Multiple Perceptions of Soil Health: A Transdisciplinary Collaborative Study of two Contrasting Grain Farms in Columbia County, NY

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Multiple Perceptions of Soil Health:  
A Transdisciplinary Collaborative Study of  
two Contrasting Grain Farms in Columbia County, NY

Senior Project Submitted to  
The Division of Social Studies  
of Bard College

by  
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Abstract

The global carbon pool located in soils is being depleted with time, partially contributing to anthropogenic climate change by means of land use changes and management of soils for food production. Farmer adoption of conservation practices geared towards soil carbon sequestration is an opportunity to reverse this depletion of the soil organic carbon pool. In this project, I investigated farmer perceptions of certain management strategies that have been shown to sequester soil carbon and improve soil health. By interviewing two prominent farmers in Columbia County, I assess options for improving their farms soil health and soil carbon, in addition to assessing the current state of soil carbon in a specific field. I investigated the various constraints to adopting new management and through the use of the COMET Farm modeling tool, quantified the differences in soil carbon currently in their soils, and the differences future changes in management would make if adopted. The results compare conventional and organic/biodynamic management. It was surprising to see more carbon sequestration in the conventional system compared to the organic, based on the assumption that organic agriculture is less environmentally harmful. I used the framework of farmer participatory research to create a beneficial collaboration between myself, the researcher, and the farm managers, taking this opportunity to learn from their experiences and perceptions, as well as generate knowledge and a report for them to take away as well.
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Chapter One: Problem Statement

1.1 The importance of soil organic matter

There is a body of scientific literature questioning how organic matter is gained or lost in soils and how increased organic matter levels increases soil health. Furthermore, there are strong linkages between soil organic matter and both carbon sequestration as a climate mitigation strategy and adaptation to the expected climate extremes as global CO₂ increases. Actively adding carbon to soil via the soil organic matter pool is necessary to maintain the essential services provided by healthy soil, such as food security, water quality, biodiversity, and ultimately resilience in the face of a changing climate (Lal 2014). Understanding soil organic matter dynamics in both conventional and organic farming systems can provide valuable insights for future policy that incentivizes the adoption of SOM building practices. Including farmers in the process of research and modeling is important to ensuring a holistic view of the balance of both the economic and environmental concerns farmers experience (Dalton et al., 2011; Snapp et al., 2019).

This project seeks to address the gaps between scientific research and implementation of soil organic matter building practices as they are applied in the local context. By working closely with two distinctly different farmers in the Hudson Valley, I evaluate their current cropping system with respect to impacts on soil carbon dynamics using a simulation model, and seek to understand why they do or do not use two specific practices known to influence soil health:
cover cropping and reduced tillage. This research relates to a broader question of how farmers can be rewarded for building soil organic matter, and how policies can make it easier to farm with lower carbon emissions in the context of our climate emergency.

1.2 Soils as a global carbon sink

The carbon cycle moves a fixed amount of carbon (C) through the atmospheric, oceanic, soil, geological (fossil carbon), and biotic (terrestrial), pools. Human manipulation of the carbon cycle has increased how much carbon the atmospheric and oceanic pools hold, and has decreased terrestrial and geologic pools. Researchers have identified the potential for carbon sequestration, or returning and storing of carbon to soil, via an increase in soil organic carbon through land management as an important component of climate change mitigation (Lal, 2004).

Soil is a major global carbon sink. The soil C pool is estimated to be about 2500 petagrams (Pg) (Lal, 2004), which includes organic and inorganic carbon. The soil organic carbon pool is estimated to be 2,460 Pg [2,710 billion tons]—1,500 Pg [1,650 billion tons] of carbon in the form of SOC (Morgan et al., 2010). Soil organic matter is 58 percent carbon (Lal, 2004). The soil C pool is about four times the above ground biotic pool and about three times the atmospheric pool (Lal, 2004). The magnitude of this sink signifies its importance in the global carbon cycle, specifically that some of the carbon flux from the soil pool is interconnected with anthropogenic land use.
Depletion of soil carbon and opportunities for reversing the trend

Historically, cultivation of land for food production has contributed to carbon emissions from soil, resulting in a net loss of soil organic matter. Post industrial revolution, degradation of soil organic matter has contributed about a third of CO$_2$ additions to the atmospheric pool (Montgomery, 2007). It is estimated that 78 billion metric tons of carbon from the soil organic matter pool have been released into the atmosphere (Montgomery, 2007). Farming practices such as soil disturbance primarily via tillage, and bare fallow periods tend to contribute to this loss.

Although agriculture contributes to emissions of all three major GHGs (carbon dioxide, methane, and nitrous oxide), land use change, the clearing of natural land for agriculture and burning biomass, is a significant source of carbon emissions, estimated at 1.5 Pg of C, (Morgan et al., 2010). Returning carbon to the soil sink is a form of climate change mitigation, and higher carbon soils provide a variety of ecosystem services. If managed properly, soil has the ability to sequester a large amount of C, which not only reduces atmospheric levels, but increases soil functioning. Soils that are low in organic matter have the highest potential for restoration.

Framing soil conservation as soil stewardship with a focus on soil health fosters active engagement between those who manage land and their soils. The soil health framework is a tool to encourage soil conservation and to remind land managers of their stake in the sustainability of productive soil as a vital resource. Soil health is enhanced when SOC is managed sustainably, meaning that managing for soil health is inherently linked to maintaining the soil organic carbon pool (Lal, 2016).

Farmers are the main stakeholders of their soils, and likely to be concerned with the concept of soil health since they bear the burden of degraded soils that aren’t resilient and require
amendments and other inputs. Soil nutrient depletion from unsustainable cultivation practices also leads to decreasing crop productivity (Lal, 2004). Loss of organic matter in soil can be reversed through changes in how soils are managed, resulting in benefits to farmers. High organic matter increases resilience, quality, and productivity of soil. Benefits include enhanced fertility, soil structure and aggregate stability, water holding capacity, and the capacity to reduce toxic elements (Morgan et al. 2010). Thankfully, losses of SOC are reversible through proactive land and soil stewardship.

Addressing farmer adoption of soil conservation strategies

There is a need to bridge the gap between scientific research and on the ground practical information for growers and other land managers. Farmers and land managers make decisions based on their past experiences, labor requirements, communication with peers, and what they perceive the risks to be (Kleijn et al., 2019). The low level of economic returns because of narrow profit margins of farming prevents farmers from taking risks in management. If farmers do not know when the benefits of implementing soil health practices will reach them, they are less likely to invest in the startup costs or technological changes associated with shifting management.

Research that allows farmers to participate in on-farm research has been proven to help farmers understand and articulate the tradeoffs associated with adopting sustainable agricultural practices. Using farmer participatory research has many benefits, one being that it strengthens the discussion of tradeoffs, and acknowledges how context plays a role in the outcomes of adoption in regards to the practices in question (Snapp et al., 2019). Another main benefit is that
it acknowledges the expertise of farmers as valuable yet provides education and training for farmers (Dalton et al., 2019). Participatory research also allows farmers to be involved in problem identification. When farmers are able to frame the problems they face, the technological solutions are more likely to succeed (Bernet et al., 2001). The success of this approach is attractive as it incorporates the interlocking goals of social and scientific research to illuminate the state of soil carbon management in a given population of farmers.

1.3 Approach and roadmap

Collaborative on farm research has been identified as a useful tool to bridge the gap between science and practice, and is the theoretical basis for my research. This work combines a scientific assessment with a social, economic and cultural analysis to determine the feasibility of recommending specific changes in crop management in order to build soil organic matter and ultimately soil health and carbon sequestration for grain farmers in the Hudson Valley (Paustian et al., 2016; Snapp et al., 2019). The collaborative research is presented as case studies of two local Hudson Valley farms, to compare and contrast their management styles, their perspectives on cover crops/no-till, the current state of soil carbon on their farms, and the potential future scenarios that would enhance their soil carbon which are tailored to reflect their interests.

This project contains four distinct elements: 1) a review of the literature on factors influencing soil carbon dynamics, 2) a review of the social science literature regarding adoption and farmer participatory research, 3) in depth interviews with two local grain farmers, and 4) a series of simulations of these farmers’ production systems to assess current and potential soil carbon sequestration. In chapter two, I begin with an overview of soil organic matter dynamics
within an agricultural soils context with a focus on reduced tillage and cover cropping, followed by a review of the social science literature on why farmers may or may not adopt conservation practices. Chapter four follows with the methodology of the social and simulation research I conducted. The results will be presented as case studies, along with the COMET Farm (http://comet-farm.com/) model output results. I discuss the differences in soil carbon sequestration between both systems and room for improvement in future increases presented as options. The discussion and interpretation of this data will follow. The final section will address policy goals, and discuss how the results of this project are relevant to the future of agricultural policy in the Hudson Valley and nationally.
Chapter 2: Understanding Soil Organic Matter Dynamics

2.1 Introduction

A baseline understanding of the scientific literature discussing organic matter cycling in soil is relevant to illuminate how agricultural practices can alter soil organic matter (SOM). There is a growing body of scientific research dedicated to deciphering the mysteries of carbon cycling in soil. This research engages the intersection between soil health and the ramifications of changing agricultural management, because practices influence not only the flux of carbon through agricultural soils, but also affect the farm system as a whole. Diving into soil organic matter cycling provides a background for comprehending the functions of the rhizosphere and the interconnection of management and soil health. This chapter will cover the mechanisms behind changes in SOM level. Using an inputs/outputs framework, I will discuss and explain how specific conditions lead to net accumulation or net loss in soil carbon. I then discuss two common management practices that influence inputs and outputs of carbon - cover crops and tillage. I close with a discussion of the barriers and opportunities to encourage the adoption of soil health practices by farmers today, and some success stories from participatory research ventures.
2.2 Inputs of carbon into soil ecosystems

*Primary productivity as the ultimate source of soil carbon*

The amount of organic matter present in soil at a given time is a product of inputs (positive accumulation of carbon), minus the outputs (mineralization and release of inorganic carbon). Simply, when C inputs exceed C outputs, there is a net gain in soil carbon and vice versa (Morgan et al., 2010). The two main processes that move carbon through soils are photosynthesis and respiration. Plants fix carbon from the atmosphere through photosynthesis to build carbohydrates. Organic carbon derived from plants enters the soil via multiple channels. Two main routes of input for plant organic carbon into the soil system are above ground plant litter, and below ground root litter and exudation (Gougoulias et al., 2014). Plants may shed biomass, die, or in the case of agriculture, crop residue is sometimes left on the soil surface to decompose. Root exudates are carbohydrates expelled from the plant's roots to feed beneficial organisms such as fungi and microbes.

The amount of plant derived carbon that enters the soil system is dependent on the net primary productivity (NPP) of the plant. The more carbon that is fixed by the plant, the more carbon enters the soil via residues and deposition of organic compounds in the rhizosphere. The relationship between root systems and the obligate symbiont group, arbuscular mycorrhizal fungi (AMF), increases the GPP (gross primary production) of the host plant (Rillig, 2004). As a plant’s NPP increases, theoretically soil carbon inputs also increase, directly through increased root growth and exudation, and indirectly through increased amounts of aboveground plant biomass returns to soil. Once organic carbon from plant material enters the soil, soil organic matter undergoes humification by microbes (Morgan et al., 2010). Using diverse crop rotations
diversifies the inputs of carbon into the system. More sources of carbon inputs and increased
time of living cover increases microbial biomass and activity (Drinkwater & Snapp, 2007).
Using a cover crop is a management choice that increases a field's days per year in living cover
and diversifies carbon inputs.

The practice of a fallow period, where soil is tilled for weed control but not replanted,
results in losses of soil carbon (Lal, 2004). Increases in the usage of chemical fertilizer has
decreased the need to grow legumes between annual crops, causing bare fallows to replace living
cover. Decreasing days in living cover to between 4-6 months per year, impacts the soil biota
that are supported by plant roots, and further decreases inputs of active carbon from plant carbon
fixation (Drinkwater & Snapp, 2007). Although mulch or other high carbon organic material can
be applied, without a live root present, direct rhizodeposition cannot occur and microbes and
fungi do not receive carbon directly from roots.

Heterotrophic organisms and their role in soil carbon cycling

Soil organic matter is composed of both living and dead organic material present in the
rhizosphere, specifically decaying plant, fungal and exudate biomass, and microbial biomass,
including microbial necromass (Gougoulias et al. 2014). The presence of fungal mycelium and
hyphae also contribute to soil carbon in the soil. Rhizodeposition is the only source of carbon for
arbuscular mycorrhizal fungi (AMF), as the fungi are obligate symbionts meaning they are
dependent on the plant for carbon, which is transported to them because of the direct connection
between plant roots and the fungal mycelium (Rillig, 2004). AMF uses root exudate carbon to
grow, function, and create secondary compounds which aid in the formation of aggregates.
AMF produces a compound called glomalin, a putative protein produced which is resistant to microbial decomposition and is itself high in carbon and highly recalcitrant (Rillig, 2004). Glomalin’s mean turnover time is reported to range from 6-40 years (Drinkwater & Snapp, 2006). Not only do AMF secrete organic compounds, carbon derived from AMF mycelium and hyphae are a significant component of SOM, ranging from 50 to 900 kg ha⁻¹ (Rillig, 2004). Variability in this estimate is a result of the inability of sampling to fully encompass the extent of fungal bodies once they are extracted from the soil ecosystem. AMF and soil microbes interact with each other in the rhizosphere. For instance, AMF mycelia can culture the growth of bacteria which also aid in stabilizing aggregates, by secreting organic compounds (Rillig, 2004). Certain fungi such as ectomycorrhizal fungi can also mineralize organic carbon (Gougoulias et al., 2014). Essentially, organic carbon and plant material is humified by microorganisms, and stabilized by microbes and fungi.

For SOM to be stable, or recalcitrant, it must be resistant to fast turnover by microbes. Stability is dependent on the type of inputs of carbon, and its vulnerability to mineralization from microbes. There is no free carbon in soil - it is either stored or decomposed. Aggregates are vital to the storage of organic matter because they are known to physically protect carbon from mineralization (Six et al., 2002). Protection in aggregates increases the mean residence time of the carbon in soil organic matter. Further, As SOC becomes incorporated into the lower soil layers, mean residence time (MRT) increases (Lal, 2004). Mean residence time is the average time an aggregate or unit of organic matter stays underground. Fungal hyphae are known to initiate macroaggregate formation (Six et al., 2002). Other soil organisms also contribute to aggregation. Actively growing roots are the sites of aggregation through the stimulation of
microbial activity via root exudates. Aggregates form around fresh plant or root derived residues by nucleating the bacterial and fungal growth. Active carbon is the fraction of SOM that is easily available for microbes, whereas SOM which is physically protected by aggregates or connected to soil mineral fractions is safe from microbial decomposition (Gougoulias et al., 2014).

Additionally, as SOM increases so do soil microbial populations, as they have more resources. The presence of beneficial microbes in the soil ecosystem is vital for nutrient holding and cycling nitrogen (Lal, 2004). Lengthening time spent under living cover, and diversity of carbon inputs increases the presence and activity of soil microorganisms (Drinkwater & Snapp, 2007). To maximize inputs of carbon in croplands, it is recommended that farmers increase cropping frequency, and grow high residue crops (Morgan et al., 2012). Management choices pertaining to fostering a beneficial microbial population are consistent with the goal of aiding soil health.

2.3 Outputs of Carbon

Soil respiration causes carbon dioxide (CO$_2$) to escape from soils. This carbon originates from organic matter inside or on the surface of soil, and is broken down by soil microbes that metabolize it (Gougoulias et al., 2014). Microbial processes drive soil organic matter turnover and the rate at which soil respires. Microorganisms process organic carbon from NPP, alter the composition of SOM and turn it into humus (Morgan et al., 2010). This process is known as mineralization, representing the decomposition of organic matter into CO$_2$ through respiration (Six et al 2002). Microbes use some of the carbon from mineralization in the structure of the bodies. Organic matter is either decomposed and released as CO$_2$, known as soil respiration, or
incorporated into more stable compounds, depending on soil physical conditions (Gougoulias et al., 2014).

Microbes utilise organic and inorganic forms of carbon as energy sources and alter the composition of carbon compounds in soil. Microbial decomposition rates vary based on soil structure, temperature, and moisture (Morgan et al., 2010). The availability of other key elements such as N and P also affect the rate of mineralization. Environmental factors such as pH, soil texture and mineralogy, temperature, and soil water content control rate of consumption and respiration of C by microbes (Gougoulias et al., 2014). Soil temperature is vital to microbial processes. Warmer temperatures in soil will increase the rate of mineralization (Lal, 2004).

An additional controlling factor determining vulnerability of soil carbon to mineralization is the quality of C inputs. While root exudate compounds can be rapidly respired by microbes (hours to days), plant derived polymers such as lignin and cellulose need to be broken down by extracellular enzymes before mineralization via microbes can occur. Nitrogen rich plant residues are decomposed more rapidly than more carbon rich ones. Active carbon is the fraction of SOM that is easily available for microbes, whereas SOM which is physically protected by aggregates or connected to soil mineral fractions is safe from microbial decomposition (Gougoulias et al., 2014).

Soil disturbance allows oxygen to enter into soil, which increases microbial respiration rate leading to an increase in mineralization rate (Montgomery, 2007). Disturbance also breaks up soil aggregates allowing once-stored carbon accessible to microbial populations (Lal, 2004). Additionally, tillage mixes crop residue into the soil profile, bringing it closer to microbes. Soil physical conditions such as moisture content favor fast mineralization, as non-oxygenated soils
allow for anaerobic microbial communities to flourish. The conversion of wetlands for agricultural production by the means of drainage has depleted SOC through respiration occurring once water exits the soil profile (Baker et al., 2007).

In sum, soil organic matter percentage represents the balance of carbon inputs and outputs. One way the below ground organic matter pool is depleted is due to an imbalance of the inputs and outputs of carbon sources. When outputs are less than inputs, SOM is built, and when outputs exceed inputs, SOM is lost. High levels of organic matter in soils provide better soil quality and function. When the SOM pool is 1.5-2.0 percent soil organic carbon, this threshold level provides a range of benefits to the soil ecosystem (Lal, 2016). Generally, the constraints to agronomic productivity can be addressed if SOM is managed sustainably. Soil quality is enhanced when SOM levels are in the 5 percent range. Among the benefits to this level of organic matter are increased water quality due to better water retention and infiltration, favorable soil structure, improved nutrient cycling, reduction of toxic elements, and lower GHG emissions (Drinkwater & Snapp, 2007; Lal, 2016; Morgan et al., 2010). Soil health can be improved by maintaining or raising soil organic carbon through management geared towards SOM building. Soil health indicators overlap with the benefits of at or above threshold SOC contents (Lal, 2016).

2.4 Management practices known to affect SOM

The agricultural practices that affect SOM are identifiable, and more broadly the land-use practices that deplete it are known. Cover crops and tillage are two prime examples of management practices that alter SOM, and will be the focus of this thesis. Using cover crops can
maximize the inputs of carbon into soil, and forgoing tillage minimizes the outputs of carbon from soil. Using the framework of inputs and outputs, the following section will review the literature on cover cropping, and reduced tillage as they relate to SOM dynamics.

**Cover crops**

Using cover crops (CC) enhances a farming system's ability to sequester carbon in soils by maximizing above and below ground C inputs (Blanco-Canqui et al., 2015; Jian et al., 2020). The literature suggests that soils where management regularly uses cover crops have higher soil carbon content than soils without cover crops (Pravia et al., 2019; Ding et al., 2006). The estimated mitigation potential of using cover crops is significant. If cover crops were used on the 88 million hectares of land used to grow the United States’ five top crops, the potential for mitigation is roughly 103 Teragrams CO$_2$ equivalent per year (Fargione et al., 2018). Poeplau and Don (2015) estimate that cover crops can sequester about $0.32 \pm 0.08$ Mg ha$^{-1}$ yr$^{-1}$ of C based on analysis down to a 22-cm soil depth. Their estimation of a maximum increase in soil C was 16.7 Mg C per hectare. A more recent meta analysis that covered 1195 comparisons from 131 studies worldwide proposed a mean sequestration rate of $0.56$ Mg Carbon per hectare per year (Jian et al., 2020).

Cover crops promote soil health providing multiple benefits beyond accumulation of soil carbon. They provide a wide range of ecosystem services such as improvement in soil physical, chemical, and biological properties, increased crop yields in regions with abundant precipitation, control of water and wind erosion, improvements in nutrient cycling, suppression of weeds, improvement to wildlife habitat and diversity, and finally the potential provision of both forage
for livestock and feedstock for cellulosic biofuel production (Blanco-Canqui et al., 2015). Many of these ecosystem services are directly connected to the ability for cover crops to sequester organic carbon, and this functionality varies based on how cover crops are managed.

Cover crops increase the SOM pool by diversifying and contributing C in the form of above and below ground biomass (Blanco-Canqui et al., 2015). When soil is provided with a year round stream of carbon from photosynthesis, cover crops add carbon to soil even after the main crop is harvested. The above ground biomass of the plant covers the soil while it is growing and then decomposes after its termination, allowing the carbon in the plant to be reincorporated into the soil. Meaning that cover crops increase the SOM pool (Ding et al., 2006). In comparison, land left to bare fallow, not planted to a cover crop, would not contribute inputs of carbon because of the lack of plant residue and lack of live root present. Cover crops prevent losses of soil carbon from erosion, by physically covering soil which prevents C losses from erosion (Blanco-Canqui et al., 2015). Cover crops also contribute to soil carbon via their root inputs of carbon, which are an indirect result of increased NPP. Cover crop mixes increase C levels because of greater above and below ground biomass production, with the added benefit of diversifying carbon inputs from different residues (Blanco-Canqui et al., 2015). The effect of cover crops on soil carbon is dependent on a number of factors: the amount of biomass provided by the cover crop, the amount of time a cover crop is used, annual temperatures, and the initial levels of soil carbon (Jian et al., 2020; Blanco-Canqui et al., 2015). The relationship between increased inputs of carbon and the ability of a soil to store SOM depends on the nutrient dynamics at play and the physical properties of soil.
The effects cover crops have on soil organic matter are diverse, ranging from improved nutrient cycling to below ground additions of carbon through exudates. Cover crops increase soil organic matter levels from their active presence in the soil, by contributing to below ground (rhizosphere) carbon inputs. In a three year high-fertility maize experiment conducted in Wisconsin, researchers found that cover crops increased active C pools, which were all positively correlated to total residue inputs and NPP metrics. But, they found that maize litter quality and decomposition rates were not changed by cover crops. In this case, the potential for increases in soil C from cover crops was reported to come from belowground processes only (Cates et al. 2019). Increases in microbially available C as particulate organic matter, but not an increase in microbial populations was found over the three year experimental period (Cates et al., 2019). These results are consistent with the idea that carbon and nitrogen dynamics are inherently linked in the rhizosphere, and in this high inorganic N input context, cover crops did more to add below ground carbon than above.

Improving the nutrient dynamics in soil is vital to SOM accumulation. Drinkwater et al. (1998) studied three cropping systems, and their relationship to soil carbon based on different nitrogen inputs. The first was manure, the second was legume derived nitrogen from BNF (biological nitrogen fixation), and the third was from synthetic fertilizer (conventional). They found that soil carbon increased more in manure and legume systems than in conventional (Drinkwater et al., 1998). Nitrate leaching was highest under the conventional system. This study shows that plant-species composition and litter quality influence SOM turnover causing differential retention of soil carbon. Even though the conventional management had more carbon inputs, soil carbon did not increase as much as rotations with legumes or pasture than manure
application followed by corn rotation. Their findings suggest that using high carbon to nitrogen ratio residues, and higher temporal diversity created conditions for better retention of C and N in the system. The restoration of the connection between carbon and nitrogen cycling can improve carbon and nitrogen balances on a global scale (Drinkwater et al., 1998). The way N cycles through the soil is dependent on microbial activity, which is tied to the microbial activity of breaking down and cycling SOM.

There is still much to be learned about the differences between crop types, combinations of cover crops (cover crop cocktails), the quality and residence time of the residue, and the challenges of managing cover crops in addition to the main crop. Still, cover cropping is a management tool that is more effective in certain agro-ecosystem contexts than others, and the potential for cover crops to maximize soil C may be strengthened when combined with other practices such as reduced tillage. Using cover crops and no-till increases soil C more than either practice alone because of the reduced residue decomposition of no-till systems (Blanco-Canqui et al., 2015) as will be discussed below.

**Impacts of tillage on SOM**

No-till is a farming practice where soil is never broken up, mixed, or inverted with machinery before seeds are sown or after they are harvested; in other words no soil disturbance. Tillage encompasses a wide range of activities that involve preparing and cultivating land for growing crops. Tillage intensity is a spectrum, ranging from no-till, to intensive tillage which is the most extreme level of disturbance. Some examples of types of tillage that are between these two extremes are reduced or conservation tillage, which is usually a function of the type of
implement used. Conventional farming systems may use machinery that penetrates feet deep into the soil horizon, or only the top few inches. Some reduced tillage practices only till where seeds are planted, leaving the rest of the field area undisturbed, this sometimes called strip tillage, and is also the method used by no-till drills. Tillage has the potential to reduce soil organic matter in soils, and studies have shown a relationship between reducing tillage and improved soil health.

Tillage influences soil health by changing its structure, disrupting microbial environments and aggregates, and exposing soil to oxygen, allowing losses of SOC. Generally, reducing tillage improves soil health. First, minimal disturbance allows for biota to flourish and SOC to stay in aggregates, and second, no-till with residue retention allows for crop residues to stay in the SOM pool for longer. No-till slows decomposition of organic matter, increasing SOC content near the soil surface. Reducing disturbance is a key recommendation for healthy soils from NRCS. Reducing disturbance can increase soil quality, organic matter levels, and soil biota (Montgomery, 2007).

Numerous studies have found higher SOM in no-till versus conventional, and reduced tillage plots in experimental settings. Total carbon is higher under no-till management compared to reduced or intensive tillage (Kahlon et al., 2013). The no-till system in this study had more total carbon and N from more aggregates and higher labile C pool from no disturbance and residue retention (Kahlon et al., 2013). From an inputs and outputs perspective it makes sense that combining mulching (adding organic matter) and reducing tillage (reducing losses of C) increases total SOC content (Kahlon et al., 2013). However, it has been found that no till changes SOC content only in the top or near the surface of soil. A lack of disturbance and residue from last year are what allow no-till to have higher carbon results (Nunes et al., 2020).
When deeper soil samples are used, the effect of tillage on SOM becomes complicated. In a study aiming to understand what the current state of tillage literature means, the authors illuminate the shortcomings of shallow soil sampling (Baker et al., 2007). Many tillage and SOC experiments’ sampling depths were not deep enough, and in comparing tillage and no-till, the researchers only measured the top 30 cm or less or the soil profile. In a study looking at organic matter fractions in soil, as expected it was found that soils under no-till had higher organic matter in the top of the sample than the conventional system (Nascente et al., 2013). In terms of reducing tillage and soil carbon sequestration, the perception of causation of lower SOM from tillage is supported by data from the surface of the soil profile (30 cm or less). This sampling fallacy renders that this data is not conclusive, and shouldn’t be taken as such. The differences in SOC are significant in the top 30 cm compared to no-till and conventional tillage. When studies using deeper sampling depths were considered, the differences in total SOC are not statistically significant. However, no-till does alter where SOM is contained within the profile (Baker et al., 2007).

In a meta analysis reviewing 69 peer reviewed papers regarding tillage experiments with sampling depths greater than 40 cm, Lou et al (2010) found that SOM was lost in both systems. In no-till systems they found soil C increased in the top 10 cm but declined in 20-40 cm. These authors found that the role of no-till in soil C sequestration is regulated by cropping systems, meaning other factors beyond tillage such as cropping frequency and crop species (Luo et al., 2010). The authors suggest there is an underlying mechanism contributing to SOC change, that is dependent on management on a more macro scale, rather than just the practice of tillage. Tillage is perceived to aid soil in its ability to be cultivated for food production.
Soil disturbance from tillage harms soil life. Disturbance from tillage breaks up existing aggregates and fungal networks in the rhizosphere (Six et al. 2002). It has been shown that tillage reduces arbuscular mycorrhizal fungi (AMF) biomass in soil (Rillig, 2004). No-tillage systems have been found to have higher microbial populations compared to conventional or intensive tillage systems (Six et al., 2002). A lack of soil disturbance allows microbial, fungal and worm populations to flourish. When it comes to fungal diversity and management, Schmidt, Mitchell, & Scow (2019) found similar levels of fungal diversity between tillage versus no-till, however, the communities of fungi were distinctly different. More specifically, the type of fungi present in soils with different tillage and cover crop treatments was evaluated. They do acknowledge that tillage reduced SOM, and stated that, under standard tillage, the increase of saprotrophs and decrease in symbiotrophs can be explained by the loss of SOM from tillage. Symbiotrophs only source of food is through their symbiotic connection to another organism, AMF is an example of a symbiotroph. Fungal saprotrophs are fungi that regulate C loss through decomposition, feeding on organic matter (Schmidt, Mitchell, & Scow, 2019). So, fungal communities are affected by tillage, and the resulting populations aid or deter the accumulation of organic matter in soils.

Tillage changes soil structure. In some contexts this is beneficial as it allows for seeds to be planted easily and germination of the crop to be uniform. However, tillage increases the erodibility of soils the longer they are cultivated (Montgomery, 2007). Relying on tillage to change the soil's physical environment, alters the water relations and pore spaces defined by root growth and fungal dispersion (Drinkwater and Snapp, 2007). No-till and residue management systems have been found to have better soil structure than plowed soil along with better water infiltration and less soil compaction (Kahlon et al., 2013).
Nunes et al. (2020) investigated the relationship between biological indicators of soil health and the impacts of tillage. They compared moldboard plow, chisel plow and no-till as their tillage means. Using a moldboard plow is considered intensive tillage, while the chisel plow does less disturbance and would be classified as reduced/conservation tillage. They found that no-till was the most effective at increasing SOM levels when paired with residue management or cover crops. And that the maximum benefit to soil health from the treatments tested was with row crops or perennial crops under no tillage. They found higher SOM in no-till treatments in the top section of soil, and attribute this finding to the lack of residue mixing in no-tillage systems, which provides organic matter from the surface to microbes only, rather than mixing in organic matter and microbes being able to reach it further down in the soil profile (Nunes et al., 2020). When no-till is combined with the use of cover crops, cover crops are able to sequester more carbon. Olson et al. (2014) tested both cereal rye and hairy vetch as cover crops and found that they sequestered 0.88 Mg ha–1 yr–1 under no-till, 0.49 Mg ha–1 yr–1 under chisel plow, and 0.1 Mg ha–1 yr–1 under moldboard plow. The depth measured in this study was 0- to 75-cm over 12 yr of management.

The rise of no-till

The economic and social benefits of using no-tillage systems may account for its rise in popularity in the United States. No-till helps farmers economically, by improving soil health and yields, reducing fuel/ time costs associated with tillage. No-till is currently practiced on various scales and in variable farming contexts. In 2004, no-till was practiced on 22 percent of farmland in the US (Huggins & Reganold, 2008). Once herbicide tolerant Round-up Ready ©) crops
came on the market, and weeds could be controlled without the use of tillage, no-till gained popularity. Conventional farmers are able to utilize no-till by applying herbicide to kill weeds, and large machinery such as roller crimpers to crush crop residues. No-till mechanisation has come a long way. Specially designed seeders drill directly into plant residues, and chemical herbicides allow no-till to be practiced on a commercial scale (Huggins & Reganold, 2008). However, N inputs need to increase during the first few years of no-till implementation in order to account for N trapped as organic matter in surface residues. Some use up to 20 percent more N inputs than conventional tillage systems. The problem of herbicide resistant weeds is the next challenge for agrochemical companies and those using mechanized no-till (Huggins & Reganold, 2008). This reliance on chemical inputs poses threats to the surrounding environment such as air, water, and soil itself.

That being said, no-till may be less GHG intensive than using tillage, all else being equal. In his book, Montgomery asserts that not plowing reduces fuel usage by half, which monetarily offsets the losses from lower yields, providing a net increase in profits (Montgomery, 2007). No-till has lower CO$_2$ emissions from both agricultural machinery and other inputs compared to conventional tillage. The C sequestration estimate from transition to no-till was cited from a database of 76 long term experiments on tillage (West & Marland, 2002). The average C sequestration was considered to be 337 +- 108 kg C ha$^{-1}$ per year. The benefit of no-till is that it requires less agricultural inputs, therefore using less carbon (West & Marland, 2002). Even if carbon sequestration estimates of no-till have been exaggerated because of sampling depth, overall, no-till reduces CO$_2$ emissions from crop production.
Essentially, knowing the details of how carbon flows through the soil as a series of different inputs and outputs allows for a connection between the literature and the results of in person interviews and modeling of specific farms. Scientific theories govern our expectations about what practices affect soil organic matter. A more nuanced discussion of the specifics of particular farming systems will give context to the application of soil health promoting farming techniques. There is a distinction between what we know about the mechanisms that control the soil organic matter pool and how farmers perceive their management to alter the health of their soils.
Chapter 3: Review of the Literature on Adoption of Farm Management Practices

3.1 Social theories and studies regarding adoption

Many publications have cited that no-till and cover crop use are connected to better soil health, but this information is not always accessible to farmers. Even when it is, there is not always practical and technical assistance available to farmers for implementation (Stephenson, 2003). Farmers have perceptions of cover crops and no-till based on their personal context. Getting farmers to adopt one of both of these practices is a challenge. Information initially provided to farmers can come from extension services, who spread awareness of new technology (Stephenson, 2003). In the following section I review social science theories regarding adoption of agricultural practices that relate to soil health, or carbon sequestration. I begin with the socio-agricultural theoretical frameworks, followed by insights gained from regionally specific studies, and finally patterns regarding the efficacy of including farmers in the research rather than excluding them.

Sociological theoretical frameworks

There are three paradigms that usefully explain how the adoption of practices in a farm context spread. In their study, Upadhyay et al. (2003) explain how, the income, the utility, and the innovation-diffusion-adoption theories can be applied to assessing farmer behavior. Income
theory is consistent with neoclassical economics, and states that if new practices increase farm profitability, they will be adopted. However, this theory fails to explain why some practices that can increase farm income are not adopted. The utility paradigm is similar to income, except it states that farmers adopt a practice because of a particular utility to adopting such as, for example practicing farming to conserve soil and water for the utility of sustaining access to the functions of preserved natural resources. Finally, the innovation-diffusion paradigm is based on information, risk factors, and the social position of the decision maker of the community.

The diffusion of innovation theory is a widely applied social theory describing the characteristics of distinct groups that appear in the process of a societal group slowly adopting a new technology or innovation. The theory states that the diffusion effect takes place over time within a given social population and eventually spreads to everyone. It was developed by E. Rogers, and the categories in order from first to last adopters are: Innovators, early adopters, early majority, late majority and finally laggards (Rogers, 1962). There are many stages that individuals, even within the distinct groups, pass through when adopting a new technology. These ideas are easily applied to agricultural innovations that are marketable as products and are sold by agribusiness. When physical products such as seeds or new fertilizers come on the market, use diffuses from the innovators all the way to the laggards eventually. It is clear that the theory was developed during the green revolution when agricultural research was about promoting new technologies to increase farm productivity. This approach to adoption has and continues to be used by cooperative extension services (Rogers, 1962; Upadhyay et al., 2003). Diffusion of technologies is a simple enough framework to base a discussion of farmer adoption
on, but the economic and social complexity of adopting soil health promoting practices presents a particular set of challenges to this simplistic notion of adoption.

**Sustainable practices as a new challenge**

What makes conservation or sustainable agricultural practices not easily fit into this theoretical explanation is that they are not tangible commodities. Rather, they are value systems individuals or farm communities may subscribe to. There are particular technologies that coincide with their application, or ideologies surrounding why certain methods should be used. The environmental concerns of farmers do not influence their likeliness to adopt conservation practices the same way increased profitability does (Cary & Wilkinson, 1997). Risks, technical and economic barriers to adopting conservation practices are valid reasons farmers are wary of changing their ways (Cary & Wilkinson, 1997). Making conservation practices economically profitable is important because influencing farmer attitudes through other means may prove to not be successful.

The diffusion of innovations theory does not always apply to sustainable practices due to a perceived lack of profitability associated with adopting. Farmers are not likely to consider a change that puts them at risk financially. In a study sampling 1,135 farmers in Montana through a mail in survey, two sets of sustainable practices were addressed (Saltiel et al., 1994). The main findings of the survey show that perceived profitability has the highest correlation with adoption of both types of practices. Secondly, the nature of the farm enterprise had an effect on adoption of both sets. Management intensive sustainable practices (MISPs) are more likely to be used by specialized producers at the large scale. Those using diversified crop and livestock systems were
more likely to favor using the low input sustainable practices (LISPs). Accounting for age and future orientation when looking at the characteristics of adopters and when they adopt is necessary to consider, as it is a part of farm context. Those concerned with the future are more likely to adopt LISPs as they feel these practices will increase net returns in the long run (Saltiel et al., 1994). The view that MISPs are profitable is influenced by the degree to which farmers agree that building soil tilth is important (Saltiel et al., 1994).

Adoption as a response to specified regionally specific challenges:

Studies about adoption often address the regionally specific problems a community of farmers face, and frame adopting sustainable or technological innovations as a solution. Many farmers adopt a practice in response to the successes of their fellow farmers who are more willing to take risks (Upadhyay et al., 2003). Farming communities are social groups that have their own system for sharing information and practical skills. Viewing the economic and cultural success of their peers motivates them to also adopt if applicable to their farm and financial situation. The information provided to producers via educational measures may be a better determinant of adoption rather than income. Extension services are able to facilitate this communication between farmers.

In response to the regional problem of soil erosion from wind, a study by Upadhyay et al. (2003), analyses Washington state farmer’s adoption of practices that mitigate soil erosion, which are connected to soil health building practices. The authors describe an important differentiation between three groups of farmers: the Zero-practice adopter, single-practice adopter, and multiple-practice adopters. The focus of this study is less about if farmers do or
don’t practice conservation practices, but if they only choose one, why and which one, and if there is a difference between those who choose only one and those who choose to adopt multiple. Results from this study show a larger difference between multiple practice adopters and zero practice adopters than multiple and single (Upadhyay et al., 2003).

This perspective acknowledges the heterogeneity of those who adopt conservation practices. The significance of researching adoption beyond the binary view of adopting or not is to evaluate the choices of farmers based on how they see problems. Contextualizing decisions based on one problem and then potential solutions as a group of practices is distinct from the view that one practice is a new technology and the choice to adopt it is an innovation. The context of what practices aim to solve or improve are what motivates farmers to change management. Clearly, those who are already engaged and interested are the first to adopt, and those who are not in the economic position to take risks with management will wait longer to shift their practices.

Risk

How much risk farmers are willing to take dominates their decisions about whether or not they try new management such as cover crops and reduced tillage. Farmers can be categorized into three groups regarding risk: Risk averse, risk neutral, risk preferring (Adusumilli et al., 2020). A calculated risk premium is the monetary amount required to induce a change in practice. Those who are risk-neutral require a lower risk premium to adopt compared with risk averse producers who would need a high premium in order to be persuaded to take the risk. Those who are the least willing to try a new practice, will respond to an incentive only if the monetary
compensation is high enough, whereas those who are more open to risks do not require such a high price incentive in order to make a shift in management. Risk neutral farmers are more likely to adopt a practice even if it’s profitability is not guaranteed, compared to risk averse farmers. The risk preferring category is the minority, but they are even more likely to experiment with adoption, no matter the context.

In a study addressing adoption of cover cropping and no-till practices in Louisiana soybean farmers, the authors found that low rates of adoption of conservation practices can be attributed to the general challenges of establishing cover crops, profitability concerns, and the lower yields associated with using no-till (Adusumilli et al., 2020). Risk management is also dependent on regional context. For instance, in the climate of the American South, there is more time after the harvest of a main crop to establish cover crops that will remain in the fields over the winter until the next growing season. In this study and cultural context, farmers are operating under the assumption that cover crops are risky for profitability. The experiment worked by estimating mean net returns per hectare under three cover crop treatments: control, hairy vetch, and winter wheat, while also testing no-till and conventional tillage. In a comparison between no-till and conventional till, they found higher returns from conventional. But, both plots under cover crops had higher returns than the control under both tillage regimes. However, under conventional tillage, the returns were more variable (Adusumilli et al., 2020). Using cover crops enhanced the resilience of the farming system, providing stability for farmers as a product of the economic risk of adopting them.

Whether or not a farmer will adopt a given practice such as reducing tillage or using cover crops is related to their willingness to take risks, what regionally specific problems they
are managing to minimize, their access to information and technology to support the practice, and if they can afford it. It’s vital to recognize the issues pertinent to farmers are more easily identified in a direct way, meaning coming from their perspective, rather than impersonal means such as surveys. Although a high number of respondents can make the data more generalizable to a larger population, the nuanced discussion of personal perceptions is paramount if the goal of research is to empower farmers to shift their management.

3.2 Farmer participatory research: efficacy and practice

Beyond an assessment of risk, demographics of farmers, their economic status, and the set of challenges that comes with managing their particular systems, there are socio-cultural barriers to adoption as well. Changing management has barriers farmers must overcome and requires trade-offs. Often, there are automatically costs associated with changing an operation. There are many reasons farmers practice the way that they do, oftentimes it is region and scale specific. Their knowledge of their work and their land is vast and valuable. This cultural knowledge should be taken into consideration when discussing adoption and changes in behavior. In short -- there is no way to get beyond the big picture in regards to what problems farmers face, other than by consulting them. Understanding the barriers to adoption is dependent on communication between those who recommended practices, and those who manage land.

The scientists researching conservation practices such as no-till and cover cropping have ideas that differ greatly from the perspective of farmers. There are drawbacks when researchers do not consult farmers before intervening and attempting to provide information to encourage changes. By addressing reputational concerns, and changing the image of how farming alters the
environment, instruments designed to change perceptions farmers and stakeholders have first, may pave a smoother path to change (Kleijn et al., 2019). Farmer participatory research (FPR) increases adoption of new technologies (Dalton et al., 2011). When farmers are included in the technological development process, the probability that they will use them increases. FPR that seeks to educate participants by improving knowledge and innovation capacity as a tool for improving technology, leaves participants better off, by empowering them (Dalton et al. 2011).

By investigating intrinsic and extrinsic motivation to evaluate the success of incentive programs encouraging the adoption of sustainable practices, Bopp et al. (2019) provide valuable insights about how risk perceptions are interrelated with the types of motivations farmers have. Extrinsic motivation is to be awarded something for behavior or to change behavior to avoid punishment, whereas intrinsic is self motivated interest to change for the sake of whatever benefits that come with the practice (Bopp et al., 2019). The study conducted was participatory and occurred in Southern Chile, where annual cropping is practiced, and its results are based on interviews with farmers. It discusses an incentive program designed to promote soil health as an example of extrinsic motivation, which was compared to a survey of farmer attitudes regarding sustainable practices which explored intrinsic motivation. The incentive program pays for the investments and co-pays necessary for implementing a group of sustainable practices. In 2015, over 19,000 farmers benefited from the program (Bopp et al., 2019).

Those who are not interested in maintaining soil health need an external factor to motivate them to change (Bopp et al., 2019). This distinction is extremely relevant to the conversation surrounding motivations for adopting cover crops and no-till, because those who are interested in innovation or want to solve the problems they face on their farms already have
adopting on their minds and they are taking their land and soil health seriously. Incentives increase adoption of sustainable practices by influencing farm economics, meaning that farmer’s perceptions don’t have to shift for their management to change (Bopp et al., 2019). This comparison is considered along with risk perception of soil erosion and behavioral responses to the decreasing stock of topsoil resulting from unsustainable agricultural practices.

Using a transdisciplinary framework, Smetschka and Gaube (2020) researched and modelled farmer behavior in a study that was manyfold and collaborative. Its intention was to be useful to farmers. The social sustainability of farming practices is relevant to understanding how farmers respond to sources of information (Smetschka & Gaube, 2020). The social impact potential of research that includes stakeholders as fundamental to the process of modeling is increased when stakeholders are included in decision making. This is especially relevant in the context of agriculture, since excluding the realities of farmers makes for research that lacks a relevant societal impact (Smetschka & Gaube, 2020). The participants worked to create scenarios and allowed for debate and discussion surrounding what information is most useful, and what conflicting issues or interests arose by beginning with sharing of perspectives. There were many stages to the engagement, and worked with the technology of modelling. The type of model in question was an agent based model, attempting to replicate human behavioral decisions. The research team began by doing preliminary research, then stakeholders were engaged in a series of workshops. Engaging stakeholders in this form of methodology is critical to its success. When the outcomes are relevant to farmers, they are more likely to be active participants (Smetschka & Gaube, 2020). Both parties are dependent on one another for the success of participatory research based projects.
If research is designed to help farmers, scientists need a way to understand the needs and priorities of farmers, and in order for a real long-lasting benefit to come out of the relationship farmers should be consulted (Schindler et al., 2016). Shifting the utilization of science in agricultural development settings to acknowledge the productivity of scientists learning from communities, dismantles the informational power dynamic explicit in the relationship. When local knowledge is as necessary as scientific knowledge, the solutions become much more likely to work for the population that needs them to (Schindler et al., 2016). A rise in adoption of conservation practices can be expected as a result of farmer participatory research. By empowering farmers, their ability to make decisions managerially improves, and so does their understanding of environmental impacts, and the connections between elements of their systems, providing efficiency gains (Dalton et al., 2011). FPR may be a method for educating farmers about how their management can alter the environment, and about the multiple benefits of adopting conservation practices beyond improvements to productivity. Using this research framework has potential to create a body of knowledge that defines soil health and increases the awareness and adoption of soil health building practices. More efforts to connect experimental work and farmer participatory research are necessary to communicate the benefits to farmers associated with increasing their soil health.

3.3 Adoption of Soil Health Practices and Farmer Connections

The potential for soil carbon sequestration is considerable, however stable soil carbon takes years to accumulate, and eventually will reach saturation. As the stable soil carbon pool reaches saturation, inputs of C can no longer be stabilized and will be lost from the system (Stewart et
Fargione et al (2018) use the framework of natural climate solutions to address the problem of SOM depletion within the larger scope of global carbon cycle imbalance. Using cover crops is one of the lowest cost opportunities, yet has one of the highest C sequestration potentials considering the second most mitigation potential is from increased carbon sequestration in soils. (Fargione et al., 2018).

Practices that enhance agricultural productivity by maintaining or improving soil health are gaining popularity with farmers. In 2017, no-till practices were used on 279,370 farms, and 104,452,339 acres respectively. Reduced tillage (excluding no-till) was used on 217,069 farms and 97,753,854 acres, compared to intensive tillage, which was practiced on 264,893 farms and 80,005,292 acres, respectively. A total of 73,306,807 more acres were managed in reduced or intensive tillage than no-till (USDA). In comparison to no-till, cover crops have a much lower rate of adoption. The number of farms and acreage managed using cover crops increased significantly between 2012 and 2017. Cover crops were used on 153,402 farms totalling 15,390,674 acres in 2017, compared with 133,124 farms and 10,280,793 acres respectively in 2012. The most important finding from a cover crop survey report released by SARE covering the years 2016-2017 is that soil health was noted by 86 percent of respondents as the key benefit of using cover crops. Fifty-four percent of respondents believe that soil health benefits from cover crops began after 1 year of use. In terms of when cover crops were planted, 73 percent of users planted after harvest. Cereal rye was the most popularly used cover crop by respondents, followed by oats, then by radish (CTIC, 2017).
Cover crops can act as a form of crop insurance by increasing soil resilience. Myers et al. (2019) show through an economic analysis that cover crops have both immediate effects and long term ones, the benefits are beyond those encompassed in short term returns, meaning it requires a multi year analysis to fully encompass the benefits of using cover crops. Although the perception is that cover crops take a long time to pay off, if cover crops would solve particular challenges farmer’s face they pay off faster (Myers et al., 2019). When cover crops and no-till are used together, they improve soil health more than either would on its own (Myers et al., 2019).

A large percentage of the global land area is dominated by agriculture, and the number of people managing that land is even greater. Engaging such a large group of people is in itself a challenge (Paustian et al., 2016). The best way to source management data is from farmer reporting, and their role as information providers is valuable and includes them in the process (Paustian et al., 2016). Farm models use location, environmental conditions to estimate GHG fluxes based on management inputs (Paustian et al., 2016). Analysing and measuring the GHG fluxes of individual operations occurs primarily in the research sector. This is due to the limits of technology, labor and expertise. The prospect of modeling individual farms is a feasible way to quantify current fluxes while simultaneously raising farmer awareness.

3.4 Conclusions

The framing of soil health is helpful, because it is in the farmers best interest to make decisions based on what is beneficial to them, rather than framing it as reducing GHG emissions. Indicators that measure soil quality measure the changes from land use practices that affect
properties or processes over years to decades (Wander et al., 2019). The adoption of farming practices that may be detrimental to short-term profitability of farms, but that will almost certainly lead to long term resilience and profit presents a challenge. Farmers’ belief systems make it difficult for them to understand the long term pay off of healthy soil.

At the current moment, making ecologically sound farming practices attractive to farmers is a prerequisite to improving soil health. Benefits to farmers should extend to all crops in the rotation in order to be effective (Kleijn et al., 2019). The tension between agro-chemical companies offering a buyable fix to farmers problems, and science encouraging ecological intensification and regenerative practices should be addressed. One proposed solution is the use of regulatory instruments to advocate for nature based practices, such as taxing agrochemicals rendering regenerative practices more profitable than conventional ones (Kleijn et al., 2019). Development of soil health standards ideally can aid in the process of creating policies or certifications that may encourage changes in practices via the market, to convince reluctant or on the fence land managers, (Wander et al., 2019).

Healthy soil benefits both farmers and the environment. The soil health framing transitions the perception of soil from exploitable and free natural capital, to a living system that needs to be managed carefully. Transitioning from the market based soil amendment strategy to integrated natural inputs management makes a difference in the health of soil. It is important to note that farmers have their own ideologies about cover crops and tillage, which is why I seek to look deeply into two case studies in order to unpack their thoughts on the science, profitability, and feasibility of cover cropping and reducing tillage. The interviews that follow allowed me to understand the farmers’ current systems, and assess some potential new practices in an attempt to
understand their willingness to adopt improved soil health practices. In the following chapter I will discuss my methodology for interviewing and collaborating with two distinct farmers in Columbia County, NY.
Chapter 4: Methodology

4.1 Research Question

The intersection between farmer ideologies and practices is complex and requires multiple angles of analysis. Are the current practices of large-scale conventional and organic grain farmers in Columbia County leading to soil carbon sequestration? And, do corresponding changes in tillage and cover crop management improve soil carbon outcomes among this set of farmers? I seek to compare what farmers do now to hypothetical future scenarios that are tailored to benefit them. I use the simulation model COMET Farm as a tool for understanding the current soil carbon dynamics on particular Columbia County farms by identifying either a net gain, steady state, or a net loss of carbon in their current systems, and explore the impact of possible future changes in management. COMET is used to give an estimate of the changes in soil carbon. Simulations were developed in collaboration with the farmer participants in an effort to both understand their values and constraints to soil health management as well as to give them some agency in designing the future management scenarios.

4.2 Research design

I conducted a series of three interviews with each of the farmer participants: 1) an initial interview to gather the data needed to model the farms in question and understand their views on
tillage and cover crops; 2) a second interview after having completed simulations of their farms, to show the farmer the estimates of soil carbon emissions or sequestration rates from their current farm management and discuss potential future management that might increase soil carbon; and 3) a final interview, intended to debrief the farmer on the results of the simulated future management and answer any questions they may have. Interview questions can be found in Appendix A. In addition to quantitative data collection the interviews were designed to collect qualitative data regarding farmers’ attitudes regarding the conservation practices of no-till and cover crop usage, and why these practices are or aren’t used by them. In addition, the interactions were designed to be collaborative such that simulation results could pass back to the farmers in a form that is beneficial to their understanding of how conservation practices work on their land.

Farmer participation

The research design follows qualitative social research methods, with a focus on case studies of two successful farmers. Before reaching out to farmers, I gained approval from Bard’s Institutional Review Board to conduct in-depth interviews with the two farmer participants. After gaining IRB approval, assistance was sought from the Columbia County Cooperative Extension office in identifying potential grain farmers in the county. I then reached out to farmers via phone and email and found two large-scale grain farmers willing to participate and scheduled times to meet with them for our first interview.

My interview sample consisted of only two farmers. The sample is not intended to be representative of the entire population of grain farmers in the Hudson Valley, rather an in-depth
look at two distinct systems. I specifically looked for a conventional farmer and an organic/regenerative farmer to challenge assumptions about soil health and GHG emissions in organic versus conventional agricultural systems. The differences between the two case studies are much more than just conventional versus organic, as they have very different scales, value systems, and motivations. The conventional farm is using no-till but not cover crops, and organic farms generally use cover crops and tillage.

Those who I interviewed are aware that I will be using their information for this thesis, in my IRB application I explained that if kept confidential the participants would be easily identifiable and there is a low risk to their livelihoods anyway, so the results shouldn’t be confidential. I interviewed John Langdon, head farmer at Langdonhurst Farms in Copake, NY and Spencer Fenniman, head farmer of Hawthorne Valley Farm in Harlemville, NY. John Langdon was interviewed the first time on Thursday January 23rd, 2020. Fenniman was interviewed the first time on Thursday January 30th, 2020. The second meetings occurred on February 25th and March 3rd respectively. Final interviews took place on March 12th and I had a virtual wrap up with Spencer in April. Modeling was done in between interviews to give results back to the farmers regarding the model results from inputting the current management information I received from the first interview. I took notes during the interviews and audio recorded the first interview conversation so that I could listen back and remember the specific wording of things and to ensure the information is consistent with what wording farmers used. The final two interviews were not taped, and I took notes to remember the main points of these conversations.
Simulations

Simulations of each farming system were conducted using COMET Farm. The COMET Farm tool is a web based crop modeling program that incorporates both empirical and process-based models by running the DAYCENT crop model (Del Grosso et al., 2009). It was developed by the USDA in conjunction with Colorado State University to estimate GHG emissions (carbon dioxide, nitrous oxide, methane), over time from farms based on spatially specific soil and climatic factors (http://comet-farm.com/). Weather inputs for COMET come from NCEP, and the years used are 1991-2000 since the model does not seek to include long term changes in weather as they might alter the results (Del Grosso et al., 2009). COMET allows farmers to enter detailed information about crop management to see results specific to a field, and which practices are implemented on it. It uses geo-located soils data, and historic weather to model current management. The service is free and confidential, meaning that the USDA does not have access to the management data farmers input. The soil carbon emissions feature provides results that suggest if a net accumulation or depletion of carbon is occurring. This measure is of interest because it is representative of the dynamics of soil carbon, and estimates if organic matter is being built or lost.

COMET requires specific crop information such as planting dates, crop rotation, tillage practices, nitrogen applications, and liming for the past 20 years. Other inputs to the model are soil texture class, land cover data from crop rotations, and daily high and low air temperature and precipitation (Del Grosso et al., 2009). It uses a detailed process model to estimate soil physical, chemical and biological processes using a daily time step to estimate results for soil carbon, carbon dioxide, nitrous oxide, and methane emissions from the baseline and any future scenarios.
the user would like to test. SOM formation and decomposition are represented in the model as functions of the availability and quality of substrate, meaning the chemical makeup of residues such as lignin percentage and carbon to nitrogen ratio, as well as water and temperature stress (Del Grosso et al., 2009).

COMET allows for exploration of conservation management options to generate recommendations. For example, to explore how much to decrease N inputs based on biological nitrogen fixation from cover crops, or the implications of reduced tillage. By using COMET Farm, I was able to deliver information back to the farmers related to soil carbon without doing field sampling or soil tests. The aim of using a crop simulation model is to assess potential improvements in soil health and resilience by quantifying the change in carbon and nitrous oxide emissions from soil if typical grain farms adopted conservation tillage and cover crops. I utilized the COMET Farm tool’s soil carbon and nitrous oxide emission estimation features. The model doesn’t directly reflect measures of soil health per se, but the results of soil carbon and nitrous oxide emissions are related to soil health. For instance, negative carbon emissions from soil implies soil carbon sequestration, through an increase of soil organic matter, which can be a proxy for soil health.

Model results were summarized into easy-to-read reports aimed at the farmer participant to assist in explaining results and facilitate discussion (Appendix B). I downloaded the results of the modeling from the COMET Farm website, and imported that spreadsheet into Google sheets where I separated the scenarios and calculated per acre averages for each year in question. I also calculated the averages across full simulation periods. I created graphs using the chart feature in Google sheets. The first results sheets were created by downloading crop management data from
COMET and generating graphs and tables from output numbers in regards to soil carbon and nitrous oxide emissions reflecting current management. Interpretations were added to the graphs and tables and given to farmers through the first results sheet. During the second interview results were presented and I added additional verbal explanations of the data. The sheet sparked a dialogue by explaining what the graphs mean, and the farmers’ responses allowed them to make connections between management and results. By facilitating conversations about soil, in one on one conversations, and by modeling soil carbon I was able to converse with farmers about the specificity of their land management. We discussed why their current management works for their production, and what their priorities are in terms of the business side of farming and health of soil.

4.3 Hypothesis:

The hypothesis assessed with this study is that organic farms are managing for higher soil carbon sequestration compared to conventional farmers. Results from the model are analysed based on the relevant science literature, while interview responses are analysed based on the relevant social science literature.
Chapter 5: Results

5.1 Description of Farms

Figure 5.1: Map of Columbia County, NY with farms in question highlighted

Langdonhurst Farm

John Langdon has been managing the 1600 acres on his farm in Copake, NY since 1992 (Figure 5.1). The farm is located in the south eastern part of the county, very close to the Massachusetts border. It is surrounded by many other farms, and covers prime soils for farming. The farm’s
land is about 40 percent owned and 60 percent rented. He grows corn, soybeans, and has recently begun growing industrial hemp. He uses a corn-soybean rotation on the vast majority of his farm, one year in corn and one year in soybeans, alternating. This has been the crop rotation the entire time he has been managing the land, and he future plan is to continue using it.

Description of the field modeled on Langdonhurst Farm

The field I modeled for the project is right next to an impressive grain storage area, and was filled with corn stubble from last year’s crop when we walked over it. The field is 40.6 acres.
The soil type is Blasdell channery loam soil. There are about 12,000 acres of Blasdell channery loam (BIA) in Columbia county, representing about 3 percent of soils in the county and 18 percent of soils considered prime farmland.

**Hawthorne Valley Farm**

Spencer Fenniman has recently taken over the role of head farmer at Hawthorne Valley Farm, a biodynamic farm, which spans 900 acres in Harlemville, NY (Figure 5.1). Hawthorne Valley is demeter certified as biodynamic and USDA certified organic. A little less than 60 percent of the land is rented and around 40 percent is owned. Fenniman has managed field crops - hay and grain - and compost at Hawthorne Valley since 2012. In addition to a dairy herd and vegetables, the farm grows wheat, rye, triticale, spelt, barley, cover crops, and grass. The field crops are geared towards small grain production and hay and forage for the cows. This small grains rotation is used on about 100 acres of the farm, and some of the rotation varies depending on the field. In other words, there is no common rotation used on the majority of the area in field crops. Fenniman’s goal is to establish a 6-7 year rotation alternating between grains and cover crops. His ideal rotation is: spring barley, alfalfa, alfalfa, triticale, red clover, rye or spelt (in the final year of the rotation either rye or spelt can be planted; they are interchangeable). The farm has recently expanded their small grain production, and there has been a shift from leaving fields in pure sod, to cultivating them to produce small grains. The motivations for grain farming are that the small grains can be used for flours and baking, for animal feed, or can be sold to breweries, while the straw is used for bedding for cows.
Description of the field modeled on Hawthorne Valley Farm

The field I modeled for this farm is called Hayley’s field. It is 9.9746 acres and is on rented land. It had been in sod for hay harvest up until 2013 which is the year the grain rotation began. When we visited this field, there was alfalfa and grasses growing from last season. The soil type is predominantly Blasdell channery loam (BlA) and (BlB) as well (Figure 5.3). There is a hill on part of the field, but the remainder of the field is extremely flat and even. It is the center field on this map.

Figure 5.3 Soil map and field location at Hawthorne Valley
5.2 Current Management

Langdonhurst

Langdon does not use cover crops but has been using no-till since 1994. He has tried using cover crops experimentally but did not find much success due to problems with insect pests, diseases, and too much moisture retention. It was his decision to change the farm to no-till. He articulated the benefits he sees in no-till as providing savings in energy and labor, building organic matter and soil carbon, and reducing erosion. He perceives the connection between soil health and no-till based on better microbial health and increases in organic matter. To practice no-till, he uses a conventional herbicide regimen to deal with weeds and terminating cover crops. He described the herbicide application rates as the same usage a conventional tillage system would use. Langdon uses the average inorganic nitrogen fertilizers for his corn crop and uses potash, a potassium amendment, for soybeans. He tests for soil organic matter and is currently in the process of expanding his soil tests to get specific soil carbon numbers for multiple depths and across soil types.

Hawthorne Valley

The farming system Fenniman uses incorporates cover crops and uses tillage. Tillage is generally used to prepare fields for the grain component while years in sod for pasture and hay production allowed for years with no tillage. There is a range of tillage implements used on this farm. They use the moldboard plow, a field cultivator, a disk harrow, and mowing to incorporate crop residues and prepare beds for planting. Tillage events occur right before planting minimizing the
time soil is bare to at most one week. His motivations for this practice are that he can transition between a living stand of cover and seeding or planting as soon as the next day. Another motivation for tillage is that it facilitates rapid germination, and tilling before planting requires less passes across the field, as he does not use tillage during the growing season for weed control.

In regards to cover crops, he uses perennials such as alfalfa, annual legumes such as clover, and complex cover crop mixes. We didn’t discuss cover crops too in depth during the first interview, but did in our second meeting. We talked a lot about the variation in rotations and choices made across the land used for grain production. Fenniman seems to be learning a lot about his goal to establish a small grains rotation incorporating cover crops whilst providing high quality forage for cows, and what is working in regards to this newer management strategy. The motivations for these shifts were essentially to reduce off farm inputs. Field crops at Hawthorne Valley receive fertility from cover crops and composted manure coming from the dairy herd. Fenniman has not recently done soil tests for organic matter.

5.3 Model results for current management

Langdonhurst

In terms of carbon, the soils at Langdonhurst are net sequestering carbon according to the model results (Table 5.1). However, the results show a decrease in sequestration over time (Fig 5.4), indicating he may be reaching a leveling off point in soil organic matter, implying soil carbon saturation. Forgoing tillage allows for soil carbon to decompose at a slower rate, and be retained in soils rather than released from tillage events. The nitrous oxide emissions from the field
follow a pattern and fluctuate based on the crop, or point in the rotation when N was applied. N\textsubscript{2}O emissions are higher in the corn years and lower in the soybean years reflecting the lower ammonium nitrate applications rates to soybean. N\textsubscript{2}O emissions fluctuate between 0.47 tons CO\textsubscript{2} equiv per acre in corn years and 0.28 tons CO\textsubscript{2} equiv per acre in soybean years. The interesting thing about this farm is that Langdon knows his soils have high organic matter, and has the tests to prove it.

Figure 5.4: Annual soil carbon emissions (tons CO\textsubscript{2} eq acre\textsuperscript{-1} yr\textsuperscript{-1}) for current management extended to 2029 for Langdonhurst Farm. Negative numbers imply net carbon sequestration. The red line is the trend indicating slowing of carbon storage.

The results show net positive carbon sequestration (negative emissions), and even when nitrous oxide emissions are included, total greenhouse gas emissions remain negative, meaning this field is preventing more emissions than it is creating, but by a small fraction (Results sheet 1, Appendix B). However, this net sequestration may not persist since the rate at which C sequestration occurs is decreasing, indicating the soil organic matter additions are leveling off
with time. It seems the soils in this field are approaching saturation, meaning the soil organic matter pool is reaching capacity, functioning of soil is improved with this kind of carbon saturation, indicating an end to net sequestration, and the rise of a steady state of carbon flux in and out of the soil.

*Table 5.1: Simulated soil emissions for current management on participating farms (2000 - 2019)*

<table>
<thead>
<tr>
<th>Farm name</th>
<th>Langdonhurst</th>
<th>Hawthorne Valley</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(tons CO₂ equivalent per acre per year)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-0.51</td>
<td>-0.21</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.38</td>
<td>0.26</td>
</tr>
<tr>
<td>Total</td>
<td>-0.13</td>
<td>0.02</td>
</tr>
</tbody>
</table>

**Hawthorne Valley**

In terms of carbon, the results show net positive soil carbon emissions, although they are very low (Table 1). Soil carbon sequestration decreases after tillage events and increases when management is under sod or in cover crops. The emissions are close to zero, indicating that sequestration is not necessarily occurring, but neither are high emissions. Even though C emissions are net positive, they are very close to zero (Figure 5.5). There is some variation year to year, but generally emissions are decreasing with time, and near zero.
Figure 5.5: Annual soil carbon emissions (tons CO$_2$ eq acre$^{-1}$ yr$^{-1}$) for current management extended to 2029 for Hawthorne Valley. Negative sloping trendline indicates reduction in emissions with time.

This result may indicate that this field’s soil is already saturated with high levels of organic matter so adding more carbon is a challenge. The current management graph shows soil carbon emissions if management for the current period (2014-2020) was repeated for the next 10 years, meaning, the exact rotation and management used up until now, but repeated. This current management is slightly different from Fenniman’s ideal rotation he is currently working to establish.

For nitrous oxide, the annual emissions stayed primarily at about 0.2 tons CO$_2$ equiv per acre per year (Results sheet 2, Appendix B). When composted manure is applied to the field, N$_2$O emissions increase for that year only. Cover crops such as clover have a smaller effect, resulting in less N$_2$O emissions than expected. The resulting spikes show higher nitrous oxide emissions when manure is applied and intensive tillage is used the same year. However, N$_2$O
emissions then return to 0.2 the year following application, indicating emissions of $\text{N}_2\text{O}$ from soil are generally low, but respond to N applications which is expected. Soil carbon emissions for the full simulation period are net negative, and nearly zero, showing the maintaining stock of soil carbon (Table 5.1).


**Comparison of emissions from current management at the two farms**

Comparing the two systems, Langdonhurst’s corn/soy no-till rotation has higher carbon sequestration per acre than Hawthorne Valley’s grain crop and cover crop rotation. This is interesting because it complicates and challenges expectations around regenerative agriculture as environmentally superior to conventional agriculture. In regards to modeled soil carbon only, not soil health, or the numerous other factors that contribute to a farm's environmental impact, Langdonhurst has a lower environmental impact. This difference is explained by the theory that Hawthorne Valley’s soils are operating at high levels of soil health because of their management, and are not net sequestering carbon currently because of that. Whereas Langdonhurst soils are recovering from years of tillage, as Langdon switched to no-till just less than 30 years ago.

Nitrous oxide emissions and nitrogen leaching into waterways is an environmental impact I am not modeling, but we can assume that in a system using inorganic N, some nitrogen is leached into aquatic systems via precipitation.

### 5.4 Future management scenarios

*Langdonhurst*
Langdon is proud of what he has accomplished and is not interested in adding too much to the management that is already working for his farm. However he is interested in replacing his current fertility management with chicken manure by partnering with an egg producer in Connecticut. He said that changing from inorganic fertilizer to chicken manure will be a very easy change to make. His motivations for changes in management are to gain better yields, ultimately leading to increases in profitability, and possibly to improve soil carbon sequestration which he is investigating getting payments for. He does soils tests every 3 years. This year is the first year he’s doing soil organic matter (soil C) tests, which he is conducting at two depths: a shallow (6 inch) and a deeper soil sample (2 feet). He is interested in quantifying his soil carbon numbers for the purpose of benefiting from carbon credit programs, as large emitter corporations have offered to purchase carbon offset credits from his farm. Changing his nitrogen source to manure is likely to further increase C sequestration in his soils.

Even though it seems like he is unwilling to adopt widespread use of cover crops on his farm in the near future, I used it as one of many future scenarios modeled to estimate how much more carbon could be potentially sequestered following such a shift. I asked if any of his neighbors have had successes with cover cropping on similar systems. Langdon described his location as not a big cover crop area (Copake, NY) as corn is harvested in November and climate makes it hard to get cover crops in in time for them to be established. I mentioned under-seeding cover crops as a solution to this issue, and he responded that aerial applications of seed are really expensive, and he does not see the benefits making that expense worth it.

We decided on the future runs as: 1. Cereal rye cover crop planted after corn harvest (even though the feasibility is low). 2. Chicken manure replacing inorganic N on a unit N basis.
Within that second scenario, I experimented with different types of chicken manure, being unsure what type of manure he would be using. In our final meeting he told me layer chicken manure from a farm in Connecticut will be used in the future on some of the fields.

Table 5.2: Simulated GHG emissions results for future scenarios at Langdonhurst

<table>
<thead>
<tr>
<th>Average emissions (tons CO₂ equiv. per acre per year) from projected future period (2020-2029)</th>
<th>Current Management</th>
<th>Chicken manure (layer)</th>
<th>Composted Chicken Manure</th>
<th>Chicken Manure (broiler litter)</th>
<th>Cover crop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil carbon</td>
<td>-0.41</td>
<td>-0.42</td>
<td>-0.47</td>
<td>-0.50</td>
<td>-0.45</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>0.35</td>
<td>0.31</td>
<td>0.39</td>
<td>0.35</td>
<td>0.36</td>
</tr>
<tr>
<td>Total GHG</td>
<td>-0.06</td>
<td>-0.11</td>
<td>-0.08</td>
<td>-0.15</td>
<td>-0.09</td>
</tr>
</tbody>
</table>

The results show essentially no difference in carbon sequestration (negative emissions) from any of the potential future scenarios compared to the current management, although the scenario using broiler litter sequestered slightly more carbon. Nitrous oxide emissions are also essentially unchanged, resulting in total emissions remaining negative for all scenarios. Layer chicken manure led to a minor increase in soil carbon but reduced nitrous oxide emissions more significantly, resulting in lower total GHG emissions. Composted chicken manure had the next highest increase in soil carbon, but had the highest N₂O emissions of the scenarios, higher than the current management, but still has a lower total GHG emissions than current management. Broiler litter as a source of N had the highest increase in soil carbon, and the lowest total GHG emissions though the difference from current management is very small. Broiler litter manure has carbon rich materials mixed into it, increasing the C:N ratio, which is probably responsible
for the highest soil C increase after application out of all scenarios. The cover crop scenario increased soil carbon, but $N_2O$ emissions remained the same.

_Hawthorne Valley_

When following up with Fenniman in our second meeting, we discussed the future plans for this field. He was talking to me about how the future goals are implied by the past rotations that have been used. He is experimenting with using a non forage based cover crop, likely a mix of different crops designed to diversify and maximize the benefits from cover cropping. His reasoning is that otherwise, what’s grown is all cereals, legumes, and forage crops. This cover crop mix includes broadleaf annuals, as well as a maximization of the number of species in cover crop mix, with those that have high carbon to nitrogen ratios. He told me that the farm has experimented with trailing sunflowers as a cover crop for the vegetable plot, and they are open to further experimentation with cover crops.

In terms of the rationale for cover crop use, he took me through a short cover crop history of Hawthorne Valley. The seed mix used is constantly changing, and he has been experimenting in recent years with a lot of turnips, however the greens don’t hold up very well. Costs of seed, above and below ground biomass all influence what the mix is. Small seed crops are more easily incorporated especially if planted with minimal tillage. Using rapeseed in the brassica components makes it so the above ground photosynthesis and grazing potential is higher than a smaller plant. Cover crop trials on vegetable ground is different entirely from those used on grain/ cereal crops. According to Fenniman, cover crop choice is based on soils, timeframes, mowing, and other management decisions. Challenges of cover crops are that if there are a lot of
weeds, tilling before establishing cover crops is necessary, also soil moisture presents issues. Cover crop mix costs about $50 an acre if costs are spread out over the whole rotation, including the costs of establishing it. Fenniman believes the benefits outweigh any costs. To quote Spencer directly, “If cover crops are grazed, it’s cost neutral”. Everyday cows are on land they are not eating forage, which ends up saving money.

Fenniman is interested in incorporating livestock into the grain rotation in the future by grazing biomass, in other words adding cow traffic to the field. Otherwise, he doesn’t see the rotation itself changing much if at all. For this farm I needed to get creative to figure out how to make beneficial future scenarios considering the goal rotation is already so complex. Given Fenniman’s interest in incorporating grazing, and also the high negative impact of tillage on carbon sequestration on this farm, I designed a series of future scenarios to increase grazing and decrease tillage.

Firstly, I designed a scenario replacing one of the three haying events that occur on a forage crop with a one day grazing event. Fenniman told me theoretically he would use a stocking rate of about 60,000 lbs cows to the acre. Next, because COMET does not have complex cover crop mixes to model, I created a future scenario which extends the time under a cover crop, rather than using a complex cover crop. I did this by expanding the years in clover cover to two full years. I then created a scenario in which grazing would function as a way to reduce tillage, using cows to clear crop residues to prepare for the next planting. These grazing events would be paired with use of a no-till drill for planting, or minimal tillage when transitioning from a sod to small grains. The final scenario I modeled combined the scenarios of an extra year in cover, and grazing to reduce tillage.
Table 5.3: Simulated results for future management at Hawthorne Valley

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Soil carbon</th>
<th>Nitrous oxide</th>
<th>Total GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 0: goal rotation (baseline)</td>
<td>0.08</td>
<td>0.35</td>
<td>0.43</td>
</tr>
<tr>
<td>Scenario 1: grazing final hay harvest</td>
<td>0.14</td>
<td>0.35</td>
<td>0.49</td>
</tr>
<tr>
<td>Scenario 2: Extra year in clover cover crop</td>
<td>0.14</td>
<td>0.35</td>
<td>0.49</td>
</tr>
<tr>
<td>Scenario 3: Grazing to reduce tillage</td>
<td>-0.16</td>
<td>0.35</td>
<td>0.19</td>
</tr>
<tr>
<td>Scenario 4: Scenario 2 and 3 combined</td>
<td>-0.09</td>
<td>0.35</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The results show no change in nitrous oxide emissions as manure application rates did not change (aside from grazing) The planned future rotation has a near net zero result for carbon emissions, showing that carbon lost in tillage events is recovered through residue and cover crop management. Incorporating livestock into this grain and forage system changes the carbon balance of soil. Scenario 1 shows higher soil carbon emissions than the baseline. The grazing in place of hay scenario showing an increase C emissions slightly may have to do with the transition from clover to a grass legume mix, or the fact that when biomass is removed from grazing rather than hay, the plants may respond differently, or the biomass removed from grazing rather than hay may be modeled differently. Adding years in clover would theoretically reduce carbon emissions by having another year without a tillage event, however because of the low carbon to nitrogen ratio of clover, the mineralization of organic matter is higher, leading to more soil respiration. The model showed a spike in emissions during the second clover year then a decrease flattening out below the baseline line. The reduced tillage through grazing and combined grazing and years in clover scenario have lower carbon emissions than the baseline.
Using livestock to reduce tillage along with an extra year in clover (scenario 4) had the greatest effect on reducing carbon emissions in this test. These results showed the most C sequestration potential, and the added length in cover crop years in scenario 4 resulted in even higher C sequestration. This scenario is a potential strategy for incorporating livestock into the grain rotation, as a way to reduce tillage.

### 5.5 Farmer Perspectives

It’s a sensitive subject, asking farmers about their willingness to change what is working for them now. Both farmers are not keen to adopt a management practice they do not currently use, cover crops for Langdon and no-till for Fenniman.

I felt some resistance arise when I brought up the cover crop discussion with Langdon. We talked about his cover crop trial experience in our initial meeting, but I wanted him to elaborate more, so I asked again. He told me that he’s tried using a rye cover crop on some smaller fields. He has previously taken advantage of grants designed to cover the costs of cover crop seeds but has found that when combining no till and cover crops the large amount of surface material mats together and harbors moisture. Also there are more insects that cause problems in a cover crop environment. When I asked about neighbors or other farms in the area using cover crops, he told me that because of climate, they aren’t very popular. On the drive back I saw many fields sprouting something green underneath the corn residue, and I assumed those might have been cover crops.

The use of broiler litter chicken manure had the greatest effect on soil carbon. Using this organic source of manure that is mixed with carbonaceous material is likely to also decrease
nutrient runoff and preserve water quality as well as increase carbon inputs to soil. Because cover crops would further increase soil carbon sequestration on the farm, Langdon could potentially be interested in it as an option, especially if he is interested in taking advantage of legislation or private projects created to reward farmers for C uptake in their soils. But the fact that he has tried cover crops and found the challenges to be too great is a sign that he will not likely adopt cover crops. When the main crop is harvested in late fall, only crops that can grow enough in winter to be effective can be used (rye is a perfect example) (Snapp et al., 2005). However, seeding a cover crop into corn before it is harvested is the most effective way to establish a winter cover crop in colder northern climates (Snapp et al., 2005). Langdon’s problems with cover crop management act as a disincentive for him to broaden the practice to the whole farm (Snapp et al., 2005). When discussing the challenges of cover cropping Langdon and Fenniman articulated similar challenges, with the most basic difference in their management being tillage.

In Hawthorne Valley’s system, tillage may create better moisture conditions especially if one of the reasons tillage is used is to prep fields for cover crop growth. Hawthorne Valley also uses the strategy of cultivating a cover crop in place of a grain or summer cash crop. It is an interesting strategy to then use the cover crop that is producing neither food or forage as a source of feed for dairy cattle. When talking to Fenniman about his rationale for cover crop use, I realized how engaged he is with understanding the intersections between science, practical needs of the farm, and markets. He told me that reading and seeing what other folks are doing influences the choices he makes. He said he’s doing this management because it’s right and he feels there's no way to formally measure the benefits. When I asked about his willingness to
respond to a cover crop grant, he said that they do not currently receive any grants for cover
crops. If one were to be relevant to what they are doing then yes, but it would need to be
applicable and the paperwork or logistics would need to be worthwhile. When I asked him what
he thought about government programs designed to increase adoption, he gave me some great
insights. He said that incentives tend to be punitive towards best practices. Fenniman feels that
oftentimes incentives are geared toward adoption and changing practices and are less geared
towards actually rewarding people for doing best practices, especially those who have been using
them for a long time.

In terms of tillage, Fenniman sees the tillage element of the operation as almost a
necessary evil to keeping up with all the other management practices. I think he believes using
tillage strategically while maximizing C inputs doesn’t do too much damage to the state of the
soil, especially as crop residues are mixed into the soil and fields are not left bare. I would
categorize Hawthorne Valley’s tillage regime as reduced, however they use intensive tillage
when necessary, but not regularly. I am unsure of what lengths Fenniman will go to in the future
to further reduce tillage in the grain rotation as there are many other management decisions on
his plate. In our final interview, we had the chance to debrief about the future scenarios I
modeled using cattle grazing to reduce tillage. He was interested in the result that grazing added
carbon emissions compared to cutting for hay, and asked if the model takes into account diesel
emissions from hay cutting. Without the soil tests to back it up, it can’t be said for sure that the
soils at Hawthorne Valley are at or near carbon saturation, however they are likely to be. In this
case, tillage is not necessarily harmful to soil carbon, if the inputs are building it back up in years
following tillage events.
5.6 Discussion

The two farmers in question have very different production systems, and with that comes alternate viewpoints. The results indicate that both parties are willing to try new things and experiment on their farms but also feel they know their system pretty well and do not want to take risks that could reduce the successful results of their current management. Both farmers would be categorized as risk neutral, as they are open to taking risks, but great leaps in management are not favorable to them (Adusumilli et al., 2020). In terms of situating the theories within practice, Langdon’s use of no-till is logical as it is management intensive and an easier transition for large scale producers (Saltiel et al., 1994). The size and ethos of Hawthorne Valley, as a certified Biodynamic farm, uses low input farming techniques, among these are the use of cover crops and manure composting (Saltiel et al., 1994).

Using the framework of farmer participatory research allowed for an exploration of the science of cover crops, no-till, soil health and SOM dynamics outside of the farm context. Meaning, the interests of farmers in regards to future management dictated what future scenarios were explored and modeled in COMET. Hearing the farmer’s perspectives regarding what they perceive the benefits of cover crops or no-till to be, and what the challenges are that prevent them from adopting another soil carbon building practice, forces the researcher to challenge their own beliefs about the practices and their benefits (Schindler et al., 2016). Generally this form of research is successful because it results in more adoption of conservation practices because of a greater awareness land managers may gain from participating (Dalton et al., 2011).

The model results are for the most part expected based on the literature regarding soil organic matter dynamics. Fenniman’s use of cover crops and residue management increase C
inputs and therefore soil carbon (Ding et al., 2006). If he decides to graze cover crops, that is another mechanism for increasing soil carbon and reducing costs associated with cover cropping (Blanco-Canqui et al., 2015). In regards to Langdon’s use of no-till, it’s expected that his soils are sequestering carbon based on this management (Kahlon et al., 2013). However, the soils do seem to be approaching soil carbon saturation with time, indicating that the C sequestration cannot occur forever, and the soils are recovering from degradation due to previous management (Stewart et al., 2007).

Conversations with successful local farmers about their experiences, and collaborating to estimate their emissions from current practices led to an understanding of the current state of soil carbon for these farms. The participants have access to the model results and the data regarding differences in soil C between a list of possible future scenarios, which should be a useful tool if they chose to change their management. I learned that they probably won’t change too much about what they are doing beyond the goals they already have in place for themselves. As the researcher, I respect and understand that choice, and it does make sense to me. If they don’t want to use cover crops or no-till when it doesn’t seem feasible to them, that’s valid.
Chapter 6: Conclusion

6.1 The importance of farmer participation in soil health research

The practical application and economic feasibility of adopting farm management practices are the most important factors for farmers. Farmers have arrived at their current state of management for many reasons, and although there is usually room for improvement, dramatic changes are often not worth the risk to farmers. The feasibility of adopting a new practice in a particular farm context is the most important metric to gauge adoption. Shifting management away from something tried and true is a risk to the profitability of a farm (Upadhyay et al., 2003). Giving farmers room to experiment and try out management without worrying about losing money from yield loss or other challenges provides a helpful safety net for farmers. However, policy aimed at trying to get farmers to adopt specific practices should be paired with participatory approaches and hands on assistance (Smetschka & Gaube, 2020). For conservation practices to be more widely implemented they must help farmers economically, as environmental concerns come after the livelihoods of farmers themselves (Cary & Wilkinson, 1997).

6.2 Implications for Policy Formulation on Soil Health and Carbon Sequestration

States are working to establish legislation promoting the use of carbon farming strategies designed to engage farmers in reducing CO₂ emissions from agriculture and sequestering carbon in agricultural soils. In New York State, Assemblymember Didi Baret introduced legislation in 2018 to create a pilot project designed to test soils and articulate best management practices for
soil carbon building (Wordon, 2018). The results from this long-term project are intended to eventually inform a tax credit for carbon farming (Wordon, 2018). However, the set of best management practices for soil C sequestration legislators chose may not work across the range of farm contexts in Columbia County, and in New York State more broadly. There is no clear way to measure carbon sequestration on a short timescale. Legislation focused on soil health which gains insights from farmer participatory research, and influences the economic barriers of adoption could be successful, based on what was gleaned from this project. No single group of practices fits economically and socially into the agenda and farm context of the range of different farm scales and types across a given state, county, even town. Additionally, harkening back to Fenniman’s perspective on adoption, farms that have been practicing soil health practices for a long time should also be able to benefit from legislation, instead of rewarding those who stop practicing management that degrades soil. Rather than naming a group of best management practices “carbon farming”, supporting farmers’ intuitive perceptions of their soils through an understanding of soil health and resilience, by fostering a participatory exploration may lead to higher adoption of management that leads to environmental goods.

6.3 Final Thoughts

It is important to challenge the assumptions we make about the duality of roles agriculture plays in both GHG emissions and climate change mitigation. Agriculture is a source of GHG emissions yet can be a sink for carbon, and generalizations based on farm scale or appearance may be unhelpful. Conventional agriculture is thought of as environmentally harmful by environmentalists which is not always the case in terms of carbon emissions. Conventional
systems can accomplish a great amount of climate change mitigation by restoring organic matter in degraded soils using large scale conservation practices such as cover cropping and no-till.

Using the framework of soil health rather than soil carbon allows all farmers regardless of environmental awareness to connect to management that will improve the quality and function of their soils. This framing engages farmers without the label of sustainability or reducing emissions attached to it, yet improves the cycling of carbon in soils. The results of the simulations performed here illustrated a situation in which C sequestration was higher in a conventional no-till system compared to a regenerative/biodynamic system using cover crops and tillage. Both systems are functioning at high organic matter levels, due to their continued use of management that protects or builds soil carbon resulting in healthy soil. When regenerative systems use tillage they lose some soil carbon, but build it up using cover crops and residue management. Additional C sequestration can’t occur if soils are already C saturated, meaning that the no-till conventional system will eventually level off sequestration, and it is likely that the soils before adopting no-till were degraded from years of tillage, so no-till functions to restore soil organic matter and sequester C but the increases will eventually reach stagnation. Clearly, both farms outlined have complexities to their historical and current management goals that are not easily generalizable based on their identifying factors.

Not every practice works in every farm context. Farmers who care to improve the health of their soil will use a combination of personal experience and experimentation as well as insights from their community to narrow down which SOM building and soil health practices fit into their scale and value system as a manager, or just what is economically and practically possible. Changing management is not easy, and occurs because of the manager’s need for a
difference, rather than because something is going to lower greenhouse gas emissions. That is not the explicit agenda for farmers. The ethos of a biodynamic/ regenerative farm is part of a value system that considers the farm an ecosystem and fundamentally integrates livestock and crop production. The consciousness of land and environment is not measured by carbon emissions, rather soil health and other measures for success. In general, I gained valuable information from my in person interviews with farmers, and have a much more complex understanding of the feasibility of changing management when there are no financial motivations to do so.
References


Gougoulias, C., Clark, J. M., & Shaw, L. J. (2014). The role of soil microbes in the global carbon cycle: Tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems: Role of soil microbes in global


Biological soil health indicators respond to tillage intensity: A US meta-analysis.


https://doi.org/10.2134/agronj2018.12.0769


https://doi.org/10.1007/s10533-007-9140-0


https://doi.org/10.1016/S0167-8809(01)00233-X


Appendix A: Interview questions for farmer participants

Meeting 1:
The goal of this meeting is to capture past and current management:

I will begin this meeting by giving the participants more information on the COMET tool. I will focus on how it can predict changes in SOM based on changes in management.

Higher level questions:
- How many acres are you farming now?
- How many are owned versus rented?
- How long have you been managing this farm?
- What do you grow?
- What is the main crop rotation you use? In other words, the rotation used on the majority of the land you farm?
- What shifts in management in regards to tillage have you made?
- How have your crop rotations changed?
- Do you test for soil organic matter?
- Do you use cover crops?
- Why did you make these shifts?

Questions pertaining to information I will put into the COMET tool

- Which of these three best describes the pre 1980 management?
  - Livestock grazing
  - Lowland non irrigated
  - Upland non irrigated
- Was this parcel enrolled in Conservation Reserve Program (CRP) before 2000?
- 1980-2000
  - Irrigated: continuous hay
  - Irrigated: orchard or vineyard
  - Non-irrigated: annual crops in rotation
  - NI: annual crops with hay/pasture in rotation
  - NI: continuous hay
  - NI: livestock grazing
  - NI: orchard or vineyard
- Tillage used from 1980-2000?
  - Intensive, reduced, or no till
- 2000-2019 current

Current Management: 2000-2019
(These questions will be repeated for each crop in rotation)
crop planting date:
crop harvest date:
yield:
tillage:
tillage date:
fertilizer application date:
fertilizer type:
total N per acre applied:
fertilizer application method:
manure or compost application?
Date applied:
Manure type:
Amount per application:
Percent N:
Carbon to nitrogen ratio:
EEP? (slow release or nitrification inhibitor):
Irrigation:
Liming:
Burning:

Tillage:
Do you use tillage?

If yes to tillage:
  ● What implements do you use?
  ● When do you till?
  ● What are the motivations for this type or uses of tillage?

No till farmers:
  ● What are your perceived benefits of using a no-till system?
  ● Is there an overlap between no till and cover crops on your farm?
  ● What are your perceptions about soil health and no till?
  ● Do you use irrigation?
  ● What do you do for weed control?
Meeting 2:
The goal of this meeting is to go over the models results and nail down what the farmers attitudes are on experimenting with cover crops as future management.

- I will go over the results from current management
- Showing how current practices influence SOM
- I will explain that my project is about cover crops/ reduced tillage and ask if we could include that as part of a future scenario

Second goal: Collaborate on new future management scenario that incorporates practices farmers do not currently have in place

Future plans:
- What are your future plans for this field?
- Our goal is to model it, how could we do that here what could we do that would work for you?
- The things we can change that will affect the model are: tillage, cover crops,
- How do you think that is going to affect changes?
- What is the feasibility of adding a cover crop to this system?
- What is the feasibility of trying no till on this field?
- What criteria are you basing changing decisions on?
- Would you respond to a grant or incentive to use cover crops?
- Have you thought about trying to use cover crops experimentally?
- Why are you or why aren’t you interested in trying cover crops?
- If yes, how specifically would you want to try to use them?
- If no: is it costs, time, effectiveness, or another reason you made this decision?

Cover crop questions:

Have you ever used cover crops?
- Do you currently use cover crops?

If yes:
- When do you use cover crops and on which parts of the farm if not all?
- What specific cover crops do you use?
- Why?
- How long?
- What caused the shift?
- What has been the general impact of using cover crops?
- Challenges to using cover crops? Please specify
- What changes have you noticed since this shift
- Specific management strategies of cover crops
- Benefits you are getting
- Can you rank those benefits?
- Costs of cover crops (monetary, labor, time)?
- How often do you do soils tests?

If no:
- What challenges do you perceive come with managing cover crops?
- If the challenges weren’t there what would you do?
- Would you try it in the future?
- What are the benefits of it?
- What have you heard?
- If costs were covered (monetary) would that influence your decision.
- Do you test for organic matter?
- If yes: What are your numbers?
- Do you want it to be higher?
- Do you experience problems with soil health and resilience?
- Have you experienced a lack of drainage on your farm?
- Do you think these would be solved with higher organic matter/better soil health?
- Can you describe the differences in soil quality during different years of a rotation?
- How often do you do soils tests?

Motivations and sources of information:
- What arguments have you heard for the use of cover crops?
- What is convincing about these arguments?
- Where did you hear this from?
- What do you think of policies surrounding these questions?

Meeting 3:
The goal of this meeting is to debrief from results of future management experiments, and understand the participant’s perceptions about soil health:

In this meeting I plan to go over the results of the future scenarios created and modeled in COMET and answer any questions the participants may have about the process or the results.
Appendix B: Results sheets discussed with farmer participants

Results Sheet 1: Current management for Langdonhurst
2/25/2020

John Langdon
Langdonhurst Farms

To calculate these values I used the management data I collected during our first conversation to set up the simulation model, COMET Farm (http://comet-farm.com/). I ran the model to show the soil carbon estimations from the current management. I also set it to project future years based on if your current management continued for 10 years. The model is using soils data for your farm from the US Geological Service and historical weather data for this location to estimate soil carbon and nitrous oxide emissions. Using the results for the field's emissions per year, I calculated per acre emissions. Results are expressed in tons of carbon dioxide equivalent per acre per year, which is a way of expressing emissions as if they had the warming potential of carbon dioxide.

Figure A1: soil carbon sequestration over time in tons CO₂ equiv. Per acre

The results show a net positive accumulation of carbon in the soil, but soil carbon sequestration is decreasing with time. This may be because soil carbon can reach a saturation point. Data up to 2019 are based on historic weather data, while years 2020-2029 use projected weather data.
Fig A2: Nitrous Oxide emissions in tons CO2 equivalent per acre over time

The emissions follow a pattern in the crop rotation. The results show that in corn years 0.47 tons CO2 equiv per acre are emitted in the form of nitrous oxide, while soybean years had lower N2O emissions with 0.28 tons CO2 equiv. per acre per year. This result reflects the difference in nitrogen fertilization between the two crops.

Table A1: average annual emissions for current management for CO$_2$, N$_2$O and combined.

<table>
<thead>
<tr>
<th>Average Annual Emissions</th>
<th>Soil carbon (tons CO$_2$ equiv. per acre per year)</th>
<th>Nitrous Oxide (tons CO$_2$ equiv. per acre per year)</th>
<th>Combined GHG emissions (tons CO$_2$ equiv. per acre per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full simulation period (2000-2029)</td>
<td>-0.51</td>
<td>0.37</td>
<td>-0.14</td>
</tr>
<tr>
<td>Current period (2000-2019)</td>
<td>-0.51</td>
<td>0.38</td>
<td>-0.13</td>
</tr>
<tr>
<td>Projected future period (2020-2029)</td>
<td>-0.41</td>
<td>0.37</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

The results show net positive carbon sequestration (negative emissions), and even when nitrous oxide emissions are included, total emissions remain negative, meaning this field is preventing more emissions than it is creating, but by a small fraction. Soil carbon is accumulating, but the rate at which C sequestration occurs is going down. Next we will discuss future management options that might change these trends.

Results Sheet 2: Current management at Hawthorne Valley
Allen 86

3/8/2020

Spencer Fenniman
Hawthorne Valley Farm

To calculate these values I used the management data I collected during our first conversation to set up the simulation model, and COMET Farm (http://comet-farm.com/). I ran the model to show the soil carbon estimations from the current management. I also set it to project future years based on if your current management continued for 10 years. The model is using soils data for your farm from the US Geological Service and historical weather data for this location to estimate soil carbon and nitrous oxide emissions. Using the results for the field's emissions per year, I calculated per acre emissions. Results are expressed in tons carbon dioxide equivalent per acre per year, which is a way of expressing emissions as if they had the warming potential of carbon dioxide.

![Figure A3: soil carbon sequestration by year](image)

Negative soil carbon emissions imply carbon sequestration or a gain in soil carbon, positive emissions implies a loss of soil carbon. The results show a net positive increase in soil carbon emissions, although they are low. Soil carbon sequestration is decreasing with time after tillage events and increases when management is under sod or in cover crops. Data up to 2019 are based on historic weather data, while years 2020-2029 use projected weather data. For future management (years 2020-2029) I copied the rotation from 2013-2020 and repeated it one time.
Figure A4: Nitrous Oxide emissions in CO$_2$ equivalent per acre.

The emissions stayed primarily at about .2 tons CO$_2$ equiv per acre per year. When composted manure is used as source of nitrogen N$_2$O emissions increase. Cover crops have a less significant effect, resulting in less N$_2$O emissions. The resulting spikes show higher emissions when manure management and intensive tillage are used together. However, N$_2$O emissions then return to .2 the year following application.

Table A2: average annual GHG emissions per acre over three time periods

<table>
<thead>
<tr>
<th>Average Annual Emissions (tons CO$_2$ equiv. per acre per year)</th>
<th>Soil carbon emissions</th>
<th>Nitrous Oxide</th>
<th>Combined GHG emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full simulation period (2000-2029)</td>
<td>-0.09</td>
<td>0.29</td>
<td>0.1</td>
</tr>
<tr>
<td>Current period (2000-2019)</td>
<td>-0.21</td>
<td>0.26</td>
<td>0.02</td>
</tr>
<tr>
<td>Projected future period (2020-2029)</td>
<td>0.15</td>
<td>0.34</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The results above show the average emissions per acre over the course of the entire modeling period. The combined GHG emissions per acre per year are higher in the future period than in the past, showing that repeating the rotation used on this field again has slightly higher emissions than the past 20 years management. Soil carbon emissions for the full simulation period are net negative, nearly zero, showing a maintaining stock of soil carbon.
For this final report I took our conversation about what future experimental scenarios you were interested in modeling using COMET Farm tool. We discussed your interest in using chicken manure as a source of nitrogen, so I created three different scenarios all using different forms of chicken manure to show the differences that this choice would make on carbon and nitrous oxide emissions, and to compare those results to the continuation of your current management. I also included a cover crop scenario which I know you are less interested in, to include this management for comparison as well. Using the results for the field's emissions per year, I calculated per acre emissions. Results are expressed in tons carbon dioxide equivalent per acre per year, which is a way of expressing emissions as if they had the warming potential of carbon dioxide. Below I’ve included a table showing what I told the model about this hypothetical future management.

<table>
<thead>
<tr>
<th>Scenario Name:</th>
<th>Cover crop</th>
<th>Chicken Manure (layer, solid)</th>
<th>Composted Chicken Manure</th>
<th>Chicken Manure (broiler, litter)</th>
<th>No Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>What Changed?</td>
<td>Cereal Rye planted after corn harvest</td>
<td>Chicken manure from laying chickens. Used instead of UAN/Ammonium Nitrate fertilizer</td>
<td>Chicken Manure that has been dried and processed, approx. 4 percent Nitrogen</td>
<td>Chicken manure from broiler chickens and the bedding/other materials included. Used instead of UAN/Ammonium Nitrate fertilizer</td>
<td>No Change from intended future management. Except I began the rotation with soybean in 2020, as you have planned.</td>
</tr>
<tr>
<td>Values for Nitrogen application</td>
<td>Same values used in current management for N application on corn and soy</td>
<td>0.4 tons per acre applied in soybean years and 1 ton per acre applied in corn years</td>
<td>0.2 tons per acre applied in soybean years and 0.8 tons per acre applied in corn years</td>
<td>0.4 tons per acre applied in soybean years and 1 ton per acre applied in corn years</td>
<td>Same values used in current management for N application on corn and soy</td>
</tr>
</tbody>
</table>
Soil Carbon Emissions Results

![Graph showing carbon emissions from future scenarios expressed as tons CO$_2$ equiv. Per acre by year)](image)

**Figure A5: Carbon emissions from future scenarios expressed as tons CO$_2$ equiv. Per acre by year**

The carbon sequestration potential of multiple future scenarios are expressed above. All future scenarios modeled express increases in soil carbon greater than from the intended future management. The usage of chicken manure litter and composted chicken manure have more of an effect on pulling carbon into the soil in corn years than the other treatments. The carbonaceous material included in chicken manure including litter may explain the higher increase in soil carbon. The lower overall sequestration in 2026 is probably due to a weather event in the projected future period. COMET uses historic weather data for future scenarios rather than predicted future weather. Use of a rye cover crop increased soil carbon, this can be explained by the higher carbon inputs to the soil system in this scenario. Generally, higher soil carbon results from using organic nitrogen sources, due to the carbon contained in manures. All organic substances have carbon to nitrogen ratios, and the higher the carbon to nitrogen ratio of compost or manure, the more carbon is added to the soil system when it is applied. Whereas chemical N fertilizers do not contain as much carbon.
Nitrous Oxide Emissions Results

The nitrous oxide emissions (N2O) from the predicted future scenarios from the last results sheet fluctuated between .46 and .27 tons CO2 equiv. per acre for corn and soybeans respectively. Even when no changes were made to nitrogen application, nitrous oxide emissions decreased slightly from the past management. Layer chicken manure resulted in the lowest N2O emissions, followed by the intended future management, which is nearly equal to the use of broiler litter chicken manure. Copying current management into the future scenario but starting with soybean in the rotation as you said is the plan for this year resulted in lower N2O emissions than the baseline (current) estimates, therefore these results may be an underestimation. The rye cover crop scenario shows slightly larger N2O emissions in corn years compared to no change in management. The same is true for composted chicken manure, which has the highest nitrous oxide emissions, also only in corn years. The emissions from soil in regards to nitrous oxide from different sources of N are related to how the microbial community cycles N in the soil, and the nitrogen content of the fertilizer relative to how much is applied. Because composted or processed chicken fertilizer has a higher nitrogen content than unprocessed manure, its emissions are likely to be higher. The application amounts used in this modeling scenario are based on the values currently used for inorganic nitrogen fertilizer on this field, so the application values are a calculated estimate.
### Table A4: Average Total GHG Emissions From Various Future Scenarios

<table>
<thead>
<tr>
<th>Average emissions (tons CO2 equiv per acre) from projected future period (2020-2029)</th>
<th>Cover crop</th>
<th>Chicken manure (layer)</th>
<th>Composted Chicken Manure</th>
<th>Chicken Manure (broiler, litter)</th>
<th>No change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil carbon</td>
<td>-0.45</td>
<td>-0.42</td>
<td>-0.47</td>
<td>-0.5</td>
<td>-0.41</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>0.36</td>
<td>0.31</td>
<td>0.39</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>Total GHG</td>
<td>-0.09</td>
<td>-0.11</td>
<td>-0.08</td>
<td>-0.15</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

The results show net positive carbon sequestration (negative emissions) from each potential future scenario. Even when nitrous oxide emissions are included, total emissions remain negative for all scenarios. Additionally all future management choices result in higher sequestration than if no changes were made. Broiler litter as a source of N had the highest increase in soil carbon, and the lowest total GHG emissions. Composted chicken manure had the next highest increase in soil carbon, but had the highest N2O emissions of the scenarios, higher than the current management, but still has a lower total GHG emissions than current management. The cover crop scenario increased soil carbon, but N2O emissions remained the same. Layer chicken manure had a minor increase in soil carbon but reduced nitrous oxide emissions more significantly, resulting in lower total GHG emissions. These results are designed to be a resource for you, please contact me if you have future questions regarding the model or the interpretation of this information.
Results Sheet 4: Future management scenarios for Hawthorne Valley
4/8/2020

Spencer Fenniman - Hawthorne Valley Farm

For this final report I have tested the future scenarios we discussed as possibilities for this field using the COMET Farm modeling tool. In our first meeting you described the goal rotation you are working toward establishing on fields where grain crops and hay/forage crops are grown. This goal is represented as scenario 0 and all other future scenarios are then compared to that baseline in the following analysis. You expressed interest in adding grazing to the grain rotations used. I've included two different grazing scenarios, and one scenario extending the years in clover. In an effort to have the future scenarios reduce carbon emissions from your planned future management, the second grazing scenario imagines if using grazing could reduce the need for tillage. Using the results for the field's emissions per year, I calculated per acre emissions. Results are expressed in tons of carbon dioxide equivalent per acre per year, which is a way of expressing emissions as if they had the warming potential of carbon dioxide. Below I've included a table showing what I told the model about this hypothetical future management.

Table A5 (showing specifics of treatments):

<table>
<thead>
<tr>
<th>Scenario name:</th>
<th>0. Goal rotation, (planned future management)</th>
<th>1. Grazing in place of final hay harvest</th>
<th>2. Extra year in grass clover added to rotation</th>
<th>3. Grazing for bed prep in place of tillage</th>
<th>4. Scenarios 2 and 3 combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation, tillage, and grazing specifics</td>
<td>Rotation is 5 years long. Modeled as: Yr (1)Barley, alfalfa, (2) alfalfa, (3) alfalfa, triticale, (4)clover, (5) rye, then repeats once. Reduced tillage used for planting between grains and before cover crops are established. Intensive tillage used in 2020 and after alfalfa to prep for triticale</td>
<td>Same rotation as baseline (scenario 0) except grass legume mix replaces clover. Cover crops are grazed in place of what would be the final hay harvest. 2 days in grazing Aug 1-3 of given year under alfalfa or clover. Utilization at 50 percent to represent the same residue removal as a hay harvest.</td>
<td>Clover re-seeded and grown two years in a row (between triticale and rye) as opposed to one. Modeled as: (1)Barley, alfalfa, (2)alfalfa, (3) alfalfa,triticale, (4)clover, (5)clover, (6)rye, (7)barley, alfalfa, (8)alfalfa, (9)alfalfa,triticale</td>
<td>Grazing used between harvest and planting, envisioned in use combined with no-till drill for planting, or reduced tillage following sod such as alfalfa. Grazing happens after alfalfa, triticale, clover, and rye. Followed by no-till planting or mulch till for the transition from alfalfa to triticale. Utilization at 75 percent to represent mob grazing</td>
<td>Grazing in place of tillage as in scenario 3 paired with, extra year in clover. Same management as scenario 3, and same rotation as scenario 2</td>
</tr>
</tbody>
</table>

All scenarios: Hay harvest at 75 percent residue removal, 4.5 tons composted manure for barley years
Soil Carbon Emissions

Figure A7: soil carbon over current and future management by year

This graph shows the soil carbon emissions of your current management and if that crop rotation was repeated for the future (blue), compared with what you described as your "goal" crop rotation and management (in red). The negative emissions imply sequestration. The future scenario representing the plans for this field has lower emissions overall than if the rotation used 2013-2020 were to be repeated.

Figure A8: Soil carbon emissions by year for future scenarios
The baseline, planned future rotation has a near net zero result for carbon emissions, showing that carbon lost in tillage events is recovered through residue and cover crop management. Incorporating livestock into this grain and forage system does change the carbon balance of soil, and using livestock to reduce tillage along with an extra year in clover (scenario 4) had the greatest effect on reducing carbon emissions in this test.

The grazing replacing hay harvest scenario and the extra year in clover have higher carbon emissions than the baseline. Whereas the reduced tillage through grazing and combined grazing and years in clover scenario have lower carbon emissions than the baseline. The results show how responsive the carbon emissions feature in COMET is to tillage events. Adding years in clover would theoretically reduce carbon emissions by having another year without a tillage event, however because of the low carbon to nitrogen ratio of clover, the mineralization of organic matter is higher, leading to more soil respiration. The model showed a spike in emissions during the second clover year then a decrease flattening out below the baseline line. For your management, you mentioned an interest in using complex cover crops, which might solve the issue stated above, as a diversity of C inputs and C:N ratios would be expected to mitigate C emissions by slowing mineralization rates.

The grazing in place of hay scenario showing an increase C emissions slightly may have to do with the transition from clover to a grass legume mix, or the fact that when biomass is removed from grazing rather than hay, the plants may respond differently, or the biomass removed from grazing rather than hay may be modeled differently. It does not seem that COMET responds to the effect of hooves in the field when it comes to the grazing practices.

The scenarios were designed to depict grazing at a high density over a short period of time to remove residue before the next planting in an effort to reduce tillage. These results showed the most C sequestration potential, and the added length in cover crop years in scenario 4 resulted in even higher C sequestration. This scenario is a potential strategy for incorporating livestock into the grain rotation, as a way to reduce tillage.

**Nitrous Oxide Emissions**

![Figure A9: Nitrous Oxide Emissions by year for future management](image)
COMET does not seem to alter N2O emissions based on manure depositions from grazing, only from whole field manure/fertilizer applications. These results were constant across all future scenarios, as manure application was only assumed on the first year of the rotation, barley, which followed another grain crop, rye, rather than an N fixing cover. In setting up the runs for the model, I assumed manure application on barley years, (2020 and 2025), which correspond with the spikes in N2O emissions.