CROSSING SCALES AND FIELDS TO EXAMINE AGRICULTURAL LAND MANAGEMENT AND WATER QUALITY: INCORPORATED WOODCHIPS AS A SOIL RESTORATION STRATEGY AND THE WAYS FARMERS KNOW

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

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August 2019

CROSSING SCALES AND FIELDS TO EXAMINE AGRICULTURAL LAND MANAGEMENT AND WATER QUALITY: INCORPORATED WOODCHIPS AS A SOIL RESTORATION STRATEGY AND THE WAYS FARMERS KNOW

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Cornell University 2019

Soil degradation, desertification, and losses in net-primary production from agricultural land use is a serious and growing problem worldwide. Bringing degraded soils back into production is crucial to stop the cycle of land degradation. To return degraded and desertified landscapes to productivity, sandy soils must first be improved to enhance water and nutrient holding capacity. In this study I examined the ability of incorporated coarse woodchips to alter water and nutrient holding capacity as well as support biomass production in very sandy, degraded soils in field, laboratory, and greenhouse settings. Coarse woodchips incorporated into the soil increased water holding capacity by 16% in the field and 18% in the laboratory through absorption of water by the woodchips. Soluble nutrient losses of nitrogen (N) and phosphorus (P) were smallest when fertilizer was applied in liquid form. Carbon dioxide emissions increased by 200% in the presence of woodchips, likely due to increased respiration by the microbial biomass. In the greenhouse incorporated woodchips increased soil water content by 350% and available water capacity 185%. Soluble N losses were reduced by 90% in the presence of woodchips when the system was not fertilized. Biomass production was reduced by 60% when soils were amended with woodchips. This work suggests incorporating coarse wood chips into soil is a viable strategy for improving soil water content and nutrient retention in very sandy and degraded soils. On-farm data

collection is crucial to decision making by farmers of all types when it comes to fertilizer and water management. In the second phase of this study, I examined the types and forms of data collected by farmers with respect to water and nutrient management. Through interviews and focus groups with farmers, I examined two kinds of data collected by farmers: technologically mediated data and sensory data. I assessed the ways these data are distinct and the ways in which they overlap, work together, or even seem to blur together, and find that they fall more on a spectrum than in two separate categories.

BIOGRAPHICAL SKETCH

Erin Menzies Pluer grew up near Chautauqua Lake in Lakewood, NY with her parents, David and Priscilla Menzies, and her twin brothers, Allan and Griffin Menzies. At long last Erin has sisters with the recent additions of Tenley Burlingame and Martha Dittoe to the family. Erin attributes her love of the natural world to the ten summers she spent in Algonquin Park, Ontario attending and working at Northway Lodge, a wilderness camp for girls. Erin received a Bachelor of Science in 2010 in the field of Environmental Engineering from the University of Vermont in Burlington, Vermont. In 2011, Erin began service in the United States Peace Corps in Ecuador. She served in a small rural community named La Esmeralda in the province of Los Rios. She was a Sustainable Agriculture volunteer and worked primarily with a Cocoa Growers cooperative and a few women's groups. Erin married Will Pluer, her graduate school desk mate, in the spring of 2017. Erin loves to travel, learn new languages, ski, hike, play outside with her dog, and cook over the top complicated meals with her husband.

This work is dedicated to my family, both long standing and new and to all the amazing women in my life; they are family, friends, mentors, inspiration and I wouldn't be who I am without them.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant Number DGE-1144153. This work was also funded in part by the Office of Engagement Initiatives at Cornell, the National Science Foundation IGERT program, and the Ningxia Forestry Institute of Yinchuan, Ningxia, China.

I am grateful to my advisers, Todd Walter, Rebecca Schneider, and Lori Leonard for their time, ideas, and generous support. I would also like to thank the members of the Cornell Soil & Water Lab who supported all phases of the work, especially Lauren Harroff, James Knighton, Christine Georgakakos, and Will Pluer.

I would like to thank Whitney Denison and Stephen Ritman for their help in the lab and the greenhouse. Numerous others made these projects possible; thank you to Judy Wright and Janice Degni of Cornell Cooperative Extension, Mark Liebig of USDA-ARS, Erika Mudrak of the Cornell Statistical Consulting Unit, and Merritt Compton of the Cornell greenhouse facilities. I would also like to thank all the farmers who gave their time for interviews or focus groups and generously shared their knowledge and experiences.

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LIST OF ABBREVIATIONS

ARS	Agricultural Research Service
AWC	Available Water Capacity
BMP	Best Management Practice
C	Carbon
CAFO	Concentrated Animal Feeding Operation
CCE	Cornell Cooperative Extension
CH_4	Methane
CNMP	Comprehensive Nutrient Management Plan
CO_2	Carbon Dioxide
CSA	Community Supported Agriculture
ECL	Environmental Conservation Law
EPA	Environmental Protection Agency
ET	Evapotranspiration
GHCN	Global Historical Climatology Network
GHG	Greenhouse Gas
GWC	Gravimetric Water Content
LTAR	Long-Term Agroecosystem Research
N	Nitrogen
N_2	Di-Nitrogen Gas
N_2O	Nitrous Oxide
ND	North Dakota
NGPRL	Northern Great Plains Research Laboratory
NOAA	National Oceanic and Atmospheric Association
NPP	Net-primary Productivity
NSE	Nash-Sutcliffe Efficiency Coefficient
NYS	New York State
P	Phosphorus
PVC	Polyvinyl Chloride
RMT	Rubber Mulch Treatment
TDR	Time-Domain Reflectometer Probe
TM	Technologically Mediated Data
US	United States
USDA	United States Department of Agriculture
VWC	Volumetric Water Content
WCT	Woodchip Treatment

INTRODUCTION

Soils around the globe have been negatively impacted by agricultural practices and mis-management, leading to degradation and loss of soil organic matter (Bridges and Oldeman 1999; Oyarzun et al. 2007). Intensifying agriculture and human population growth contribute to degradation through an increase in the quantity of land being continuously cultivated and intensified management of land already in production. As a result, soils lose their ability to effectively sustain plant life and to provide valuable ecosystem services such as food production and carbon (C) sequestration. To counteract agricultural soil degradation, there has been an escalation of fertilizer use (Foley et al. 2005), often in excess. As a result, nutrient pollution from agriculture is a significant concern worldwide as soluble nutrients, such as nitrogen and phosphorus, are carried into surface waters and eventually the ocean, causing eutrophication and hypoxia (Bouwman et al. 2002; Carpenter et al. 1998). While efforts to reduce fertilizer use can reduce nutrient pollution, improved soil health could help retain nutrients in the landscape.

Organic amendments, such as manure, green manures, and compost, are commonly used in reclaiming soils and combating degradation (Larney and Angers 2012a). While these amendments have proven to be helpful in improving soil properties, they are generally nutrient rich and easily degradable by soil microbes, therefore requiring regular application to sustain the amendments' benefits (Larney and Angers 2012b). Amendments with longer term impacts have been the subject of study more recently, including biochar and industrial wastes such as coffee waste (Gardner et al.

2010; Kasongo et al. 2011; Laird et al. 2010).

Bringing severely degraded soils back into production in a sustainable way, by increasing their potential to support biomass generation, will require an input of stable organic matter. In Chapters 1 and 2, I examine coarse woody amendments as a strategy to improve water and nutrient holding capacity of degraded soils, while creating an environment in which plant life can flourish.

The process by which farmers make decisions about when, where, and how to adopt BMPs, such as that proposed in Chapters 1 and 2, is a topic of much debate, with many studies indicating contradictory results (*i.e.,* Kabii and Horwitz 2006; Knowler and Bradshaw 2007; Prokopy et al. 2008). However, these studies have been largely unsuccessful in identifying farmer attitudes and social factors that influence adoption (Prokopy et al. 2008). The task of developing and evaluating BMPs falls largely to research scientists and engineers; yet it is farmers who are carrying out the work crucial to reducing nutrient losses and protecting water quality. Therefore, it is farmers who are best positioned to evaluate the viability and effectiveness of such tools and recommendations on their own land. Farmers' close relationship with their land situates them in a unique position to collect vast amounts of information and develop an intimate understanding of the ways in which water and fertilizers interact (Carolan 2008). The first step to bringing farmers and the knowledge they have into the research process is to understand the types of data they collect on their land and the forms this data takes. In Chapter 3, I explore these questions and examine the knowledge held by farmers.

CHAPTER 1

RETURNING DEGRADED SOILS TO PRODUCTIVITY: AN EXAMINATION OF THE POTENTIAL OF COARSE WOODY AMENDMENTS FOR IMPROVED WATER RETENTION AND NUTRIENT HOLDING CAPACITY

Introduction

Soils around the world have been degraded by agricultural practices and chronic soil mismanagement (Bridges and Oldeman 1999; Oyarzun et al. 2007). The growing human population and concomitant intensification of agriculture has led to continuous cultivation and plowing of increasingly larger swaths of land. As soils are plowed, organic matter is lost in two primary ways. The first pathway of loss is to the atmosphere as carbon dioxide (CO_2) through microbial respiration. Through the mechanical process of turning the soil, oxygen, an important component of respiration, is introduced into the soil, and soil aggregates are broken up to reveal carbon (C) compounds that previously were isolated from microbial activity (Barnwell et al. 1992; Reicosky et al. 1997). Loss of organic matter can also occur when agricultural soils are frequently plowed and soil particles are carried away by wind and water erosion (Lal 2003). These losses can reduce a soil's productivity and, in extreme cases, initiate the process of desertification (D'Odorico et al. 2013). Subsequently, unproductive soils are often abandoned, leading to the conversion of more land plowed for cultivation, thus feeding a vicious cycle of land use and degradation.

As a major contributor to soil health, organic matter plays an important role in the ability of a soil to retain water, and its loss can have compounding effects. It is well established that soil organic matter increases water holding capacity and, subsequently, plant available water capacity (Hudson 1994). Among other properties, increased organic matter can result in larger pore spaces as soil aggregates form, creating more spaces for the water to occupy (Larney and Angers 2012). Water is also absorbed into the components of organic matter itself after a rain event, and released back into the soil matrix as the system dries (Lyon and Buckman 1943). In addition, organic matter increases infiltration capacity, and can create flow pathways allowing rainwater to move more quickly into the matrix of the soil, avoiding surface runoff generation and subsequent loss from the system. All told, chronic loss of organic matter is one of the key drivers of degradation of agricultural soils.

With the intensification of agriculture, and the loss of nutrients has come a steady escalation in fertilizer use, resulting in a global increase in excess of 700% in the past few decades (Foley et al. 2005). Loss of organic matter can diminish the ability of soils to retain nutrients, because a primary mechanism of retention is through cation exchange capacity (Larney and Angers 2012), which is greater in organic matter than the surrounding mineral soil. Accordingly, an increase in organic matter in the soil contributes to increased cation exchange capacity (Parfitt et al. 1995). Conversely, the inability of the degraded soil to retain excess nitrogen (N) and phosphorus (P) from fertilizers, can cause eutrophication and hypoxia in estuarine and fresh water systems, respectively, (Bouwman et al. 2002; Carpenter et al. 1998). These and other excess nutrients enter adjacent surface water bodies via precipitation (wet deposition), surface runoff, leaching, and groundwater return flows.

While the presence of sufficient organic matter is important to note when determining the capacity of soils to retain nutrients, the method by which fertilizers are applied is also an important consideration. To reduce losses of soluble nutrients from fertilized land, it is recommended that fertilizers be incorporated into the soil in a dry form (Roberts 2007). Incorporation reduces losses from surface runoff, while dry fertilizers reduce losses by slowing the release of nutrients and reducing immediate losses through preferential flow pathways.

Along with soluble losses of nutrients, it is important to consider the likelihood of gaseous losses. Agricultural land is a significant contributor to greenhouse gas (GHG) emissions, contributing to the changing global climate through the degradation of soils and an increase in fluxes (Oertel et al. 2016; Smith et al. 2008). Plowed and aerated soil not only increases availability of C, which is respired and emitted as CO_2 by soil microbes, but also yields production of nitrous oxide (N_2O) by soil microorganisms through incomplete denitrification. Indeed, N fertilizers provide the necessary substrate to stimulate denitrification and subsequent N_2O production (McSwiney and Robertson 2005).

Although increased fertilizer can help sustain crop yields, chronic degradation of soils often ultimately leads to abandonment of farmlands. One strategy for combating soil degradation, reclaiming soils, and halting the cycle of degradation and abandonment is the use of organic amendments, which add both organic matter and nutrients and have proven more effective in improving soil properties than adding nutrients alone (Gardner et al. 2010). Historically, the most commonly employed organic amendments are manure, green manures, and compost, all materials that are nutrient rich and easily degradable by soil microbes (Larney and Angers 2012). As a result, they need to be applied at regular intervals to maintain the benefits of the amendment. More recently, organic amendments with longer-term stability in the soil have included biochar and industrial wastes (Gardner et al. 2010; Kasongo et al. 2011; Laird et al. 2010).

An area of interest in our studies is the use of woody materials, which could be used as a stable source of organic matter that would improve soil structure for an extended period of time. In a number of settings, woodchips are used as a surface mulch for ecosystem restoration (Fang et al. 2011; Ferrini et al. 2008; Głąb and Kulig 2008; Buchanan et al. 2002; Prats et al. 2012), and have been used as media for denitrifying bioreactors (Ghane et al. 2014, 2016; Pluer et al. 2016). In addition, sawdust can be used to "reverse fertilize", to immobilize N and reduce soluble losses, in situations where soils have become overly N rich (Bugbee 1999). However, there are limited instances in the literature in which woodchips have been incorporated into the soil. In one example, Meffe et al. (2016), soil columns were used to examine the impact of incorporated woodchips on vegetative buffer strips used to treat household wastewater. Incorporated woodchips resulted in higher volumetric water content (VWC) and lower rates of N losses, compared to woodchips applied on the surface.

We propose that restoring severely degraded soils in a sustainable way will require an input of stable organic material that can impart benefits on a time scale of many years. To that end, we expect the incorporation of coarse woodchips to behave similarly to other organic amendments that have been previously studied (Ajwa and Tabatabai 1994; Dempster et al. 2012; Fueki et al. 2012; Hudson 1994; Khaleel et al. 1981; Larney and Angers 2012; Li et al. 2018), improving soil health by enhancing structure and facilitating important functions, while resisting rapid decomposition. In this study, we investigated two facets of the use of incorporated coarse woodchips as a soil reclamation strategy for very sandy, degraded soil. First, we investigated the ability of incorporated coarse woodchips to increase water holding capacity of sandy soils in the field and followed up by examining mechanisms driving the changes using soil columns in the laboratory. Second, using the soil columns, we quantified both soluble and gaseous losses of N and P applied as wet and dry fertilizers to determine best practices to reduce nutrient losses from fertilizers applied in conjunction with incorporated coarse woodchips. We hypothesize that (1) coarse woodchips will increase water holding capacity of sandy soils and (2) that dry fertilizers will generate less soluble nutrient loss because nutrient releases into the soil are slower than for dissolved fertilizers.

Materials and Methods

This project was an extension of an ongoing project conducted in the Ningxia province of China, a region that has experienced severe grassland degradation due to agricultural conversion (for review, see Li et al. 2018). Thousands of years of agriculture in northern China have left vast expanses of severely degraded sandy soils where few plants can grow without irrigation. Historical evidence, *i.e.* petroglyphs from nearby Helan Mountains, suggest that these landscapes once were productive grasslands, despite limited rainfall in the region. The overarching aim of our research is to develop an intervention to improve the ability of the soils in the region to capture more of the limited rainfall. As a complement to the research in Ningxia, we chose an additional site in the northern Great Plains of North America for comparable experimentation: the United States Department of Agriculture (USDA) Northern Great Plains Research Laboratory (NGPRL) which is part of the Long-term Agroecosystem Research (LTAR) network located near Mandan, North Dakota (ND), USA (latitude 46° 48′ 38″ N, longitude 100° 54′ 35″ W). This present-day grassland site in the northern United States (US) was selected for experimentation for several reasons. First, it also is a grassland that has been altered from its original state, although it is much earlier on in the degradation process. Importantly, it has a climate very similar to Ningxia, although, the LTAR site in Mandan receives slightly more precipitation, with an annual pattern similar to that observed in Ningxia (Figure 1.1a). In general, Ningxia mean temperatures are approximately 10 °C higher than Mandan but mean high and low monthly temperatures in both locations follow nearly identical annual patterns and are very similar in magnitude of change (Figure 1.1b). Soils found in each location have similar textures with soils from Ningxia classified as sand with 93.8% sand, 2.6% silt, and 3.6% clay and the Tally-Parshall soils from Mandan classified as a sandy loam with 70.3% sand, 18.3% silt, and 11.4% clay. Soils found in Ningxia, however, are very low in organic matter, by the loss on ignition method, reporting only 0.1% organic matter while soils from the Mandan LTAR site have 2.67% organic matter. Both locations are historical grasslands, the differences in organic matter are indicative of the comparative severity of soil degradation in each location.

Weather data were obtained from the National Oceanic and Atmospheric Association (NOAA) Global Historical Climatology Network (GHCN) of weather stations, using the meteorological station (Number USC00325479) located at the Mandan Experimental Station in Mandan, ND (NOAA, 2015). Weather data from Ningxia, China were obtained from an onsite weather station.

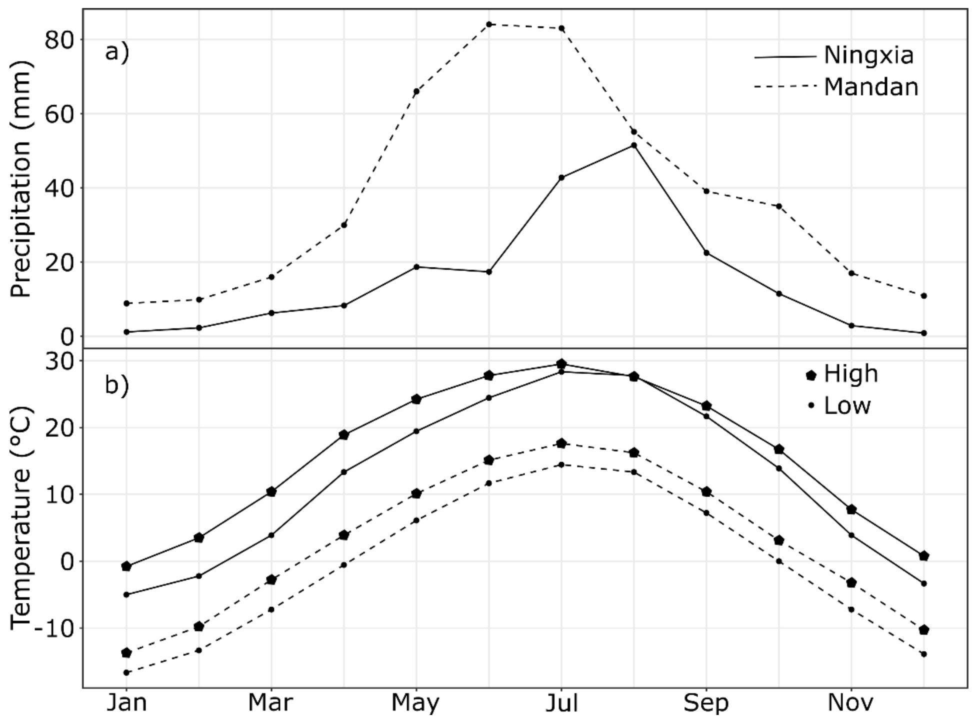


Figure 1.1 Mean monthly precipitation in mm (a) and high and low temperatures in degrees Celsius (b). Solid lines represent data from Ningxia while dotted lines are data from Mandan. High and low monthly mean temperatures are denoted by pentagons and circles, respectively.

Field Experiment

In the first phase of this study, a field experiment was implemented at the NGPRL near Mandan to evaluate water holding capacity of soils when amended with incorporated woodchips. Six plots, 0.5 meters by 1 meter, were established and three plots were selected at random and then amended by incorporating woodchips into the soil at 20% by volume, to a depth of 20 cm, *i.e.,* woodchip treatment (WCT). The other three plots were used as a control: the soil was mixed in the same fashion as the treatment plots but did not receive any amendment. In each plot, soil moisture data loggers (Decagon Devices) were installed at a depth of 10 cm and soil moisture was recorded every 30 minutes for 60 days from June 18 to August 17, 2015. Simultaneous meteorological data were obtained from the USDA Agricultural Research Service (ARS) weather station located near the study site.

In order to detect differences in water holding capacity, our analyses focused mainly on the 48-hour period immediately following rain events with precipitation amounts greater than 5 mm. One event in late July was omitted from this analysis because it was highly localized and did not generate a response from all test plots. In the 48-hour period following the rain events, we quantified the rate at which the soil dried by calculating the slope of the line between the maximum and the minimum VWC values that occurred in the 48-hour period following the storm. To determine differences between maximum and minimum VWCs, as well as the rate of drying between treatment and control plots, we used linear mixed models with fixed effects and random effects. Linear mixed models were also used to examine the relationships between the magnitude of a given storm and the response variables. Data processing and statistical analyses were conducted using R v3.0.2..

Lab Soil Columns Experiments

Mechanisms of water retention

In subsequent laboratory experiments, soil columns were used to examine the relative influence of two physical processes, absorption and flow path disruption, on changes in water retention in woodchip-amended soils. Columns were constructed from rigid polyvinyl chloride (PVC) pipes, 10 cm in diameter, cut to a length of 35.5 cm, with a perforated cap attached to the bottom. Soil fill for the columns was a mixture of lab-grade sand and Tally-Parshall soil that was collected from the field plots at Mandan, ND. The two media were mixed to achieve a soil with a very sandy texture (87.1% sand, 10.6% silt, 2.3% clay) reflective of those observed in Ningxia, China (94% sand). Nine soil columns were constructed and separated equally into three treatments, with three replicates per treatment. All columns were first filled with 5 cm of the base soil on the bottom. The top 20 cm of the column was then filled with one of three treatments: base soil mixed with 10% by volume oven-dried woodchips from the tree species *Populus tremuloides* (woodchip treatment, WCT); base soil with 10% by volume shredded rubber mulch (Rubberific® Premium) (Rubber mulch treatment, RMT); or base soil only (control). Both woodchip and rubber mulch amendments were sieved to exclude fragments smaller than 5 mm in any dimension and larger than 100 mm in any dimension to ensure consistent texture among treatments. Rubber mulch was chosen as a means to determine the effect of flow path disruption by eliminating the possibility of retention by absorption. Due to the high sand content of the soil, it was easily poured into the columns and did not require incremental compaction as is common in soil column experiments.

After filling the columns with soil, 100 mL of deionized water was added to each. This was equivalent to a 1.2 cm rain event and represented 12% of the soil pore volume in the control treatment. Columns were then left for approximately 24 hours to allow time for the sand to settle and to allow for an initial wetting period of the media in the column. Columns were then subjected to three consecutive simulated rain events, with 7(±3) days between each event. Rain events were consistent with an expected 5-year storm in Mandan, ND, with a volume of 535 mL, or 66 mm in depth (NOAA 2017). This sizeable storm magnitude was chosen to ensure the generation of leachate and to amplify the impacts of the treatments. Water that leached from each column was collected until drainage had largely ceased, a period lasting between 5 and 8 minutes. The total quantity of water lost from the columns was recorded. A linear mixed model with fixed and random effects, as well as a one-way ANOVA, were used to determine significant differences between water retained by each treatment over the course of the three rain events.

Nutrient losses from fertilizers

A similar column experiment was used to evaluate and compare losses from directed fertilization in the presence of or absence of incorporated woodchips. In this portion of the experiment, twenty-four soil columns were constructed and separated equally into two soil amendment treatments and four fertilizer treatments, with three replicates per combination of soil amendment and fertilizer. All columns were first filled with 5 cm of the same base soil used in the previous phase of the experiment. The top 20 cm of the column was then filled with one of two soil amendment treatments: base soil mixed with 10% by volume oven-dried woodchips from the tree species *Populus tremuloides* (woodchip treatment, WCT) or base soil only (control). Woodchip amendments were sieved to exclude fragments smaller than 5 mm in any dimension and larger than 100 mm in any dimension to ensure consistent texture among replicates. Columns were then separated equally into four fertilizer treatments: 1) none - no fertilizer applied; 2) liquid - dry fertilizer was dissolved in the 100 mL of deionized water added during the setup phase; 3) dry incorporated - dry fertilizer was stirred into the dry soil before it was poured into the columns; and 4) dry surface - dry fertilizer was applied to the soil surface after filling had occurred before the 100 mL of deionized water was applied.

Columns that were fertilized each received 7.4 g P m^{-2} (74 kg P ha^{-1}) as dipotassium phosphate (K_2HPO_4) and 19.7 g N m^{-2} (197 kg N ha^{-1}) as potassium nitrate (KNO_3). Values were determined based on the upper limits of the recommended fertilization rates of prairie grasses (Kidd et al. 2017). After filling the columns, 100 mL of deionized water was added to each. This was equivalent to a 1.2 cm rain event and represented 12% of the soil pore volume in the control treatment. Columns were then left for approximately 24 hours to allow time for the sand to settle and to allow for an initial wetting period of the media in the column. Columns were then subjected to three consecutive simulated rain events, with an average of 7(±3) days between each event. Simulated rain events were consistent with an expected 5-year storm in Mandan, ND, with a volume of 535 mL, or 66 mm in depth (NOAA 2017).

At the beginning of the experiment, initial dry weights of the columns, were recorded before any water was applied. Columns were then weighed during the experiment before and after each simulated rain event and every 24 hours for 3 days after each rain event. Column dry weight was subtracted from wet weight to determine mass of the water retained which was then divided by the initial dry weight of the column to determine gravimetric water content (GWC). GWC was converted to VWC. In addition, gas flux samples were collected before and after each rain event to observe both ambient and post-rain gas fluxes. Water that leached from each column was collected until all drainage had largely ceased, a period lasting approximately one hour. The quantity of water lost from the columns was recorded and water was immediately filtered using a 0.45 µm filter. Samples were then acidified to a $pH < 2$ and refrigerated until analysis. Water samples were analyzed for orthophosphate using EPA method 365.1 (Heinonen and Lahti 1981) and for nitrate-nitrite using EPA method 353.2

(O'Dell 1993). Linear mixed effects models with random and fixed effects were used to determine significant differences between VWCs. Student t-tests were used to determine significant differences in N and P leachate losses with and without incorporated coarse woodchips.

To examine the influence of the treatments (*i.e.* soil amendment, fertilizer) and simulated rain events on GHG emissions we determined fluxes of CO_2, N_2O, and methane (CH_4) from the columns using a static chamber method (Parkin and Venterea 2010). Sampling for GHGs was conducted before and after rain events, before each simulated rain event was applied, each column was fitted with an enclosed PVC cap with two septa for sampling as described by McPhillips et al. (2016). Four gas samples were taken from each column at 10-minute intervals for a period of 30 minutes. This process was again repeated after the simulated rain event was completed. When water could no longer be observed standing on the soil surface, which occurred in a matter of seconds, the enclosed PVC cap was again fitted to the column and four gas samples were collected in the exact same manner as before the simulated rain event. Three pre-rain gas sampling efforts and three post-rain sampling efforts were conducted on each column, with an average of 7(±3) days between each event. All gas samples were analyzed for CO_2, N_2O, and CH_4 using an Agilent 6890N gas chromatograph with a HP 7694 Headspace Autosampler, equipped with an electron capture detector and a flame ionization detector with a methanizer. We determined fluxes by fitting a linear model to the concentrations at the four time points sampled (0, 10, 20, and 30 minutes) and the ideal gas law allowed for conversion of volumetric to mass-based fluxes. Only flux calculations with an r-squared value of 0.75 or higher for CO_2 were included in the data analysis as is common with the static chamber method (Truhlar et al. 2016). A linear mixed effects model with fixed and random effects was used to examine significant predictors of fluxes. Student t-tests were used to determine differences in samples taken from columns with and without incorporated coarse woodchips as well as before and after rain events. A one-way ANOVA was used to determine significant differences in gas fluxes under differing fertilization regimes.

Results and Discussion

Field Data

Results from soil moisture probes in the field soils of Mandan, ND from the summer of 2015 supported earlier studies (Li et al. 2018; Li et al. 2019; Li et al. 2019) in which incorporated woodchips increased water holding capacity of sandy soils, as compared to control plots (Figure 1.2). Over the course of the study period approximately 150 mm of rain fell. To examine the soil moisture characteristics in response to rain events, we evaluated the four large (>5 mm) precipitation events where a response was seen from all treatments. Chronologically, rainfall for the four events totaled 45 mm, 18 mm, 8 mm, and 20 mm. In the 48 hours after each of the rain events, we examined three response variables: minimum VWC, maximum VWC, and the rate of drying (Figure 1.3). Following the first rain event, during the drying phase, soil with incorporated woodchips had a higher mean minimum VWC than the control soil, with the effect becoming more pronounced with each successive rain event. A similar pattern was observed for maximum water content. We observe systematic differences indicating that soils with incorporated woodchips have increased water holding capacity but, potentially due to low sample size, mean values were not significantly different.

There was no significant difference in the rate of drying between the WCT and the control soils following a rain. Linear mixed models indicated that the rain event itself, a proxy for antecedent conditions, was a significant predictor for all three response variables. For the minimum VWC, the interaction between event and soil amendment was a significant predictor as well. A linear mixed model also revealed that the amount of precipitation in a rain event was not a significant predictor of maximum VWC nor rate of drying after a rain event.

These findings indicate that the incorporation of woodchips into the soil influenced the minimum VWC following a storm. However, the magnitude of a given storm was not a significant predictor of the response indicating that antecedent conditions or another factor are influencing the maximum VWC and rate of drying following storm events. The lack of statistical significance observed in what are clearly systematic differences might be attributable to the small sample size. Knighton and Walter (2016) similarly found that storm characteristics other than magnitude play important roles in hydrologic responses. Values for VWC observed in this woodchip experiment are consistent with those found in the literature for soils undergoing reclamation through other organic amendments (Khaleel et al. 1981; Kinney et al. 2012; Li et al. 2018; Meffe et al. 2016).

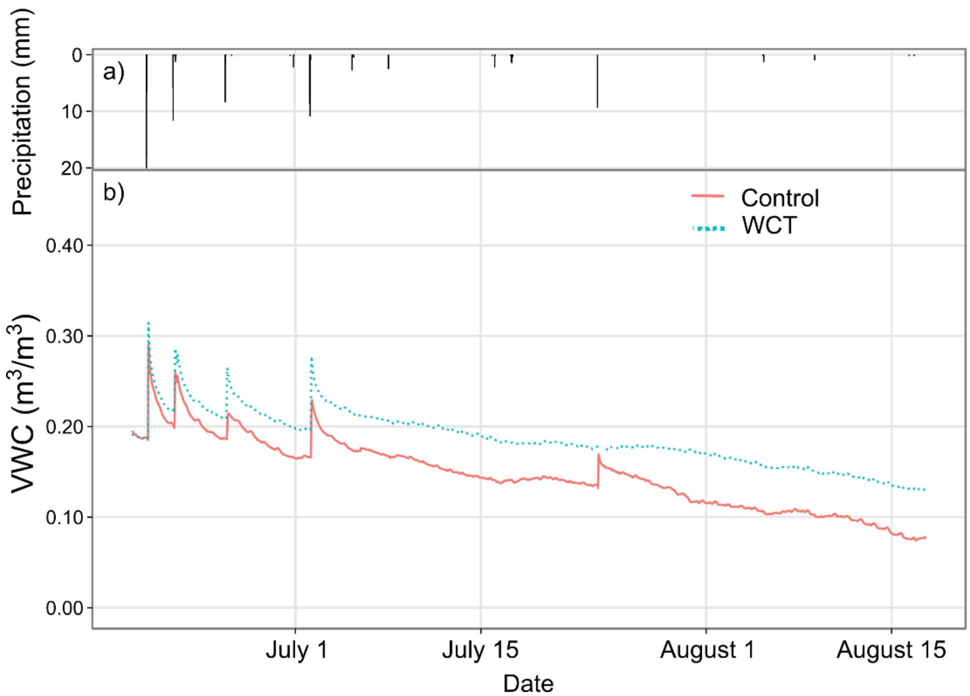


Figure 1.2 Precipitation in mm (a) and mean volumetric water content (VWC) (b) measured over the summer of 2015 in Mandan, ND. The dotted blue line represents the woodchip treatment (WCT) plots and the solid pink line represents the control plots. Note the y axis is in half hour intervals and as a result multiple precipitation bars may overlap.

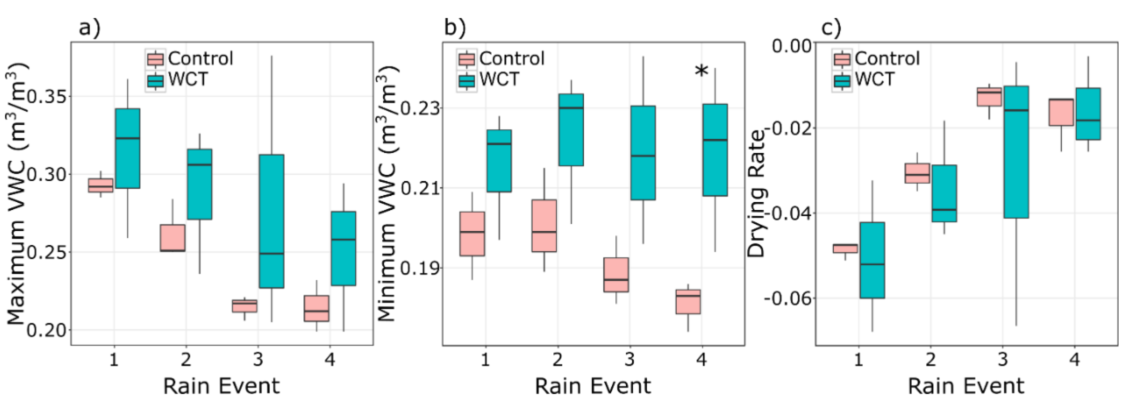


*Figure 1.3 Maximum (a) and minimum (b) volumetric water content (VWC) (m^3/m^3) as well as drying rate (change in VWC over time) (c) in the 48 hours following each of the four large (>5mm) rain events which generated a response from all test plots. The dark (blue) boxes represent the woodchip treatment (WCT) plots while the lighter (pink) boxes represent the control plots. Mixed models with fixed effects of soil amendment and rain event and random effects of plot number were used to determine significance, a * indicates significance at $p<0.05$.*

Lab Columns

Mechanisms of water retention

Water retention in WCT soil columns was significantly greater than in RMT columns after all three rain events, and significantly greater than control columns after the second and third rain events (Figure 1.4). Water retention in rubber mulch treated columns was lower and significantly different than the control columns only after rain event 1, but in rain events 2 and 3, RMT and control soils were not significantly different. The results from the first event likely reflected a wetting phase for all treatments. It is possible that the rubber mulch, with virtually no absorption and a tendency towards hydrophobicity (Pelisser et al. 2011), created preferential flow pathways through the soil during this initial wetting phase, but the differences diminished after wetting, *i.e.*, by the second rain event. In contrast, the significant differences in water retention between the WCT and the RMT after all simulated rain events can be attributed to water absorption by the wood.

A linear mixed model with fixed effects of treatment and rain event, and with random effects of column number indicated that treatment, rain event, and the interaction between the two, were significant predictors ($p<0.05$) of water retention. Values for VWC in this experiment, which ranged between 3% and 14%, are consistent with those found in the above described field-based experiment as well as in other reports in the literature (Khaleel et al. 1981; Kinney et al. 2012; Li et al. 2018; Meffe et al. 2016).

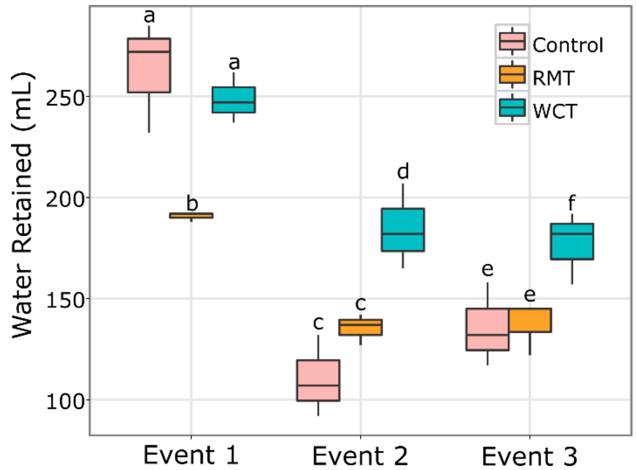


Figure 1.4 Water retained (mL) in the soil columns after each of three simulated rain events. Soil amendment treatments displayed include control soil represented by the lightest (pink) boxes, soil with incorporated rubber mulch (RMT) represented by the medium shade (orange) boxes, and soil with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. A mixed model with fixed effects of treatment and rain event, and random effects of column number, were used to determine significance; letters indicate significance at p<0.05 for treatments after each rain event.

Soluble nutrient losses from fertilizers

The subsequent experiment used to evaluate and compare losses from directed fertilization showed similar patterns of absorption and retention of water by soils with incorporated woodchips. Fertilized soils with incorporated woodchips displayed significantly higher VWC's than the fertilized control soils 48 h after all three simulated rain events (Figure 1.5). Indeed, a linear mixed model, with fixed effects of soil amendment, and random effects of rain event, rain date, and column number, indicated that soil amendment was a significant ($p<0.05$) predictor of VWC. This reinforced the findings in the previous two experiments, underscoring that incorporated woodchips increase water holding capacity of sandy soils.

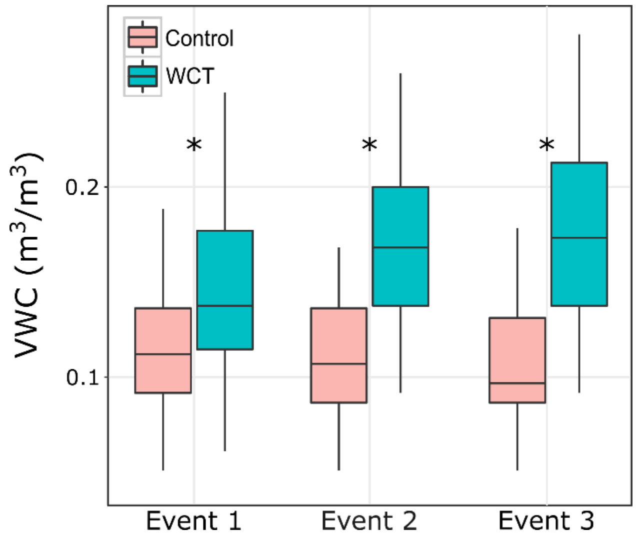


*Figure 1.5 Volumetric water content (VWC) (m^3/m^3) of fertilized lab columns over three simulated rain events. Soil amendment treatments displayed include control columns represented by the lightest (pink) boxes and columns with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. A mixed model with fixed effects of soil amendment, rain event, and the day on which the rain event was applied, and random effects of column number and experiment number were used to determine significance, a * indicates significance at $p<0.05$ for each rain event.*

Increased absorption and retention of water by woodchips was accompanied by the smallest losses of both soluble N and P from the columns when fertilizer was applied in a liquid form. In addition, when fertilizer was applied as a liquid and when it was applied in a dry surface application, there were significantly greater losses of soluble N from the control columns than from the woodchip-amended columns (Figure 1.6). There also was greater loss of P in the control soil than in the WCT where liquid fertilizer was applied ($p = 0.06$), and the loss of P was significantly higher in the control soils where dry fertilizer was incorporated into the soil (Figure 1.6). Overall, despite the better performance of woodchip-amended soil in reducing N and P losses in soil columns in some dry fertilizer applications, we conclude that nutrients should be applied in liquid form to soils with incorporated woodchips in order to limit the losses of both N and P.

This finding runs counter to our original hypothesis and indicates that the potential for interaction with woodchips is more influential in determining losses than the speed of release as we had originally theorized.

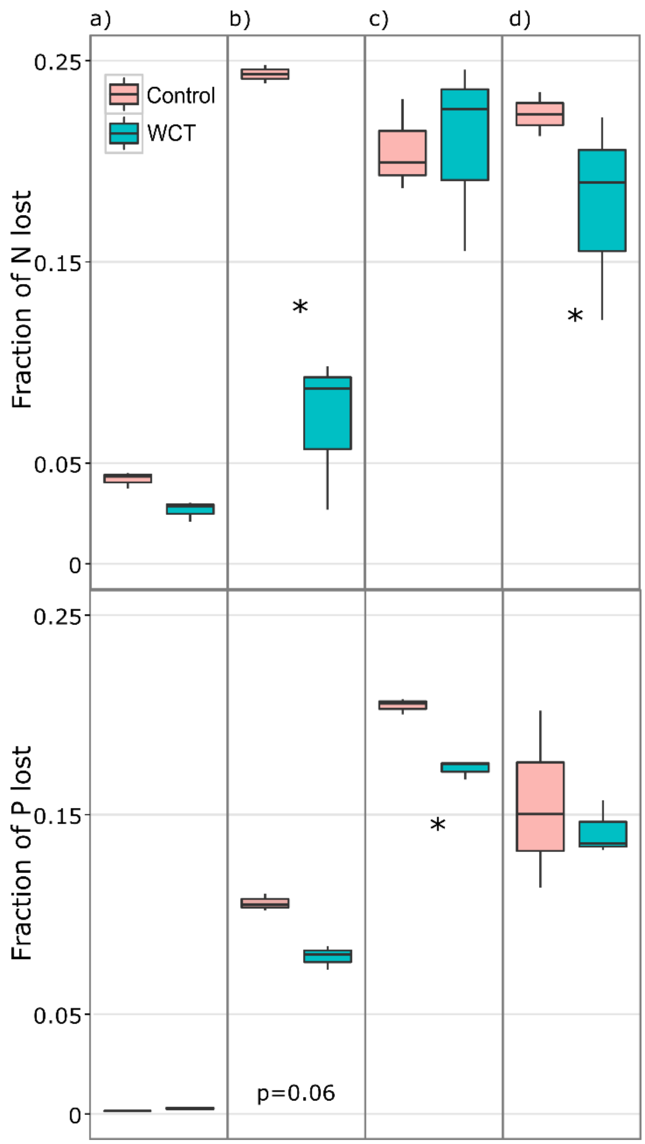


*Figure 1.6 Fraction of nitrogen (N) and phosphorus (P) demand by grasslands lost from soil columns. Soil amendment treatments displayed include control columns represented by the lightest (pink) boxes and columns with incorporated coarse woodchips (WCT) represented by the darkest (blue) boxes. The vertical panels separate the results by fertilizer treatment: none (a), liquid application (b), incorporated dry application (c), surface applied dry (d). Linear models with fixed effects of soil amendment and fertilizer application method were used to determine significance, a * indicates significance at $p<0.05$ within each fertilizer application method.*

Although this result seems to run counter to recommended best management practices in agriculture, which encourage dry incorporation of nutrients (Roberts 2007), it is consistent with our findings of the mechanisms of water retention by incorporated woodchips. Given that the primary method of water retention is absorption, and organic matter retains nutrients through cation exchange capacity, it follows that nutrients in liquid form would have more time and opportunity to be absorbed into the woodchips after application and before a rain event. By comparison, dry granules of fertilizer are more likely to be quickly dissolved, flushed through the column during a rain event, and not interact with the woodchips enough to be absorbed. Observed losses of N were lower than losses of P, this is consistent with findings by van Es et al. (2006) and van Es et al. (2004), which indicate that sandy soils below P saturation pose less risk to P losses than to N losses. Losses of N and P observed from all columns in this experiment are lower than those observed by other studies examining agricultural soils (Oyarzun et al. 2007).

Gaseous nutrient losses from fertilizers

All GHG fluxes observed in this study were similar to or lower than what is normally observed in cropland (Oertel et al. 2016), with emissions of N_2O and CH_4 being particularly low (Figure 1.7). GHG fluxes were evaluated using linear mixed effects models with fixed effects of soil amendment, sampling time, and fertilizer application, and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions for each gas. Significant terms ($p<0.05$) included both main effects and interaction terms (Figure 1.7). We observed significant differences in CO_2 production between control columns and WCT as a main effect (Figure 1.7), indicating that the presence of woodchips in the columns is likely increasing microbial respiration. Soil amendment (presence or absence of woodchips) was significant as part of a pair-wise interaction term for N_2O or CH_4 fluxes. Sampling time (pre vs. post rain) was significant as part of pair-wise interaction terms for all three gases. In our experiment, rain suppressed CO_2 and CH_4 fluxes and increased N_2O emissions. Although N_2O emissions increased, the decrease in fluxes of CO_2 and CH_4 following a rain event is in contrast to previous work indicating that rain events are hot moments of GHG fluxes (Sponseller 2007). The difficulty in capturing hot moments of GHG fluxes is well documented and it is possible that we simply missed the moment of increased fluxes in our sampling efforts. Fertilizer application method as a main effect was significant only for CO_2 but was significant as part of pair-wise interactions for all three gases. Fluxes for all GHGs measured were low, less than the median value reported for croplands and grasslands by Oertel et al. (2016), when compared to other studies. We speculate that this is due to a low level of labile C in all soil treatments.

Overall, the results of the mixed effects models indicate that the three variables work together to create differences between the soil columns and result in a nuanced story about the drivers of GHG production in lab soil columns. The authors include two figures in the supplementary materials which provide a more detailed presentation of the gas flux data presented in Figure 1.8 (Supplementary Figures S1.1 and S1.3). Predicted values from the linear mixed effects model are presented with significance letters which support the conclusions from Figure 1.8; the three variables presented, soil amendment, sampling time, and fertilizer application method work together to drive GHG emissions and that the impact of the predictor variables is not easily separated from one another.

The conclusions that we are able to draw from the GHG sampling effort outlined here is limited. This is because many samples did not meet the minimum r- squared values for the linear models used to calculate fluxes. This severely limited the number of samples included in the analysis and limited our ability to conduct a robust analysis of the data. A total of 42 gas flux calculations were included in this analysis which represents only 30% of the sampling effort. Thus, further investigation is required to explore relationships between GHG emissions and incorporated coarse woodchips.

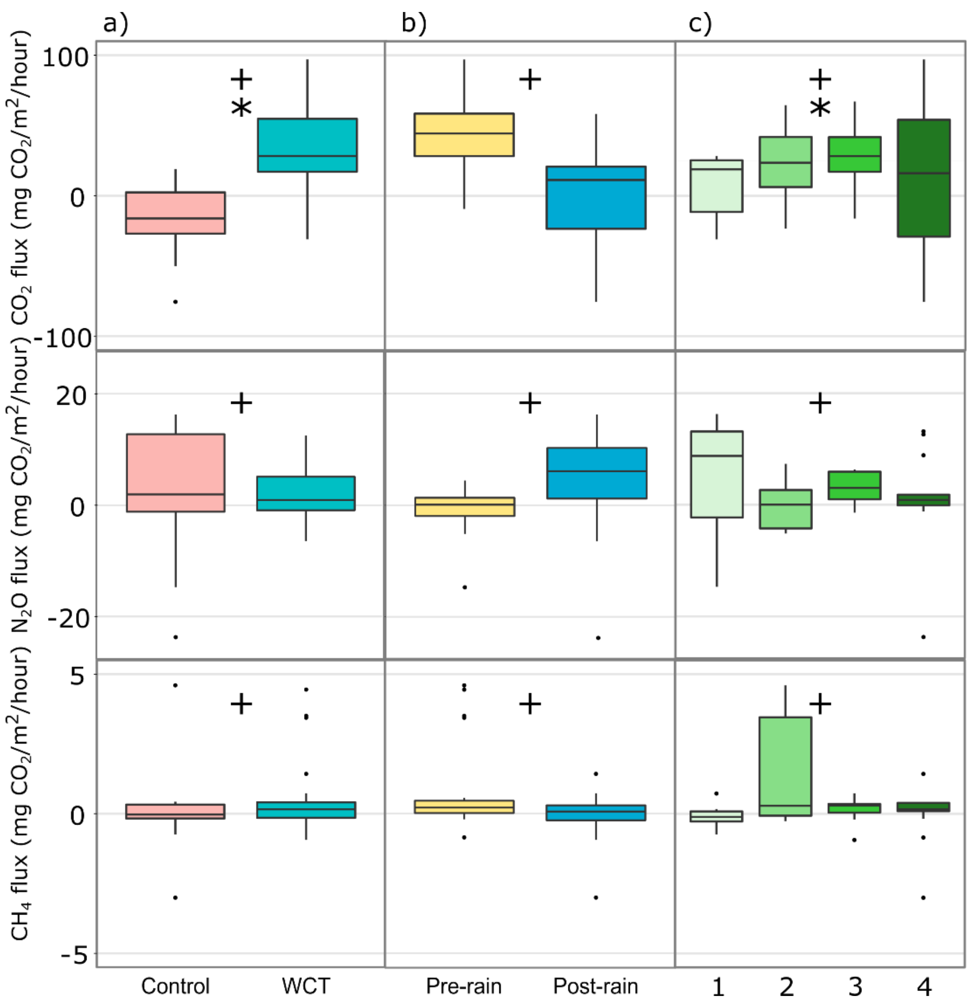


Figure 1.7 Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) fluxes presented in CO_2 equivalents (mg CO_2/m^2/hr) from soil columns by soil amendment: control and woodchip treatment (WCT) (a), by wetness: Pre-rain and Post-rain (b), and by fertilizer treatment (c). Fertilizer treatments are none (1), liquid application (2),

*incorporated dry application (3), surface applied dry (4). Linear mixed effects models with fixed effects of soil amendment, wetness, and fertilizer application and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions for each gas were used to determine significance. A * indicates main effect significance and a + indicates interaction significance at the $p<0.05$ level. Refer to Supplementary Figure S1.2 to view data presented by analyte rather than in CO_2 equivalents.*

Conclusion

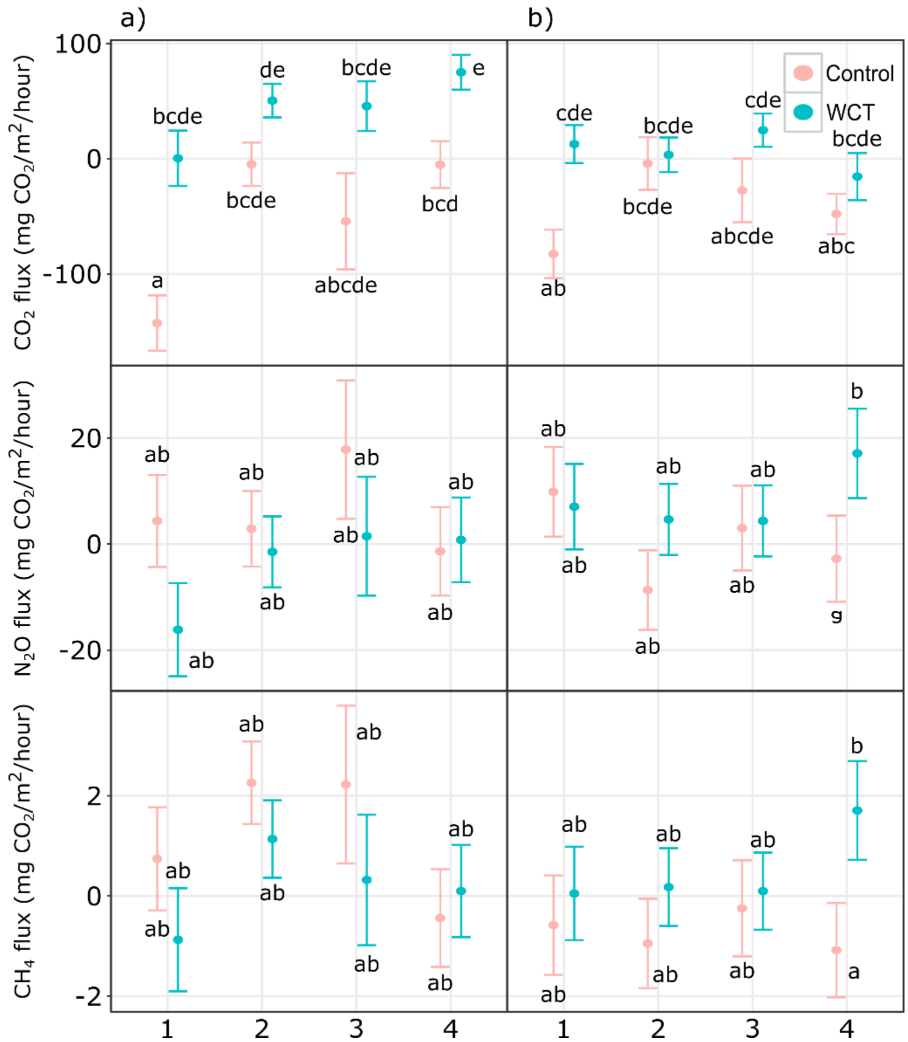
This study examined the use of coarse woodchips incorporated into the soil as a restoration strategy for severely degraded sandy soils. We evaluated the ability of incorporated coarse woodchips to retain water and explored some of the mechanisms driving the process. We found that, in the field, incorporated coarse woodchips increase the baseline water content of soils, by capturing rainfall and retaining moisture at higher levels than the control soils. We also observed systematic differences indicating the ability of incorporated woodchips to increase minimum VWC as well. Similarly, the lab column portion of the study substantiated that woodchips incorporated into the soil increase VWC following simulated rain events, and concluded that the primary mechanism of increased water retention is absorption by the woodchips.

We also examined the influence of incorporated woodchips on soluble N and P losses and GHG emissions. We conclude that in a system with incorporated woodchips, fertilizers should be applied in liquid form to maximize retention of both N and P. Gas flux data from this study indicate similar results to other previous studies examining GHG emissions from cropland. From woodchip-amended soils, we saw increased CO_2 fluxes, likely indicating an increase in microbial respiration.

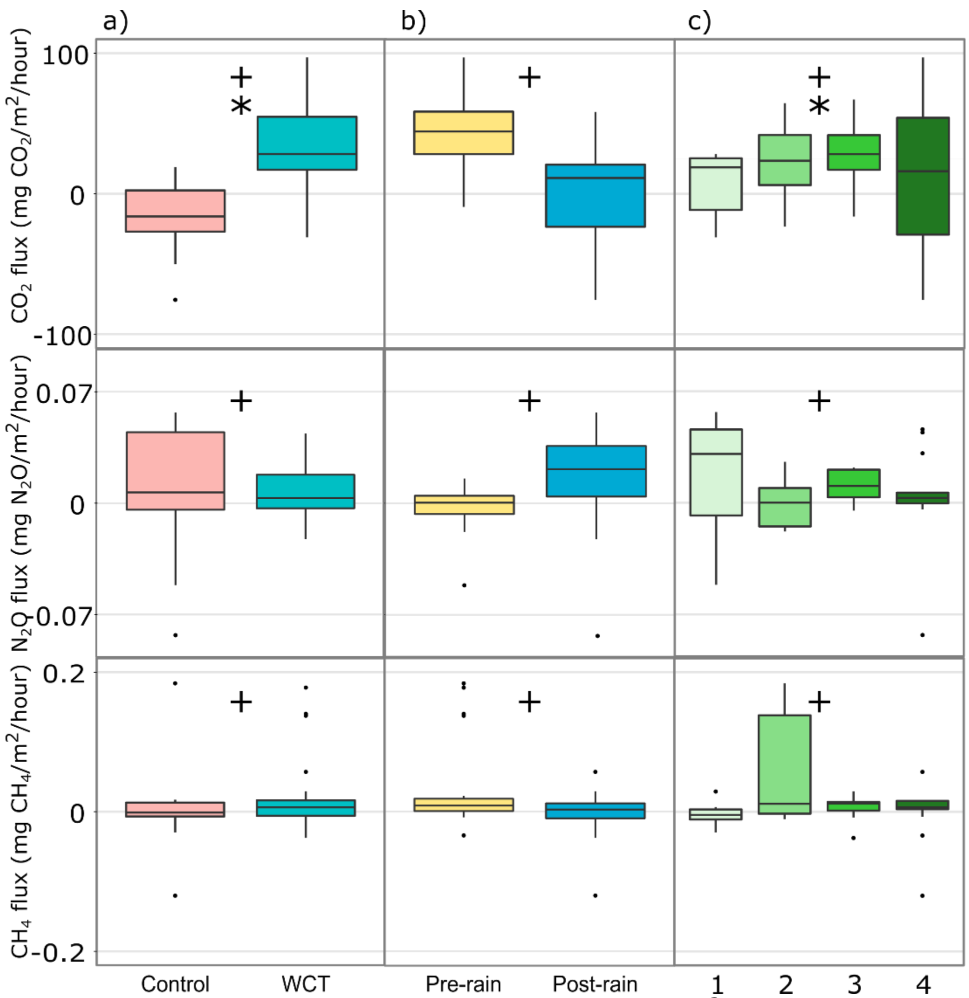
There are many opportunities to build on this work and continue examining incorporated coarse woodchips as a soil restoration strategy. The most obvious next step is to examine the behavior of woodchip amendments in the presence of plants over the growing season to examine the availability of retained water and nutrients for biomass production.

The work presented here takes some of the first steps to evaluate coarse woodchips as a viable restoration strategy for sandy soils. As a foundation and a vital provision for reviving sandy and degraded soil, we established the ability of incorporated coarse woodchips to increase initial capture and water holding capacity of sandy soils. While more investigation is necessary before implementation of this technology on a larger scale, we believe incorporated coarse woodchips to be a viable strategy for restoration of sandy soils degraded through centuries of conversion to agriculture, and other human pressures.

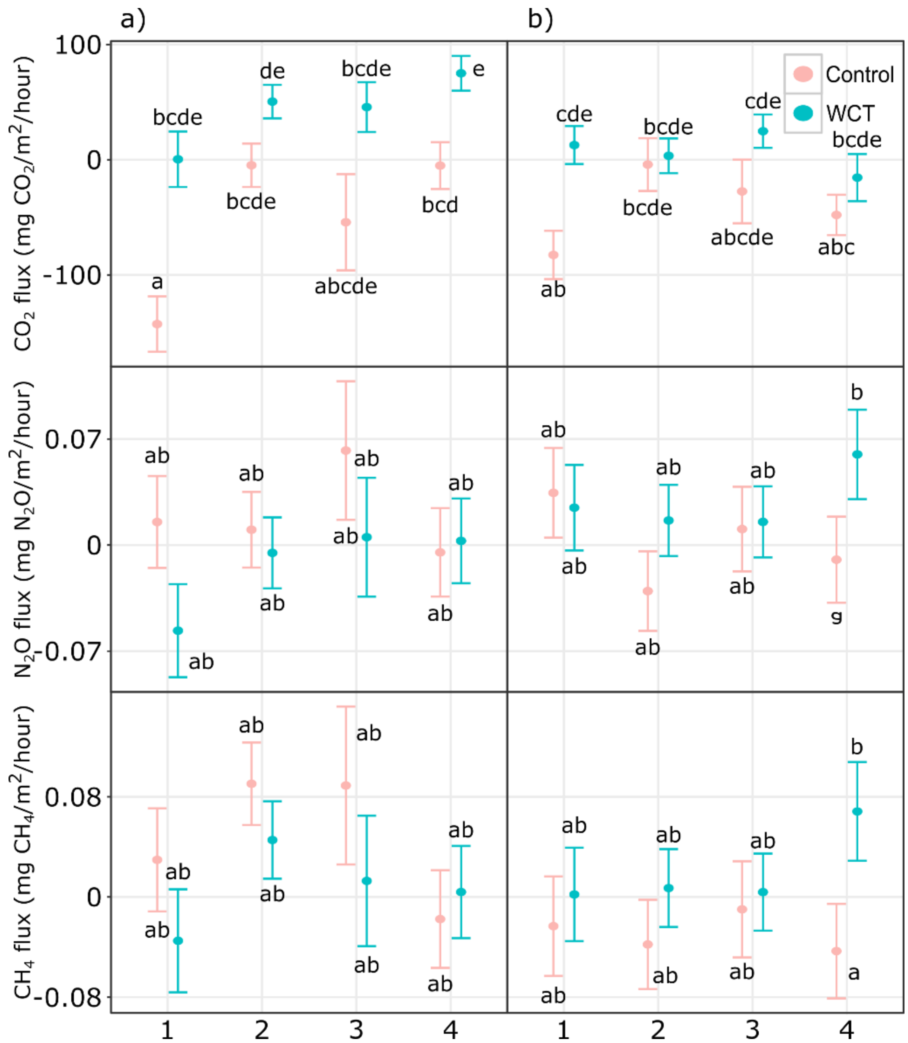
Supplementary Material



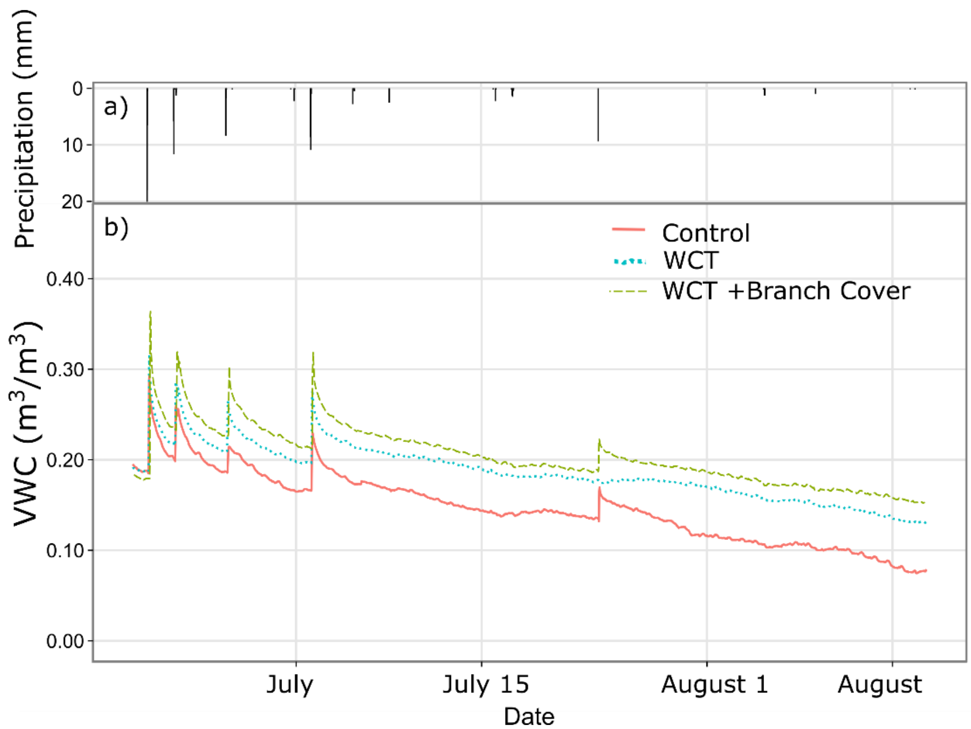
Supplementary Figure S1.1 Predicted values of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) fluxes in CO_2 equivalents (mg $CO_2/m^2/hr$) from soil columns by sampling time: Pre-rain (a) and Post-rain (b) by soil column amendment: control being the lighter (pink) points and woodchip treatment (WCT) being the darker (blue) points, and by fertilizer treatment by linear mixed effects models with fixed effects of soil amendment, wetness, and fertilizer application and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions . Fertilizer treatments are none (1), liquid application (2), incorporated dry application (3), surface applied dry (4). Letters indicate significance at the $p<0.05$ level.



*Supplementary Figure S1.2 Carbon dioxide (mg CO_2/m^2/hr), nitrous oxide (mg N_2O/m^2/hr), and methane fluxes (mg CH_4/m^2/hr) from soil columns by soil amendment: control and woodchip treatment (WCT) (a), by wetness: Pre-rain and Post-rain (b), and by fertilizer treatment (c). Fertilizer treatments are none (1), liquid application (2), incorporated dry application (3), surface applied dry (4). Linear mixed effects models with fixed effects of soil amendment, wetness, and fertilizer application and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions for each gas were used to determine significance. A * indicates main effect significance and a + indicates interaction significance at the $p<0.05$ level.*



Supplementary Figure S1.3 Predicted values of carbon dioxide (mg CO_2/m^2/hr), nitrous oxide (mg N_2O/m^2/hr), and methane fluxes (mg CH_4/m^2/hr) from soil columns by sampling time: Pre-rain (a) and Post-rain (b) by soil column amendment: control being the lighter (pink) points and woodchip treatment (WCT) being the darker (blue) points, and by fertilizer treatment by linear mixed effects models with fixed effects of soil amendment, wetness, and fertilizer application and random effects of soil column number and analysis batch with all main effects and all pair-wise interactions . Fertilizer treatments are none (1), liquid application (2), incorporated dry application (3), surface applied dry (4). Letters indicate significance at the p<0.05 level.



Supplementary Figure S1.4 Precipitation in mm (a) and mean volumetric water content (VWC) (b) measured over the summer of 2015 in Mandan, ND. The dashed green lines represents treatments with a woodchip treatment and branch shelters covering (WCT + Branch Cover) the plot, the dotted blue line represents the woodchip treatment (WCT) plots, and the solid pink line represents the control plots.

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CHAPTER 2

RETURNING DEGRADED SOILS TO PRODUCTIVITY: WATER AND NITROGEN CYCLING IN DEGRADED SOILS AMENDED WITH COARSE WOODY MATERIAL

Introduction

Soils around the globe have been negatively impacted by agricultural practices and mismanagement, leading to degradation and loss of soil organic matter (Bridges and Oldeman 1999; Oyarzun et al. 2007). This degradation has an enormous impact on net primary production (NPP). Dryland degradation or desertification in agricultural areas results in losses of NPP that amount to between 20-40% of potential NPP in the global average and up to 55% in particular regions (Zika and Erb 2009). Intensifying agriculture and human population growth contribute to degradation through an increase in the quantity of land being continuously cultivated and intensified management of land already in production. As a result, soils lose their ability to effectively sustain plant life and to provide valuable ecosystem services such as food production and carbon (C) sequestration. To counteract agricultural soil degradation, there has been an escalation of fertilizer use (Foley et al. 2005). As a result, nutrient pollution from agriculture is a significant concern worldwide as soluble nutrients, such as nitrate, make their way into surface waters and eventually the ocean, causing eutrophication and hypoxia (Bouwman et al. 2002; Carpenter et al. 1998). While efforts to reduce fertilizer use can reduce nutrient pollution, improved soil health could help retain nutrients in the landscape.

Organic matter is a major contributor to soil health and plays an important role in the ability of soils to retain water and nutrients. Soil organic matter increases water holding capacity as well as plant available water capacity (AWC) (Hudson 1994). An increase in soil organic matter can result in an increase in soil aggregates and subsequently, larger pore spaces for water to occupy (Annabi et al. 2011; Larney and Angers 2012a). Organic matter also increases soil water holding capacity helping to maintain water content longer after precipitation (Lyon and Buckman 1943). Organic matter can reduce surface runoff generation by increasing infiltration capacity and macropore flow (Fueki et al. 2012). With increased tillage and draining, soil organic matter decreases significantly under cultivation (Mann 1986). Organic matter is crucial to the health of agricultural soils and its loss is one of the key drivers of degradation.

Organic amendments, such as manure, green manures, and compost, are commonly used in reclaiming soils and combating degradation (Larney and Angers 2012a). These amendments add both organic matter and nutrients to soils, and studies show that they are more effective in improving soil properties than adding nutrients alone (Gardner et al. 2010). While these amendments have proven to be helpful in improving soil properties, they are generally nutrient rich and easily degradable by soil microbes, therefore requiring regular application to sustain the amendments' benefits (Larney and Angers 2012b). Due to high respiration rates, these amendments can result in high carbon dioxide (CO_2) emissions as well as nitrous oxide (N_2O) from incomplete denitrification (Ajwa and Tabatabai 1994; Ammann et al. 2007; McSwiney and Robertson 2005). Amendments with longer term impacts have been the subject of study more recently, including biochar and industrial wastes such as coffee waste (Gardner et al. 2010; Kasongo et al. 2011; Laird et al. 2010). These may also decrease greenhouse gas (GHG) emissions and help sequester C.

Coarse woodchips have primarily been used as a surface dressing for ecosystem restoration (Fang et al. 2011; Ferrini et al. 2008; Głąb and Kulig 2008; J. R. Buchanan et al. 2002; Prats et al. 2012). Sawdust has been used to "reverse fertilize" soils, a process by which nitrogen (N) is immobilized, in systems where soils have become overly rich in N (Bugbee 1999). There are few instances in the literature in which coarse woodchips are incorporated into the soil. One such example indicated that incorporated woodchips resulted in higher volumetric water content and lower rates of N losses in vegetative buffer strips used to treat household waste (Meffe et al. 2016). Recent studies by the authors have demonstrated similar results, showing that woodchip incorporation in sandy soils increases retention of water and nutrients when they are applied in liquid form (Li et al. 2018; Chapter 1).

Bringing severely degraded soils back into production in a sustainable way, by increasing their potential to support biomass generation, will require an input of stable organic matter. We hypothesized that coarse woody amendments would improve water and nutrient holding capacity, while creating an environment in which plant life can flourish. In this study we examined the impact of incorporated coarse woodchips on water and N cycling, and biomass production in a sandy soil. We conducted a growing-season long (~100 days) greenhouse experiment designed to mimic the soil and climate of a grassland ecosystem desertified by extensive agriculture. This study is part of a larger effort to develop an intervention to improve the ability of soils in regions with limited rainfall to capture more water and support increased plant growth. We hypothesized that coarse woodchips would increase water and nutrient holding capacity in the greenhouse and subsequently lead to increased biomass production in sandy soils.

Materials and Methods

Experimental Setup

Thirty standard 3-liter plastic pots, with a diameter of 15 cm and a height of 17 cm, were broken into six treatment groups, 5 replicates per treatment, representing differences in soil amendment, seeding, and fertilizer. A nozzle was installed in the bottom of each pot to create a single outlet for leachate collection. Pots were filled with a mixture of lab-grade sand and Tally-Parshall soil collected from field plots located at the United States Department of Agriculture (USDA) Northern Great Plains Research Laboratory (NGPRL) which is part of the Long-term Agroecosystem Research (LTAR) network located near Mandan, North Dakota, USA (latitude 46° 48′ 38″ N, longitude 100° 54′ 35″ W). The two media were mixed to achieve a very sandy soil texture (87.1% sand, 10.6% silt, 2.3% clay) reflective of those observed in Ningxia, China (92% sand). Soil from Ningxia was used as a reference because the region used to be highly productive grasslands that no longer support plant growth without irrigation due to intensive agriculture. Pots in three treatment groups were filled with the bulk sandy soil media (control), and pots in three treatment groups were filled with the bulk sandy soil media mixed with 5% by volume oven-dried *Populus tremuloides* woodchips and 5% by volume *Robinia pseudoacacia* woodchips (woodchip treatment, WCT). Woodchip amendments were sieved to exclude fragments smaller than 5 mm in any dimension and larger than 100 mm in any dimension to ensure consistent texture among treatments. A subset of pots, three from each treatment, were fitted with a polyvinyl chloride (PVC) coupler sunk into the soil media immediately following filling to allow for gas flux measurements. Pots in four treatment groups were seeded with Buffalo grass, *Bouteloua* *dactyloides*, a native prairie grass. One hundred individual seeds were placed in each seeded pot to a depth of approximately one centimeter. Germination rates were determined by counting the number of visible seedlings one week after vegetation was observed on the soil surface. Of the seeded treatment groups, two were fertilized, pots received quantities of N consistent with recommended Buffalo grass management (Bush and Van Auken 2010); three applications of fertilizer resulted in a total of 140 mg N (75 kg N/ha) as potassium nitrate (KNO_3). Fertilizer was applied as a liquid as part of the scheduled water application to ensure all pots received the same amount of water over the course of the experiment regardless of fertilizer treatment. Based on previous work, Not Seeded-Fertilized treatments were excluded from the experimental design (Chapter 1). A summary of experimental treatments can be found in Table 2.1.

Table 2.1 A summary of the six experimental treatments used. Column titles indicate the soil amendment applied, cells indicate the fertilizer and seeding treatment. Five replicates per treatment were used.

Control	**Woodchip Treatment (WCT)**
Not Fertilized-Not Seeded	Not Fertilized-Not Seeded
Not Fertilized -Seeded	Not Fertilized -Seeded
Fertilized-Seeded	Fertilized-Seeded

Pots were placed in the greenhouse in a randomized complete block design. The greenhouse was used to mimic the climate of the Ningxia province of China. A HOBO logger in the greenhouse collected hourly temperature and solar radiation for the duration of the experiment. Observations were aggregated to daily minimum, maximum, and mean values for analysis. Daily mean temperature varied from 17 to 52

°C over the course of the experiment. During an initial germination phase of three weeks, frequent rain events were applied to ensure that seeds were given the proper conditions to germinate. During this time 10 mm of water were applied every other day. Subsequently, rain events were applied to mimic precipitation patterns observed in the Ningxia province of China with smaller precipitation events of 4 mm (73 mL) occurring every 4 days and a larger event of 25 mm (450 mL) occurring every 30 days. For each event, the appropriate amount of water was gently poured on the soil surface.

Sample Collection and Analysis

Pots were weighed immediately after filling to determine dry weight. Pots were then weighed daily throughout the course of the experiment. Pot dry weight was subtracted from wet weight to determine the mass of the water retained, which was then divided by the weight of the pot soil media to determine gravimetric water content (GWC). After the germination phase of the experiment was completed, daily measurements of soil moisture and temperature were taken using a hand-held time domain reflectometer (TDR) probe and a hand-held temperature probe. Leachate from the pots was collected continuously in acidified bottles and aggregated every 10 days. Water samples were then acidified to $pH<2$, filtered using a 0.45 µm glass-fiber filter, and refrigerated until analysis. Samples were analyzed for nitrate-nitrite using the Environmental Protection Agency (EPA) Method 353.2 (O'Dell 1993).

GHG flux samples were collected using the static chamber method every 14 days. Couplers in the soil surface fit to a PVC cap with two septa for sampling as described by McPhillips et al. (2016). Four gas samples were taken from each pot at 10-minute intervals for 30 minutes (*i.e.*, 0, 10, 20, 30 minutes). All gas samples were analyzed for CO_2, N_2O, and methane (CH_4) using an Agilent 6890N gas chromatograph with a HP 7694 Headspace Autosampler equipped with an electron capture detector and a flame ionization detector with a methanizer. Fluxes were determined by fitting a linear model to the concentrations at the four time points sampled (0, 10, 20, and 30 minutes) and the ideal gas law allowed for conversion of volumetric to mass-based fluxes. Only flux calculations with an r-squared value of 0.75 or higher for CO_2 were included in the data analysis as is common with the static chamber method (e.g., Truhlar et al. 2016). This experiment was conducted over the course of 100 days, the approximate length of the growing season in the Ningxia province of China. At the beginning as well as at the completion of the experiment, soils were analyzed for total N and C, organic matter, and nitrate-nitrite by soil extraction. In all of these analyses, soils were not sieved in order to include the incorporated woodchips (where relevant) in the analyses. Above and below ground biomass were air dried and weighed to determine water content and analyzed for total N and C at the completion of the experiment. Analyses for total N and C were conducted by the Cornell Nutrient Analysis Lab. Organic matter was determined using the loss on ignition EPA Method 160.4 (Ball 1964) and soil ion extraction was performed as outlined by Barrett et al. (2009) and Robertson et al. (1999) and subsequent nitrate-nitrite was determined using EPA Method 353.2 (O'Dell 1993).

Budget Determinations

Budgets were constructed to examine the sources and losses of water and N, throughout the course of the experiment. The water budget consists of one source, simulated rainfall, and several losses (*i.e.*, leachate and evapotranspiration (ET)) or sinks (*i.e.*, soil retention and plant retention). Total simulated rainfall over the course of the experiment was 245 mm (4,438 mL) for each pot. The volume of leachate was recorded every 10 days and values for each pot were summed to determine total leachate over the course of the experiment. Net water retention for each pot was determined by subtracting the initial dry weight of the pot and the wet weight of biomass (if present) from the final weight of the pot. The water content of the biomass in each pot that contained biomass was determined at the completion of the experiment. Measured daily actual ET values for each pot were determined through daily measurements of pot mass. The daily change in pot mass and leachate losses were subtracted from daily precipitation to determine ET. Values were then summed, and dry biomass was subtracted from the cumulative ET to determine total ET over the course of the experiment. Sinks and losses were subtracted from the source and discrepancies in accounting were designated as a missing fraction. Mean values by treatment for each pool were calculated.

The N budget for the system consisted of two measured sources (*i.e.*, fertilizer applied and N in rainwater) and several sinks (*i.e.*, soil retention, plant retention) and losses (*i.e.*, soluble and gaseous losses). Throughout the course of the experiment, unfertilized pots received N only from the rainwater, a total of 0.5 mg N (0.26 kg N/ha); pots that were fertilized received a total of 140 mg N (75 kg N/ha) from both fertilization and rainwater N. Soluble losses from each pot were summed to determine the total N lost over the course of the experiment. Soil N of the pot fill at the beginning of the experiment was subtracted from soil N of each pot at completion of the experiment to determine the change in soil N and, given the large skew in these data, the median value for each treatment was used. Measured gaseous losses of N from the system were in the form of N_2O. Flux calculations were converted to a total amount of N_2O over the course of the experiment by determining a mean flux value for each pot and multiplying by the area of the pot and the duration of the experiment. We believe the gas flux measurements to be a representative sample of temperature and moisture conditions over the course of the experiment (Supplementary Figure S2.3), though this likely introduced error and smoothed temporal variability (*i.e.*, hot moments) known to be important to GHG fluxes (Groffman et al. 2009). Sinks and losses were subtracted from the sources and discrepancies in accounting were designated as a missing fraction. Mean values by treatment for each pool were calculated. Our budget does not account for any possible N losses due to N fixation or dinitrogen gas (N_2) losses due to complete denitrification.

Available Water Capacity

AWC for each pot was determined through the application of the Thornthwaite Mather water budget model. Briefly, daily ET from each pot was determined by first calculating potential ET using the Priestly-Taylor equation (1972) found in the EcoHydRology R package (Archibald and Walter 2014). Hourly observations of temperature were aggregated to daily maximum and minimum temperatures, which served as inputs to the function. Potential ET was then converted to actual ET using the method first proposed by Thornthwaite and Mather (1955). AWC serves as an input to this calculation and was calibrated to measured soil moisture values. AWC was allowed to move between 0.02 and 0.3, common values for sandy soils, and the Nash-Sutcliffe Efficiency (NSE) coefficient was used to select and optimize AWC for each pot.

Statistical Analyses

Data processing and statistical analyses were conducted using R v3.0.2.. For statistical analyses, three management levels, outlined in Table 2.1, were used. Fertilizer and seeding treatment were combined into three management levels: (1) Not Fertilized-Not Seeded; (2) Not Fertilized-Seeded; and (3) Fertilized-Seeded. This was necessary as the experiment was not fully factorial. Each pot's location in the greenhouse was characterized for inclusion as a random effect in the statistical analysis, each pot was assigned an x and a y coordinate. Y coordinates (*i.e.*, 1, 2, or 3) indicate which block the pot was in. X coordinates (*i.e.*, 1, 2, or 3) indicate whether the pot was on the edge (1 or 3) or the middle (2) of the block. Linear mixed effects models with fixed effects of soil amendment and management level and random effects of location of the pot in the greenhouse were used to examine soil water content, total N leaching load, and optimized AWC. For models used to evaluate biomass and germination rate, unseeded pots were excluded, resulting in only two management levels (*i.e.*, Not Fertilized-Seeded and Fertilized-Seeded). Soluble N leaching over the course of the experiment was evaluated with an additional fixed effect of date and an additional random effect of pot number to account for repeated measures and changes over time. All data for these models were log transformed. GHG fluxes were also examined with mixed effects models with fixed effects of soil amendment, management level, soil temperature, and soil moisture, and random effects of pot number and the location of the pot in the greenhouse. These data were not log transformed. Differences were considered significant at the $p<0.05$ level.

Results and Discussion

Water Budget

Sources and sinks in the constructed water budget were very closely matched, with the missing fraction accounting for between only 1% and 6% of the total simulated rain for each treatment (Figure 2.1). ET represented the largest flux of water out of the system. Over the course of the experiment, soil amendment was the largest driving factor of ET indicating that fluxes due to transpiration were minimal compared to evaporation from soil surface. We observed less cumulative ET in pots with incorporated woodchips indicating that incorporated woodchips reduce evaporation from the soil surface (Figure 2.2). To that same end, pots with incorporated woodchips resulted in increased water retained in soils, as reflected in the GWC of the experimental soils at the completion of the experiment (Figure 2.3). Pots with incorporated woodchips had significantly higher GWC than pots with no amendment regardless of fertilizer application. Similarly, optimized AWC values indicate that treatments with incorporated woodchips have higher AWC values (Figure 2.4).

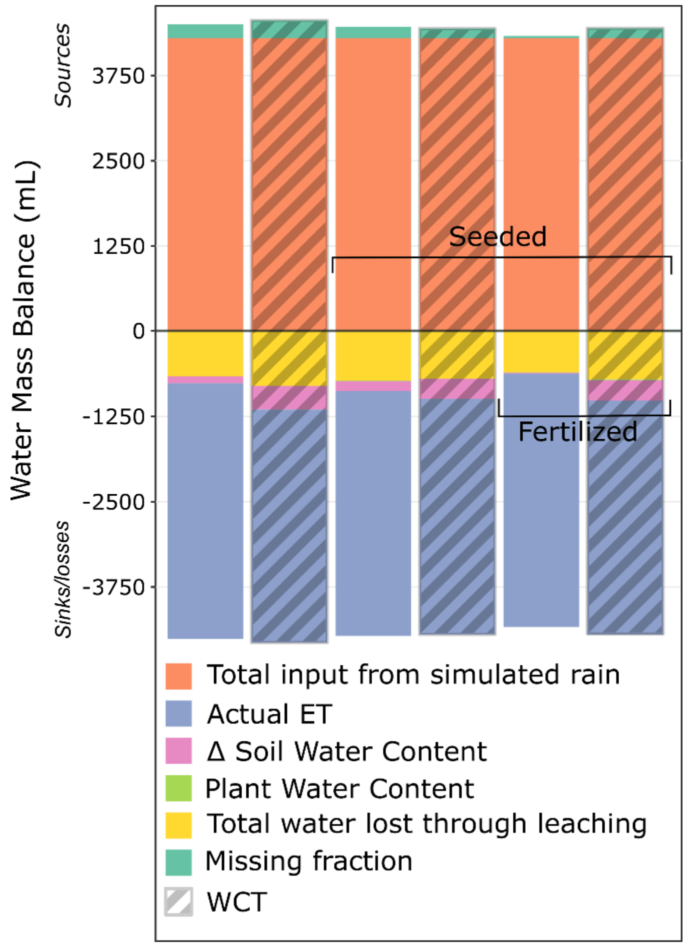


Figure 2.1 Mass balance of water (mL) by treatment. All combinations of soil amendment, fertilizer, and seeding are presented here with fertilizer and seeding indicated on the plot and woodchip treatment (WCT) indicated by the hatching. The different colors in each bar represent different sources, sinks, or pools of water in the system with each color identified in the legend. Mean values for each source, sink, or pool by treatment are displayed. Some fractions may be too small to easily discern.

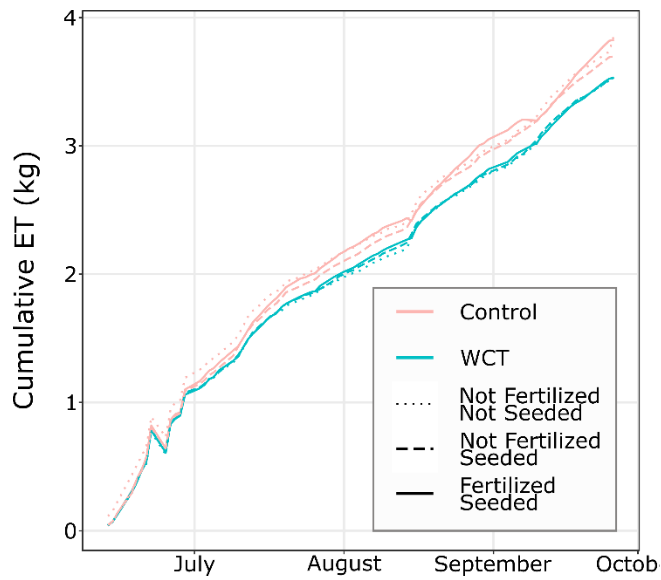


Figure 1.2 Cumulative evapotranspiration (ET) (kg) over the course of the experiment by soil amendment. Control soil are shown in the light (pink) lines and woodchip treatment (WCT) in the darker (blue) lines. Lines are additionally separated by management level, with dotted lines representing Not Fertilized-Not Seeded, dashed lines representing Not Fertilized-Seeded, and the solid lines representing Fertilized-Seeded.

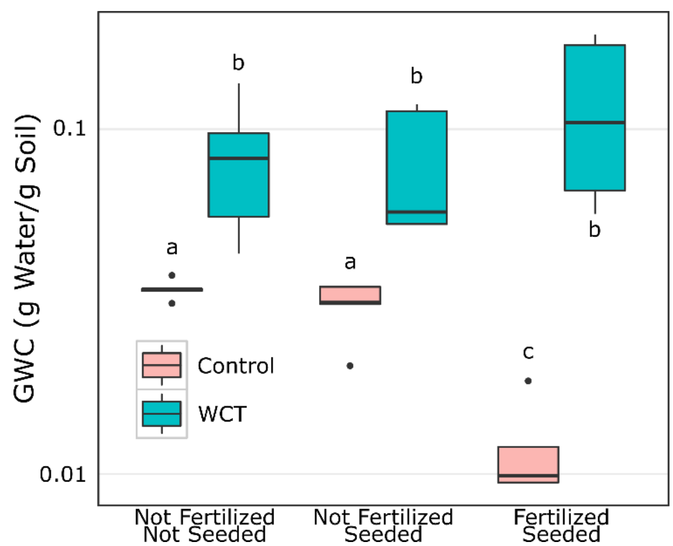


Figure 2.3 Gravimetric water content (GWC) (g water/g soil) at the completion of the experiment by soil amendment. Control soil are shown in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. Boxes are additionally separated by management level. The y-axis is presented on a log scale. Letters indicate significant differences between treatments (p<0.05) based on a linear mixed effects model with

fixed effects of soil amendment and management level, and random effects of the location of the pot in the greenhouse.

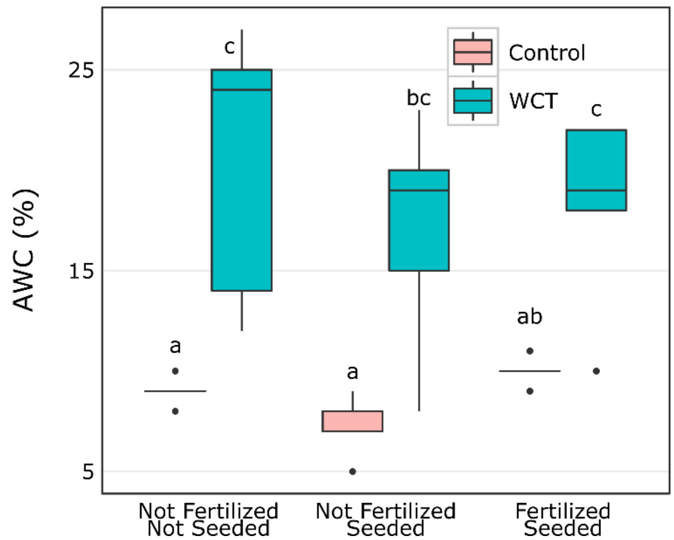


Figure 2.4 Available Water Capacity (AWC) (%) as determined by calibration to measured soil moisture values over the course of the experiment by soil amendment. Control soil are shown in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. Boxes are additionally separated by management level. Letters indicate significant differences between treatments ($p<0.05$) based on a linear mixed effects model with fixed effects of soil amendment and management level, and random effects of the location of the pot in the greenhouse.

Nitrogen Budget

The largest losses of N in all treatments occurred as soluble losses in leachate (Figure 2.5). Gaseous losses (N_2O) as well as soil and plant retention of N represented small portions of the overall budget. No significant differences were observed in N_2O fluxes (Supplementary Figures S2.2).

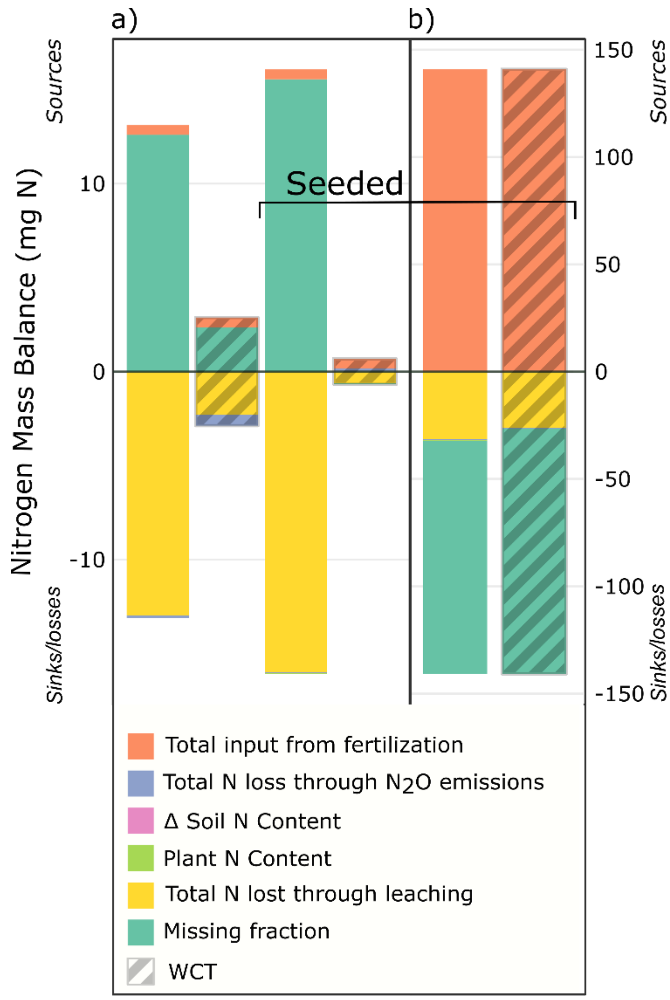


Figure 2.5 Mass balance of nitrogen (mg N) by fertilizer application. Note differences in y-axes with unfertilized (a) and fertilized (b) treatments. All combinations of soil amendment, fertilizer, and seeding are presented here with seeding indicated on the plot and woodchip treatment (WCT) indicated by the hatching. The different colors in each bar represent different sources, sinks, or pools of nitrogen in the system with each color identified in the legend. Mean values for each source, sink, or pool by treatment are displayed, with the exception of change in soil N content for which a median is used. Some fractions may be too small to easily discern.

In fertilized pots, a large fraction of the applied N was unaccounted for and in unfertilized pots there was a fraction of N lost from the system whose origin is unclear. N fixation is a possible source of N that was not measured or estimated but likely contributes to sources of N, especially in the unfertilized pots, similar to findings by Ledgard et al. (1999). One pathway for N loss which we did not measure is N_2 fluxes from the pots. Weier et al. (1993) examined N_2/N_2O ratios as a tool for predicting N_2 emissions when they cannot be measured. Their study found that in a fertilized sandy soil, without a source of readily available C, the ratio of N_2/N_2O would fall between 0.4 and 0.8. This indicates that losses of N through N_2 fluxes might account for some of the missing fraction in the fertilized treatments albeit small. There was some potential for contamination or deposition of N in the greenhouse facility which would account for some of the missing fraction on the sources side of the budget. A key factor controlling N cycling is microbial immobilization, which occurs to such an extent that amendments of green composts are assumed to drive N limitation of plants. In this study, microbial N content was not examined, however soil respiration appeared to increase in the presence of woodchips (Supplementary Figure S2.2) indicating that microbial activity is likely increased with a woodchip amendment creating the conditions for N immobilization by microbes. Other studies have had similar difficulties in closing the N budget (i.e., Anderson et al. 2014; Boyer et al. 2002; Van Breemen et al. 2002). It is clear that more research into the mechanisms by which wood chips are impacting soil biogeochemistry are needed.

Total soluble N losses from fertilized treatments were not significantly different in woodchip amended soils and unamended soils (Figure 2.6). In the unfertilized treatments, woodchip amended soils resulted in less soluble N losses than the unamended soils. In examining this through time, it appears that this trend is driven by the timing of fertilizer applications (Supplementary Figure S2.1). Immediately following fertilizer applications at the start of the experiment and then again on August 15th, losses from WCTs were higher than unamended treatments. However, during the interim, between fertilizer applications, WCTs were not significantly different but generally lower. Indeed, leachate losses in the fertilized control soil were lower in the last nine rain events compared with the first four rain events while the fertilized WCT had more steady losses throughout. In unfertilized treatments, N leachate from woodchip amended pots was consistently lower over the course of the experiment than in unamended pots. This finding is consistent with our previous work where we documented that woodchips reduce N losses in leachate when unseeded pots are fertilized (Chapter 1). These findings indicate that there are multiple factors controlling N losses in woodchip amended soils and indicates there may be an N tipping point controlling the biological response to fertilizer applications. More work is needed to examine the ways in which these factors interact and if there is a threshold of fertilizer application, over which, N retention by woodchips decreases.

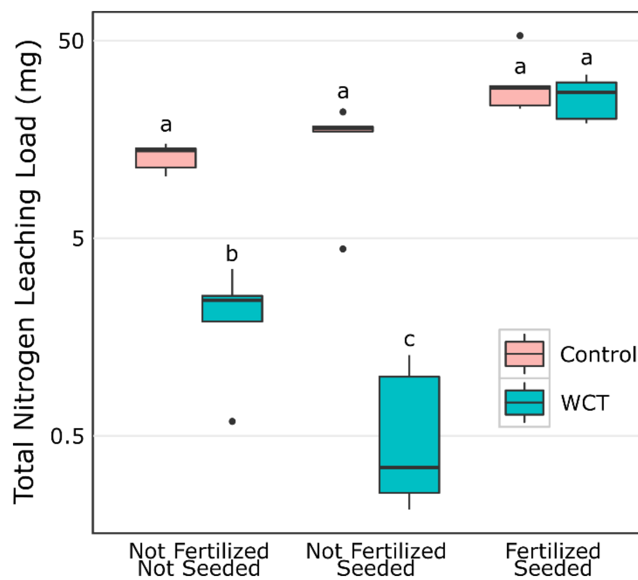


Figure 2.6 Total soluble nitrogen load (mg) over the course of the experiment by soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. On the x-axis is the management level. The y-axis is presented on a log scale. Letters are the result of a linear mixed effects model with fixed effects of

soil amendment and management level, and random effects of the location of the pot in the greenhouse and indicate significance at p<0.05.

Biomass Production

Germination rates were not significantly different regardless of soil amendment or fertilizer application indicating that any differences in biomass production were not a result of differences in germination success (Figure 2.7). Fertilizer treatments increased biomass production; however, biomass production was decreased in WCTs as compared to unamended pots. The competing influences resulted in no significant differences in total biomass between control pots and WCT pots with fertilizer application (Figure 2.8a). Fertilized pots without incorporated woodchips resulted in significantly more total biomass production than all other treatments. These trends were consistent for total biomass (Figure 2.8a) as well as below-ground biomass (Figure 2.8c). Above-ground biomass showed a similar though not identical trend; in above-ground biomass, fertilized pots produced more above-ground biomass than the unfertilized treatments. Fertilized pots without incorporated woodchips resulted in significantly more above-ground biomass production than all other treatments, as was the case with the other two fractions of biomass (Figure 2.8).

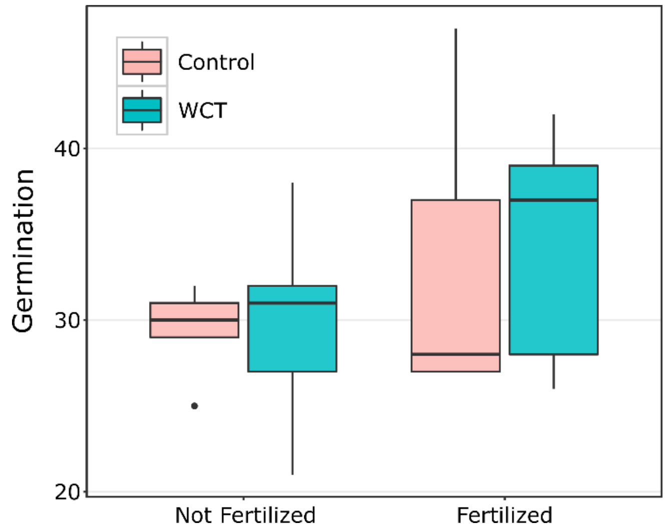


Figure 2.7 Germination in number of visible seedlings by fertilizer application on the x-axis and soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. A linear mixed effects model with fixed effects of soil amendment and fertilizer application and random effects of the location of the pot in the greenhouse was used and found no significant differences at p<0.05.

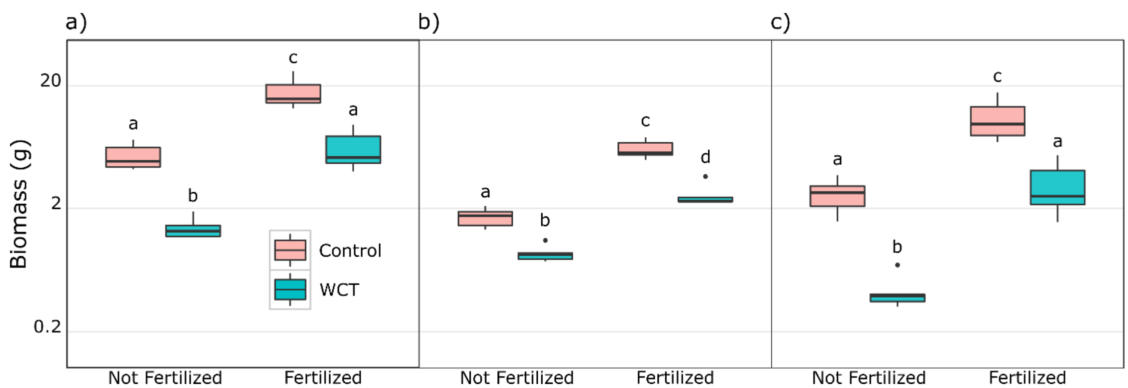


Figure 2.8 Biomass production in grams by fertilizer application on the x-axis and soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. The y-axis is presented on a log scale. The fractions of biomass presented are total (a), above-ground (b), and below-ground (c). Letters are the result of a linear mixed effects model with fixed effects of soil amendment and fertilizer application and random effects of the location of the pot in the greenhouse, performed on each panel, and indicate significance at p<0.05.

Biomass production is the goal of soil and ecosystem restoration in arid regions with degraded soils. In this study we did not observe improved biomass production by prairie grasses immediately following woodchip incorporation. The availability of water was likely not the deciding factor as soil moisture and AWC were increased in the WCT. In these extremely degraded soils, the greater biomass production in unfertilized pots without a woodchip amendment as compared to unfertilized pots with a woodchip amendment strongly suggests that the incorporated woodchips were contributing to nutrient limitation. We hypothesize that rapidly growing microbes likely outcompeted the plants for nutrients in woodchip amended pots documented by increased CO_2 respiration (Supplementary Figure S2.2) (Morse et al. 2018). N fertilizer increased plant growth but maintained the disparity between the WCTs and the unamended treatment which suggests that it created an environment in which phosphorus may have become the limiting nutrient. The results of this study emphasize how absolutely limiting nutrients have become in severely degraded grassland soils and additional research is needed to determine the optimum amounts inputs of both macro- and micro-nutrients to improve soil health and maximize plant growth without resulting in excess runoff and leachate. Previous studies conducted by the authors have observed results contrary to our findings, documenting increases in biomass production with incorporated woodchips and fertilizer applications immediately following implementation (Ledgard et al. 1999; Li et al. 2018, 2019).

The decrease in biomass production following a dramatic intervention observed in this study is consistent with other research examining dramatic alterations to soil management in agriculture. Studies conducted on apple orchards indicate that the benefits of the soil management interventions are observed after a number of years, 6 to 8 depending on the metric (Merwin et al. 1994; Merwin and Stiles 1994; Oliveira and Merwin 2001). Similar instability in plant production is seen in the first few seasons when farms are converted from conventional management to organic; this "transition period" has been documented in rice production (5 years), as well as grain production (4 years) (Delate and Cambardella 2004; Hokazono and Hayashi 2012).

Overall Evaluation and Next Steps

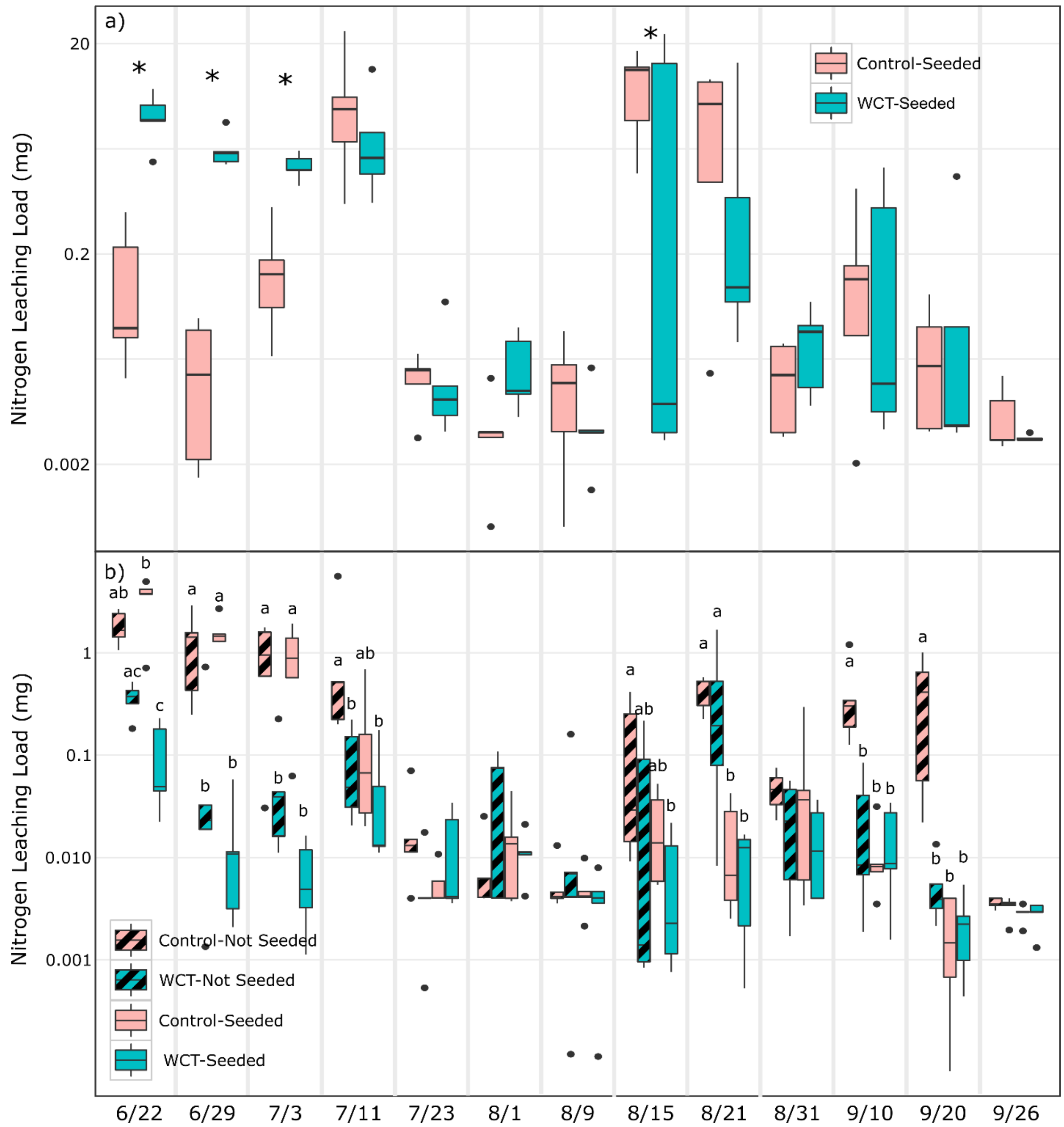
To evaluate the viability of incorporated coarse woodchips as a soil amendment strategy in sandy soils degraded by agriculture, we aimed to evaluate four central things, water retention, N retention, biomass production, and adverse environmental impacts (*i.e.*, soluble N losses and GHG emissions). Regarding changes in water retention, we observed decreased ET as well as increased soil water content in both measured GWC and calibrated AWC, indicating that incorporated coarse woodchips offer an important benefit of additional soil water to degraded soils. Changes in soil N were extremely small and not significantly different between amended and unamended soils. The end goal of soil and agro-ecosystem restoration is to increase production, in this study, incorporated woodchips did not result in increased biomass production, indicating that more work is needed before this intervention can be implemented in the field. It is possible that the decrease is due to deficiencies in micro- or macro-nutrients not measured here. It is also possible that N immobilization occurred with the large influx of C (Han et al. 2017). A long term study would be an important next step to determine if the results presented here are representative only of the first year after woodchip incorporation and if successive years would produce similar or different results. An obvious next step is to continue the experiment through more than one growing season and examine trends over time.

Soluble N losses were less straight-forward, in unfertilized environments, soluble N losses were significantly lessened with incorporated woodchips but in fertilized environments soluble N losses from woodchip amended soils were not significantly different from unamended soils. Given the variability in soluble N losses it would also be valuable to examine the impact of fertilizer treatments of varying magnitude, source, and ratios of N to phosphorus and other nutrients to see if the results presented here are consistent over a range of treatments. Fluxes of N_2O and CH_4 were not significant in magnitude or significantly different (Supplementary Figure S2.2) indicating that the intervention is not contributing to a substantial increase in fluxes of these harmful gases to the environment.

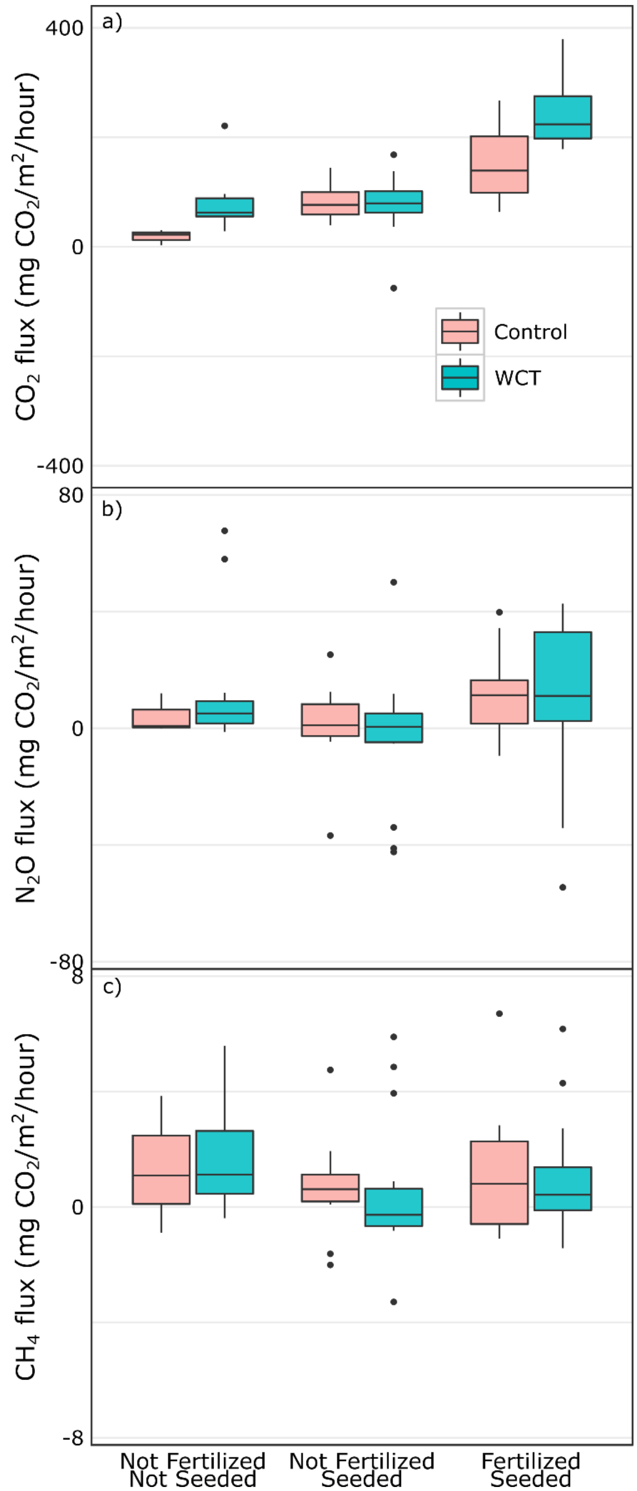
Conclusion

This study examined the use of coarse woodchips incorporated into the soil as a restoration strategy for severely degraded sandy soils in a greenhouse experiment. As a foundation and a vital provision for reviving sandy and degraded soil, we established that the amendment increases water holding capacity and decreases N leaching when the system is not fertilized. We observed no significant GHG fluxes and more work is needed to identify the missing fractions found in the N budget. While more investigation is necessary before implementation of this technology on a larger scale, we believe incorporated coarse woodchips to be a viable strategy for restoration of sandy soils degraded through centuries of conversion to agriculture, and other human pressures. The work presented here takes some of the first steps to evaluate coarse woodchips as a viable restoration strategy for sandy soils.

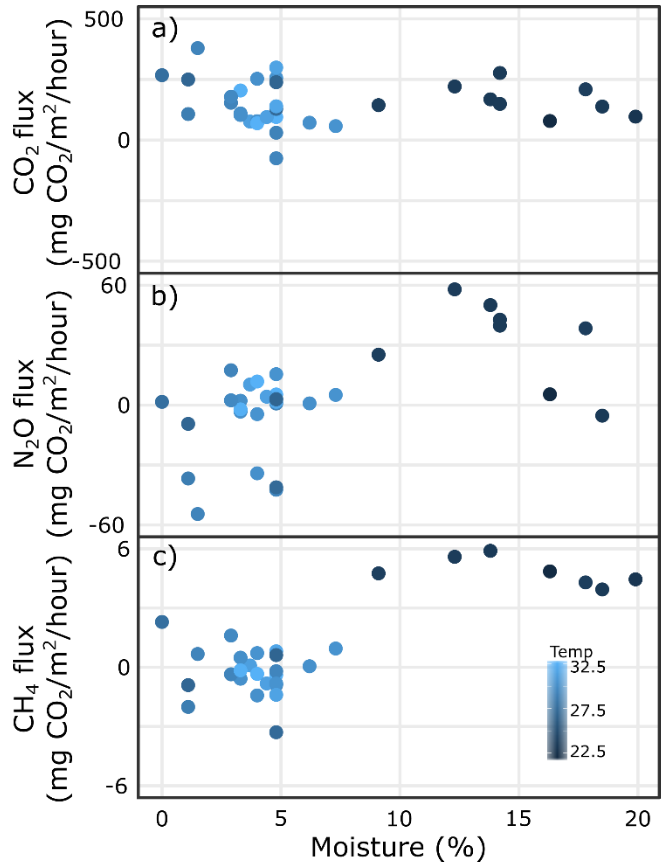
Supplementary Material



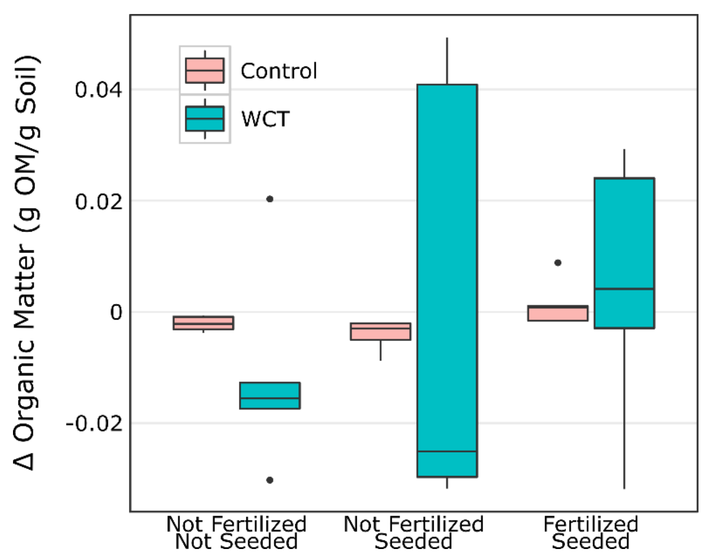
Supplementary Figure S2.1 Soluble nitrogen (N) load (mg) over the course of the experiment from fertilized (a) and unfertilized (b) treatments. Soil amendment is displayed with control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. Boxes with hatching indicate the pots were not seeded. All dates on the x-axis are from 2018 and values are the total cumulative load since the last date. The y-axis is presented on a log scale. Stars and letters are the result of a linear mixed effects model with fixed effects of date and experimental treatment, and random effects of the pot number and the location of the pot in the greenhouse, and indicate significance at p<0.05.



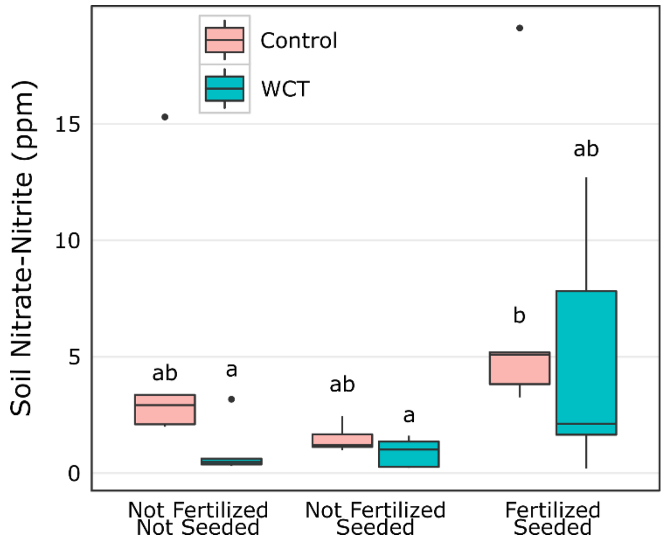
Supplementary Figure S2.2 Carbon dioxide (CO_2) (a), nitrous oxide(N_2O) (b), and methane fluxes (CH_4) (c) presented in CO_2 equivalents (mg $CO_2/m^2/hr$) from pots by soil amendment with control in the light (pink) boxes and woodchip treatment (s) in the darker (blue) boxes. On the x-axis is the management level.



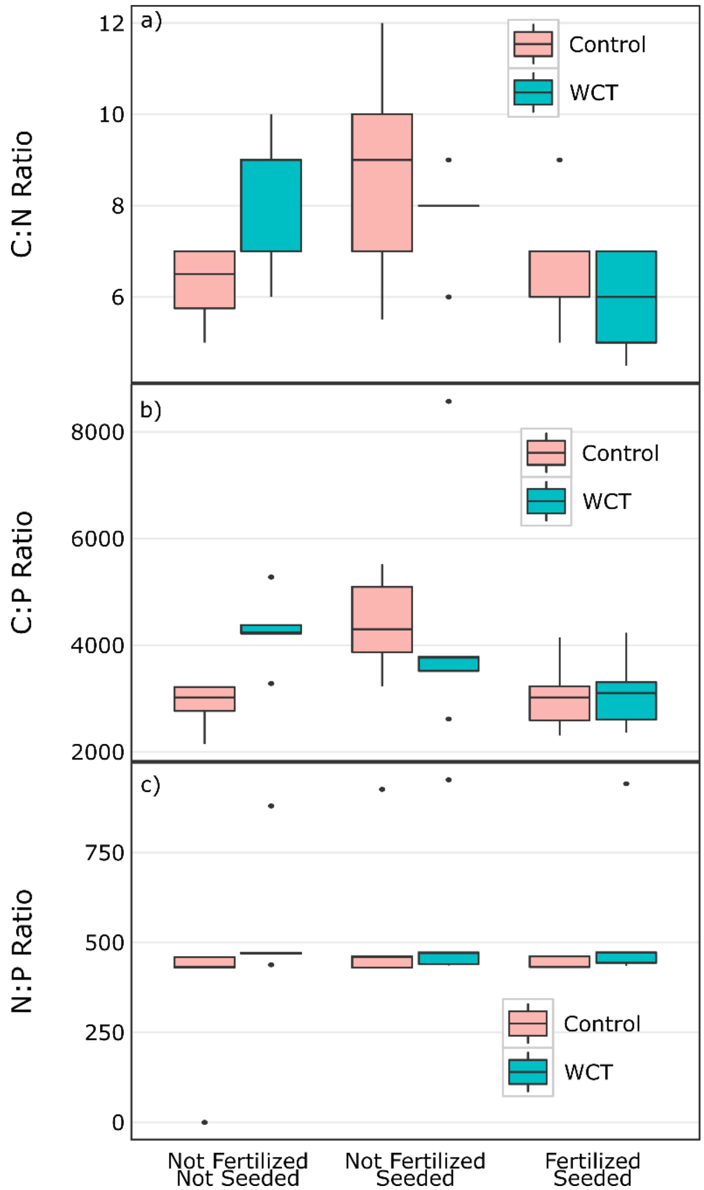
Supplementary Figure S2.3 Carbon dioxide (CO_2) (a), nitrous oxide (N_2O) (b), and methane fluxes (CH_4) (c) presented in CO_2 equivalents (mg CO_2/m^2/hr) from soil columns by soil moisture (%) and temperature (°C) with lighter dots indicating warmer temperatures and darker dots indicating cooler temperatures.



Supplementary Figure S2.4 Change in soil organic matter (OM) (g OM/ g soil) by soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the *darker (blue) boxes. On the x-axis is the management level. No significant differences were detected using a linear mixed effects model with fixed effects of soil amendment and management level, and random effects of the location of the pot in the greenhouse.*



Supplementary Figure S2.5 Soil nitrate-nitrite (ppm) by soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. On the x-axis is the management level. Letters indicate significant difference between treatments ($p<0.05$) based on a linear mixed effects model with fixed effects of soil amendment and management level, and random effects of the location of the pot in the greenhouse.



Supplementary Figure S2.6 Nutrient ratios of carbon (C), nitrogen (N), and phosphorus (P), C:N (a), C:P (b), and N:P (c), by soil amendment, control in the light (pink) boxes and woodchip treatment (WCT) in the darker (blue) boxes. On the x-axis is the management level

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CHAPTER 3

THE WAYS FARMERS KNOW: WATER AND NUTRIENT MANAGEMENT ON NEW YORK STATE FARMS

Introduction

Water quality is a primary concern of the public, researchers, natural resource managers, and policy makers across the United States. Hydrologists and agricultural scientists have focused much of their research efforts on agricultural land use and fertilizer application practices due to the significant contribution of fertilizers to nonpoint source pollution in the surrounding landscape and downstream bodies of water (Carpenter et al. 1998). Fertilizers of all kinds (*i.e.* manure, compost, inorganic fertilizers, poultry litters, etc.) pose a problem to surface water quality when not managed properly. Nutrients from these fertilizers are carried downstream through surface runoff into lakes, rivers, and eventually oceans, where, in excess, they can cause water quality degradation and eventually eutrophication (Carpenter et al. 1998; Smith et al. 1999; Bouwman et al. 2002; Diaz and Rosenberg 2008).

Agricultural best management practices (BMPs) are interventions designed to reduce the impact of farming activities on downstream water quality, and adoption of such changes is crucial to a sustainable food system for the future (Pretty 2008). A wide array of BMPs are available to farmers, these options range from changes to farm management having little upfront economic cost, such as targeted fertilization, buffer strips, cover crops, and crop rotation, to large investments in infrastructure or equipment such as manure containment structures, manure digesters, edge-of-field bioreactors, equipment for reduced tillage, and precision agriculture tools (Hill 1996; Isse et al.

1999; Mitsch et al. 2001; Głąb and Kulig 2008; Robertson and Vitousek 2009; Pluer et al. 2016). The process by which farmers make decisions about when, where, and how to adopt these BMPs is a topic of much debate with many studies indicating contradictory results (*i.e.,* Kabii and Horwitz 2006; Knowler and Bradshaw 2007; Prokopy et al. 2008). A meta-analysis of United States (US) based studies found that access to, and quality of, information, financial capacity, and being connected to an agency, such as local, state, or federal extension networks or regulatory agencies, or local networks of farmers or watershed groups had the biggest impact on a farmer's decision to adopt a BMP (Baumgart-Getz et al. 2012). However, these studies have been largely unsuccessful in identifying farmer attitudes and social factors that influence adoption (Prokopy et al. 2008).

The task of developing and evaluating BMPs falls largely to research scientists and engineers; yet it is farmers who are carrying out the work crucial to reducing nutrient losses and protecting water quality. Therefore, it is farmers who are best positioned to evaluate the viability and effectiveness of such tools and recommendations on their own land. Farmers' close relationship with their land situates them in a unique position to collect vast amounts of information and develop an intimate understanding of the ways in which water and fertilizers interact (Carolan 2008). The knowledge amassed by farmers influences their land management decisions and could inform the development of new recommendations and practices (Carr and Wilkinson 2005).

The objective of this work is to better understand the ways in which farmers collect, store, and share data, information, or knowledge about their land in the context of water and manure management. This study was conducted in the Finger Lakes Region of New York State (NYS) in the Owasco and Cayuga Lake watersheds. These watersheds were chosen for this study because year-round residents, summer-time residents, as well as researchers at universities in the area, are actively engaged in nutrient management efforts in these two watersheds. Local residents have become concerned about the increased frequency and severity of observed harmful algal blooms and in response local universities have begun to investigate the root cause of the change.

The Regulatory Environment in New York State

The NYS Department of Environmental Conservation (NYSDEC), which reports to the Environmental Protection Agency (EPA) at the federal level, regulates certain farms and farm activities related to BMPs and nutrient management. The EPA was established in 1970 by President Richard Nixon as a response to increasing concern about environmental pollution and in an effort to consolidate a variety of federal activities relating to environmental protections such as research, monitoring, and enforcement (US EPA 2016). The EPA administers the Federal Water Pollution Control Act or, as it is more commonly referred to, the Clean Water Act (CWA), and delegates some permitting, monitoring, and enforcement to the states. In the case of NYS, the NYSDEC was formed in 1970 and is a department of the NYS government. The NYSDEC is tasked with conservation, improvement, and protection of NYS's natural resources as well as a number of other duties (About DEC - NYS Dept. of Environmental Conservation 2019). The NYSDEC issued its first concentrated animal feeding operation (CAFO) permits in 1999 to comply with EPA regulations. Then in 2009, the state, in response to the *Water Keeper et al. vs. the EPA* decision, developed its own guidelines to ensure the industry continued with best practices even as federal regulations were loosened in the 2008 revisions of the CAFO rule (Hribar and Schultz 2010). This loosening on the federal level meant that fewer farms were required to apply for discharge permits and could operate with less oversight from regulators. In 2009, permits were issued under the Environmental Conservation Law (ECL) enacted by NYS. Currently, farms in NYS can choose whether to operate under the 2004 CWA version of the permit or the more restrictive ECL permits. When the shift occurred, most farms were not prepared to ensure no discharge would occur as required by the ECL permits and therefore elected to remain under the CWA permit. Since then, the state has clarified what is required under the ECL permit and has dedicated funding to improve manure containment facilitates on farms and subsequently there has been a shift toward the ECL permits (Concentrated Animal Feeding Operations - NYS Dept. of Environmental Conservation 2019).

As of this writing, a CAFO, is defined in NYS as being an animal feeding operation of a certain size that confines animals for at least 45 days each year. The majority of CAFOs in NYS are dairy farms, a dairy farm with 300 or more cows is considered a CAFO. This number was increased from 200 cows to 300 cows in 2012 in an effort to support the presence and expansion of yogurt companies in NYS. The primary way by which NYS regulates nutrients found on these farms is through comprehensive nutrient management plans (CNMP); each farm must develop a CNMP annually. These plans are unique to each farm and take into account the specific context of that piece of land but generally, with respect to manure management, these plans provide guidelines as to how on-farm collection, handling, storage, application, and utilization of animal waste will occur (United States Department of Agriculture 2005).

Manure management is a significant concern for CAFOs in NYS as they collectively must manage approximately 50 million pounds of manure each day. Farmers must keep detailed records about where, when, and how much manure they spread throughout the year. They must also document weather conditions on the days they spread manure to ensure they spread in dry conditions and in the case of a spill or accident involving water pollution they have a record of how the decision to spread was made (United States Department of Agriculture 2005). NYS has provided winter spreading guidelines, first in 2005 and revisions in 2015, to help farmers make informed decisions about the risks associated with winter spreading on snow or frozen ground but has not prohibited it as other states in the northeast US have done (Czymmek et al. 2005; Czymmek et al. 2015). When farms are unable to spread manure due to season or weather, they must store it in a containment facility as outlined in their CNMP (United States Department of Agriculture 2005).

In general, the public is becoming increasingly aware of farm activities and less tolerant of declining water quality. There is increased focus and pressure on farmers and regulatory agencies to deal with environmental pollution or perceived environmental pollution. Cayuga Lake was recently the subject of a study conducted by the NYSDEC to determine the state of impairment of the lake and whether regulatory action was warranted to reduce phosphorus and sediment pollution entering the lake (Menzies Pluer et al. 2019). Residents around Owasco Lake and the Owasco Lake Association have begun a similar process to determine the extent of pollution and evaluate the need for local regulatory action. Both of these projects were motivated by residents of the area concerned about harmful algal blooms they perceived to be occurring with greater frequency in the later summer impairing the ability of the lake to be used for drinking water and recreation activities. To date, these concerns have been evaluated through watershed scale modeling efforts as well as water sampling campaigns conducted in the lake itself and the tributaries feeding into the lake. The changing sociopolitical environment created by the activity in these two watersheds has increased awareness of water and nutrient management for farmers and is therefore an interesting setting in which to conduct this study.

Digital Agriculture

As pressure has increased to reduce the environmental impact of agricultural activities large scale data collection on a number of scales has become more prevalent. Digital agriculture is on the forefront of data collection in agriculture. The scope of digital agriculture covers a sweeping array of tools available to farmers ranging from cell phone applications for market tracking to big data networks for production optimization. To date, these tools are primarily geared towards data that is easily measured and quantified for collection and analysis. Much work has been conducted on mapping tools (*i.e.*, geographic information systems, remote sensing, and global positioning systems) and sensors (i.e., wireless sensors and remote sensing) combined into large scale data networks to monitor crops and optimize production (Cassman 1999; Haboudane et al. 2004; Chen and Jin 2012; Zhang and Kovacs 2012). Other smaller scale initiatives include cell phone applications built to give farmers access to more information about markets, land management practices, and pest and disease treatment (Mboyah 2018). There is enormous potential to include other types of data, beyond that which is easily measured and quantified, mediated by digital agriculture's tools.

In other fields, such as Ecology, it is easier to find examples of data collection occurring through large networks of individuals and their observations rather than through large networks of sensors or satellites. This is sometimes referred to as citizen science or community science (Wandersman 2003; A. J. L. Carr 2004). For example, Maine has begun a program titled “Maine Turtle Roadkill Survey” through which people can submit photographs of roadkill, particularly turtles, they find on the states’ roadways for species identification and enumeration (Maine Turtle Roadkill Survey 2019). Through this collection of photographs researchers plan to establish which stretches of road are most dangerous to turtles and develop strategies to reduce deaths. Similarly, PlantWatch Canada has been using observations made by community members all over the country to track changes in plant phenology and examine how it relates to the changing global climate (Gonsamo et al. 2013). These sorts of initiatives that bring data collected by many people in diffuse networks into the discussion have led to important discoveries. For example, Project FeederWatch, run by the Cornell lab of Ornithology, exclaims “Embrace the winter, count feeder birds for science!” on their website. The data is collected by birders all over the US, Canada, and Mexico. The project has led to numerous publications on a myriad of topics surrounding bird populations (*i.e.*, Bonter and Cooper 2012; Greig et al. 2017).

Currently, digital agriculture focuses on connecting farmers with large networks of sensors, remote sensing tools or data sets that can help farmers reduce inputs, improve production, or connect them to markets. However, there is the potential for the tools of digital agriculture to view farmers in the same way the field of Ecology views “backyard” naturalists, as a source of data rather than solely the recipient of data. The ability of farmers to record and share data amongst themselves using cell phone apps or websites that mimic the ways they already collect and synthesize information on-farm would provide the farmers themselves with a wealth of information to make better decisions on their own land.

Methods

This study seeks to examine the ways farmers collect data on-farm with respect to water and nutrient management. Data was collected in two phases; first, interviews were conducted with farmers in the Finger Lakes region of NYS and second, a focus group was conducted with a number of farmers and extension agents in the same geographical area. All data collection was conducted by the first author. In the first phase, names of potential interview participants were collected through snowball sampling. In order to ensure a wide range of respondents and to avoid a homogenous sample, we began with several different "snowballs" to ensure that respondents represented differing social networks and agricultural activities. We began by collecting contacts from several sources. For larger farms or commodity farms we started with farmers known to Cornell Cooperative Extension (CCE) and Agricultural Consulting Service. For smaller farms or vegetable farms we used the network of local Community Supported Agriculture (CSA) enterprises and farmers known to the authors as our starting points.

The first author conducted semi-structured interviews (Hermanowicz 2002) in a "walking and talking" manner, when possible. The interview was conducted as the farmer gave the first author a tour of his or her land. This generated rich conversation and brought out additional themes and lines of inquiry due to the spatial nature of water and nutrient management and farming at large. At the completion of the interview, respondents were asked to give the name of someone who they thought might be interested in participating in an interview.

A total of 34 individuals were interviewed over the course of 26 interviews. Participants represented 9 dairy farms, 6 vegetable farms, 3 livestock farms, 4 exclusively crop farms, and 4 diversified farms. Some dairy farms were also crop farms. Participants were primarily men, with 16 interviews conducted with only men, 3 interviews conducted with only women, and 7 interviews conducted with a man and a woman present and active in the discussion. The length of time that respondents had been participating in farming activities varied from only a season or two to essentially their whole lives on a multi-generational operation. A number of farmers had received degrees from Cornell University, the most common being a Bachelor’s degree in Animal Science or Agronomy, but others mentioned masters or doctoral degrees as well. Interviews lasted between 45 minutes and 2 hours. The length of each interview was largely dependent on the time the farmer was willing to give and their interest in or enthusiasm for the topic of conversation. Interviews were conducted until thematic saturation was reached and new categories ceased to emerge from additional interviews (Guest et al. 2006; Mason 2010).

The second phase of the study consisted of one focus group. The group consisted of four farmers, large crop and dairy farmers, and two CCE educators. The CCE educators were meant to be moderators in the focus group but functionally acted more as participants. Additional focus groups were planned but due to time constraints and structural changes within CCE they could not be conducted. The focus group lasted 90 minutes and was used to collect another layer of data and deepen our understanding of the themes that had emerged during the interviews (D. L. Morgan 1996; D. Morgan 1998).

The conversations in both the interview phase and the focus group phase covered on-farm data collection, off-farm data collection, off-farm information sources, record keeping, data storage, data analysis, data sharing, and challenges pertaining to data collection, storage, and sharing. Conversations were wide-ranging and frequently moved beyond water and nutrient management.

This study was conducted in partnership with CCE of Tompkins and Cayuga counties. CCE was consulted in all phases of data collection. The project was deemed exempt by the Institutional Review Board for Human Participants at Cornell University as the focus of the study was data, knowledge, and information, not the human participants themselves.

Analysis and Discussion

Two primary types of data collected by farmers on their own land emerged as important to on-farm water and nutrient management: technologically mediated (TM) data and sensory data. The analysis presented here of these two data types is limited to on-farm data collection and observations.

Description

Technologically mediated data

TM data, as farmers described them, were largely but not exclusively quantitative. They generally can be easily measured or quantified, they are often generated by an instrument, a sensor, or an "expert". The source could be as simple as a graduated cylinder set up to be a rain gauge or as complex as a harvester with a GPS unit and sensor to automatically generate harvest maps. An "expert" is someone whose job it is to provide advice and support to farmers; these are generally engineers, agricultural consultants, or conservation professionals. This type of data can be used to meet regulatory requirements, or it can be self-motivated. These data are often the kinds of data that CAFO farmers are required to collect. As discussed above, farmers that manage CAFOs are required to have a CNMP, to record information about manure applications, and weather conditions on days when manure is applied.

The most common occurrence of TM data in this study was the use of soil tests or maps. Almost all the farmers interviewed mentioned soil tests or maps. One small vegetable farmer remarked:

"For nutrient management, we take semi-annual soil tests to get a baseline."

Another small dairy farmer discussed how they use the results of the soil tests:

"Everything up here is phosphorus and potassium are high…We don't push the ground read hard. It's not like we're trying to get four or five cuttings of hay. It's usually two or three, but we've gone to just buying some fertilizer to replace what the soil tests say."

Another common way in which TM data were discussed is through the description of on-farm quantitative mass balances of nutrients. A large dairy farmer discussed the way he conceptualizes the contributions of manure and nutrient balances on his land:

"*We get very good yields off each acre …we can stay below a target level of nutrients and fill that gap with commercial fertilizer at our discretion instead of trying to find more acres for distributing the nutrients."*

Lastly, in order to meet regulatory needs, many large farmers discussed their nutrient management plans. A large dairy farmer stated:

"*We have a nutrient management plan and a(n) annual fertility plan and they're* *all tied together. So when it comes to just implementing the practice out in the field, we'll turn to our fertility plan...you can see by the tabs just how the nutrients are distributed for crop production based on the analysis and the crop needs and the soil analysis…We're very detailed, as well as regulated."*

Farmers made it clear that TM data are not without their challenges. Respondents expressed that the benefits of such data are sometimes unclear or intangible to them. A large vegetable farmer, when asked about soil tests and how they inform management, stated:

"*At least once every two years. I don't know that I find them super helpful. They do indicate that our nutrients are in a good spot…I don't really see things changing drastically from year to year with the soil tests. I know that our soil is really heavy clay soil so as long as I keep increasing the organic matter, that's a good thing, but it seems pretty stable. It doesn't seem to change much year to year at this point."*

A small diversified farmer expressed concern about the costs of acquiring such data, saying:

"*I have had my soil tested through Cooperative Extension …technically I should be checking that every year but I'm a little delinquent. Maybe I think probably every two or three years is sufficient for me…I'm not sure if I would benefit from a high expense testing program."*

Deliberations on uncertainty about the accuracy of data were also common when TM data were discussed, particularly with respect to weather forecasts. A large dairy farmer, when asked what data he gathered when determining when to apply manure, explained the need to check multiple weather sites because he considers them unreliable:

> "*Lots of different weather sites, because they all stink. Their predictions are horrendous, so I usually check at least three of them. We're required to check at least one. The day before you're planning to apply, you have to have a written piece of paper with the forecast so that they know you actually checked. Then everyday you're [spreading manure], you have to [check the weather]. And then for another day after you've completed [spreading], you have to have another [weather printout] just so they know you didn't quit and then five minutes later you have eight inches of rain."*

Another large dairy farmer expressed the same sentiment:

> "*Generally, on any given day, you'll get three different forecasts, if you look at three different things. One could be rainy, the other could be sun…If I know that I'm going to do manure roughly a week from now, I'll start looking a week ahead to see what the forecast generally looks like and then see whether it acts like it's improving or getting worse."*

Lastly, some farmers expressed a lack of interest in the work necessary to collect TM data. A small vegetable farmer said:

> "*Just the time that goes into collecting data, and that's my resistance to having any kind of additional certifications or anything else is keeping track of the data. It doesn't actually seem really to have any real helpful impact, any direct impact on my farm. It is hard to want to keep track of that information…it would require me to do a whole bunch of work that I don't really enjoy, so I'd rather stick with what I'm doing that I actually do enjoy."*

A medium vegetable farmer indicated that he didn't feel collecting TM data resulted in better management practices:

> *"Well, we don't keep a lot of records. We could, but I think, in general we just feel like sometimes you can keep too many records and not do a good job."*

Overall, the challenges experienced by farmers relating to TM data are a lack of clear benefits, uncertainty management, and a lack of interest or motivation.

This type of data is collected by nearly all farmers that we spoke to in some way or another. Farmers who are managing large amounts of land or large herds of livestock rely heavily on TM data, but smaller farmers are also collecting and storing this kind of data as well.

Sensory Data

The second type of data commonly collected by farmers is what we call "sensory data". Sensory data are experiential data, they are collected with the senses on a day to day basis. Sometimes they are externally recorded in a notebook, journal, or spreadsheet and sometimes they are stored in a mental record. They are collected through time, over the course of one or many growing seasons, as well as space. These data are largely qualitative, but not exclusively. Through sensory data, farmers are collecting and accumulating observations and experiences of their land and creating a deep knowledge of their surroundings.

Some farmers expressly acknowledge this type of data collection as crucial to their operation. A large vegetable farmer discussed where he first encountered on-farm sensory data collection methods:

> "*You talked to any permaculture folks? Because I feel like with the site planning,*

they definitely have it down for sure. Anyone with a permaculture background, that's the first thing you learn a lot about, is observing the landscape, and how to work with it, and things that could go wrong or not."

A small dairy farmer, relatively new to farming, mentioned this type of data as making up part of her identity as a farmer:

"I'm kind of an intuitive farmer."

Farmers made clear that they have deliberate methods they use to collect these data. A small livestock farmer discussed his methods:

"The mapping is the main thing. I think maybe just in my head. There's a practice of just like, walking your farm at various times of year, various times of rain events, non-rain events, etc. ... I've got a mental map that I've been building over the past few years."

In discussing what sort of data they are collecting with these methods, farmers primarily talk about the things they notice or experience on their land. A medium-sized diversified farmer talked about the ways he collects information about the grass and subsequently, how that influences its management:

"All of our land right now is pasture, but all summer long, we watch the growth of the grass and we make decisions about this grass is the right height to graze chickens or cows, or the grass has gotten away from us, we'll make hay off of it. So everything moves around, every piece of land is multi-purpose."

Similarly, a small dairy farmer discussed observations about his grass and evaluated a change in his management as a tool to explain or hindcast deviations from the norm:

"[The cows] were just going out there and just didn't seem to want to eat what

seemed to me like fine grass, or perfectly good grass. Since we turned it over, and that was five or six years ago, it seemed like it kind of freshened things up."

Frequently, water management, noticing and managing wet areas, fell into the category of sensory data collection. Farmers knew where saturated areas and water features could be found through their experience on their land. A vegetable farmer discussed the water bodies and structures found on their land:

"It's almost seasonal. [The pond] really dries up in the summer, less than half the size of that…There's a wetland back here and this drainage swale here, that's standing water all year."

It was common for respondents to reference the amount of time they have spent farming in reference to sensory data collection. A medium vegetable farmer stated:

"I mean, I guess it's just sort of accumulated from being in school and then from farming. Been farming for 20 years now, so you just sort of absorb things from reading."

A large dairy farmer noted how their experience contributes to their knowledge base and their ability to forecast their needs and plan for the coming season:

"We have a whole farm plan in terms of how many gallons need to go on each field. Like this time of year, I'll sit down and make a plan, I got a rough idea about how many gallons of manure, just from experience that we're going to have to move in the spring, and then crop rotation, quite a bit of thought, quite a bit of work goes into planning where we need to go with all the stuff. "

The challenges associated with sensory or experiential data include the farmers feeling that they need to spend more time farming to accrue enough experiential knowledge. Farmers also expressed a sense that the methodology around sensory data collection is insufficient to answer certain questions, such as those around fertilizer applications. When asked about how he accrued knowledge and made decisions, one small vegetable farmer described his lack of experience as a challenge to data collection:

> *"I think just by being a green horn for a lot of years, maybe. I'm still green."*

Another large vegetable farmer discussed the impacts of installing a drainage system and acknowledged the limits of his ability to notice the subsequent changes after tile drains were installed on his land:

> *"I thought they were installed well and made sure to put them in the wettest spots. It seemed like, I don't know. It seems like it should be helping more than it is, but maybe it is helping and I just don't notice. You know?"*

Similarly, another small vegetable farmer acknowledged the limits to his sensory data collection in regard to manure applications:

> *"I couldn't get a sense of whether we were over applying the manure."*

Overall, the challenges associated with sensory data collection are related to the experience of the farmer as well as limitations in the ways sensory data can be collected and analyzed.

Sensory data collection was more at the forefront for smaller farmers who were capable of being more intimately acquainted with every square foot of their land, but all farmers discussed sensory or experiential data collection in one way or another. The prevalence of sensory data collection is connected to experience as a farmer but is not exclusive to long-time practitioners.

Intersections, Overlap, and Conflict

While we have set TM and sensory data apart, as separate categories, these two types of data commonly overlap or relate to one another. Farmers discussed the ways in which TM data and sensory data work together to arrive at a solution to a problem or a question. A large dairy farmer discussed the ways the two work together:

> *"There's this little plot where the higher yields and the lower yields are. You can overlay those with soil maps, nutrient maps and figure [it] out."*

Another dairy farmer discussed using one to build upon and improve the other:

> *"Think about things as rainfall amount vary [over time] ... these [nutrient management] plans are put together let's say in April and you're only basing it on what you see today in April, but if we get rains like last year throughout June and July, now we've lost nutrients due to excessive rainfall. And we need to come back in make some adjustments so that we don't have a complete failure of crop yields."*

In this way the two types of data, nutrient management plans and impressions of rain patterns, are being used in concert to compensate for the uncertainty or limitations of the other and reduce the exposure to risk.

In addition to using the two types of data in concert, at times farmers discussed using sensory data to validate TM data. A small vegetable farmer said:

> *"Even though you might not be able to quantify a lot of these different metrics for health and how things are doing and whether its linked to how much nutrients you're adding to the soil, I think over the years you develop a better sense as an individual and then talking to more experienced growers…It's still nice to say,*

read something…and see how that aligns with your intuition.”

Another vegetable farmer discussed how they evaluate their fertilizer applications:

“We do five pounds per week of potash and nitrogen… and then, you know, there's feedback, obviously, if something isn't working.”

It is less common to hear farmers discuss using TM data to validate sensory data, but it was present in the interviews. One large dairy farmer discussed using soil tests to confirm their soil management methods were improving the soil organic matter;

“I tried to focus that more on maybe more sensitive areas… or places where the organic matter is just low on these fields, and you were relying to build that organic matter a little bit faster. That comes back to the soil sampling, and the whole task.”

Lastly, there were occasions on which the two kinds of data were in conflict. In these cases, farmers fall back on their own experiential knowledge and sensory data collection methods. A large dairy farmer talked about using experiential data to correct or spot-check TM data:

“[It’s important to] be able to say, have a sense for that and say, "No, I think these loads actually went over here," or "I think this data is actually from this field, not this field." That’s a challenge"

A small dairy farmer discussed using his sensory knowledge to evaluate potential changes to management on his land:

“Then what's appropriate to our place, our situation because sometimes you try things that worked great for Jim over in Trumansburg or something, but it just doesn't work here.”

Farmers also rely on their sensory data collection when there is a conflict with recommendations from experts. A large dairy farmer discussed a failed project implemented on his land by outside "experts":

> *"So we spent a bunch of money even though we got some grants for the collection system, and it was a total failure. I knew that from the beginning, and I said, this isn't going to work…It [isn't that it] didn't work because we didn't give it a good try, I tried as hard as I could to make it effective. And it wasn't from a lack of trying but it was just an impractical means of dealing with [the problem]."*

While it might be tempting to place the two kinds of data discussed here, TM and sensory data, in separate groups, they are clearly not conceptualized that way by the farmers collecting and synthesizing them. They appear more on a spectrum where farmers use both in concert and in overlapping ways to solve problems and answer questions.

Farm to Watershed Connection

The analysis presented here, and the data types discussed, focus almost exclusively on data collection at the farm scale. The quotes presented privilege data collected on-farm for the purpose of on-farm decision making surrounding nutrient and water management. This is not to imply, however, that farmers are unaware of their place in the larger landscape or how their decisions might impact downstream water quality. This was not the primary focus of the authors data collection, but it was nevertheless present in the majority of interviews.

When asked about soil testing and fertilizer application, one vegetable farmer acknowledged the connection between fertilizer application and downstream pollution:

> *"And from what we've learned from other farmers and people that are knowledgeable about that. You don't wanna keep applying too much animal manure compost, because then it's just essentially pollution if you're adding way more than you will ever use."*

A large dairy farmer, who has invested heavily in reducing his impact on the larger watershed, lamented the way his operation is perceived by the public:

> *"In Cayuga County there's all this about Owasco Lake and it's got to be manure, there's no other way it could be anything else for the algae blooms. And every farmer is bad in the citizen's mind, we all are bad because we have manure."*

Another farmer, when discussing algae blooms, acknowledged that runoff from poorly managed farms may be a contributing factor:

> *"I myself kind of think it's farm runoff… My sense is most farms have gotten cleaner, although they've gotten more intense. You know, you got a lot of potential crud at one spot, but most farms are ... I don't know. There's some places that are slop holes. Most farms I think are containing their runoff and pollutants."*

A small dairy farmer went so far as to describe some back of the envelope calculations he had done concerning the quantities of water moving during a precipitation event:

> *"We're here at the top of the hill, but as it goes to ditch to the creek to the next creek and all of a sudden you got this huge water event ...I figured it out one day. I mean, just the roads. Roads in the town of Caroline, there's 75 miles of road and figure they're 40 feet wide. If we get an inch of rain, that's 10 million*

gallons of water all of a sudden got to go somewhere. You know?"

While most farmers do not appear to be focused on off-farm data collection on a day to day basis they are all aware of the impact their on-farm decisions might have on downstream water quality. The primary analysis presented here is focused on the types of data collected by farmers on their land. These data inform decision making that impacts the larger landscape and downstream water quality, farmers are aware of these connections whether they acknowledge the direct impacts of their decisions or whether they view it through a peripheral lens maintaining distance between their own activities and the downstream impacts. This concept of epistemic distance in the context of agriculture is discussed by Carolan (2006).

Conclusion

As the world continues to move toward digital agriculture, it is crucial to recognize and place value on the array of data that farmers use when making decisions around water and nutrient management. Knowledge held by farmers is important to consider when addressing the challenges of nutrient runoff and subsequent downstream water contamination. While TM data are more readily recognizable by agricultural researchers, regulators, and other "experts", sensory data are an extremely important part of on-farm data collection when it comes to water and nutrient management. Farmers use the two types of data together to solve problems and answer questions; they are not used in isolation. Each type fills in methodological holes for the other; together they protect against uncertainty or risk. Perhaps the most important message is that, we consistently found that when the two types of data are in conflict the farmers trust and rely on their observational data. This highlights the critical need to respect the local farmers' knowledge and identify ways to incorporate it into BMP development and evaluation.

In on-farm decision making, these data are not distinct, the lines between the two are blurred and they appear on a continuum rather than in two separate groups. As such, we must begin to think about how the whole spectrum of data can be incorporated into digital agriculture and decision support tools made available to farmers to support preservation of our natural resources. Sharing of data, particularly that which appears, on the surface, to be only attainable through experience, can improve productivity and economic viability of farms of all sizes and flatten the learning curve for new farmers by connecting them with more experienced farmers. For example, farmers who evaluate soil moisture through visual cues to indicate when it's time to turn on an irrigation system could upload photos for other farmers to reference when making decisions on their own land. Certainly, there are things which can only be attained through time and the embodied experience of farming but there are other things that can be taught and shared through connections with other farmers. Digital agriculture is poised to help create those connections and add value to sensory data collected by farmers. Digital tools for data access and sharing in the agricultural sector show great promise for incorporating sensory data and expanding the ways we think about agricultural data and its importance to decision making and conservation of our most precious natural resource, water, at both the farm and the watershed scale.

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CONCLUSION

These studies examined two facets of water and nutrient management in agricultural landscapes. First, I examined the use of coarse woodchips incorporated into the soil as a restoration strategy for severely degraded sandy soils in an effort to improve production without creating adverse environmental pollution. Second, I investigated the types and forms of data collected by farmers on their land with respect to water and nutrient management.

The work presented in Chapters 1 and 2 take some of the first steps to evaluate coarse woodchips as a viable restoration strategy for sandy soils. As a foundation and a vital provision for reviving sandy and degraded soil, we established the ability of incorporated coarse woodchips to increase initial capture and water holding capacity of sandy soils and began to explore the complexity of the nitrogen cycle in woodchip amended soils. While more investigation is necessary before implementation of this technology on a larger scale, we believe incorporated coarse woodchips to be a viable strategy for restoration of sandy soils degraded through centuries of conversion to agriculture, and other human pressures.

When developing best management practices or agricultural interventions it is crucial to consider the knowledge held by farmers and it is particularly important to consider this knowledge when addressing the challenges of nutrient runoff and subsequent downstream water contamination. In Chapter 3, I explored the types and forms of data collected and held by farmers. While technologically mediated data may be more readily recognizable by agricultural researchers, regulators, and other “experts”, sensory data are an extremely important part of on-farm data collection when it comes to water and nutrient management. In on-farm decision making, these data are not distinct, the lines between the two are blurred, and they appear on a continuum rather than in two separate groups. As such, we must begin to think about how the whole spectrum of data can be incorporated into digital agriculture and decision support tools made available to farmers to support preservation of our natural resources.