMP-G	0.835**	-0.415**	0.866**	0.026	-0.773**	0.672**	-0.514*	0.305
	GMP-I	0.661**	-0.446**	0.472**	-0.046	-0.130	-0.234	0.210	-0.914**
Fall	GMP-N	0.198	0.239*	0.665**	0.397**	-0.839**	0.109	-0.013	0.241
	GMP-S	0.070	-0.242*	0.384**	0.327**	-0.062	0.147	0.391	-0.012
	GMP-G	-0.120	0.107	-0.048	0.133	-0.557**	0.394	0.109	-0.095
	GMP-I	-0.103	-0.231*	-0.058	-0.516**	-0.863**	0.017	-0.464*	-0.357
Spring	GMP-N	0.194*	-0.128	0.136	0.168	0.130	-0.065	0.391	-0.231
	GMP-S	0.426**	-0.182*	0.262**	-0.251**	0.449*	-0.288	0.482*	-0.241
	GMP-G	0.806**	-0.642**	0.817**	0.179	-0.611**	0.321	-0.311	-0.182
	GMP-I	0.511**	-0.422**	0.642**	-0.484**	0.052	0.250	0.375	-0.413

* indicates significance $p<0.05$, **indicates significance $p<0.01$

was not significant for the fall sampling period. GMP-S CO_2 flux also showed significant strong correlation with air and soil temperature annually, but the strength of the correlation was moderate for the summer (r : air temperature = 0.624, soil temperature = 0.550), and relatively weak for the spring period (r : air temperature = 0.426, soil temperature = 0.262). For the fall period GMP-S CO_2 flux did not show a significant correlation with air temperature but did show a weak significant correlation with soil temperature (r = 0.384). GMP-N correlation of CO_2 flux with soil and air temperature was moderately strong for the annual period, relatively much weaker for the summer period (r : air temperature = 0.479, soil temperature = 0.230), and very weak to non-significant in spring. However, fall soil temperature was moderately correlated with soil CO_2 flux for GMP-N (r = 0.665), representing the most significant correlation for any sample location for the fall period. GMP-I CO_2 flux was moderately correlated with soil and air temperature for the annual, summer, and spring periods, and not significantly correlated for the fall period.

Correlations of soil moisture and CO_2 flux appear to have the most variability among sample locations and sample periods. GMP-G has consistently low or insignificant correlations for all periods. GMP-I has low or insignificant correlations for the annual and summer periods, but moderate negative correlations for the fall and spring periods. GMP-N and GMP-S display the strongest correlations between annual soil moisture and CO_2 flux; however they are opposite one another, GMP-N being negative ($r = -0.519$) and GMP-S positive ($r = 0.492$).

Correlations between NEE and environmental factors bear some significant differences with CO_2 flux correlations. GMP-G NEE displayed strong or moderately strong negative correlations with air temperature for all seasonal periods, though interestingly the correlation for the annual period is not significant. Soil temperature at GMP-G does not correlate with NEE except possibly in the summer period when there is a moderate negative correlation. GMP-N annual NEE was strongly correlated with both soil and air temperature, but only moderately for the summer period, strongly for only air temperature in the fall period, and insignificantly for all others. GMP-S NEE was strongly correlated with air temperature during the summer period, but other sample locations were either weakly correlated for soil and air temperature during the summer or not at all. GMP-I only showed significant seasonal NEE correlation with air and soil temperature during the fall season but showed an overall moderately positive correlation for the annual period.

Soil carbon-nitrogen correlation with afternoon CO_2 flux

Comparing correlations of seasonal and annual CO_2 flux with carbon and nitrogen soil characteristics among land-use types reveals some potentially significant variation. Table 4 shows weighted means of soil characteristics to 10 and 30 cm depth, and afternoon soil CO_2 flux for each sample site. However, correlation analysis of this data is limited by small sample sizes. Soil CO_2 flux survey chamber measurements were taken twice in the summer, and once in both the fall and the spring; and each land-use type is represented by 4-7 sample locations. Some of the correlations found in this study would likely be statistically significant if more measurements were taken, so Pearson correlation significance values (p) between 0.05 and 0.1 are also considered.

Table 4 – Weighted average of SOC, SON, $\delta^{13}C$ and $\delta^{15}N$ to 10 cm and 30 cm depth, and average seasonal afternoon CO2 flux for each sample location.

		10 cm Depth Wtd. Avg.				30 cm Depth Wtd. Avg.				Seasonal Afternoon CO_2 Flux ($\mu mol\ m^{-2}\ s^{-1}$)			
		SOC ($g\ cm^{-3}$)	SON ($g\ cm^{-3}$)	$\delta^{13}C$	$\delta^{15}N$	SOC ($g\ cm^{-3}$)	SON ($g\ cm^{-3}$)	$\delta^{13}C$	$\delta^{15}N$	Summer	Fall	Spring	Annual
VG	GMP-N	4.69	0.48	-	-	3.01	0.30	-	-	10.25	0.84	2.42	3.48
	GMP-S	2.49	0.27	-26.47	3.55	1.82	0.19	-26.56	3.83	6.19	0.79	1.53	2.23
	GMP-G	2.24	0.21	-26.69	4.32	1.35	0.14	-26.40	4.86	7.79	0.89	2.50	2.91
	G-WN	4.69	0.51	-27.39	3.19	2.51	0.27	-27.03	3.41	4.04	1.01	5.69	2.81
	G-EM	1.88	0.20	-26.46	3.63	1.48	0.15	-26.50	4.31	2.86	0.63	1.05	1.21
	G-ES	1.53	0.16	-26.68	3.86	1.37	0.14	-26.38	4.10	2.38	0.84	2.10	1.43
HF	TF-N	2.89	0.25	-27.34	4.60	1.32	0.12	-26.58	4.95	9.81	2.22	1.61	3.69
	TF-S	2.16	0.20	-26.21	4.86	1.13	0.11	-25.99	5.18	7.68	1.18	2.05	2.88
	BF-N	1.22	0.12	-25.52	4.37	0.84	0.09	-25.39	4.54	5.22	1.60	1.94	2.39
	BF-S	1.20	0.11	-25.76	4.03	0.81	0.08	-25.65	4.12	6.15	1.36	2.18	2.59
	PF-N	1.42	0.13	-26.80	3.83	0.66	0.06	-26.17	4.10	7.30	1.82	3.93	3.49
	PF-M	1.11	0.11	-25.33	3.54	0.60	0.06	-25.10	3.89	7.32	2.04	2.37	3.19
	PF-S	1.22	0.12	-26.41	4.05	0.79	0.08	-25.62	4.50	7.04	1.09	2.08	2.69
UF	E-SB	1.30	0.10	-26.68	2.52	0.84	0.07	-25.90	2.75	0.51	1.37	1.88	1.11
	WN-SB	1.99	0.15	-26.35	3.41	0.98	0.08	-25.89	3.16	0.86	1.21	3.46	1.54
	WS-SB	0.66	0.06	-26.26	2.18	0.54	0.05	-25.44	2.37	0.32	2.43	1.83	1.45
	E-T	2.46	0.16	-27.38	2.17	1.17	0.08	-26.98	2.46	2.43	2.56	2.38	2.16

When comparing all of the soil C and N data to annual soil CO_2 flux data, there appears to little to no relationship other than a moderate correlation between soil CO_2 flux and $\delta^{15}N$. However, comparing all land-use type characteristics to individual sample period CO_2 fluxes shows apparent associations at different times of year (Table 5). The summer period showed moderate negative correlation (r = 0.611) between flux and C/N to 30 cm depth, and a strong correlation (r = 0.805) with $\delta^{15}N$ to 30 cm depth. During the fall the relationship between flux and C/N shifts to become positive and more correlated with the upper 10 cm of the soil profile (r = 0.616). This season also displays moderate negative correlation with flux and SON, but not $\delta^{15}N$. Then in the spring all correlations become very weak, except for potentially significant moderate correlation with SOC and SON in the upper 10 cm of the soil profile.

Table 5 – Pearson correlation coefficients between seasonal afternoon CO2 flux and weighted average of SOC, SON, C/N, $\delta^{13}C$, and $\delta^{15}N$ to 0-10 cm and 0-30 cm depth. Sample sizes listed in column n.

			10 cm Depth Weighted Average					**30 cm Depth Weighted Average**				
		n	**SOC g cm^{-3}**	**SON g cm^{-3}**	**C/N**	**$\delta^{13}C$**	**$\delta^{15}N$**	**SOC g cm^{-3}**	**SON g cm^{-3}**	**C/N**	**$\delta^{13}C$**	**$\delta^{15}N$**
Annual	**All**	16	0.404	0.396	-0.264	-0.060	0.560**	0.295	0.322	-0.434	-0.035	0.564**
	VG	5	0.935**	0.923**	0.239	-0.749	-0.857	0.977***	0.978***	0.928**	-0.916*	-0.935*
	HF	7	0.593	0.563	0.798**	-0.692*	-0.078	0.390	0.320	0.525	-0.643	0.030
	UF	4	0.721	0.632	0.734	-0.716	-0.252	0.729	0.650	0.721	-0.813	-0.303
Summer	**All**	16	0.358	0.379	-0.453*	0.076	0.775**	0.341	0.392	-0.611***	0.012	0.805***
	VG	5	0.653	0.620	0.181	0.064	-0.423	0.814*	0.784	0.820*	-0.246	-0.536
	HF	7	0.837**	0.823**	0.870**	-0.768**	0.285	0.684**	0.642	0.556	-0.727*	0.426
	UF	4	0.865	0.768	0.942*	-0.913*	-0.235	0.899*	0.821	0.936*	-0.977**	-0.198
Fall	**All**	16	-0.308	-0.420*	0.616***	-0.056	-0.386	-0.460	-0.545**	0.494**	0.195	-0.397
	VG	5	0.661	0.686	0.288	-0.898*	-0.590	0.539	0.580	0.541	-0.919*	-0.666
	HF	7	0.347	0.313	0.509	-0.241	-0.233	0.177	0.112	0.228	-0.239	-0.220
	UF	4	-0.026	-0.174	0.227	-0.437	-0.834	0.029	-0.117	0.275	-0.348	-0.909*
Spring	**All**	16	0.455*	0.462*	-0.005	-0.335	-0.122	0.299	0.303	0.035	-0.292	-0.182
	VG	5	0.711	0.742	0.144	-0.995***	-0.788	0.529	0.579	0.417	-0.977**	-0.797
	HF	7	-0.359	-0.378	-0.035	-0.117	-0.536	-0.442	-0.486	0.101	-0.075	-0.537
	UF	4	0.604	0.724	0.184	0.110	0.868	0.029	0.620	0.274	-0.158	0.807

* indicates significance $p<0.1$, ** indicates significance $p<0.05$, ***indicates significance $p<0.01$

VG land area reveals significant ($p < 0.01$) robust relationships between annual soil CO_2 flux and 10 cm and 30 cm depth soil profile SOC ($r = 0.977$) and SON ($r = 0.978$). However C/N correlation was dramatically different between upper 10-cm ($r = 0.239$), and 30-cm depth ($r = 0.928$). These relationships are somewhat weaker during the summer period with potentially significant ($p < 0.1$) relationships between flux and 30-cm depth SOC and C/N ratios. The spring period shows one significant, but strong ($r = -0.995$), negative correlation with $\delta^{13}C$, and potential significant negative relationships between $\delta^{13}C$ and annual ($r = -0.916$) and fall ($r = -0.919$) CO_2 flux.

HF land area CO_2 flux display potential significant annual relationships between only upper 10 cm C/N ($r = 0.798$) and $\delta^{13}C$ ($r = -0.692$). During the summer period however there are several strong correlations with flux and soil organic matter in the upper 10 cm, including SOC ($r = 0.837$), SON ($r = 0.823$), C/N ($r = 0.870$), and $\delta^{13}C$ ($r = -0.768$), with correlations becoming weaker when incorporating increased depth of the soil profile. HF flux does not appear to have any relationship to analyzed soil properties during the fall and spring periods.

UF land area soil chemistry does not show any significant ($p < 0.1$) correlations with CO_2 flux during the annual period, but it should be noted that statistical significance is more limited since this land-use area had the fewest sample locations ($n = 4$). Despite low significance UF soil properties SOC, SON, C/N, and $\delta^{13}C$ showed moderate correlations ($r > 0.650$) with annual CO_2 flux. Summer period did show significant correlations with C/N, $\delta^{13}C$, and SOC to 30 cm depth, with suggestion of correlation for SON. The fall period did not show meaningful relationships to soil properties other than $\delta^{15}N$ to 30 cm depth ($r = -.909$), but spring again shows the suggestion of strong correlations with SOC and SON despite not meeting the significance criteria.

Discussion

This research suggests that primary controls on soil CO_2 flux variation, such as temperature, moisture, SOC and SON, can differ according to land-use regimes and seasonal environmental shifts.

Environmental Factors

Observations of continuous CO_2 flux and concurrent environmental factors in this study agree with the accepted understanding that air and soil temperature, relative humidity, and soil moisture are primary factors influencing continuous and diurnal soil surface CO_2 flux rates (e.g., Liu et al, 2010; Contasta et al., 2011). This study furthers highlights how the influences of these environmental factors shift through annual seasonal progression in temperature regions. During the summer period, CO_2 flux for each sample location was shown to be strongly influenced primarily by air and soil temperature with a moderate inverse association with relative humidity (Figure 5). This represents the warm and sunny growing season in which root respiration, heterotrophic respiration, and above-ground plant respiration are all strongly active (Yu et al., 2017, Zhou et al., 2009; Fitter et al., 1998). During the fall period, however, air temperature and relative humidity were no longer influential factors. The CO_2 flux rates of the composted VG plots during this time were dominated by the influence of soil temperature and moisture (Figure 5. B.). CO_2 flux at these plots was likely dominated by the heterotrophic decomposition of the plentiful SOC in the organic compost amendments. This decomposition was being driven by soil moisture and elevated soil temperature relative to air temperature during this period, consistent with other research demonstrating that increasing availability of easily decomposable SOM substrates increases heterotrophic soil respiration (e.g., Fontaine et al., 2004). Also, during the

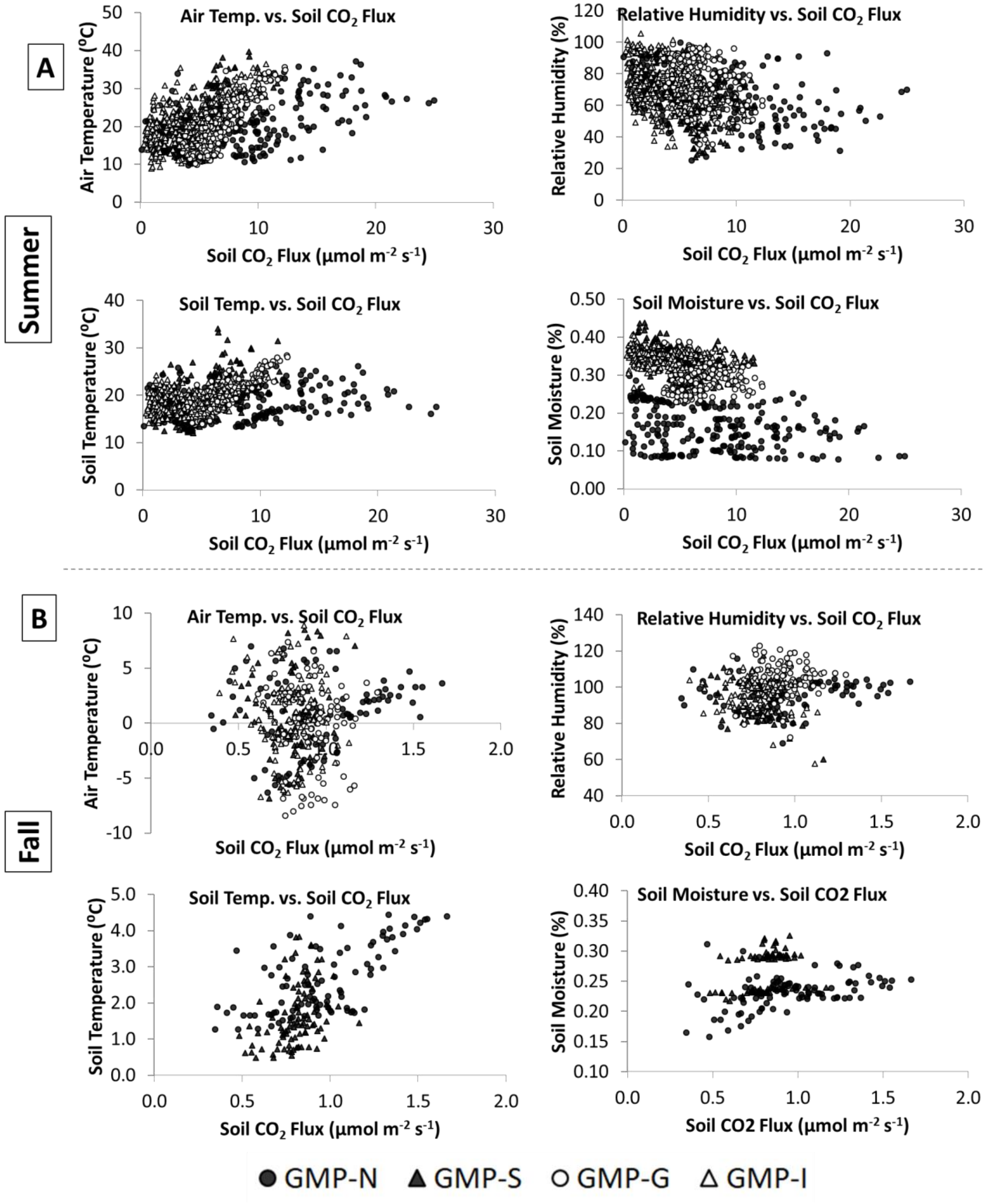

Figure 6 – Environmental factors (air temperature, relative humidity, soil temperature and soil moisture) compared with concurrent soil CO_2 flux measurements for continuous chambers during the summer (A) and fall periods (B).

fall period, CO_2 flux of grass-dominated GMP-G plot lost association with all measured environmental factors, likely limited by low temperatures and levels of solar radiation for cellular respiration (Taiz et al., 2015). Then during the spring period GMP-G and GMP-I plots return to the same relationships, where CO_2 flux was controlled by air temperature, soil temperature and inversely correlated with relative humidity, while the compost plots (GMP-N and GMP-S) become uncorrelated with all measured environmental factors.

The influence of environmental factors on both soil CO_2 flux and NEE appears to be largely dependent on overall vegetation density for the sites in this study. Vegetation density can be likened to leaf area index, which studies have demonstrated to be negatively correlated with NEE (Flanagan et al., 2002). Soil CO_2 flux and NEE of all sample locations without regular vegetative growth (GMP-N, GMP-S, and GMP-I) show similar annual relationships with air and soil temperature, namely increased temperatures occur in association with increased CO_2 flux and NEE. The composted sample locations (GMP-N and GMP-S) have a similar relationship during the summer period. In contrast, the grass-dominated sample location (GMP-G) showed no annual relationship between NEE and air or soil temperature, though a clear influence of seasonal photosynthetic radiation (Figure 6). The inverse summer NEE of GMP-G is likely due to periods of high photosynthetic active radiation, associated with high temperatures, encouraging high rates of CO_2 removal from the atmosphere resulting in negative NEE. These represent periods of net carbon dioxide input into the soils (Wang et al., 2017). Sample locations showing comparable CO_2 flux and NEE relationships with temperature indicate that relatively little photosynthesis occurred and thus soil CO_2 flux must be dominated by heterotrophic and/or root respiration (Dyukarev, 2017). Locations GMP-N and GMP-S have collars placed in bare soil and are not adjacent to high density vegetation; thus it is likely that soil CO_2 flux for these locations is dominated by heterotrophic respiration via decomposing SOC.

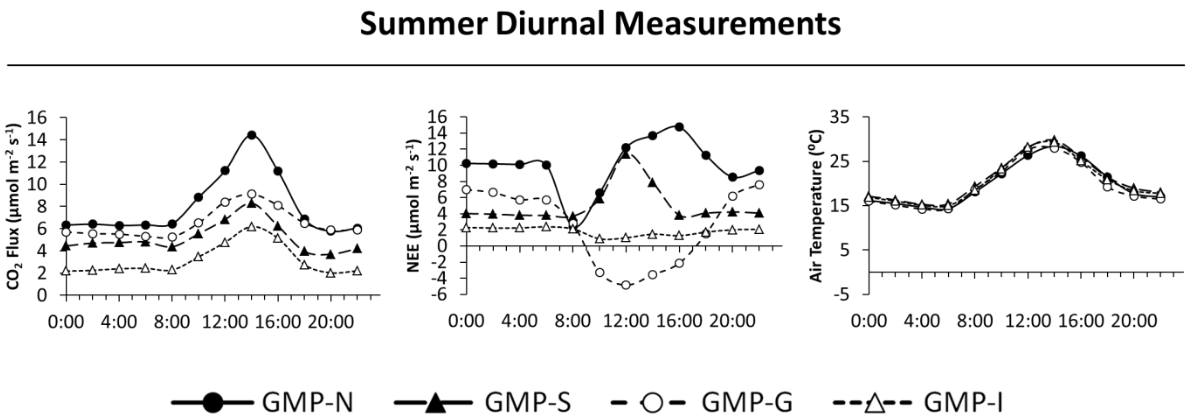

Figure 7 – Observed summer diurnal soil CO_2 flux, NEE and air temperature variation of continuous sample locations.

Soil carbon-nitrogen characteristics

This research suggests that relationships between annual or seasonal soil surface CO_2 flux and soil carbon-nitrogen properties are largely driven by alternate factors associated with varying land-uses such as type and density of vegetation, presence or absence of irrigation, or organic matter amendments. When considering sample locations from all land-use types as a whole, there are very limited correlations amongst the soil C and N characteristics analyzed; but some potentially significant relationships become apparent when examining each land-use types individually (Figure 7). High intensity addition of organic matter amendments and nitrogen fertilizers in the VG land-use area lead to a very strong relationship, in which higher SOC and SON stocks result in higher annual average afternoon soil CO_2 flux. Total annual carbon additions from compost inputs to VG garden beds is approximately 1.9 kg m^{-2}, while annual carbon lost from garden beds calculated from seasonal soil CO_2 fluxes is approximately 0.91 kg m^{-2}. This leaves about 1.0 kg m^{-2} of carbon from compost remaining in garden bed soils. The long-term storage of net carbon inputs is unknown due to elevated soil CO_2 respiration from organic matter amendment additions.

HF and UF land-use areas show similar annual relationships between organic content and soil CO_2 flux, but the correlations are weaker and their significance is less clear. However, annual correlations amongst each land-use area are stronger individually than as a whole, supporting the conclusion that the relationship between SOC-SON and soil CO_2 flux are more relevant within the context of other land-use characteristics.

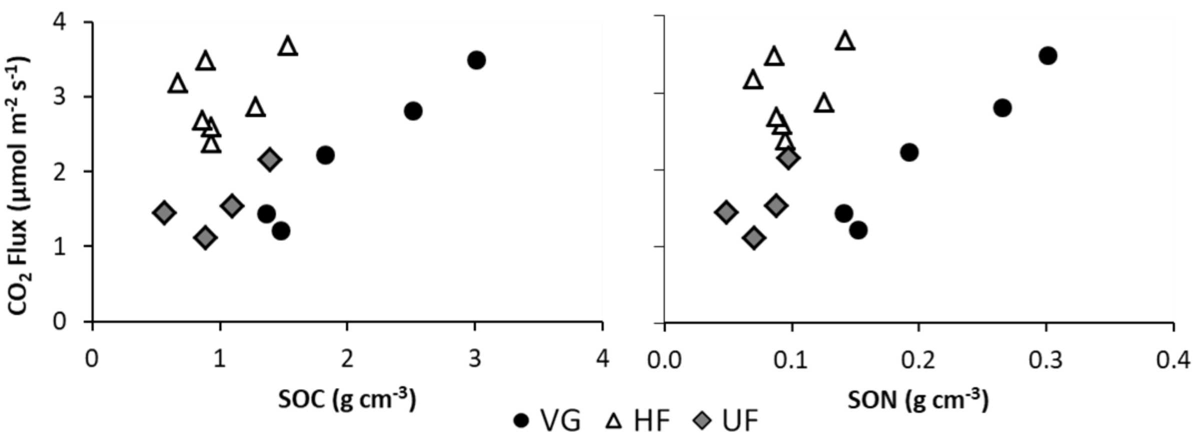

Figure 8 – Annual afternoon CO2 flux versus weighted average of SOC and SON to 30 cm depth for sample locations under each land-use type; vegetable garden (VG), hay fields (HF), and unfarmed (UF).

Strong connection between summer CO_2 flux and SOC is found amongst all land-use types individually to 30 cm depth as shown in Figure 8. This influence is common to land-use types dominated by either heterotrophic (VG) or autotrophic (HF and UF) respiration during the summer. Peak annual solar radiation causes greatest autotrophic respiration during summer, while heterotrophic respiration is largely influenced by associated high air and soil temperatures (Fitter et al., 1998; Yu et al., 2017).

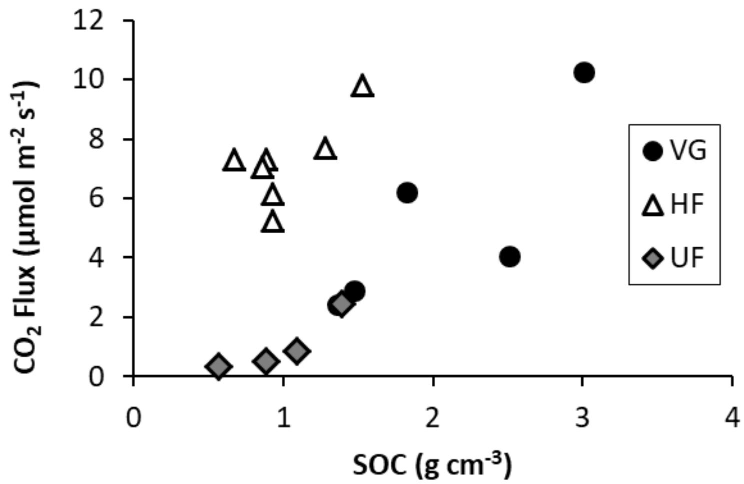

Figure 9 – Average summer afternoon CO2 flux versus weighted average of SOC to 30 cm depth for sample locations under each land-use type; vegetable garden (VG), hay fields (HF), and unfarmed (UF).

SOC, SON and C/N of HF surface soils (0-10 cm) appears to have a much stronger influence on summer CO_2 flux than soils deeper in the profile. HF 30 cm depth SOC had a moderate relationship (r = 0.684) with summer CO_2 flux, and non-significant relationships with SON and C/N, while summer flux shared strong relationships with upper 10 cm of HF SOC (r = 0.837), SON (r = 0.823) and C/N (r = 0.870) (Figure 9). This suggests that, during the summer, carbon-nitrogen dynamics of the upper layer are much more involved in the observed soil respiration than deeper in the soil profile in these hay fields. Rapid hay growth of HF plots promoted by irrigation during the summer-period results in dominantly autotrophic afternoon soil CO_2 flux, and is accompanied by accelerated root zone activity in the upper 10 cm of the soil profile. The summer correlation between soil organic content and CO2 flux at shallow depths supports the idea that root-available SOC and SON have a direct impact on CO_2 flux rates (Lal, 2006; Brady et al, 2015; Maltas et al., 2013).

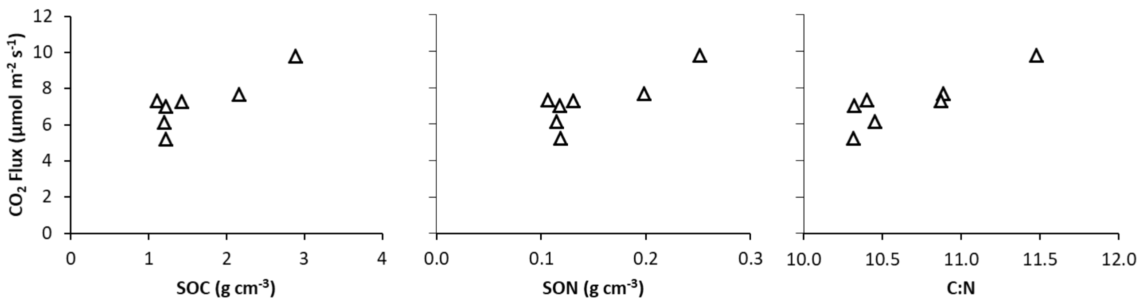

Figure 10 – Average summer afternoon CO_2 flux versus weighted average of SOC, SON and C:N to 10 cm depth for hay field (HF) sample locations.

There appears to be a moderate relationship between increased annual and summer CO_2 flux with increased $\delta^{15}N$ when considering all sample locations as a whole, though VG shows a strong negative relationship between $\delta^{15}N$ and CO_2 flux (Figure 10). UF flux during the fall also exhibits a strong negative relationship with $\delta^{15}N$. There is also an apparent grouping of each land-use type when considering these parameters. Other studies have concluded that decomposition of ^{15}N depleted SON can lead to $\delta^{15}N$ enrichment (Nadelhoffer and Fry, 1988). It is possible that higher CO_2 flux is associated with higher fluxes of N_2O favoring ^{14}N, thus leading to fractionation and higher $\delta^{15}N$. Alternatively, addition of assorted types of nitrogen-rich fertilizers over both of the farmed sites (VG and HF) has resulted in different degrees of nitrogen isotope fractionation related to fertilizer uptake and denitrification processes.

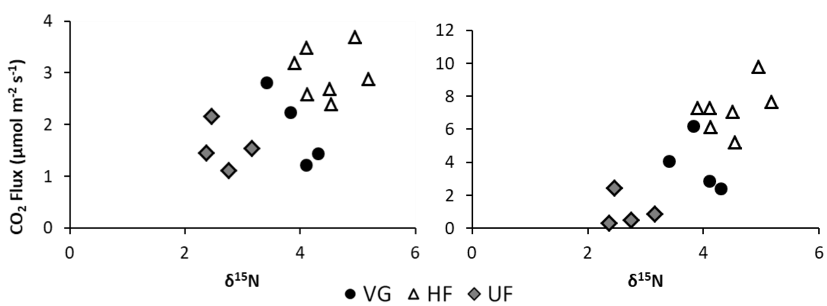

Figure 11 – Average annual (left) and summer (right) afternoon CO_2 flux versus weighted average of $\delta^{15}N$ to 30 cm depth for sample locations under each land-use type; vegetable garden (VG), hay fields (HF), and unfarmed (UF).

This study also suggests an inverse relationship between $\delta^{13}C$ and CO_2 flux of various combinations of seasons and land-use. Strongly negative $\delta^{13}C$ and CO_2 flux relationships are generally accompanied by positive SOC-CO_2 flux relationships. These relationships are correlated with depth-relationships in which enriched SOC near the surface is accompanied by relatively depleted $\delta^{13}C$ amongst all sample locations in the study area, resulting in a strong negative correlation between $\delta^{13}C$ and SOC (Figure 11). Whether or not the rate of CO_2 flux is directly connected to $\delta^{13}C$ is unclear, though it is possible that isotopic fractionation leading to $\delta^{13}C$ enrichment is directly influenced by elevated CO_2 flux (Yakir and Sternberg, 2000).

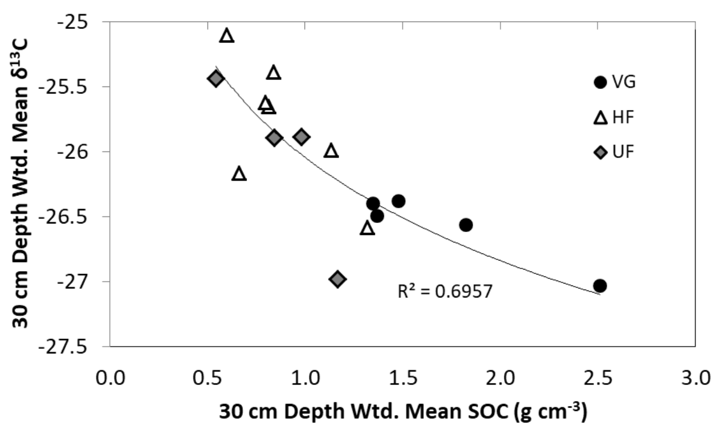

Figure 12 – Weighted average of SOC to 30 cm depth versus weighted average of $\delta^{13}C$ to 30 cm depth for sample locations under each land-use type; vegetable garden (VG), hay fields (HF), and unfarmed (UF).

CHAPTER IV

CONCLUSION

This study holistically examines relationships between soil CO_2 flux and multiple potential influencing factors for irrigated agricultural soils in the semi-arid Central Washington State environment. Like Liu et al., (2010), and Wang et al., (2017), we conclude that soil CO_2 flux is largely controlled by air and soil temperatures. However, this study also demonstrates that these relationships can shift seasonally; the correlations between air and soil temperature is strongest during the summer, while there is moderate soil temperature dependence and no air temperature influence during the fall. This pattern may only hold for climates similar to this study area with high temperature – low precipitation summers and low temperature – high precipitation winters.

This research suggests that increased SOC concentration results in increased soil CO_2 flux in land areas heavily treated with organic matter amendments. This result agrees with studies by Zhou et al. (2009), and Dai et al. (2017), which concluded that higher organic matter concentrations increase the temperature sensitivity of organic carbon mineralization and heterotrophic respiration. Our study builds upon this concept, suggesting that that strength of temperature sensitivity of organic matter decomposition also depends on seasonal and land-use differences. During the summer period, each land-use types individually demonstrated positive relationships between SOC and soil CO_2 flux, but this relationship did not hold true when compared across land-use types. Additionally, these significant positive relationships are not apparent when considering the fall and spring seasons.

Continued analysis of relationships of soil CO_2 flux with environmental factors, soil properties and land-use characteristics may assist in the development of management practices which optimize soil fertility and the capacity for atmospheric soil carbon sequestration. This study demonstrates that approximately 0.9 kg of the 1.9 kg m^{-2} SOC added to bare vegetable garden beds is lost through decomposition each year, and that increased SOC content of these beds results in increased CO_2 emissions and NEE. Further evaluation of impacts of compost amendments to soil emissions and garden productivity could lead to improved compost management; reducing needless SOC loss while retaining soil fertility.

Assessing relationships of land management with soil properties and soil CO_2 respiration will help predict how large-scale land-use alteration can be expected to impact regional soil CO_2 cycling dynamics and soil quality. Comparing unfarmed and hay farmed locations showed that this transition did not significantly alter SOC, SON, and $\delta^{13}C$, but continuous conventional hay farming has increased $\delta^{15}N$ of this soil. Hay farmed locations also showed more than double the rate of CO_2 flux annually than unfarmed. Conversely, the transition from hay farmed sites to no-till vegetable garden with organic amendments has significantly increased SOC and SON, and reduced $\delta^{13}C$, with comparable rate of annual CO_2 flux. More detailed comparison of annual NEE amongst land-use types would improve the evaluation of land-use alteration as a method of increasing carbon sequestration.

Additional research

The agricultural carbon sequestration research project at Spoon Full Farm is in a preliminary stage and much of the data collection methods can be improved upon. More transparent chamber measurements should be taken to more accurately gauge the net movement of carbon to and from the soil according to changing agricultural practices throughout the year. This study was limited by the relatively small amount of soil CO_2 flux data that is able to be gathered using survey chambers across the farm. Expanding the mobility of the multiplexer unit for continuous measurements to other parts of the study area would greatly increase the confidence of the reported CO_2 flux rates, and give a much better representation of seasonal and daily variations of CO_2 flux and environmental factors across the farm. Quantification of carbon inputs including compost amendment, plant litter, crop residue, and root exudates is needed to fully quantify the mass balance between carbon inputs and outputs. Finally, one of the major limitations of this study was the small number of sample locations where soil cores and seasonal CO_2 flux data was gathered for each of the three land-use types. Increasing these sample numbers would serve to reveal and increase confidence in suggested relationships between soil CO_2 flux of the various land-use types and their specific soil carbon-nitrogen characteristics.

REFERENCES Abawi, G., and Widmer, T., 2000, Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops: Applied Soil Ecology, v. 15, p. 37-47, doi: 10.1016/s0929-1393(00)00070-6.

Al-Kaisi, M., Yin, X., and Licht, M., 2005, Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn–soybean rotation: Applied Soil Ecology, v. 30, p. 174-191, doi: 10.1016/j.apsoil.2005.02.014.

Alliaume, F., Rossing, W., García, M., Giller, K., and Dogliotti, S., 2013, Changes in soil quality and plant available water capacity following systems re-design on commercial vegetable farms: European Journal of Agronomy, v. 46, p. 10-19, doi: 10.1016/j.eja.2012.11.005.

Arce, G., Carvalho, J., and Nascimento, L., 2014, A time series sequestration and storage model of atmospheric carbon dioxide: Ecological Modelling, v. 272, p. 59-67, doi: 10.1016/j.ecolmodel.2013.09.006.

Boone, R., Nadelhoffer, K., Canary, J., and Kaye, J., 1998, Roots exert a strong influence on the temperature sensitivity of soil respiration: Nature, v. 396, p. 570-572, doi: 10.1038/25119.

Boström, B., Comstedt, D., and Ekblad, A., 2007, Isotope fractionation and 13C enrichment in soil profiles during the decomposition of soil organic matter: Oecologia, v. 153, p. 89-98, doi: 10.1007/s00442-007-0700-8.

Brady, M., Hedlund, K., Cong, R., Hemerik, L., Hotes, S., Machado, S., Mattsson, L., Schulz, E., and Thomsen, I., 2015, Valuing Supporting Soil Ecosystem Services in Agriculture: A Natural Capital Approach: Agronomy Journal, v. 107, p. 1809, doi: 10.2134/agronj14.0597.

Cambardella, C., and Elliott, E., 1992, Particulate Soil Organic-Matter Changes across a Grassland Cultivation Sequence: Soil Science Society of America Journal, v. 56, p. 777, doi: 10.2136/sssaj1992.03615995005600030017x.

Carlyle, J., and Than, U., 1988, Abiotic Controls of Soil Respiration Beneath an Eighteen-Year-Old Pinus Radiata Stand in South-Eastern Australia: The Journal of Ecology, v. 76, p. 654, doi: 10.2307/2260565.

Chen, J., Luo, Y., Li, J., Zhou, X., Cao, J., Wang, R., Wang, Y., Shelton, S., Jin, Z., Walker, L., Feng, Z., Niu, S., Feng, W., Jian, S., and Zhou, L., 2017, Costimulation of soil glycosidase activity and soil respiration by nitrogen addition: Global Change Biology, v. 23, p. 1328-1337.

Clapp, C., Allmaras, R., Layese, M., Linden, D., and Dowdy, R., 2000, Soil organic carbon and 13C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota: Soil and Tillage Research, v. 55, p. 127-142, doi: 10.1016/s0167-1987(00)00110-0.

Contosta, A., Frey, S., and Cooper, A., 2011, Seasonal dynamics of soil respiration and N mineralization in chronically warmed and fertilized soils: Ecosphere, v. 2, p. art36, doi: 10.1890/es10-00133.1.

Dai, S., Li, L., Ye, R., Zhu-Barker, X., and Horwath, W., 2017, The temperature sensitivity of organic carbon mineralization is affected by exogenous carbon inputs and soil organic carbon content: European Journal of Soil Biology, v. 81, p. 69-75, doi: 10.1016/j.ejsobi.2017.06.010.

Don, A., Schumacher, J., Scherer-Lorenzen, M., Scholten, T., and Schulze, E., 2007, Spatial and vertical variation of soil carbon at two grassland sites — Implications for measuring soil carbon stocks: Geoderma, v. 141, p. 272-282, doi: 10.1016/j.geoderma.2007.06.003.

Dumale, W., Miyazaki, T., Nishimura, T., and Seki, K., 2009, CO2 evolution and short-term carbon turnover in stable soil organic carbon from soils applied with fresh organic matter: Geophysical Research Letters, v. 36, doi: 10.1029/2008gl036436.

Dyukarev, E., 2017, Partitioning of net ecosystem exchange using chamber measurements data from bare soil and vegetated sites: Agricultural and Forest Meteorology, v. 239, p. 236-248, doi: 10.1016/j.agrformet.2017.03.011.

Garten, C., and Wullschleger, S., 1999, Soil carbon inventories under a bioenergy crop (Switchgrass): Measurement limitations: Journal of Environment Quality, v. 28, p. 1359, doi: 10.2134/jeq1999.00472425002800040041x.

Feng, X., Peterson, J., Quideau, S., Virginia, R., Graham, R., Sonder, L., and Chadwick, O., 1999, Distribution, accumulation, and fluxes of soil carbon in four monoculture lysimeters at San Dimas Experimental Forest, California: Geochimica et Cosmochimica Acta, v. 63, p. 1319-1333, doi: 10.1016/s0016-7037(99)00048-4.

Fitter, A., Graves, J., Self, G., Brown, T., Bogie, D., and Taylor, K., 1998, Root production, turnover and respiration under two grassland types along an altitudinal gradient: influence of temperature and solar radiation: Oecologia, v. 114, p. 20-30, doi: 10.1007/s004420050415.

Flanagan, L., Wever, L., and Carlson, P., 2002, Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland: Global Change Biology, v. 8, p. 599-615, doi: 10.1046/j.1365-2486.2002.00491.x.

Fontaine, S., Bardoux, G., Abbadie, L., and Mariotti, A., 2004, Carbon input to soil may decrease soil carbon content: Ecology Letters, v. 7, p. 314-320, doi: 10.1111/j.1461-0248.2004.00579.x.

Garten, C., and Wullschleger, S., 1999, Soil carbon inventories under a bioenergy crop (Switchgrass): Measurement limitations: Journal of Environment Quality, v. 28, p. 1359, doi: 10.2134/jeq1999.00472425002800040041x.

Harper, C., Blair, J., Fay, P., Knapp, A., and Carlisle, J., 2005, Increased rainfall variability and reduced rainfall amount decreases soil CO2 flux in a grassland ecosystem: Global Change Biology, v. 11, p. 322-334, doi: 10.1111/j.1365-2486.2005.00899.x.

Horváth, B., Opara-Nadi, O., and Beese, F., 2005, A simple method for measuring the carbonate content of soils: Soil Science Society of America Journal, v. 69, p. 1066, doi: 10.2136/sssaj2004.0010.

IAEA (International Atomic Energy Agency), 2017, Use of Carbon Isotopic Tracers in Investigating Soil Carbon Sequestration and Stabilization in Agroecosystems: Vienna, IAEA. https://inis.iaea.org/collection/NCLCollectionStore/_Public/48/094/48094630.pdf?r=1&r=1

IPCC (Intergovernmental Panel on Climate Change), 2001, The Third Governmental Panel on Climate Change Assessment Report, 2001: Climate Change 2001: Impacts, Adaptations and Vulnerability. https://www.ipcc.ch/site/assets/uploads/2018/03/WGII_TAR_full_report-2.pdf

Janzen, H., 2004, Carbon cycling in earth systems—a soil science perspective: Agriculture, Ecosystems & Environment, v. 104, p. 399-417, doi: 10.1016/j.agee.2004.01.040.

Johnston, A., 1986, Soil organic matter, effects on soils and crops: Soil Use and Management, v. 2, p. 97-105, doi: 10.1111/j.1475-2743.1986.tb00690.x.

Kahn, Brian, 2017, Earth's CO2 passes the 400 ppm threshold--maybe permanently: Scientific American, https://www.scientificamerican.com/article/earth-s-co2-passes-the-400-ppm-threshold-maybe-permanently.

Kaiser, K., Mikutta, R., and Guggenberger, G., 2007, Increased stability of organic matter sorbed to ferrihydrite and goethite on aging: Soil Science Society of America Journal, v. 71, p. 711, doi: 10.2136/sssaj2006.0189.

Kanchikerimath, M., and Singh, D., 2001, Soil organic matter and biological properties after 26 years of maize–wheat–cowpea cropping as affected by manure and fertilization in a Cambisol in semiarid region of India: Agriculture, Ecosystems & Environment, v. 86, p. 155-162, doi: 10.1016/s0167-8809(00)00280-2.

Köchy, M., Hiederer, R., and Freibauer, A., 2015, Global distribution of soil organic carbon – Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world: SOIL, v. 1, p. 351-365, doi: 10.5194/soil-1-351-2015.

Kuzyakov, Y., 2006, Sources of CO2 efflux from soil and review of partitioning methods: Soil Biology and Biochemistry, v. 38, p. 425-448, doi: 10.1016/j.soilbio.2005.08.020.

Lal, R., 2004, Soil carbon sequestration impacts on global climate change and food security: Science, v. 304, p. 1623-1627, doi: 10.1126/science.1097396.

Lal R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development 17:197–209.

Lal, R., 2010, Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security: BioScience, v. 60, p. 708-721, doi: 10.1525/bio.2010.60.9.8.

LeBauer, D., and Treseder, K., 2008, Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed: Ecology, v. 89, p. 371-379, doi: 10.1890/06-2057.1.

Liu, Y., Li, S., Yang, S., Hu, W., and Chen, X., 2010, Diurnal and seasonal soil CO2 flux patterns in spring maize fields on the Loess Plateau, China: Acta Agriculturae Scandinavica, Section B - Plant Soil Science, v. 60, p. 245-255, doi: 10.1080/09064710902878121.

Luo, Z., Feng, W., Luo, Y., Baldock, J., and Wang, E., 2017, Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions: Global Change Biology, v. 23, p. 4430-4439, doi: 10.1111/gcb.13767.

Maaroufi, N., Nordin, A., Hasselquist, N., Bach, L., Palmqvist, K., and Gundale, M., 2015, Anthropogenic nitrogen deposition enhances carbon sequestration in boreal soils: Global Change Biology, v. 21, p. 3169-3180, doi: 10.1111/gcb.12904.

Maltas, A., Charles, R., Jeangros, B., and Sinaj, S., 2013, Effect of organic fertilizers and reduced-tillage on soil properties, crop nitrogen response and crop yield: Results of a 12-year experiment in Changins, Switzerland: Soil and Tillage Research, v. 126, p. 11-18, doi: 10.1016/j.still.2012.07.012.

Marin Carbon Project, 2018, About Marin Carbon Project: https://www.marincarbonproject.org/about (accessed 7/26/19)

Natelhoffer, K., and Fry, B., 1988, Controls on natural nitrogen-15 and carbon-13 abundances in forest soil organic matter: Soil Science Society of America Journal, v. 52, p. 1633, doi: 10.2136/sssaj1988.03615995005200060024x.

NOAA CDO, 2019, 1980-2010, Ellensburg Temperature and Precipitation Data; Accessed: 6/24/19.

Owen, J., Parton, W., and Silver, W., 2015, Continuous impacts of manure amendments on carbon and greenhouse gas dynamics of rangelands: Global Change Biology, v. 21, p. 4533-4547, doi: 10.1111/gcb.13044.

Paul, E., Follett, R., Leavitt, S., Halvorson, A., Peterson, G., and Lyon, D., 1997, Radiocarbon dating for determination of soil organic matter pool sizes and dynamics: Soil Science Society of America Journal, v. 61, p. 1058, doi: 10.2136/sssaj1997.03615995006100040011x.

Prentice, I., Farquhar, G., Fasham, M., Goulden, M., Heimann, M., Jaramillo, V., Kheshgi, H., Le Quéré, C., Scholes, R., Wallace, D., 2005, The carbon cycle and atmospheric carbon dioxide: Third Assessment Report of the Intergovernmental Panel on Climate Change Climate Change 2005: The Scientific Basis, Cambridge University, p. 183-238.

Rumpel, C., and Kögel-Knabner, I., 2010, Deep soil organic matter—a key but poorly understood component of terrestrial C cycle: Plant and Soil, v. 338, p. 143-158, doi: 10.1007/s11104-010-0391-5.

Ryals, R., and Silver, W., 2013, Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands: Ecological Applications, v. 23, p. 46-59, doi: 10.1890/12-0620.1.

Ryals, R., Hartman, M., Parton, W., DeLonge, M., and Silver, W., 2015, Continuous climate change mitigation potential with organic matter management on grasslands: Ecological Applications, v. 25, p. 531-545, doi: 10.1890/13-2126.1.

Rumpel, C., and Kögel-Knabner, I., 2010, Deep soil organic matter—a key but poorly understood component of terrestrial C cycle: Plant and Soil, v. 338, p. 143-158, doi: 10.1007/s11104-010-0391-5.

Schillinger, W., Kennedy, A., and Young, D., 2007, Eight years of annual no-till cropping in Washington's winter wheat-summer fallow region: Agriculture, Ecosystems & Environment, v. 120, p. 345-358, doi: 10.1016/j.agee.2006.10.017.

Smith, P., 2006, Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol: Soil Use and Management, v. 20, p. 264-270, doi: 10.1111/j.1475-2743.2004.tb00367.x.

Soil Survey Staff, Natural Resources Conservation Service (NRCS), 2019, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Kittitas County, WA. Available online: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. (Accessed 02/18/19)

Sperazza, M., Moore, J., and Hendrix, M., 2004, High-resolution particle size analysis of naturally occurring very fine-grained sediment through laser diffractometry: Journal of Sedimentary Research, v. 74, p. 736-743, doi: 10.1306/031104740736.

Taiz, L., Zeiger, E., Møller, I., and Murphy, A. 2015, Plant physiology and development 6th edition: Sunderland, Massachusetts : Sinauer Associates, Inc., Publishers.

Terra Global Capital, 2014, Methodology for Compost Additions to Grazed Grasslands: American Carbon Registry Carbon Accounting Standards and Methodologies.

USDA NASS Census of Agriculture, 2012, Vol. 1, Ch. 2, Washington County Level: Washington, Government Printing Office.

Van Dam D., Veldkamp E., VanBremen N., 1997, Soil organic carbon dynamics: variability with depth in forested and deforested soils under pasture in Costa Rica: Biogeochemistry v. 39, p. 343–375.

Wang, B., Jin, H., Li, Q., Chen, D., Zhao, L., Tang, Y., Kato, T., and Gu, S., 2017, Diurnal and seasonal variations in the net ecosystem CO_2 exchange of a pasture in the three-river source region of the Qinghai−Tibetan Plateau: PLOS ONE, v. 12, p. e0170963, doi: 10.1371/journal.pone.0170963.

West, T., and Post, W., 2002, Soil organic carbon sequestration rates by tillage and crop rotation: Soil Science Society of America Journal, v. 66, p. 1930, doi: 10.2136/sssaj2002.1930.

Wang, B., Jin, H., Li, Q., Chen, D., Zhao, L., Tang, Y., Kato, T., and Gu, S., 2017, Diurnal and seasonal variations in the net ecosystem CO_2 exchange of a pasture in the three-river source region of the Qinghai−Tibetan Plateau: PLOS ONE, v. 12, p. e0170963, doi: 10.1371/journal.pone.0170963.

Yakir, D., and Sternberg, L., 2000, The use of stable isotopes to study ecosystem gas exchange: Oecologia, v. 123, p. 297-311, doi: 10.1007/s004420051016.

Yu, S., Chen, Y., Zhao, J., Fu, S., Li, Z., Xia, H., and Zhou, L., 2017, Temperature sensitivity of total soil respiration and its heterotrophic and autotrophic components in six vegetation types of subtropical China: Science of The Total Environment, v. 607-608, p. 160-167, doi: 10.1016/j.scitotenv.2017.06.194.

Zheng, Z., Yu, G., Fu, Y., Wang, Y., Sun, X., and Wang, Y., 2009, Temperature sensitivity of soil respiration is affected by prevailing climatic conditions and soil organic carbon content: A trans-China based case study: Soil Biology and Biochemistry, v. 41, p. 1531-1540, doi: 10.1016/j.soilbio.2009.04.013.

Zhou, T., Shi, P., Hui, D., and Luo, Y., 2009, Global pattern of temperature sensitivity of soil heterotrophic respiration (Q10) and its implications for carbon-climate feedback: Journal of Geophysical Research: Biogeosciences, v. 114, p. n/a-n/a, doi: 10.1029/2008jg000850.

APPENDIXES

APPENDIX A

ANALYZED CHEMICAL PROPERTIES OF SAMPLES AT EACH DEPTH INTERVAL

-$CaCO_3$ % determined using the pressure calcimeter method from Horvath et al. (2005).

-Wt. % N and C, N and C g/cm^3, δ^{15}N, δ^{13}C, and bulk density methods described in thesis.

Sample Name	Depth Interval (cm)	$CaCO_3$ %	Wt %N	Wt %C	N g/cm^3	C g/cm^3	C/N	δ^{15}N	δ^{13}C	Bulk Density (g/cm^3)
GMP-N	5	0.41	1.44	12.71	0.58	5.10	8.84	2.11	-23.63	0.40
	10	0.12	0.68	7.45	0.39	4.27	11.03	3.37	-26.30	0.57
	20	0.06	0.37	4.02	0.23	2.44	10.75	4.27	-26.60	0.61
	30	0.06	0.21	2.06	0.20	1.91	9.76	5.05	-25.93	0.93
GMP-G	5	0.26	0.32	3.53	0.18	2.02	11.01	4.38	-27.00	0.57
	10	0.10	0.26	2.78	0.23	2.45	10.61	4.26	-26.30	0.88
	20	0.06	0.09	0.76	0.10	0.84	8.66	5.99	-25.61	1.11
	30	0.07	0.12	1.13	0.11	0.97	9.20	5.46	-26.10	0.86
GMP-S	5	0.26	0.90	7.61	0.36	3.06	8.44	3.27	-26.19	0.40
	10	0.10	0.33	3.35	0.19	1.92	10.21	4.32	-27.12	0.57
	20	0.06	0.24	2.46	0.15	1.49	10.19	4.44	-26.55	0.61
	30	0.07	0.17	1.60	0.15	1.49	9.68	4.45	-26.89	0.93
GW-N	5	0.26	1.95	16.97	0.78	6.81	8.72	3.02	-27.53	0.40
	10	0.10	0.42	4.47	0.24	2.56	10.53	3.97	-26.85	0.57
	20	0.06	0.20	2.04	0.12	1.24	10.09	4.37	-26.09	0.61
	30	0.07	0.17	1.73	0.16	1.60	9.97	4.79	-25.93	0.93
	40	0.09	0.11	1.04	0.10	0.96	9.37	5.08	-25.69	0.93
GE-S	5	0.12	0.50	4.33	0.18	1.54	8.73	3.44	-26.63	0.36
	10	0.08	0.27	2.96	0.14	1.51	11.16	4.66	-26.74	0.51
	20	0.07	0.19	1.93	0.14	1.42	10.00	4.83	-26.43	0.74
	30	0.09	0.14	1.27	0.14	1.15	9.30	5.18	-26.10	0.91
GE-M	5	0.26	0.47	4.21	0.14	1.50	8.93	3.57	-26.14	0.36
	10	0.10	0.44	4.42	0.14	2.25	10.10	3.69	-26.77	0.51
	20	0.06	0.22	2.25	0.14	1.66	10.34	4.48	-26.61	0.74
	30	0.07	0.11	0.99	0.14	0.90	8.97	5.40	-25.51	0.91
TF-N	10	0.12	0.28	3.18	0.14	2.89	11.48	4.60	-27.34	0.91
	20	0.12	0.10	1.01	0.14	1.02	9.99	5.29	-25.50	1.01
	40	0.14	0.08	0.71	0.14	0.68	9.44	5.75	-24.73	0.96
	60	0.14	0.06	0.53	0.14	0.51	8.77	5.85	-24.51	0.96
TF-S	10	0.12	0.22	2.37	0.14	2.16	10.89	4.86	-26.21	0.91
	20	0.12	0.10	0.96	0.14	0.97	9.74	5.02	-25.67	1.01
	40	0.14	0.08	0.73	0.14	0.70	8.89	6.19	-25.69	0.96
BF-N	10	0.12	0.13	1.34	0.14	1.22	10.31	4.37	-25.52	0.91
	20	0.10	0.10	0.98	0.14	1.00	9.84	4.81	-25.55	1.01
	40	0.13	0.07	0.59	0.14	0.57	8.77	4.45	-24.82	0.96
	60	0.12	0.05	0.43	0.14	0.41	8.32	4.92	-23.53	0.96
BF-S	10	0.12	0.13	1.31	0.14	1.20	10.45	4.03	-25.76	0.91
	20	0.10	0.11	1.09	0.14	1.11	10.25	4.03	-26.13	1.01

	40	0.13	0.06	0.50	0.14	0.48	8.75	4.52	-24.35	0.96
	60	0.12	0.05	0.39	0.14	0.37	8.20	3.91	-23.77	0.96
PF-N	10	0.10	0.14	1.56	0.14	1.42	10.87	3.83	-26.80	0.91
	20	0.16	0.07	0.68	0.14	0.68	9.53	4.44	-25.45	1.01
	30	0.27	0.06	0.57	0.14	0.55	9.84	4.36	-25.28	0.96
PF-M	10	0.10	0.12	1.22	0.14	1.11	10.40	3.54	-25.33	0.91
	20	0.16	0.06	0.50	0.14	0.51	8.91	4.17	-24.81	1.01
	40	0.27	0.05	0.41	0.14	0.39	8.42	4.42	-24.79	0.96
PF-S	10	0.10	0.13	1.34	0.14	1.22	10.32	4.05	-26.41	0.91
	20	0.16	0.08	0.73	0.14	0.74	9.12	4.76	-25.02	1.01
	40	0.27	0.07	0.64	0.14	0.61	9.44	5.07	-24.65	0.96
	60	0.30	0.06	0.57	0.14	0.55	9.48	5.46	-24.61	0.96
UF-WN-SB	10	0.10	0.18	2.35	0.14	1.99	13.07	3.41	-26.35	0.85
	20	0.15	0.06	0.69	0.14	0.64	11.53	2.37	-25.35	0.92
	40	0.15	0.05	0.62	0.14	0.65	11.86	3.20	-24.75	1.05
	60	0.12	0.05	0.61	0.14	0.64	12.05	3.43	-24.96	1.05
UF-WS-SB	10	0.07	0.07	0.78	0.14	0.66	11.77	2.18	-26.26	0.85
	20	0.09	0.05	0.61	0.14	0.56	11.82	2.60	-25.18	0.92
	40	0.13	0.04	0.45	0.14	0.47	11.06	2.38	-24.36	1.05
UF-E-T	10	0.10	0.28	4.26	0.14	2.46	15.30	2.17	-27.38	0.58
	20	0.15	0.09	1.21	0.14	1.21	13.29	2.79	-26.27	0.99
	40	0.13	0.06	0.72	0.14	0.50	12.20	3.33	-25.79	0.70
UF-E-SB	10	0.12	0.12	1.54	0.14	1.30	13.24	2.52	-26.68	0.85
	20	0.20	0.06	0.70	0.14	0.65	11.99	2.62	-25.32	0.92
	40	0.12	0.06	0.67	0.14	0.71	12.02	3.39	-24.71	1.05

APPENDIX B

ANALYZED PARTICLE SIZE DISTRIBUTION OF SAMPLES AT EACH DEPTH INTERVAL

-Samples were weighed and sieved to 2 mm, then organics were removed by adding water removing light floating fraction and dried again. Samples were then sieved to 1 mm. % Very coarse sand is % weight between 1-2 mm. Particles < 1 mm were measured using MasterSizer 3000 with Hydro LV using methods by Sperraza et al. (2004). Particle size ranges and name of soil type based on USDA soil classification.

Sample Name	Depth Interval (cm)	% Very Coarse Sand (1-2 mm)	% Coarse Sand (0.5-1 mm)	% Medium Sand (0.25-0.5 mm)	% Fine Sand (0.1-0.25 mm)	% Very Fine Sand (0.05-0.1 mm)	% Silt (0.002-0.05 mm)	% Clay (< 0.002 mm)	Soil Type
GMP-N	5	17.54	9.31	28.96	11.35	12.19	15.33	5.32	Loam Sand
	10	15.24	6.62	32.21	16.20	17.92	11.81	0.00	Sand
	20	9.85	5.97	30.97	14.57	18.87	19.75	0.02	Loam Sand
	30	11.52	4.88	30.55	11.66	15.47	25.74	0.19	Loam Sand
GMP-G	5	9.25	5.64	29.97	14.91	18.78	21.32	0.12	Loam Sand
	10	6.15	3.29	27.58	13.61	19.27	29.86	0.25	Sandy Loam
	20	12.81	3.88	28.27	10.51	11.29	32.55	0.69	Sandy Loam
	30	10.25	2.29	25.33	12.88	16.96	31.85	0.44	Sandy Loam
GMP-S	5	13.42	9.58	33.85	10.85	12.01	20.26	0.03	Loam Sand
	10	17.94	4.26	28.76	13.02	15.35	20.57	0.11	Loam Sand
	20	13.30	4.85	30.29	11.04	13.84	26.46	0.23	Loam Sand
	30	15.82	4.61	29.67	11.10	12.93	25.64	0.23	Loam Sand
GW-N	5	27.20	13.92	31.79	8.39	7.69	11.01	0.00	Sand
	10	14.81	7.21	30.35	12.99	15.50	19.07	0.07	Loam Sand
	20	11.77	2.87	26.65	11.91	16.11	30.44	0.25	Sandy Loam
	30	14.02	2.39	24.04	11.70	15.46	32.11	0.27	Sandy Loam
	40	11.80	3.47	27.88	11.72	13.34	31.40	0.39	Sandy Loam
GE-S	5	11.13	6.07	26.71	13.17	18.37	24.47	0.08	Loam Sand
	10	12.54	2.09	20.89	15.20	24.47	24.72	0.10	Loam Sand
	20	16.57	1.86	20.59	13.86	21.07	25.92	0.13	Loam Sand
	30	14.81	1.28	19.81	12.92	21.56	29.43	0.19	Loam Sand
GE-M	5	9.88	5.14	26.27	13.03	19.85	25.75	0.08	Loam Sand
	10	12.59	5.01	23.89	14.90	21.52	22.06	0.03	Loam Sand
	20	13.89	2.94	23.79	13.13	20.05	26.09	0.11	Loam Sand
	30	14.36	2.02	18.39	12.25	20.51	32.17	0.29	Sandy Loam
TF-N	10	7.68	1.96	21.15	14.18	19.82	34.86	0.35	Sandy Loam

	20	7.67	0.98	23.39	12.44	15.00	39.91	0.59	Sandy Loam
	40	7.32	1.13	22.11	13.23	16.83	38.29	1.10	Sandy Loam
	60	5.76	1.32	24.22	14.02	17.83	35.01	1.83	Sandy Loam
TF-S	10	5.75	2.62	22.69	14.74	21.63	32.31	0.27	Sandy Loam
	20	7.59	1.48	23.22	14.87	19.19	33.33	0.32	Sandy Loam
	40	8.96	1.53	22.99	14.53	19.06	32.47	0.48	Sandy Loam
BF-N	10	6.03	2.79	23.53	15.53	21.04	30.77	0.31	Sandy Loam
	20	5.66	1.36	22.97	15.07	20.42	34.03	0.49	Sandy Loam
	40	4.76	0.58	20.80	17.07	22.12	34.10	0.57	Sandy Loam
	60	3.87	2.09	29.46	15.05	17.38	31.50	0.66	Sandy Loam
BF-S	10	8.34	3.05	27.53	16.08	20.99	23.77	0.22	Loam Sand
	20	6.50	1.53	24.72	16.62	22.31	28.02	0.29	Loam Sand
	40	7.32	2.87	25.53	13.85	18.67	31.26	0.51	Sandy Loam
	60	7.27	3.11	26.79	14.67	17.76	29.84	0.56	Sandy Loam
PF-N	10	6.18	1.24	21.42	17.50	23.64	29.64	0.37	Sandy Loam
	20	7.62	2.57	38.48	14.22	11.20	25.44	0.46	Loam Sand
	30	10.29	3.40	33.50	12.43	12.06	27.73	0.57	Loam Sand
PF-M	10	3.94	7.36	40.47	14.58	14.25	19.27	0.13	Loam Sand
	20	3.08	4.00	41.58	16.29	14.58	20.21	0.25	Loam Sand
	40	3.41	2.76	37.43	18.93	16.50	20.73	0.25	Loam Sand
PF-S	10	2.37	1.86	23.24	15.16	20.25	36.66	0.45	Sandy Loam
	20	3.12	1.59	27.69	14.95	17.65	34.49	0.52	Sandy Loam
	40	2.07	0.85	23.28	15.35	19.50	38.32	0.63	Sandy Loam
	60	2.28	0.59	23.83	17.17	20.10	35.34	0.68	Sandy Loam
UF-WN-SB	10	5.23	8.90	35.64	15.16	17.86	17.17	0.03	Loam Sand
	20	3.32	4.26	30.73	13.83	18.56	29.04	0.25	Loam Sand
	40	5.21	3.15	27.27	12.47	18.06	33.49	0.36	Sandy Loam
	60	8.96	4.87	25.48	11.14	16.93	32.29	0.33	Sandy Loam
UF-WS-SB	10	7.24	3.06	31.23	14.08	17.63	26.45	0.31	Loam Sand
	20	7.29	5.68	32.28	12.11	16.39	25.99	0.26	Loam Sand
	40	7.25	4.56	32.84	14.00	16.42	24.57	0.36	Loam Sand
UF-E-T	10	6.85	8.62	29.68	14.70	19.28	20.82	0.04	Loam Sand
	20	5.65	4.52	25.27	12.99	19.83	31.47	0.27	Sandy Loam
	40	5.04	6.24	33.54	10.13	15.37	29.43	0.25	Loam Sand
UF-E-SB	10	7.04	3.00	27.25	14.74	17.98	29.57	0.41	Loam Sand
	20	8.03	2.65	28.25	15.37	16.35	28.93	0.42	Loam Sand
	40	10.12	2.02	24.40	13.61	16.83	32.57	0.44	Sandy Loam