THE EFFECT OF COVER CROP ON SOIL CARBON AND SOIL WATER RETENTION IN TOPOGRAPHICALLY DIVERSE TERRAIN

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ABSTRACT

THE EFFECT OF COVER CROP ON SOIL CARBON AND SOIL WATER RETENTION IN TOPOGRAPHICALLY DIVERSE TERRAIN

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Farmers must consider real-world landscape variability to maximize yields and minimize environmental impacts when using cover crops in corn-based cropping systems. In the Midwest corn belt much of the variability farmers encounter is due to the topographical diversity of the undulating landscape. The objectives of this study are to explore the interactive effects of the presence or absence of cover crops and topography (summit, slope, and depression positions) on total soil organic carbon, on its labile form, particulate organic carbon, carbon dioxide emissions, cover crop decomposition, soil water retention, and crop growth. A cereal rye cover crop was established each fall after the main crop (corn and soybean) harvest from 2011-2015 at two experimental sites, Kellogg Biological Station (Kellogg) and Mason, which have loam and fine sandy loam soils, respectively. Main crop and cover crop growth were both higher in the depression, but did not differ in topographical position and main crop growth did not differ in the presence/absence of the cover crop. In the absence of the cover crop, topography affected particulate organic carbon but not in the presence of the cover crop ($p<0.1$). Decomposition and carbon dioxide emission followed the trend depression>summit>slope, but no one variable accounted for the distribution of particulate organic carbon. Total organic carbon and water retention were not affected by the cover crop in this study. A long-term study may reveal additional significant changes in the presence of a cover crop not detectable in a five-year study.

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I would like to thank, first and foremost, my family and friends for all their help and support. Also a big thank you to the undergraduate students, graduate students, and my advisor for their support and guidance in the field and in the office and for sharing many laughs with me along the way.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

POC	Particulate organic carbon
CO_2	Carbon dioxide
C	Carbon

CHAPTER ONE - INTRODUCTION

Overview

Farmers must consider real-world problems and variability to maximize yields and minimize environmental impacts when using cover crops in corn-based cropping systems. In the Midwest corn belt, much of the variability that farmers encounter is due to the topographical diversity of the undulating landscape. This topographical diversity is a controlling factor for many soil properties, including the distribution of soil organic carbon.

Enhancing a rotation by the inclusion of a cover crop has the potential to accumulate soil organic carbon (West and Post, 2002; Follet, 2001). Cereal rye (*Secale cereale* L.) is especially suited for this purpose because it is a high biomass grass and is shown to increase soil organic carbon (Kuo and Jellum, 2000; Kaspar et al., 2005; Reicosky and Forcella, 1998). Even though rye is beneficial for soil organic carbon accumulation, it can have negative effects, for example, decreasing the soil moisture or nitrogen availability for the subsequent main crop, or inhibiting emergence or growth of the main crop through allelopathic effects (Duiker and Curran, 2004; Wagner-Riddle et al., 1994; Munawar et al., 1990). The advantages and disadvantages of the use of rye as a cover crop in regards to soil organic carbon improvement are not homogeneously spread across landscapes with topographical diversity. Cover crops, such as rye, can grow at variable rates across topographies, commonly with better biomass accumulation in the flat, depression positions (Munoz et al., 2014). Thus, one can expect that greater soil organic carbon benefits from a rye cover crop can occur in topographical depressions. Yet, recent observations from topographically diverse agricultural fields in Michigan demonstrated that the magnitude of the cover crop effect on soil organic carbon was higher in the summit and slope positions, as compared to depressions (Ladoni et al., 2016). This indicates that other factors, besides the overall amount of the aboveground cover crop biomass production, influence the magnitude of the soil organic carbon benefits in topographically diverse agricultural landscapes.

Spatial distribution patterns of soil moisture and temperature are among the factors that likely contribute to soil organic carbon accrual. Topographical differences control soil moisture and soil temperature, both of which regulate the environment for microbial growth and activity as well as provide the environment for crop growth. These factors greatly affect the decomposition of freshly added plant residue. In addition to the topographical controls on physical properties effecting soil microbes, the presence of cover crops in rotation promotes microbial activity. This effect can further enhance the role of topographical differences in the environment for crop growth and decomposition (Wickings et al. 2016).

Decomposition rates of a rye cover crop at different topographical positions have not been extensively studied, but it is possible to hypothesize the anticipated effects. Prime decomposition conditions are difficult to obtain in topographically diverse terrain. The summits and slopes tend to be too hot and dry, while depressions are too cool and wet. Despite this, decomposition often happens at a faster rate in depression positions. This may be caused by an increase in microbial activity by up to 55% in depression positions relative to summits and slopes (Wickings et al., 2016). This could be due to many reasons, one of which is the spatial distribution of nitrogen in topographically diverse terrain. Nitrogen, in the form of nitrate, is a mobile nutrient which leads to an accumulation of available nitrogen in the depression positions.

Higher biomass accumulation and faster decomposition rates of labile organic matter in depression areas leads to a larger magnitude and faster turnover of carbon relative to summits and slopes. This has a few implications regarding the sequestration, or protection, of carbon in the soil. Carbon can be sequestered in the soil by three main methods; physical stabilization, attachment to silt and clay particles, and biochemical transformation (Six et al., 2002). A faster turnover of carbon in depression positions may lead to greater physical stabilization of soil organic matter by the promotion of increased soil structure through the formation of microaggregates, which protect the soil organic matter (Six et a., 2002).

The other two methods of soil sequestration, attachment to silt and clay particles and biochemical transformation, rely on a slower carbon turnover to most effectively protect carbon in the soil. Physiochemical protection, or the sorption of carbon to existing soil surfaces, relies on many factors which are promoted through a slower turnover of carbon including decomposition resulting in smaller C particles, reorientation of particles, and chemical bonding (Jastrow et al., 2007). Biochemical transformation is when soil organic carbon is transformed from an organic to a mineral form of carbon. This is a biologically driven process that is initiated by decomposers who release molecules which can then react to form stable carbon (Jastrow et al., 2007). Since these methods are promoted by slower C turnover, they could be more prominent in the summit and slope positions and not in the depression position.

There are many complications in studying impacts of topographical gradients on soils. For example, topographical controls on soil moisture and soil temperature add variability that impact many stages of the carbon cycle in relation to sequestering soil carbon, most of which have not been extensively studied. Root exudates, underlying geological differences, and the nutrient flow path along the topographical gradient may affect cover crop growth and decomposition. In addition, the potential for movement of soil and plant material through erosion and deposition may have a large impact not only on plant growth and decomposition through the availability of nutrients, but the distribution (or redistribution) of soil carbon along the topographical gradient.

In addition, topography plays a role in the distribution of nutrients, especially nitrogen, which can impact the variability of biomass accumulation. Nitrogen, most commonly in the form of nitrates, collect at the footslope (depression) leading to higher above ground biomass in that position than in the shoulder (slope) position (Mbonimpa et al., 2016). Biomass growth variability is not only spatially along the topographical gradient but vertically within the plant. Plants are able to direct the allocation of energy to the growth of above or below ground biomass based on soil resources. For example, when there are limited soil resources, plants promote belowground biomass growth but when nutrient availability is high, growth is favored in the above ground biomass (Tateno et al., 2004).

Changes in atmospheric carbon, along with other factors, are leading to a modification in climate which is resulting in greater variability of precipitation patterns (Trenberth, 2011). This variability means that precipitation patterns are less predictable, but we can expect that historically wet areas will become more wet, while historically arid areas will become more dry (Dore, 2005). As a result of the altered precipitation patterns, it is expected that soil moisture patterns along topographical gradients, which are normally drier in the upslope position and wetter in the downslope position, will be exacerbated (Western et al., 1999).

The objectives of this study are to explore the effect of rye cover crop on soil carbon accrual and changes in soil water retention characteristics in a topographically diverse agricultural landscape. Figure 1 outlines the hypothesized influences of cover crops on soil carbon processes in a corn-based cropping system that were considered in this study, the solid arrows are an observed effect and the dotted arrows are a hypothesized effect. It also indicates, by the outlined boxes, the measurements that were conducted in order to explore the interacting contribution of topography and cover crop use on soil carbon processes. The effects of a rye cover crop have the potential to impact the amount of long-term soil organic carbon but only by going through other processes.

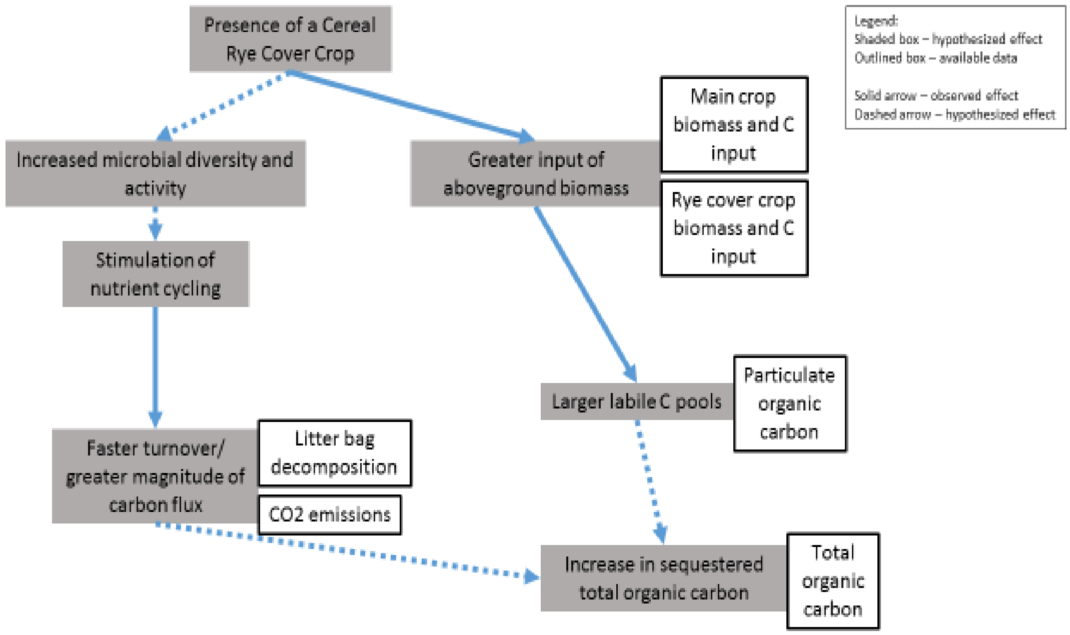


Figure 1. Flowchart depicting hypothesized and observed effects of cover crop presence on carbon cycling in this study.

Importance of cover crops in corn-based systems

The use of cover crops, like rye, is a beneficial management practice in corn-based cropping systems in the Midwest. Cover crops, which are grown when the soil would otherwise be fallow, have many positive effects on the biological, chemical, and physical properties of the cropping system in general, such as suppression of weeds and pests, improvements of soil and water quality, and stimulation of nutrient cycles (Snapp et al., 2005). A cereal rye (*Secale cereale* L.) cover crop, used in this study, is appropriate when looking to increase biomass production and decrease soil erosion in the fall and winter in Midwest corn and soybean rotations (Raimbult et al., 1989; Bruin et al., 2005). Biomass production and protection from soil erosion are two important characteristics of rye; not only does it facilitate the addition of organic matter through biomass, it also decreases (but does not eliminate) the movement of organic matter through erosion. Both characteristics can facilitate keeping organic matter in the cropping system, which is commonly used as an indicator of soil health (Reeves, 1997).

Continuous crop growth and tillage without returning plant residue to the soil can deplete soil organic matter which is why, when returned and incorporated into the soil of the cropping system, cover crops can increase soil health. The absence of soil organic matter leads to reduced soil health and productivity by way of reduced microbial action, increased compaction, and less stable aggregates (Allison, 1973; Van Doren et al., 1976; Campbell and Souster, 1982; Cambardella and Elliott, 1993). Cover crops, especially high biomass, non-leguminous grasses like cereal rye, can provide an additional input of organic carbon into corn-based cropping rotations which can reverse those effects (Sainju et al., 2002; Dabney et al., 2001; Papadopoulos et al., 2006).

Labile carbon pools as the first stage of cover crop driven improvement in soil health

I hypothesize that the additional input of aboveground biomass from the rye cover crop leads to greater soil organic carbon levels (Figure 1). However, initially I expect to see increases in soil labile carbon pools, e.g., particulate organic carbon. This hypothesis is based on the relatively slow response of total soil organic carbon to management practices (Plaza-Bonilla et al., 2014; Haynes, 2000). Labile carbon, like particulate organic carbon, can show changes on the scale of a few days to a few years (Nascente et al., 2013). Particulate organic matter is an indicator of the amount of stable carbon that will be protected and stored in the soil (Post and Kwon, 2000; Six et al., 2000). Therefore, by using particulate organic carbon as a metric in this five-year study, the changes in soil carbon due to the cover crop can be more easily detected

For this study, particulate organic carbon is defined as the active fraction of the total organic carbon pool that consists of organic carbon particles between 0.053 and 2 mm in size which react quickly to changes in management practices (Cambardella and Elliot, 1992; Sequeira et al., 2011; Ladoni et al., 2015). Even though it is highly variable, particulate organic carbon is reflective of management changes (Ladoni et al., 2015). This fraction of the organic carbon pool is also especially prone to redistribution related to downhill erosion and eventually collects in the depression areas, but does not always lead to higher concentrations in the intermediate slope positions when compared to the summits (Dungait et al, 2013). This pattern is likely because of particle size distribution, since high organic matter content is usually correlated with fine material which because of its size and mobility is more likely found in depressions, rather than summits or slopes (Dungait et al., 2013; Parton et al., 1987). Particulate organic carbon can constitute 42-74% of the total organic carbon pool and is preferentially lost during cultivation (Chan, 2001). This loss can be observed through the decomposition rates and carbon dioxide emissions in and from the soil.

Effect of topography on decomposition of cover crop residue

I hypothesize that greater decomposition of rye residue after rye incorporation in spring will take place in topographical depressions (Figure 1). Greater decomposition will happen in topographical depressions because of more ideal conditions for decomposition including soil moisture and soil temperature leading to an increase in microbial activity. However, the magnitude of topographical effect will vary from year-to-year depending on temporal patterns in spring temperature and precipitation. Decomposition rates and the factors that control them are the major influences on carbon inputs into the system (Henriksen and Breland, 1999). The type and composition of the decomposing litter exerts less control on the rate of decomposition of the labile and long-term pools of organic carbon than other controlling factors, such as soil moisture and temperature (Adair, 2008). The main controlling factors of the rate of decomposition are soil moisture and climate variables, such as rainfall and temperature (Eijsackers and Zehnder, 1990; Andren, et al. 1993; Adair, 2008). In addition, soil texture influences decomposition because in general, coarser textured soils have a slower decomposition rate (Rovira, 2002). However, regardless of controlling factors, rye decomposition was reported to be the highest the week after incorporation because the input of the rye organic matter produced a short-term boost of microbial growth and activity (Lundquist, 1999). This short-term burst of microbial action, lasting about a week after incorporation, happens during the time between the termination of the rye cover crop and the planting of the subsequent main crop.

Effect of topography on soil respiration

Greater organic inputs and their faster decomposition typically result in greater soil respiration, that is greater CO_2 emissions from soil. Thus, increases in CO_2 emissions due to cover crop use can be regarded as precursors of subsequent increases in soil organic carbon. I hypothesize that greater increases in soil CO_2 emissions due to cover crop use will be observed in topographical depressions because of their greater biomass inputs and faster decomposition (Figure 1).

Carbon dioxide emissions from the soil are mainly controlled by soil moisture and climate variables, such as temperature and rainfall which drive microbial action, as well as soil organic matter content (Raich and Potter, 1995; Trumbore et al., 1996; Srivastava et al., 2012; Harrison-Kirk et al., 2013). A preceding study at the two experimental sites used in my work examined effects of topography, cover crop presence, and tillage on soil CO_2 emissions during growing seasons of 2012-2013. Across all topographical positions the presence of cover crops resulted in greater CO_2 emissions. The magnitude of that effect differed between summits, slopes, and depressions, with the greatest increase occurring in depressions and the smallest in summits, and was inversely proportional to the biomass input from the cover crop (Negassa et al., 2015). The effects of topography and cover crops on CO_2 emissions have not been extensively published, so this study aims to add to this area of impact on the soil carbon cycle in corn-based cropping rotations.

Importance of soil water retention

Topography also plays a role in the spatial variability of soil physical properties, which are themselves highly correlated to soil organic carbon content (Moore et al., 1992; Tromp-van Meerveld and McDonnell, 2006; Romano and Palladino, 2002). One such property of significant value to plant growth is soil water retention which is strongly related to soil organic carbon. On a per volume basis an organic matter increase significantly affects the physical properties of the soil by changing bulk density and in turn, water retention (Hudson, 1994; Adams, 1973; Rawls, 1983; Gupta and Larson, 1979). An increase in organic matter in sandy soils, like the soils in this study, can lead to an increase of water retention (Rawls et al., 2003). Organic matter content in the soil also affects soil aggregation, a key component of soil structure and water retention capability (Franzluebbers, 2002). The effect of organic matter content on water retention can be observed most clearly at field capacity, which can have an effect on cover crop and main crop growth (Jong et al., 1983). By understanding the effects of topography and cover cropping on water retention we can better understand the long-term implications on soil carbon and soil health.

Implications

It is important to better understand where and how organic carbon cycles in the soil, which holds roughly three times as much carbon as the atmosphere and five times as much carbon as Earth's vegetation, since scientists continue to observe increases in atmospheric carbon dioxide leading to climate change that will impact agricultural systems, especially in the Midwest corn belt (Lal, 2004).

Some agricultural lands have lost one-half to two-thirds of their original total soil organic carbon pool, so by gaining a better understanding of the dynamic turnover and flux of carbon in agricultural systems enhanced with cover crops we will be able to sequester carbon back in to agricultural lands (Lal, 2004). By increasing the soil organic carbon pool in a corn cropping system by 1 ton/ha, corn yield may increase by up to 20 kg/ha, making carbon sequestration not only environmentally advantageous but also potentially financially profitable (Lal, 2004). Increasing soil organic carbon can also increase infiltration and soil fertility, decrease erosion, minimize compaction, and impede pesticide movement, all of which are signs of a healthy, productive soil (Reicosky, 2003).

Although this may seem like a very straightforward chain of events – grow a cover crop, add more organic carbon to the soil, and then reap the benefits - spatial variability from topographical diversity that impacts cover crop growth and the subsequent impacts on the other variables observed in this study is not extensively researched (Munoz et al., 2014). Real-world, field-scale topographical diversity is often under-represented in agricultural research and experiments. To minimize variability in scientific research, plots chosen are often on flat land with no topographical variance (Munoz, 2014). Despite this, cover crop growth and biomass production can be influenced by the distribution of soil water, which is highly controlled by topography (Munoz et al., 2014; Corre et al., 2002). Topography also affects the distribution of nutrients, like nitrogen, and soil temperature which impacts the growth and microbial environment along the topographical gradient (Moore et al., 1993; Kang et al., 2003; Zhu and Lin, 2011; Bennie et al., 2008; Yimer et al., 2006). The differing environments between topographical positions that drive the growth of cover crop biomass provide highly variable inputs of organic carbon. In addition, topography significantly affects the redistribution (erosion and deposition) of soil across the landscape which is correlated with the distribution of soil organic carbon after the initial carbon input from the cover crop (Ritchie et al., 2007). Both modeling and field studies have found a strong correlation with slope (i.e. topographical position) and soil organic carbon distribution (e.g. Moore et al., 1992; Terra et al., 2004; Kunkle et al., 2011).

An increasing popularity in precision agriculture makes studying topographical differences in corn-soy cropping rotations even more pertinent. By adding topographical variables into precision ag management, farmers will be able to be more effective in their use of the land and more efficient in their productivity. Adding topography as a factor in observing the impacts of a rye cover crop in a corn-based cropping rotation makes this study novel and necessary because topography indirectly or directly impacts every variable involved in production agriculture as well as soil carbon sequestration.

Hypotheses

The principal hypothesis of this study is that topography will be the main cause of observable differences in soil carbon, particulate organic carbon, rye decomposition, CO_2 emissions, and water retention because topography plays an important role in spatial variation of biomass growth, distribution of soil organic matter, and soil physical properties (Dharmakeerthi et al., 2005). It is also hypothesized that cover crop effects will be observed through a greater input of aboveground biomass, greater magnitude of carbon flux through CO_2 emissions and rye decomposition, and a larger labile carbon pool (Figure 1). Adding cover crops as an additional source of carbon into topographically diverse terrain adds a new and not extensively studied layer of complexity into the understanding of carbon dynamics in corn-based cropping systems in the Midwest.

CHAPTER TWO – MATERIALS AND METHODS

Site description

The two experimental sites are located at the Kellogg Biological Station (Kellogg) and the Mason Research farm in southwest Michigan and mid-Michigan, respectively. Both sites average around 76 cm of rainfall in addition to 76 cm of snowfall annually. Temperatures at both sites average -3C in the winter and 20C in the summer. The Mason site, located in Ingham County, is situated near the Michigan State University (MSU) campus. The Kellogg site, located in Barry County, is on the grounds of the Kellogg Biological Station, a large off-site research campus operated by MSU. Soils at the Mason site are classified as Marlette fine sandy loams (Oxyaquic Glossudalfs) and soils at the Kellogg site are classified as Kalamazoo loams (Typic Hapludalfs). A complete description of soil texture at all depths and topographical positions can be found in the Appendix.

Experimental design

Both experimental sites have contrasting topographies, which enabled incorporating topographical position as a studied factor. At Kellogg, blocks 1 and 2 are slope, blocks 3 and 4 are depression, and blocks 5 and 6 are summit (Fig. 2a). At Mason, blocks 1 and 2 are summit, block 3 and 4 are slope, and block 5 and 6 are depression (Fig. 2b). At each of the sites the experimental design was a split-split plot with whole plot factor, topographical position, in a randomized complete block design with two replications, sub-plot factor, main crop (corn and soybean), and sub-sub-plot factor cover crop (presence and absence) (Fig. 3). The study was conducted from 2011 to 2015.

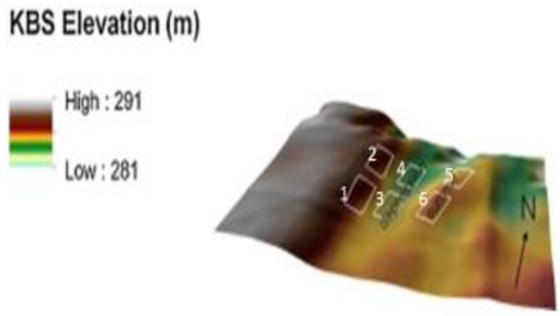


Figure 2a. Digital elevation map of Kellogg site. *Whole plots (blocks) are outlined and numbered.*

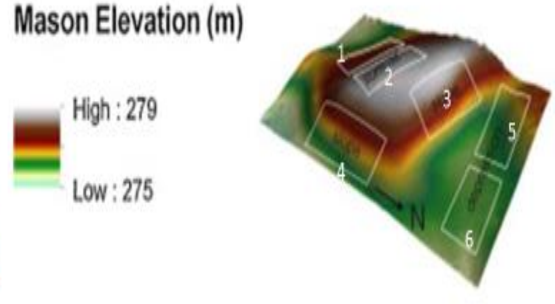


Figure 2b. Digital elevation map of Mason site *Whole plots (blocks) are outlined and numbered.*

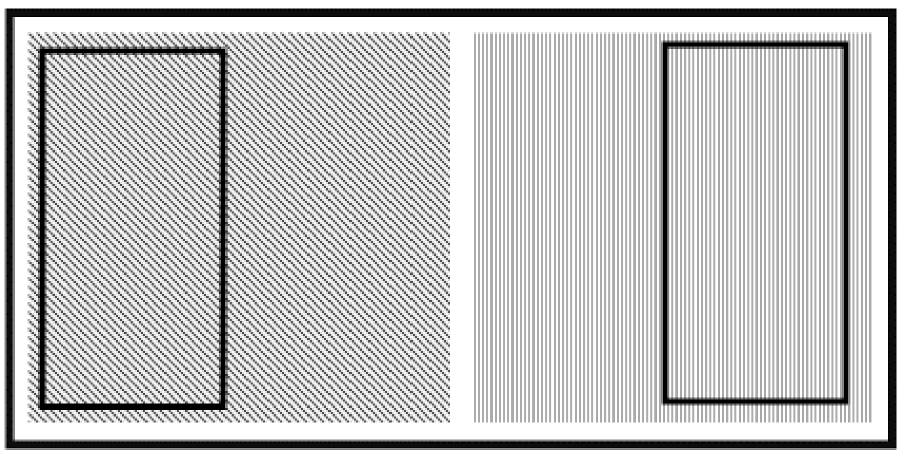


Figure 3. Representation of treatment splits within each block. *Each block is replicated twice within the whole plot topography. Each block (thick outer box) has both corn (diagonal lines) and soybean (vertical lines). Each crop is then split into two halves: with and without winter rye cover crop (thick inner box).*

Field management and data collection

Field sites were managed by our research group with help from farm assistants associated with each research site. Conventional practices were used in plowing, planting, fertilizing, spraying herbicides, and harvesting consistent with practices in the region. An overview of field operations and the timing of those operations can be found in Table 1.

Task	Projected Date to Complete Task
Rye Cover Crop and Weed Sampling	First week of May
Rye Cover Crop Termination	First week of May (approximately 2 weeks before corn planting)
Spring Fertilizer and Lime Application	Third week of May (before tillage)
Tillage	Third week of May
Plant Corn	Last week of May
Plant Soybean	Last week of May
Post Emergence Herbicide Spray	Mid-June
Corn Harvest	First or second week of October
Soybean Harvest	First or second week of October
Plant Rye Cover Crop	Second week of October (after harvest)

Table 1. Overview of field operations and timing for research plots at Kellogg and Mason.

The cereal rye cover crop was established each fall in early October, beginning in 2011.From 2011-2013, rye was sown at 112 kg/ha with a John Deere 15 foot no-till drill. In 2014-2015 rye population was increased to establish a better stand and was sown at 145 kg/ha. Nitrogen fertilizer was applied based on yearly soil tests and recommendations from the Michigan State Soil and Plant Nutrient Laboratory. A summary of nitrogen fertilizer application can be found in the Appendix. Rye was terminated by herbicide then was chisel plowed, followed by a soil finisher to establish a seed bed for the subsequent main crop. Weed growth was terminated by the use of herbicides at least once per growing season with additional weed control by herbicide if necessary.

Three composite soil cores were taken in the spring of 2011, 2013, and 2015 from depths 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm. Total soil organic carbon was measured at all depths for those three sampling events. Particulate organic carbon samples were collected separately once a year in the spring from 2012 to 2014 at the 0-10 cm depth. Water retention samples were also collected separately in the spring of 2011, 2013, and 2015 at depths of 0-10 cm and 10-20 cm. Carbon dioxide emissions were taken during the main crop growing season in 2012, 2013, and 2014. The litter bag decomposition study was done during the growing season of 2015 and 2016. Plant biomass, both cover crop and main crop, were collected in relation to growth and harvest or termination. Data collected from these sites was based on standardized protocols outlined by Kladivko et al., 2014. Detailed descriptions of the specific data collection/measurement procedures are provided below.

Plant yield biomass and carbon content sampling

Biomass of corn and soybean was collected at harvest every year. Whole plants of corn and soybean in previously assigned yield rows were collected, then the grain was separated from the vegetative biomass and both were weighed to obtain measurements for yield and vegetative biomass. The remaining plant material in the field was harvested mechanically. For corn, average yield was calculated using the grain collected from the yield rows. For soybean, yield was recorded by the combine.

Rye biomass was collected immediately before the termination of the cover crop every year. Three random samples per plot were collected by using a 1' by 1' sampling square. All the rye in the sampling square was cut at the soil surface to obtain an aboveground biomass. The rye was weighed, dried at 40 C, and then weighed again to obtain a dry biomass measurement.

After being dried, corn, soybean, and rye were finely ground in preparation for combustion analysis. The carbon content of the ground plant material was found using a Costech ECS 4010 CHNSO Analyzer (Costech Analytical Technologies, Inc, Valencia, CA).

Particulate organic carbon

Approximately 20 g of soil was subsampled from the sieved and air dried soil cores to use for particulate organic carbon analysis. Particulate organic carbon was chemically dispersed using a 5% sodium hexametaphosphate solution. The soil solution was then passed through a 53-micron sieve. The contents of the sieve were oven dried at 60 C and ground in the 8500 Shatterbox (Spex Sample Prep, Metuchen, NJ) (Cambardella and Elliott, 1992). Final carbon analysis of the sample was done using a Costech ECS 4010 CHNSO Analyzer (Costech Analytical Tech Inc., Valencia, CA).

Rye decomposition

Rye was collected from each field site prior to termination by pulling the plant, gathering both aboveground and belowground biomass, to use for decomposition by litter bag methodology. Litter bags were 10 cm by 10 cm and constructed with 0.028 cm plastic mesh. The rye was oven dried at 40C and a random subsample of 5 to 7 grams of hand-cut dried rye, measuring approximately 5-7 cm in length, was placed in each litter bag. In 2015, approximately 60 litter bags were buried about 10 cm deep in plots with cover crop at the Mason site. In 2016, approximately 340 litter bags were buried about 10 cm deep in plots with and without cover crop at the Mason and Kellogg site. Litter bags were removed at three time points, 1, 3, and 5 weeks, at which time the decomposed rye was then carefully cleaned of soil and other debris by hand dusting, at which time the decomposed rye was oven dried at 40C and weighed (Alef, 1995). Commonly in litterbag decomposition studies, a portion of the contents are ashed after decomposition (Nadelhoffer et al., 1999) but no portion of decomposed material was ashed in this study.

CO_2 emissions

Carbon dioxide gas samples were taken biweekly from 8:00 AM to 12:00 PM during the growing season of 2012, 2013, and 2014 from cover and no cover plots in corn and soybean across all topographical positions at both sites. Aluminum static flux chambers (0.375 m x 0.75 m) were manufactured locally (Parkin and Venterea, 2010). The chambers consisted of the anchor, which was installed in the field after planting of the main crop, and a removable cap with a vent tube and sampling port. Once the chamber and cap were in place, CO_2 concentration was sampled from the surface soil every two minutes for at least 14 minutes by using an infrared Photoacoustic Spectroscopy (PAS) (INNOVA Air Tech Instruments, Ballerup, Denmark). Soil temperature using a pocket thermometer (Taylor Precision Products, Oak Brook, Illinois) and soil moisture using time domain reflectance (IMKO HD-2 IMKO GmbH, Ettlingen, Germany) were measured at the time of CO_2 sampling at three points around the chamber. Calculations from the CO_2 concentration, soil temperature, and soil moisture were completed to obtain the rate of CO_2 – C (CO_2) emissions (Iqbal et al., 2013).

Total soil organic carbon

Soil samples were collected using a Giddings hydraulic probe (Giddings Machine Company, Windsor, CO) (7.6 cm in diameter). Approximately 0.7 kg of soil from each depth increment was wet sieved to pass a 2 mm sieve and air dried. A small subsample, approximately 5 g, was then ground to a fine powder using an 8500 Shatterbox (Spex Sample Prep, Metuchen, NJ) in preparation for flash combustion analysis by the Carlo Erba EA 1108 (CE Elantec Inc., Lakewood, NJ). Combustion analysis of soil samples was completed by the USDA-ARS in St. Paul, Minnesota under the direction of Dr. Kurt Spokas. Samples were sent to that lab so that values could be corrected for small amounts of inorganic carbon at the Mason site through the acetic acid neutralization method, which was an unnecessary correction for the Kellogg site.

Water retention

Soil samples for water retention analysis were collected one time per year in the spring before corn or soybean planting in brass rings 5.5 cm in diameter and 3 cm in height. There was no continuous measurement of soil moisture dynamics. Pressure plates were used to extract water at pressures of 0.05 bar, 0.1 bar, 0.33 bar, 1 bar, and 3 bar. The water content at 15 bar was measured by drying subsamples of the soil used from the pressure plate method and placing them in a desiccator above an oversaturated KCl solution (500 g KCl/1 L water) for two months. For both methods, the difference in mass was used to calculate water content.

Statistical analysis

Statistical analysis was performed using MIXED procedure of SAS 9.4 (SAS Institute Inc., Cary, NC). The statistical model for the analysis included presence/absence of cover crop, topographical position, and the interaction between them as fixed factors. The previous crop, corn or soybean, was not used because it introduced too much error into the model to be a useful interaction in this study. Block was nested in topography at each site was included in the model as the random factor and was used as an error term for testing the main effect of topography. When the interaction between topography and cover crops was statistically significant ($p<0.1$), we used slicing to assess the effect of cover crop presence at each topography level and the effect of topography at each level of the cover crop factor. When slicing effects were statistically significant ($p<0.1$), comparisons between the means were conducted using t-tests. Because of high variability of the collected field data we reported the results that were statistically significant at both 0.05 and 0.1 levels of significance. For the analysis of total soil carbon, 2011 total organic soil carbon data from both Mason and Kellogg was added to the model and used as a covariate when assessing 2015 values from both sites together.

CHAPTER THREE – RESULTS

Overview

The results are presented in the order consistent with the diagram of the hypothesized influences of cover crops on soil carbon processes that were considered in this study (Fig. 1). It starts with topographical and cover crop effects on main crop biomass, followed by topography effect on rye biomass and C inputs, then topographical and cover crop effects on particulate organic carbon (POC), litter decomposition, and CO_2 emissions from soil, and finally on total soil organic C and soil water retention.

Aboveground biomass

Total carbon from aboveground biomass was split into two categories, rye cover crop and main crop (both corn and soybean). The average total carbon in the rye cover crop showed different trends at the two sites. At Kellogg, the slope exhibited a statistically significant higher average total carbon in rye cover crop biomass than the summit and depression positions. At Mason, the depression exhibited a higher average total carbon of rye biomass, but there were no statistically significant differences between the topographies (Fig. 4).

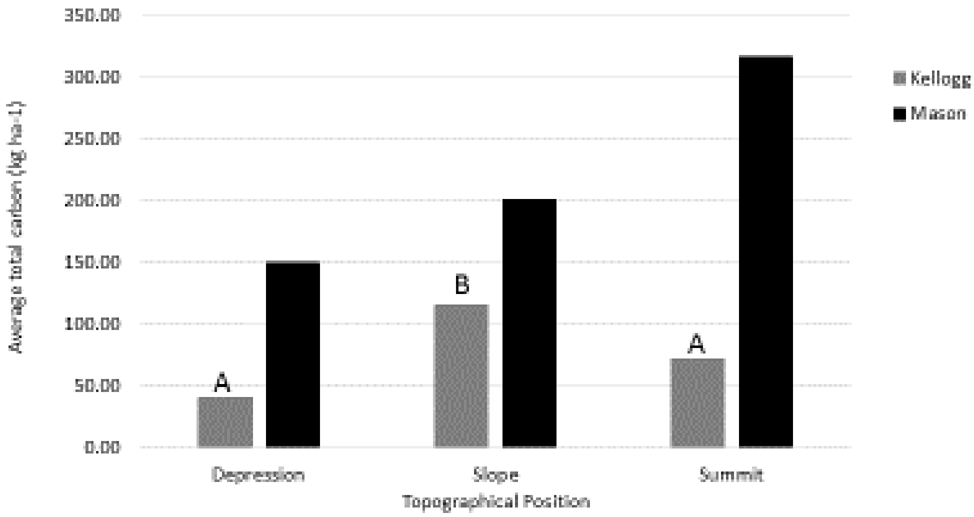


Figure 4. Average total carbon (kg ha^{-1}) of rye biomass across topographical position for each site. *Letters represent statistically significant differences among the topographical positions at each site (p<0.1).*

Average total carbon from the main crop aboveground biomass did not differ between sites. It also did not differ in the presences or absence of the rye cover crop. Main crop total carbon was statistically higher in the depression position than in the summits and slopes (Fig. 5).

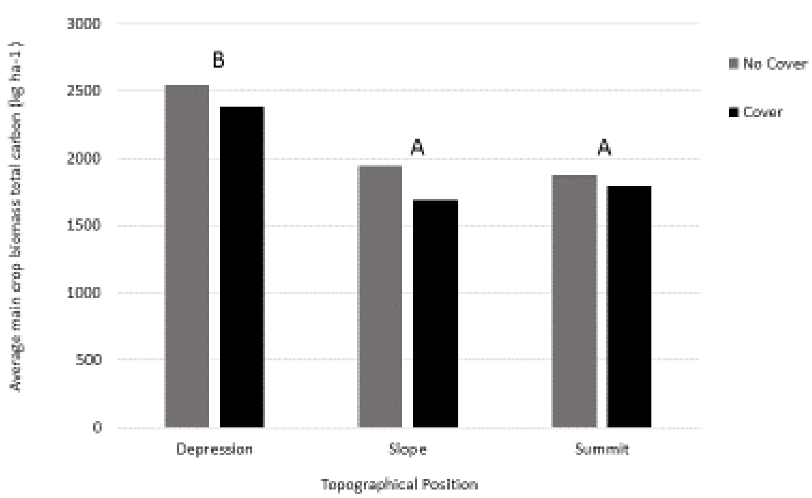


Figure 5. Average main crop (corn and soybean) total carbon for all years. *Letters mark statistically significant differences between topographical positions (p<0.1).*

Particulate organic carbon

Overall, the depression positions tended to have more particulate organic carbon than summits and slopes, however the magnitude of the differences varied in cover and no cover treatments (Fig. 6) In the absence of the rye cover crop, POC was significantly lower in summit and slope positions compared to the depression position (α=0.1). In the presence of the rye cover crop, the differences followed the same numeric pattern as those in in the no cover treatment, but the differences were not statistically significant.

Overall, presence of cover crop tended to result in greater POC, however, the size of the effect varied depending on topography. The presence of the cover crop resulted in significantly higher particulate organic carbon in the slope and summit topographical positions (α=0.1), but its effect in the depression positions was not statistically significant.

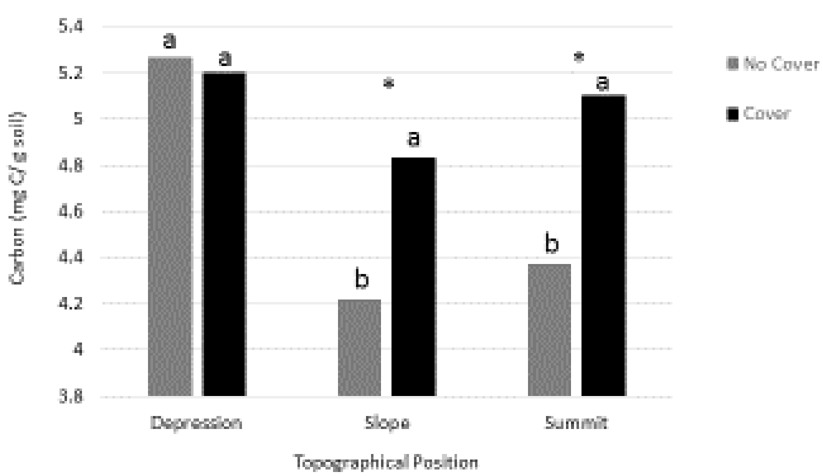


Figure 6. Particulate organic carbon across both experimental sites at 0-10 cm depth for no cover and cover plots. *Letters within each cover treatment represent statistically significant differences among the topographical positions (p<0.1). Asterisks mark the topographical positions where the differences between the presence and absence of the cover crop was statistically significant (p<0.1).*

Rye decomposition

At each topographical position (summit, slope, and depression) in both 2015 and 2016, each time point was statistically different ($p<0.1$), indicating the occurrence of decomposition. In 2016, there were no differences in mass loss between the presence and absence of a cover crop. In 2015, the study was only completed in the presence of a cover crop, so no comparison can be made.

In 2015, topographical differences only existed at week 5, where the depression position had significantly higher mass loss than the summit and slope positions (Fig. 7). In 2016, decomposition followed the trend depression>summit>slope, which was statistically significant at week 1 and week 3 (Fig. 7).

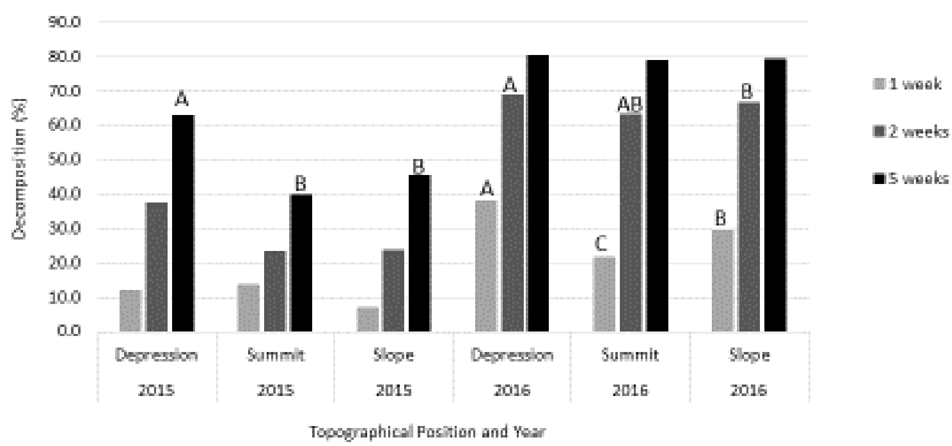


Figure 7. Rye decomposition (%) at Kellogg and Mason for 2015 and 2016. *Letters indicate topographical differences in each year for each sampling date ($p<0.1$).*

CO_2 emissions

Carbon dioxide emissions differed significantly between the topographical positions ($p<0.1$). For both sites and all years studied, the amount of CO_2 released followed the trend slope<summit<depression. There was no significant difference between the cover and no cover treatments (Fig. 8).

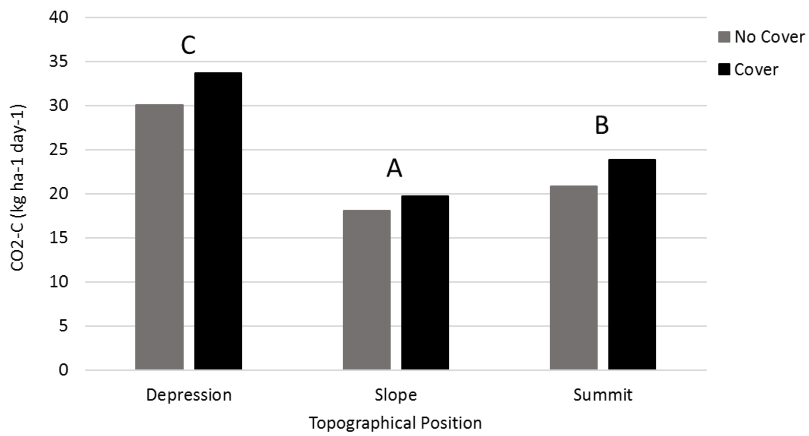


Figure 8. CO_2 emissions from 2012, 2013, and 2014 across topographical positions in no cover and cover. *Letters represent statistically significant differences among topographical position ($p<0.1$).*

Total soil organic carbon

At the 0-10 cm depth topography was the only factor that significantly influenced total organic carbon and at both sites. On average, at Kellogg and Mason there was the least amount of total organic carbon in the slopes, followed by summits, with the most in the depression positions. At Mason, the topographical depression had a significantly higher percent of total soil organic carbon than the summit and slope. At Kellogg, the topographical depression was significantly higher than the slope ($\alpha=0.1$) but not different than the summit at the 0-10 cm depth (Table 2).

At the 10-20 cm depth, total organic carbon from treatments with and without cover behaved the same as in the 0-10 cm depth but with smaller differences between the summit and depression positions. At Kellogg in plots with no cover at 10-20 cm, there was no significant difference in topography but the trend of amount of carbon was consistent with the shallower depths (slope having the least amount of carbon and depression having the most amount of carbon).

At depths of 20-40 cm and 40-60 cm, there were no significant differences between topographical positions (Table 2).

At both Kellogg and Mason, there was no significant change in total soil organic carbon at 0-10 cm over the course of the study. There were no significant differences between cover crop and no cover crop treatments.

Site	Topographic Position	Depth							
		0-10 cm		10-20 cm		20-40 cm		40-60 cm	
		With cover	Without Cover	With cover	Without cover	With cover	Without Cover	With cover	Without Cover
Kellogg	Depression	0.81 b*	0.83 b	0.71 b	0.71	0.44	0.45	0.24	0.30
	Slope	0.54 a	0.52 a	0.43 a	0.51	0.33	0.39	0.17	0.25
	Summit	0.69 ab	0.71 ab	0.55 ab	0.61	0.37	0.39	0.20	0.21
Mason	Depression	1.09 b	0.99 b	0.93 b	0.80 b	0.42	0.50	0.30	0.17
	Slope	0.79 a	0.74 a	0.56 a	0.54 a	0.42	0.34	0.39	0.23
	Summit	0.76 a	0.76 a	0.59 ab	0.58 a	0.35	0.27	0.28	0.25

Table 2. Soil organic carbon concentration (%) at the four studied depths of the two experimental sites in spring 2015. **Within each site, each depth, and each cover treatment, the letters mark the statistically significant differences among the topographical positions (p<0.1).*

Water retention

At field capacity (0.33 bar), water retention does not significantly differ between the presence or absence of cover crop or topographical position (Fig. 8). There was no change at either site in water retention at 0 bar, 0.003 bar, 0.05 bar, 0.01 bar, 0.33 bar, 1 bar, 3 bar, or 15 bar at the 0-10 cm or 10-20 cm depth from 2011 to 2015. There was no difference in water retention in the presence or absence of the rye cover crop from 2011 to 2015 (Table 3). At Mason at 0-10 cm with a cover crop, there were three pressures where differences in topography was observed (0 bar, 0.05 bar, 0.01 bar). At Mason at 10-20 cm with a cover crop, there were only significantly significant differences between topographical positions at the 0 bar pressure. No topographical differences were seen at the 0-10 cm or 10-20 cm depth in the absence of the cover crop at Mason. At Kellogg 0-10 cm, topographical differences were observed in the presence and absence of cover crops at three pressures (0.003 bar, 0.05 bar, 0.01 bar) and in the presence of cover crop at 1 bar. At Kellogg 10-20 cm, topographical differences were observed in the presence of cover crop at 0.05 bar and in both the presence and absence of the cover crop at 15 bar (Table 3).

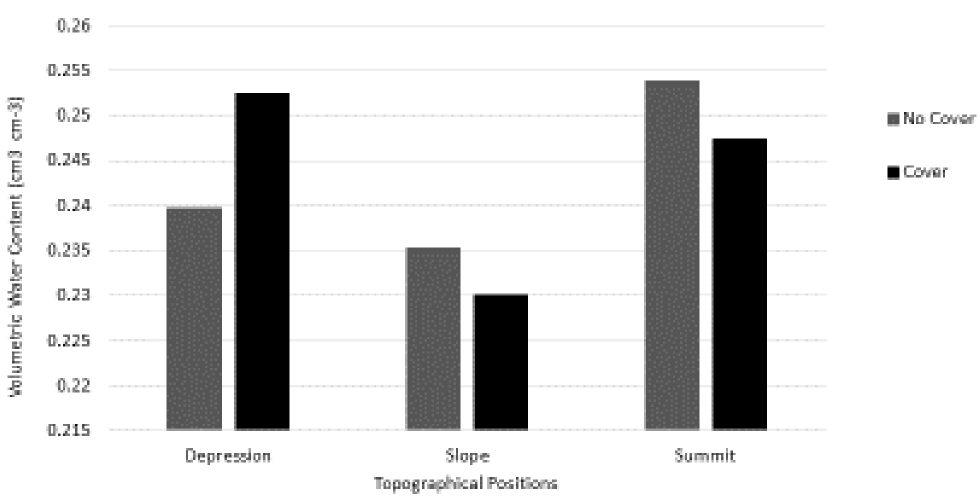


Figure 9. Volumetric water content (water retention) ($cm^3\ cm^{-3}$) at field capacity (-0.33 bar) for all years at both sites.

Site	Topographic Position	Depth																
			0 bar		0.003 bar		0.05 bar		0.01 bar		0.33 bar		1 bar		3 bar		15 bar	
			With cover	Without Cover	With cover	Without cover	With cover	Without Cover	With cover	Without Cover	With cover	Without Cover	With cover	Without cover	With cover	Without Cover	With cover	Without cover
Mason	Depression	0-10	0.46 b*	0.41	0.40	0.38	0.34 b	0.29	0.33 b	0.28	0.28	0.24	0.26	0.22	0.26	0.21	0.026	0.022
	Slope	0-10	0.40 a	0.40	0.36	0.35	0.31 a	0.30	0.31 ab	0.30	0.27	0.27	0.25	0.24	0.24	0.24	0.028	0.028
	Summit	0-10	0.42 a	0.39	0.35	0.36	0.30 a	0.30	0.29 a	0.30	0.26	0.26	0.23	0.24	0.22	0.24	0.024	0.023
Mason	Depression	10-20	0.44 b	0.44	0.39	0.37	0.30	0.29	0.33	0.28	0.25	0.24	0.24	0.22	0.23	0.22	0.025	0.026
	Slope	10-20	0.40 a	0.39	0.34	0.33	0.30	0.29	0.29	0.28	0.27	0.26	0.25	0.24	0.24	0.24	0.027	0.030
	Summit	10-20	0.40 ab	0.42	0.35	0.35	0.28	0.30	0.28	0.29	0.26	0.27	0.24	0.25	0.24	0.25	0.030	0.026
Kellogg	Depression	0-10	0.47	0.47	0.44 b	0.44 b	0.35 b	0.36 b	0.32 b	0.33 b	0.29	0.29	0.27 b	0.27	0.25	0.27 b	0.026 a	0.025
	Slope	0-10	0.42	0.43	0.37 a	0.39 a	0.25 a	0.26 a	0.23 a	0.24 a	-----	0.26	0.17 a	0.18	0.18	0.18 a	0.034 b	0.031
	Summit	0-10	0.47	0.48	0.43 b	0.45 b	0.35 b	0.35 b	0.32 b	0.32 b	0.29	0.28	0.27 b	0.26	0.25	0.24 ab	0.023 a	0.022
Kellogg	Depression	10-20	0.44	0.44	0.42	0.41	0.34 b	0.34	0.32	0.32	0.30	0.30	0.28	0.28	0.26	0.27	0.027 a	0.028 a
	Slope	10-20	0.39	0.39	0.37	0.36	0.26 a	0.27	0.25	0.25	0.19	0.27	0.20	0.22	0.19	0.22	0.037 b	0.037 b
	Summit	10-20	0.47	0.45	0.43	0.41	0.32 a	0.32	0.30	0.30	0.27	0.28	0.26	0.27	0.24	0.25	0.023 a	0.025 a

Table 3. Volumetric water content at all pressures at the two studied depths of Kellogg and Mason in the spring of 2015.
**Within each site, each depth, and each cover treatment, the letters mark the statistically significant differences among the topographical positions (p<0.1).*

Weather

At both Kellogg and Mason from 2011-2015, weather trends followed a temperate pattern with high monthly average temperatures in the summer around 20 C and low monthly average temperatures in the winter around -5 C. Precipitation varied between the sites. Kellogg had consistently higher monthly average precipitation than Mason. Graphs of the monthly averages of temperature and precipitation can be found in the Appendix.

CHAPTER FOUR – DISCUSSION

The highest carbon content of main crops, corn and soybean, were observed in depressions, followed by summit, and were lowest in the slope. However, an opposite trend was observed in above ground rye biomass. There were no significant differences in carbon content of main crops in the presence or absence of the cover crop. Positive effects of lower topography on main crop yield observed in this study are consistent with published results where the yield of both corn and soybean are higher in depression or concave sites in the field (Kravchenko and Bullock, 2000; Jiang and Thelen, 2004; Da Silva and Alexandre, 2005; Timlin et al., 1998).

Ladoni et al. (2016), a study that used micro-plots located inside of large agricultural fields close to the Kellogg site, observed greater rye growth in depression positions compared to summit and slope, which is not consistent with my observations. There are two possible reasons: differences in actual topographical characteristics, and differences in weather patterns. Even though both the sites in this study and the micro-plots in the Ladoni et al study are classified as depression, slope, and summit, this classification is a relative classification at each field site, and pieces of land that are classified the same have many different characteristics. In my study topography was classified as the extremes of each the summit, slope, and depression while in the Ladoni et al. study's larger fields it was more difficult to find the extreme differences between the three classifications. In addition, the Ladoni et al. study was done before my study, so the weather patterns were not the same most importantly in the spring time when a warm, dry spring encourages growth in the depression positions and a cold, wet spring discourages growth in depression positions. Negassa et al. (2015), a study done at the same sites that focused on rye growth and greenhouse gas emissions, observed rye growth and impact consistent with the observed results of my study.

Not included in my study is the portion of carbon that may come from underground biomass including roots and root exudates, which may be significant in explaining the greater impact of the cover crop on the summit and slope positions even though there was less above ground biomass carbon added by the rye cover crop (Gale and Cambardella, 1998). In the summit and slope positions there may have been higher amounts of below ground biomass when compared to the depression position. Plants in the summit and slope would need to devote more energy to finding soil water and extending their root system than the plants in the depression, as shown by the water retention results from my study (Unger and Kaspar, 1993). At most depths and pressures, the depression position had a high water holding capacity than the summits and slopes. Although the differences were not statistically significant between topographical positions, the slightly higher water holding capacity could impact underground biomass. In addition to soil water, nitrogen availability would follow much of the same trend because of the solubility of the nutrient. The impacts on growth from nitrogen availability would favor the depression position.

Opposite trends in main and cover crops can be explained by different growing seasons. Rye's growing season is during the cold and wet time of the year, when growth is the depression is difficult because of the addition coolness and wetness and growth on the summits and slopes are promoted because they are slightly drier and warmer. The main crop, corn and soybean, grow during the summer when, if the weather is dry, it is advantageous to be in the depression because of the increased water holding capacity. Carbon inputs from above ground biomass, including the main crop and the cover crop, were slightly higher in the no cover treatment in the depressions and slope. This is attributed to the more optimal growing season of the main crop for those positions. In the summit position, the cover treatment had a slightly higher carbon input than in the treatment with no cover. These rough estimates of above ground carbon inputs along with substantial rye growth and a smaller difference in main crop yield between cover and no cover indicates that in my study the largest effect in terms of carbon inputs from cover crop presence could be expected in the summit position.

Even though my study did not include a microbial component, it is important to note the microbial differences when utilizing a cover crop in rotation with corn and soybean. In the presence of cover crops, microbial activities are promoted which can increase topographical differences in the soil environment in regards to decomposition (Wickings et al., 2016). Despite each position having drawbacks to microbial activity (e.g. summits and slopes tending to be too hot and dry in the summer and depressions tending to be too cool and wet in the winter) decomposition often happens at a faster rate in depression positions. This may be caused by microbial activity being up to 55% higher in depression positions when compared to summits and slopes (Wickings et al., 2016) Decomposition rates on topographically diverse terrain are difficult to obtain and are not extensively studied because of the spatial variability of factors including soil temperature, soil moisture, and microbial activity. I hypothesized that such differences in microbial activities could have resulted in difference in decomposition rates of the cover crop residues added to the soil.

Consistent with my expectations, rye decomposition was highest in the depression, then slope, and lowest in the summit, a trend that was apparent in both 2015 and 2016 although the magnitude of decomposition was different between those years. CO_2 emissions were also highest in depression, but lowest in the slope. The presence of the cover crop on CO_2 emissions was only significantly different in the depression position. In a study done at the same site as mine, the presence of cover crops increased CO_2 emissions across all studied topographical positions; summits, slopes, and depressions (Negassa et al., 2015). In the same study, the magnitude of the effect of cover crops on CO_2 emissions was inversely proportional to the biomass input from the cover crop, meaning that the less cover crop biomass accumulated the less of an impact it had on increasing CO_2 emissions (Negassa et al., 2015). These findings are consistent with the findings in my study.

Decomposition and CO_2 emissions are mainly controlled by soil moisture, climate variables, and C/N ratios that drive microbial activity (Raich and Potter, 1995; Trumbore et al., 1996; Harrison-Kirk et al., 2013). Better soil moisture and soil temperature conditions leading to an increase of microbial activity and diversity explain the higher decomposition and CO_2 emissions in depressions. Weather patterns in 2015 and 2016 were markedly different during the rye litter decomposition study, which accounts for the difference in magnitude of decomposition between the years. The spring of 2015 was dry, while the spring of 2016 was wet, which led to higher rates of decomposition in the 2016 study year. C/N ratios vary by crop and may be augmented by a fertilizer routine, further fostering microbial activity. Higher rates of decomposition and soil respiration lead to a faster turnover of the added carbon from the main and cover crop, which diminished the impact of cover crops on soil carbon, especially in the depression position.

Particulate organic carbon is the labile form of SOM which responded to differences in topographical gradient and to cover crop presence and is used as an indicator of the amount of stable carbon that will be protected and stored in the soil (Post and Kwon, 2000; Six et al., 2000). Particulate organic carbon was highest in the depression, then summit, and lowest in the slope. In the presence of the cover crop, particulate organic matter was the same across all topographical positions but that was not true in the absence of the cover crop, where significant differences between particulate organic matter values were observed. Particulate organic matter is prone to downhill redistribution through erosion, eventually becoming concentrated in depression areas (Dungait et al., 2013; Cambardella et al., 1994). In my study, erosion could only be in the form of a loss of particulate organic matter. No gains in particulate organic matter could be made because the plots were split by a wide grassed area, so although there may have been a loss of particulate organic matter through erosion from the topographical positions, there was not any POM added through this process. Despite this, if erosional deposition of particulate organic matter is the reason for the distribution of particulate organic carbon, and therefore eventually a more stable form of soil carbon, other factors like main and cover crop growth may not contribute to spatial particulate organic carbon as much. But one of the benefits of using a cover crop is the reduced erosion during the part of the year when the main crop is not growing so erosional deposition of particulate organic matter may not be a large contributor to the spatial variability in topographical gradients in cover crop studies.

Total organic soil carbon followed the trend depression > summit > slope but there were no significant differences between the presence and absence of the cover crop. Kaspar et al. (2006) also observed no significant differences in total soil carbon between the presence and absence of a rye cover crop. Simulated experiments have also found that the presence of a rye cover crop does not increase total soil organic carbon compared to the absence of the cover crop (Basche et al., 2016). Since changes in total soil organic carbon may not be seen until 7 to 10 years or more after changing management practices, like the addition of a cover crop into rotation, the results from the literature and my study are consistent and expected (Duiker and Lal, 1999; Al-Kaisi et al., 2005). This study is shorter than the time it takes to detect significant changes in the long-term pool of carbon. The topographical differences observed in the study were expected as they are controlled by factors with a stronger effect on carbon distribution than the presence of a cover crop. These factors include soil physical properties, such as texture, temperature, and soil water distribution, as well as the erosion and deposition of soil particles across the topographical gradient (Rovira, 2002; Eijsackers and Zehnder, 1990; Andren et al., 1993). For long-term carbon storage, it is important to consider the topographical effects and focus on locations where the effects of cover crops can be used to their highest potential.

Conclusions

General trends in carbon content of the main crop, the cover crop, particulate organic matter, decomposition, and CO_2 emissions cannot by themselves explain the soil carbon results. As shown in Figure 10, the magnitude of the effect of the cover crop on these factors are only significant in the slope and summit positions in relation to particulate organic carbon and the depression position in CO_2 emissions. Overwhelmingly, there is no significant difference between the presence and absence of the cover crop. However, by comparing my study with the literature, a few conclusions can be drawn: 1) Better rye growth and a smaller gap in main crop yield between cover and no cover indicate that the largest effect in terms of carbon input from the presence of a rye cover crop is in the summit position; 2) Higher rates of decomposition and soil respiration (CO_2 emission) lead to a faster turnover of labile carbon, which diminished the impact of cover crops on soil carbon, especially in the depression position; 3) Erosional deposition and redistribution of particulate organic carbon may lessen the effect of the cover crop on the spatial distribution of carbon along the topographical gradient and is an important factor to remember when studying soil carbon on topographically diverse terrain. For long-term carbon storage, it is important to consider the topographical effects and focus on locations where the effects of cover crops can be used to their highest potential. This means that by focusing on cover crop establishment on summits and slopes, cover crops could have the most impact on long-term carbon storage in Midwest corn cropping systems.

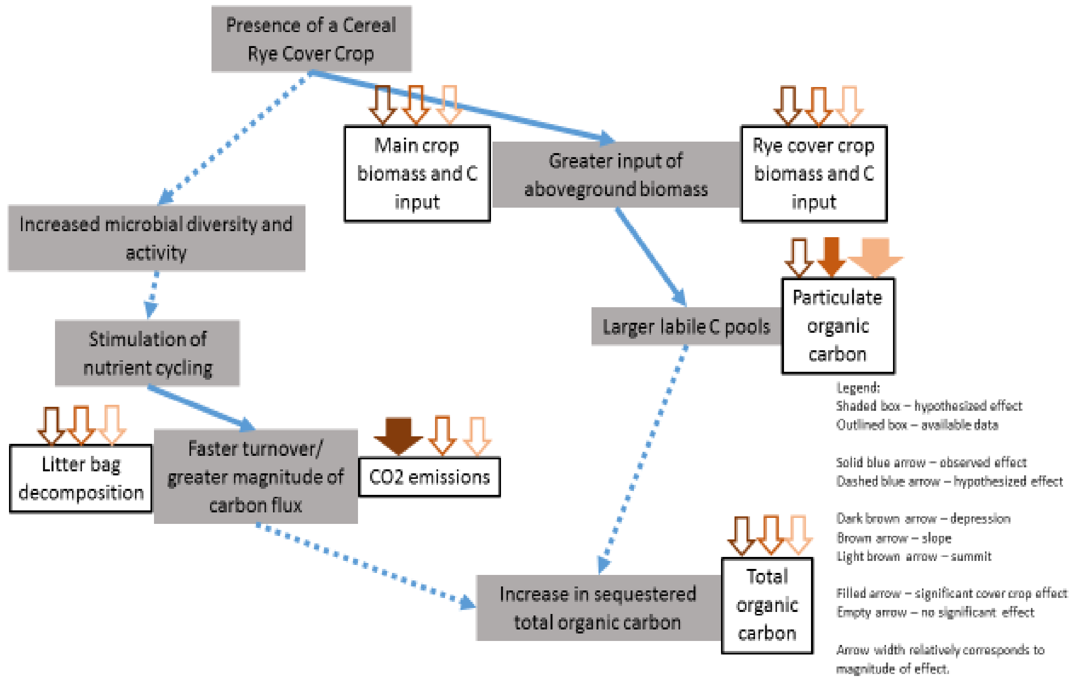


Figure 10. Flowchart depicting hypothesized and observed effects with the factors in this study. *The magnitude of the effect of cover crop on measured variable shown by brown arrows.*

APPENDIX

APPENDIX

Site	Topographical Position	Depth (cm)	Sand (%)	Silt (%)	Clay (%)
Kellogg	Depression	0 - 10	57.5	11.5	31.0
Kellogg	Depression	10-20	46.2	18.7	35.0
Kellogg	Depression	20 - 40	48.0	23.0	29.0
Kellogg	Depression	40 - 60	50.1	22.6	27.3
Kellogg	Slope	0 - 10	64.6	14.0	21.5
Kellogg	Slope	10-20	68.2	16.1	15.8
Kellogg	Slope	20 - 40	72.1	13.0	14.9
Kellogg	Slope	40 - 60	76.7	11.7	11.7
Kellogg	Summit	0 - 10	57.3	8.4	34.4
Kellogg	Summit	10-20	54.1	10.6	35.4
Kellogg	Summit	20 - 40	65.4	21.5	13.1
Kellogg	Summit	40 - 60	82.9	14.0	3.1
Mason	Depression	0 - 10	69.0	7.1	24.3
Mason	Depression	10-20	65.0	7.0	28.4
Mason	Depression	20 - 40	73.8	11.0	15.1
Mason	Depression	40 - 60	70.6	14.3	15.3
Mason	Slope	0 - 10	62.6	12.3	25.5
Mason	Slope	10-20	61.0	14.4	24.9
Mason	Slope	20 - 40	53.9	25.0	21.5
Mason	Slope	40 - 60	54.6	24.0	21.4
Mason	Summit	0 - 10	66.8	9.3	24.1
Mason	Summit	10-20	61.8	13.5	25.1
Mason	Summit	20 - 40	53.9	26.9	19.3
Mason	Summit	40 - 60	56.4	23.5	20.3

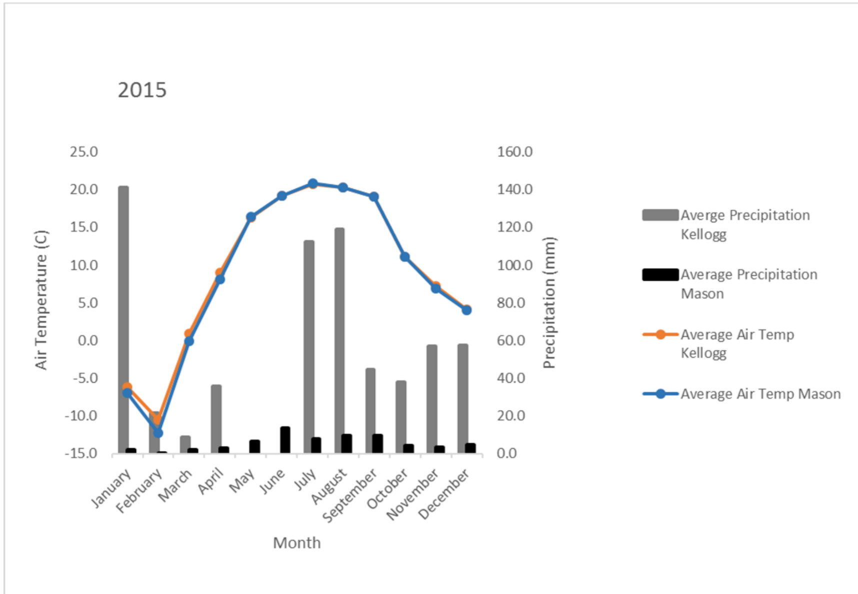
Table 4. Soil texture at Mason and Kellogg for depths 0-10 cm, 10-20 cm, 20-40 cm, and 40-60 cm at three topographical positions (depression, slope, summit) measured at the beginning of the study in 2011.

Site	Year	Date	Fertilizer Form	Fertilized Crop	Fertilizer Application Type	Fertilizer	Nitrogen Applied (kg ha-1)
Kellogg	2011	7/13/2011	liquid	corn	injected between rows	28% UAN	135
Kellogg	2012	5/15/2012	liquid	corn	injected in every row	28% UAN	28
Kellogg	2012	6/29/2012	liquid	corn	injected between rows	28% UAN	135
Kellogg	2013	7/22/2013	solid	corn	broadcast	urea	150
Kellogg	2014	6/12/2014	solid	corn	broadcast	urea	46
Kellogg	2014	7/17/2014	solid	corn	broadcast	urea	46
Kellogg	2015	5/27/2015	solid	corn	broadcast	urea	30
Kellogg	2015	7/6/2015	solid	corn	broadcast	urea	90
Mason	2011	7/11/2011	liquid	corn	broadcast between row	28-0-0	151.2
Mason	2012	5/17/2012	solid	corn	broadcast	urea	46
Mason	2012	7/3/2012	liquid	corn	injected between rows	28% UAN	135
Mason	2013	7/22/2013	solid	corn	broadcast	urea	150
Mason	2014	7/16/2014	solid	corn	broadcast	urea	150
Mason	2015	5/28/2015	solid	corn	broadcast	urea	30
Mason	2015	7/14/2015	solid	corn	broadcast	urea	90

Table 5. Summary of nitrogen fertilizer type, timing, and amount for both sites.

Figure 11. Monthly average air temperature and precipitation at Kellogg and Mason for each year of the study.

A



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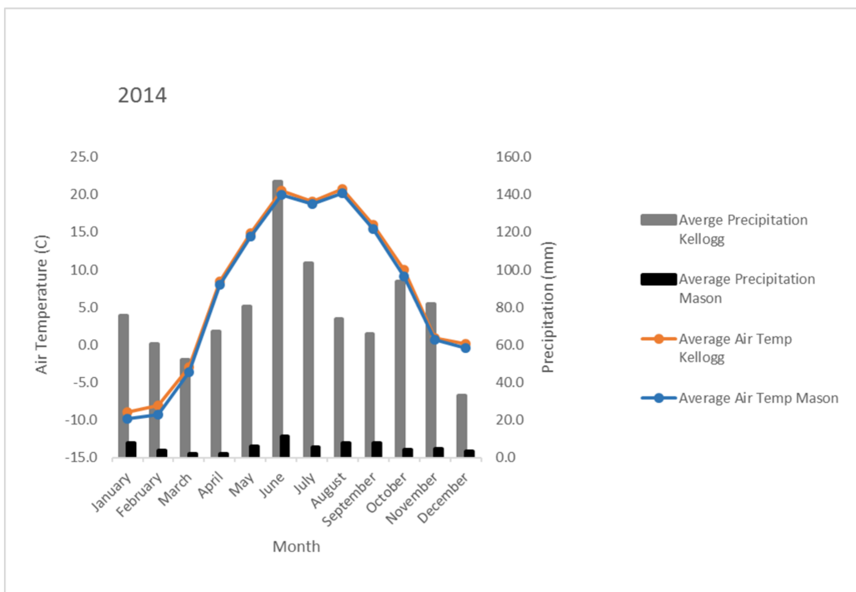

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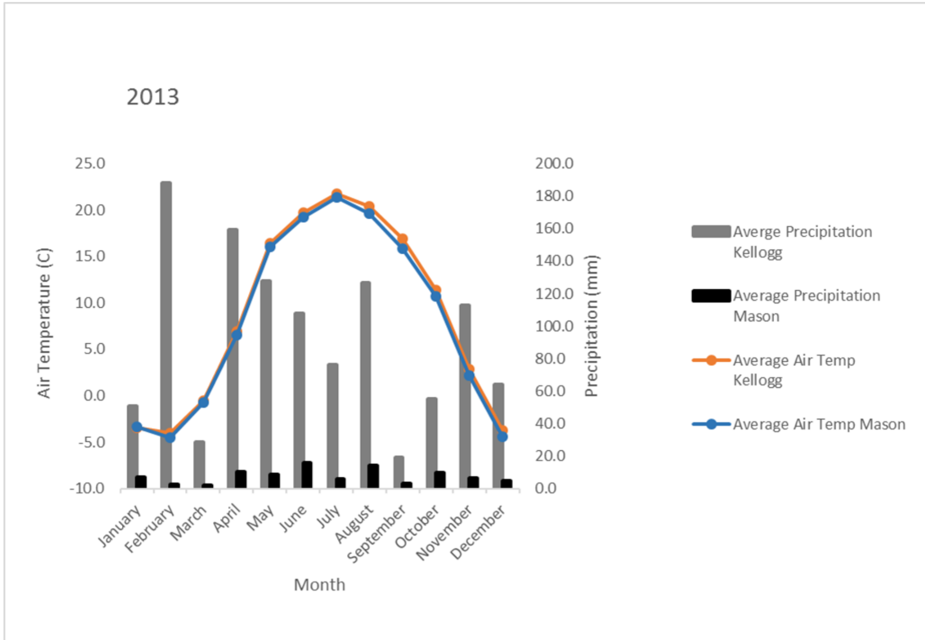

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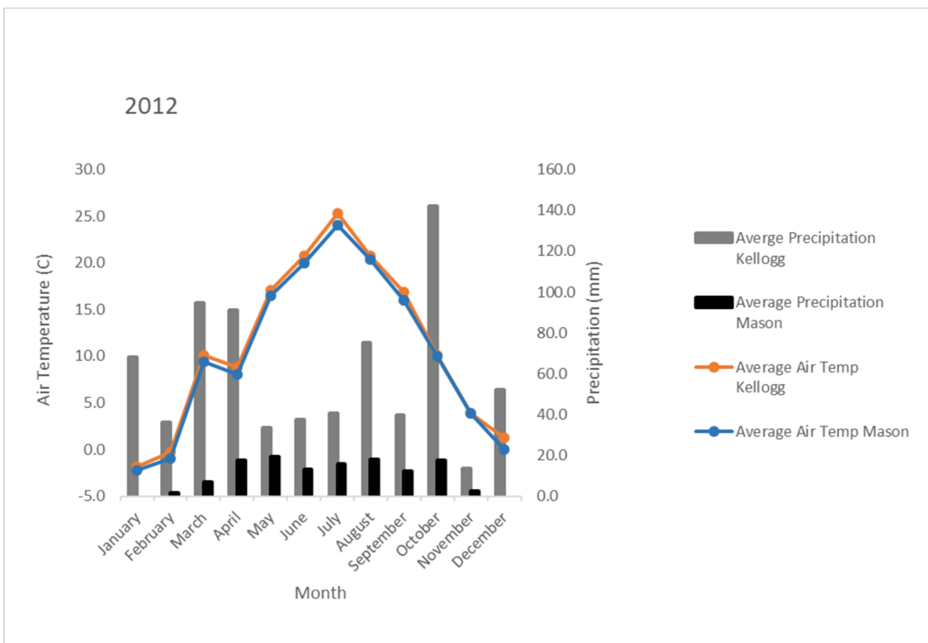

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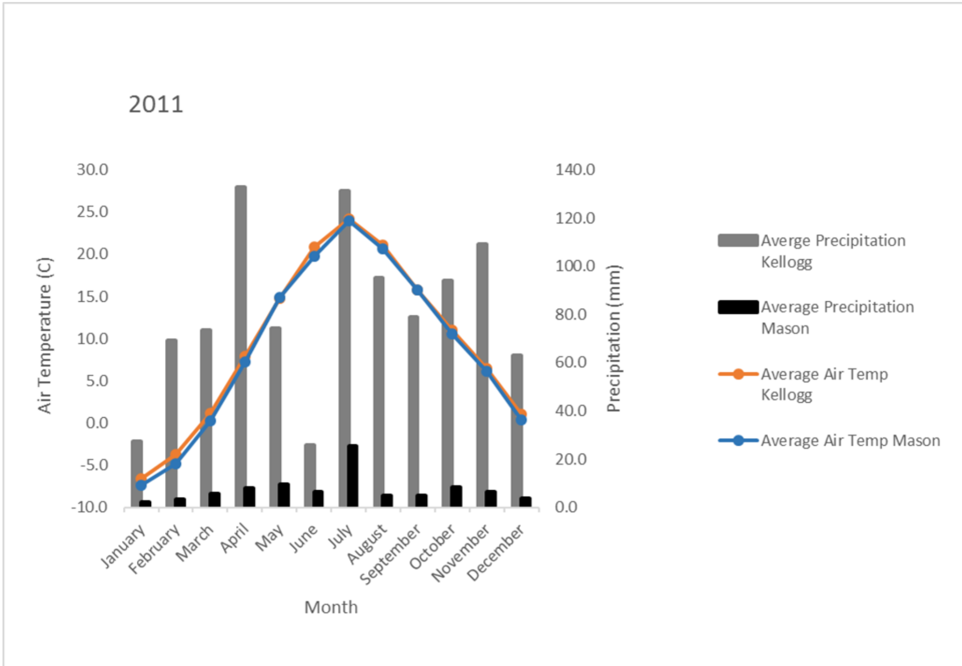

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