

ASSESSING THE POTENTIAL OF PEARL MILLET AS A COVER CROP IN THE
WISCONSIN CENTRAL SANDS

An Abstract of a Thesis
Submitted
In Partial Fulfillment
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Master of Science in Agroecology

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ABSTRACT

The Wisconsin Central Sands (WCS) is a region characterized by sandy and well-drained soils with shallow depths to groundwater, making irrigation important to supporting the profitable potato and vegetable growing industry that resides there. Though research is currently underway to quantify the effects of irrigation on groundwater recharge and evapotranspiration rates, the role played by cover crops has received relatively little attention. Pearl millet (*Pennisetum glaucum*) is of particular interest because it has been shown to repress a common root-lesion nematode (*Pratylenchus penetrans*) found in potato. Pearl millet (PM) has the potential to become an important cover crop grown in the WCS, however, there is information lacking on phenology, photosynthesis, productivity, and water use. This study aims to fill some of the current data void by measuring phenology, productivity, and quantifying water use efficiency (WUE) of PM on a 28 ha commercial vegetable production field in the WCS near Plover, WI. An additional qualitative study was performed through the completion of grower interviews to learn more about cover cropping preferences and adoption in the region. Together with the quantitative data collected, this information will aid in determining how PM can provide for the environmental and ecological needs of the region.

Important metrics for determining PM's significance as a cover crop in the WCS include productivity and water use efficiency. Several different measurements were taken to help gauge these metrics. Above and below ground biomass and leaf area index (LAI) were measured to determine net primary productivity (NPP) and rate of phenologic development, respectively. Water use and evapotranspiration were quantified using hydrological data from infield passive capillary lysimeters and soil moisture probes in a companion study. Soil

electrical conductivity (EC) was mapped and data used to evaluate relationships between EC, elevation, and productivity. Impact of soil texture and soil organic carbon (SOC) on productivity was assessed using soil samples taken at two depths. An end of season plant tissue analysis was performed to determine percent carbon and nitrogen. Finally, leaf photosynthetic response to light, temperature, and vapor pressure deficit were measured in the field.

Pearl Millet consistently had high photosynthetic rates over its growing period of 75 days, but reached a peak rate of $49.1 \mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$ at 35°C , the highest temperature at which measurements were taken. Soil texture significantly impacted SOC and EC. Elevation and EC had no significant effect on productivity independently, but significant differences were present at certain combinations of EC and elevation categories. Mean NPP across the field was $14.3 \text{ Mg DM ha}^{-1}$ and the average root to shoot ratio was 0.11. Average maximum LAI of $6.24 \text{ m}^2\text{m}^{-2}$ was attained only 45 days after planting. Water use efficiency was high relative to other cover crops grown in the region with an average of $55.4 \text{ kg DM ha}^{-1} \text{ mm}^{-1}$. The ability of PM to rapidly accumulate biomass and efficiently use water aligns with the water conservation goals of the WCS. Growers interviewed from the region were generally willing to experiment with new cover crop varieties, such as PM, but requested more comprehensive research be performed first.

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Dr. Christopher Kucharik, Professor, Department of Agronomy and
the Nelson Institute, Advisor

DEDICATION

For my family, Greg, Julie, Alison, and Andrew Leytem who have helped me grow and develop into the person I am today, and for my fiancé, Lexy Frautschy, who has encouraged me throughout this whole process and is there for me always. I couldn't have completed this degree without all of your continued love and support.

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CHAPTER 1:

INTRODUCTION AND LITERATURE REVIEW

The concept of multifunctionality is rife in farming. The Organisation for Economic Co-operation and Development published a report in 2001 that explained the meaning of multifunctionality as the fact that an economic activity may have multiple outputs and, therefore, may contribute to several societal objectives at once. “Multifunctionality is thus an activity oriented concept that refers to specific properties of the production process and its multiple outputs” (Maier and Shobayashi 2001). Farming is certainly a business that produces multiple outputs, some intentional, others less so. These outputs impact the surrounding community and occasionally cause tension. For example, agricultural runoff has been linked to hypoxia in the Gulf of Mexico and unsafe nitrate levels in drinking water (Mitsch et al. 2001). Reconciling these negative externalities with individual farming practices for necessary food production is a challenge for farmers worldwide.

Growers must consider a number of factors when planting their crops and/or raising their livestock. These factors include inputs, irrigation rates, seed source and variety, planting date, efficient and ethical ways to harvest crops and livestock, how to manage employees, who to buy and sell equipment or products to, and much more. All of these elements impact the health of the land and those that rely on it for their livelihood. A great deal of pressure is placed on growers to make both the most economic and environmentally conscious business decisions. While it may seem that these two factors are at odds, perhaps there is a way to reconcile the two. Practices that may help decrease the environmental impact of farming whilst allowing it to remain an economically positive venture are being investigated worldwide. One such practice is cover cropping. Though not a new practice, cover cropping

is promising as an agricultural best management practice and is encouraged as such. Many growers in the Wisconsin Central Sands (WCS) region rely on cover cropping as a means of soil preservation. For the purposes of this study, cover crops are defined as crops grown during the shoulder seasons with the intent to protect and improve soil. This thesis will look at the multifunctional benefits of cover cropping systems and their adoption drivers in the WCS and present new data on phenology, productivity, and water use efficiency, including drivers of variability in above and below ground productivity such as soil texture and soil volumetric water content, of a lesser studied cover crop: pearl millet.

The WCS is a 630,000 ha region characterized by sandy, well drained soils located between the Wisconsin River to the west and the Fox and Wolf rivers to the right. The area was settled in the mid 1800's, several decades later than its surrounding areas as the land was not well suited for agricultural production. Prior to settlement, native prairies, oak savannas, and wetlands dominated the landscape. Within a few decades, the majority of the region was converted for use as agricultural land. Alteration of the native landscape increased soil erosion, depleted already low soil organic carbon (SOC) stocks, and further reduced soil water holding capacity (Goc 1990; Lal 2004). Intensive crop rotations reduced the nutrient content of the soil further reducing its fertility. The combination of dry weather and bare, extremely sandy soils eventually led to the "Wisconsin Dust Bowl" in the 1930's. The event was a smaller scale, more localized version of the Dust Bowl that engulfed the South West United States. Record low rainfall in combination with the quickly draining soil led to extremely low productivity agriculture, famine, and hardships for the people of the WCS. (Goc 1990) Most of the farmers who made it through the disaster had abandoned grain farming in the early 20th century and switched to dairying, much like the rest of Wisconsin.

Eventually farmers began growing cash crops, like potatoes, and harvesting wild crops such as wiregrass, sphagnum moss, berries, and trees for milling to supplement their income. (Goc 1990)

Eventually modern farming techniques began to take hold. The adoption of irrigation technologies in the 1950s allowed for the return of productive agricultural to the region. Wisconsin is now one of the nation's top producers of canning vegetables (i.e. sweet corn, peas, green beans), and potatoes; a large portion of which are grown in the WCS. Several large food manufacturing and distribution companies, such as Del Monte and Frito Lay, reside and invest in the region, further justifying its economic importance to the state.

The unique geology of the WCS provides an ideal environment for the crops grown there. A thick (>30m) mantle of sandy quaternary sediment overlying low permeability rock affords optimal drainage while irrigation assures that there is a constant supply of water to crops. However, the region is also characterized by shallow glacial aquifers that are strongly connected to local surface waters (Kraft and Stites 2003). Studies have linked the decreased base flows in many stream headwaters to groundwater pumping for irrigation. The Wisconsin department of natural resources (WDNR) reports that there are approximately 3,000 high capacity wells in the region; representing half of all irrigation wells in Wisconsin. In addition to decreases in surface water depths, groundwater pumping has also been hypothesized as a potential cause for increased evapotranspiration in the region (Kraft et al. 2012).

The high rates of irrigation in the region have led to water use becoming an increasingly important and controversial issue in the WCS. Though research is currently underway to quantify the effects of irrigation on groundwater recharge and evapotranspiration rates, relatively little attention has been paid to the role of cover crops.

Cover cropping is a nearly universal practice in the WCS, primarily as a means of preventing soil erosion. Cover crops are also useful for increasing soil organic matter, improving soil structure, adding nutrients to the soil through mineralization, weed suppression, and increasing soil water holding capacity over time (Creamer and Baldwin 2000; Clark 2007). Cover crops could play an important role in improving soil composition and fertility, and increasing water holding capacity, thus helping to reduce the amount of irrigation needed in the future.

Oats and cereal rye are some of the most common cover crop choices in the WCS, but others, such as winter wheat and sorghum sudan grass are grown as well. Pearl millet (PM) (*Pennisetum glaucum*), a C4 warm season annual grass species, is a lesser-known cover crop in the WCS. The drought and heat tolerance of PM and the potential use of it as a biological control for the root lesion nematode (RLN), *Pratylenchus penetrans* (Ball-Coelho et al. 2003; Dauphinais et al. 2005; Bélair et al. 2005; MacGuidwin and Knuteson 2012) make it a promising cover crop choice for the region. Relatively little research has been conducted on PM in the WCS resulting in a biological and biophysical data void for the region.

Much of the interest in pearl millet as a cover crop in the WCS stems from its ability to suppress the root lesion nematode in subsequent potato crops. The RLN is a common plant parasitic nematode found in the soil that can reduce yields in many crops including potato (Ball-Coelho et al. 2003). It also contributes to potato early dying (PED), a disease that reduces tuber yield and quality through its interactions with the soil pathogen *Verticillium dahliae* (MacGuidwin and Rouse 1990; Saeed et al. 1997). To combat PED, many potato growers in the WCS choose to apply synthetic fumigants. Sodium N-methyldithiocarbamate (metam sodium) is most commonly used in the WCS and is very effective at controlling both

RLN and verticillium populations. However, fumigants like metam sodium have also been shown to decrease positive soil microbial populations and negatively effect soil processes like C and N mineralization (Ibekwe et al. 2001; Collins et al. 2005).

Agricultural fumigants also pose a threat to humans and other animals at or near the site at which they are administered. When applied, metam sodium produces the bioactive respiratory irritant methyl isothiocyanate (MITC), which is rapidly transformed into methyl isocyanate (MIC). MIC is a toxic respiratory irritant that can be deadly if inhaled (Woodrow et al. 2014). These risks prompted the Environmental Protection Agency (EPA) to put forth a new set of safety requirements for soil fumigants in 2013 to protect agricultural workers and nearby individuals. The Wisconsin Department of Agriculture, Trade, and Consumer Protection has its own set of requirements that growers must adhere to in addition to the EPA's regulations. For instance, growers must provide a 72-hour written notice to the county public health agency and to residences within a 0.4 km prior to fumigating. Some measures differ depending on the method of application. For instance, metam sodium may not be applied by chemigation if the air temperature exceeds 27°C, the soil temperature at 13-15cm exceeds 21°C, or more than 2 cm of rain is forecast within 6 hours after application. Fumigants can also be injected beneath the soil surface by knife rig injection, but only if the soil temperature at 13-15cm is at or below 24°C. If fumigant is applied directly to a site it must be covered with a tarp or other impermeable barrier after application. In addition, proper certification and licensing, monitoring, and recordkeeping are imperative when it comes to safe application of agricultural fumigants. (DATCP 2013a; DATCP 2013b).

Prior to the strengthening of regulations regarding fumigation many growers applied fumigants themselves. Currently, many operations contract out their fumigation needs

because they do not have the proper equipment or licensing. Larger operations that can afford to purchase necessary equipment and pay for labor and licensing may still choose to do their own application. However, for many small and mid-sized growers this is not an option. Custom application through a chemical company costs about \$185 ha⁻¹ in the Central Sands (TH Agri-Chemicals, Inc. 2016). Custom application of metam sodium through a chemical company in the WCS at a typical rate of 228 L ha⁻¹ costs between \$568 and \$618 ha⁻¹ including custom application fee of \$185 ha⁻¹ (TH Agri-Chemicals, Inc. 2016). Chemical manufacturers recommend applying 351- 468 L ha⁻¹ depending on the crop, which would raise fumigation costs considerably (AMVAC 2005; AMVAC 2013). In contrast, pearl millet costs between \$50 and \$70 per 22.7 kg bag depending on the supplier, variety, and quantity available (Jay-Mar, Inc. 2016). Central Sands pearl millet grower, and farmer collaborator for this study, seeds 11.2 kg ha⁻¹ resulting in an average planting cost around \$74 ha⁻¹. Compared to fumigation at >\$560 ha⁻¹ those savings are significant.

Yet despite the risks, challenges, and expense associated with fumigation, many growers still choose to include it in their management schemes because of its ability to effectively manage soil pests and pathogens. In Fall 2014 there were 2.2 million kg of metam sodium applied to potato fields across Wisconsin (USDA-NASS 2014). This represents 46% of the total planted potato acres that year. When additional fumigants, such as chloropicrin, are taken into account total fumigated acres of potatoes in Wisconsin become closer to 80% (MacGuidwin and Knuteson 2007). Cover crops used as biological controls for pests like the RLN could offer a safe, less expensive, and more environmentally friendly alternative to fumigation for growers.

Biofumigation has been defined as a sustainable strategy to manage soil-borne pathogens, nematodes, insects, and weeds. Initial research focused strictly on the suppressive properties of *Brassica* crop tissues such as oilseed radish, mustards, and arugula. However, the topic has since been broadened to include other plant and animal residues (Ploeg 2008). The biofumigant effects found in brassicas are caused by the production of glucosinolates in plant tissues. Various breakdown compounds form from these glucosinolates when plant tissue is damaged, including isothiocyanates or ITCs (Sarwar et al. 1998). ITC is the same chemical found in the fumigant metam sodium. The specific mechanism responsible for pearl millet's nematode suppressing abilities, however, is not well understood.

Pearl millet's potential to suppress the RLN has been demonstrated in several studies in and around the region. Research carried out in Quebec and Ontario investigated varieties of forage and grain pearl millet as possible biological controls for the RLN in potato and tobacco production. They found that subsequent crop yields following a pearl millet treatment were greater than or equal to treatments using other crops with or without fumigation (Ball-Coelho et al. 2003; Bélair et al. 2004; Bélair et al. 2005; Amankwa et al. 2006). They concluded that pearl millet has RLN repressive properties and is a viable alternative for their management. Other cover crops, such as oats, rye, brassicas, and legumes, are good hosts for the RLN, allowing it to multiply in their roots and putting subsequent crops at higher risk of infection (Bélair et al. 2005; Amankwa et al. 2006; Macguidwin et al. 2012).

One study compared forage pearl millet and rapeseed (*Brassica napus*) cover crops managed as green manures, both with and without solarization, to determine which treatment best controlled RLN populations (Macguidwin et al. 2012). On-farm trials were also

evaluated in the WCS comparing forage pearl millet to a commercial biofumigant mustard mix, oat, and legumes. Results from the field study confirmed that brassicas are good hosts for the RLN, allowing population densities to greatly increase in the roots by the time plant tissues are incorporated for biofumigation. Solarization of brassica crop residues was also recommended to ensure maximum biofumigant effectiveness. Pearl millet was not a good host for the RLN and did not appear to benefit from the use of soil covers for solarization, but did effectively manage RLNs both in the field study and on-farm trials. It was also discovered that PM is extremely frost sensitive and requires a spring or mid summer planting date to ensure adequate production of biomass prior to first frost. This could make it more challenging for growers to fit PM into their crop rotations.

Though the mechanism responsible for PM's nematode suppression is unknown, the grower and farmer collaborator on this study believes the plant roots are responsible for limiting nematode populations based on his experiences. When there is a shortage of livestock forage in the area he harvests the pearl millet biomass and sells it for roughly \$250 ha⁻¹. He does not feel removing above ground biomass affects the ability of the millet to adequately control nematodes and he benefits from the additional income the sale of the crop provides (Isherwood per comm.). Additional research quantifying the typical productivity of PM in the WCS would be useful for determining expected biomass harvest, and therefore the potential to sell PM as forage while still realizing its nematode suppression benefits.

Despite its sensitivity to frost, PM has been recommended as a cover crop and biological control for the RLN in the WCS (MacGuidwin and Knuteson 2007). A widespread shift toward using pearl millet instead of fumigation could have profound environmental and economic impacts for the region. Like other cover crops, pearl millet can help improve soil

structure and quality, water infiltration, and reduce wind erosion. In addition to these benefits research has confirmed its effectiveness at controlling the RLN is similar to synthetic fumigants, but unlike commercial chemicals, pearl millet is not dangerous to humans. Pearl millet has been successfully fed to livestock including beef and dairy cattle, broilers, and goats (Mustafa 2010). Selling pearl millet as a forage crop could provide another source of income for growers, further increasing the viability of pearl millet as a cost effective cover crop option.

The purpose of the research involved in this thesis was to learn more about grower perceptions and drivers of cover cropping in the WCS, and specifically the phenology and productivity of PM. The quantitative research performed can help to determine whether or not PM is well suited for production in the region and if it has the potential to be a profitable cover crop option. The effects of several soil and water variables, including soil texture, EC, and soil moisture, were measured on above and belowground biomass production and photosynthesis. Data collected can be used to motivate further research, assess drivers of production variability, and to parameterize, calibrate, and validate numerical agroecosystem models. These models can be applied across large landscapes to characterize the regional impacts of land use policy/decision-making on water, carbon, and nutrient cycling and in general ecosystem services such as groundwater. Incorporating pearl millet into Agro-IBIS, an agroecosystem model already being used to study the WCS region, will allow more representative rotations to be modeled and thus produce improved environmental predictions. These predictions can be used to shape agricultural and environmental policy for the region.

The second chapter of this thesis will discuss the biophysical attributes of pearl millet. Phenological growth, productivity, and water use of pearl millet were studied on a 28 ha

commercial vegetable production field in the Central Sands. Data was collected on leaf area index using a LI-COR 2200 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE), leaf photosynthetic response to light, temperature, and vapor pressure deficit using a LI-COR 6400 portable photosynthesis system (LI-COR Inc., Lincoln, NE), and above and belowground net primary productivity (NPP) using replicated biomass sampling and in-growth root cores, and end of season plant tissue analysis to determine percent carbon and nitrogen. Data from soil electrical conductivity mapping and particle size analysis of soil samples were used to assess the impact of soil texture on productivity. Hydrological data from in-field passive capillary lysimeters and soil moisture probes were used to quantify water use efficiency (WUE; kg of dry matter per mm evapotranspiration). Because of the potential as a multifunctional cover crop, it is important to learn more about pearl millet's phenology, growth, and WUE to better understand how it fits into the Central Sands agroecosystem.

The third chapter of this thesis summarizes qualitative research performed on cover cropping practices in the Central Sands. Twelve growers were interviewed from the region to learn more about how they make decisions regarding cover crops on their respective operations. The goals of this research were to gain a better understanding of what factors influence the cover crops growers select, and what functionality they are looking for in new cover crop varieties. These data can be used to better understand cover crop adoption practices and drivers. It can also guide future research on specific cover crop varieties by helping researchers understand what factors are important to growers when considering various cover crops options.

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CHAPTER 2
PRODUCTIVITY AND WATER USE OF PEARL MILLET IN THE WISCONSIN
CENTRAL SANDS

ABSTRACT

Pearl millet (*Pennisetum glaucum*) has the potential to become an important cover crop in the Wisconsin Central Sands (WCS), a region characterized by sandy and well-drained soils with shallow depths to groundwater. Irrigation is common practice in the region; however, water use is becoming increasingly controversial. Pearl millet (PM) is a C4 annual grass species known for its heat and drought tolerance. It has also been shown to suppress the root-lesion nematode (*Pratylenchus penetrans*), a common potato pest. Information is lacking on PM photosynthetic response, productivity, phenological growth, water use, and impact of soil variability on productivity in the WCS. This study was performed on a 28 ha commercial vegetable production field in the WCS to study PM phenology, productivity, and water use efficiency. Pearl millet photosynthetic response to light, temperature, and vapor pressure deficit were studied using a LI-COR 6400 portable photosynthesis system (LI-COR Inc., Lincoln, NE). Assimilation rates favored high temperatures and soil volumetric water content but were also maintained in cool, dry conditions. Above and belowground net primary productivity (NPP) were measured using biomass sampling and in-growth root cores. Mean aboveground net primary productivity (ANPP) across the field was 13.1 Mg DM ha⁻¹ and average root to shoot ratio was 0.11. Soil particle size and carbon content were measured using samples from two soil layers and a Coulter LS230 (Beckman-Coulter Inc., Miami, FL). Data were used to assess the impact of

soil texture on productivity. End of season plant tissue analysis of PM dry matter revealed a carbon to nitrogen ratio of 30.7. Leaf area index was measured using a LI-COR 2200 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE) and peaked at $6.24 \text{ m}^2 \text{ m}^{-2}$ approximately 45 days after planting. Water use was quantified using hydrological data from infield passive capillary lysimeters and soil moisture probes (Drain Gauge G3, Decagon Devices Inc., Pullman, WA). Water use efficiency averaged at $55.35 \text{ kg DM ha}^{-1} \text{ mm}^{-1}$. An assessment of data from soil electrical conductivity mapping showed that elevation and EC had no significant effect on productivity independently, but significant differences were present at certain combinations of EC and elevation categories. Soil texture was significantly related to SOC, EC, and elevation to some degree at both sampling depths, but had little overall affect on productivity. Pearl Millet maintained high levels of productivity and water use efficiency throughout the study despite variations in soil and environmental conditions in the WCS.

1. INTRODUCTION

The Wisconsin Central Sands (WCS) is a 630,000 ha region characterized by sandy, well drained soils located between the Wisconsin River to the west and the Fox and Wolf rivers to the right. The area was settled in the mid 1800's, several decades later than its surrounding areas as the land was not well suited for agricultural production. Prior to settlement, native prairies, oak savannas, and wetlands dominated the landscape. Within a few decades, the majority of the region was converted for use as agricultural land. Alteration of the native landscape increased soil erosion, depleted already low soil organic carbon (SOC) stocks, and further reduced soil water holding capacity (Goc 1990; Lal 2004). Intensive crop rotations reduced the nutrient content of the soil further reducing its fertility. The combination of dry weather and bare, extremely sandy soils eventually led to the "Wisconsin Dust Bowl" in the 1930's. Record low rainfall in combination with the quickly draining soil led to extremely low productivity agriculture, famine, and hardships for the people of the WCS. Most of the farmers who made it through the disaster had abandoned grain farming in the early 20th century and switched to dairying, much like the rest of Wisconsin. They also began growing cash crops, like potatoes, and harvesting wild crops to supplement their income. (Goc 1990)

Eventually modern farming techniques began to take hold. The adoption of irrigation technologies in the 1950s allowed for the return of productive agriculture to the region. Wisconsin is now one of the nation's top producers of canning vegetables (i.e. sweet corn, peas, green beans), and potatoes; a large portion of which are grown in the WCS.

The unique geology of the CS provides an ideal environment for the crops grown there. A thick (>30m) mantle of sandy quaternary sediment overlying low permeability rock

affords optimal drainage while irrigation assures that there is a constant supply of water to crops. However, the region is also characterized by shallow glacial aquifers that are strongly connected to local surface waters (Kraft and Stites 2003). Studies have linked the decreased base flows in many stream headwaters to groundwater pumping for irrigation. The Wisconsin department of natural resources (WDNR) reports that there are approximately 3,000 high capacity wells in the region; representing half of all irrigation wells in Wisconsin. In addition to decreases in surface water depths, groundwater pumping has also been hypothesized as a potential cause for increased evapotranspiration in the region (Kraft et al. 2012). Because of this, water use is becoming an increasingly important and controversial issue in the WCS. Though research is currently underway to quantify the effects of irrigation on groundwater recharge and evapotranspiration rates, relatively little attention has been paid to the role of cover crop water use. Cover cropping is a nearly universal practice in the WCS, primarily as a means of preventing soil erosion. They are also useful for increasing soil organic matter, improving soil structure, adding nutrients to the soil through mineralization, weed suppression, and increasing soil water holding capacity over time (Creamer and Baldwin 2000; Clark 2007). For the purposes of this study, cover crops are defined as crops grown during the shoulder seasons with the intent to protect and improve soil. In short, cover crops are an important management tool in the WCS and have the potential to help reduce the amount of irrigation needed in the future.

Oats and cereal rye are some of the most common cover crop choices in the WCS, but others, such as winter wheat and sorghum sudan grass are grown as well. Pearl millet (*Pennisetum glaucum*), a C4 warm season annual grass species, is a lesser-known cover crop in the WCS. It's drought and heat tolerance, and potential use as a biological control for the

root lesion nematode (RLN), *Pratylenchus penetrans* (Ball-Coelho et al. 2003; Dauphinais et al. 2005; Bélair et al. 2005; MacGuidwin et al. 2012) make it a promising choice for the region. Relatively little research has been conducted on Pearl millet (PM) in the WCS resulting in a biological and biophysical data void for the region.

One caveat to growing PM in the WCS is that it is extremely frost sensitive and therefore requires a spring or mid summer planting date to ensure adequate production of biomass prior to first frost (MacGuidwin and Knuteson 2012). This could make it more challenging for growers to fit PM into their crop rotations.

Despite its sensitivity to frost, pearl millet has been recommended as a cover crop and biological control for the RLN in the WCS (MacGuidwin and Knuteson 2012). Like other cover crops, pearl millet can help improve soil structure and quality, water infiltration, and reduce wind erosion. In addition to these benefits research has confirmed its effectiveness at controlling the RLN is similar to synthetic fumigants, but unlike commercial chemicals, pearl millet is not dangerous to humans. It is a sensible choice for growers in the WCS, as it is highly productive even on dry, sandy soils (Ong and Monteith 1985; Lee et al. 2012). High water use efficiency contributes to PM's ability to produce high biomass yields with relatively little water (Payne 1997). This is an increasingly important attribute for cover crops in the WCS as agricultural water use becomes more controversial in the region. In addition, PM has been successfully fed to livestock including beef and dairy cattle, broilers, and goats (Mustafa 2010). Selling pearl millet as a forage crop could provide another source of income for growers, further increasing the viability of pearl millet as a cost effective cover crop option.

This study aims to improve the overall understanding of PM's phenology, productivity, water use, and response to variations in soil texture and water content in the WCS. This information will help determine whether it is a good cover crop choice for the region based on the ecosystem services provided. Specifically, does it require an excessive amount of water to produce high levels of biomass? How quickly does it germinate and emerge after planting? How much time after planting is needed to reach peak biomass? How much root biomass is produced relative to aboveground biomass? How does assimilation vary as a function of air temperature and soil moisture? Is productivity significantly affected by variation in soil texture, soil carbon, soil electrical conductivity, or elevation? To answer these questions, several soil and water variables were measured, as well as above and belowground biomass production, and photosynthesis. The study took place on a 28 ha commercial vegetable production field in the WCS.

2. MATERIALS AND METHODS

2.1 Study Site

2.1.1 Land Use History

The study was conducted in the WCS on a 28 ha commercial vegetable production field in Plover, WI. The field (center) is located at 44° 25' 11" N and 89° 29' 36" W. Average elevation across the field is 334.6 m. Prior to its settlement in the 1850s the area was comprised of native prairies, oak savannas, and wetlands. Settlers began converting lands for agricultural use, beginning with grain farming, (i.e. corn, rye, and buckwheat), but shifted to dairying (alfalfa and other forage crops) in the early 20th century. Irrigation practices began in the 1950's and led to the present farming system in the WCS. (Goc 1990)

2.1.2 Soil Classification

The field site is gently sloping and the majority of soils present are classified as the well-drained Richford series (loamy, mixed, superactive, mesic Arenic Hapludalfs) (Figure 1.1; Table 1.1) with some well-drained Rosholt series (Coarse-loamy, mixed, superactive, frigid, Haplic Glossudalfs) and Billet series (Coarse-loamy, mixed, superactive, mesic Mollic Hapludalfs) also present (Otter and Fiala 1978; USDA-NRCS 2016).

2.1.3 Regional Climate

Mean summer temperature and precipitation for the region are 19.83 °C and 31.01 cm total respectively (Table 1.2). Average temperature in July and August 2015 was generally consistent with historic summer and monthly averages. Temperature in September, however, was 3.19 °C higher than the 30-year average for September. Total precipitation in July, August, and September was 12.17 cm higher than the 30-year average.

2.2 Site Management

Production crops are grown rotationally and include potatoes, sweet corn, sweet peas, soybean, and occasionally wheat. Cover crops typically grown at the study site include oats, rye, and pearl millet, with oats being the most common. Sweet peas were planted on the study field 5/22/15 and harvested 7/23/15. Pearl millet was planted shortly after (7/24 and 7/25) using a Brillion drill with bed packer at a $\sim 11 \text{ kg ha}^{-1}$ seeding rate to an approximate depth of 1cm. The crop was irrigated after planting to swell the seed, promote germination, and to help with establishment. Plants began germinating on 7/27/15 and irrigation ceased August 16. Total irrigation in that three-week period amounted to 43.2 mm. No fertilizers, herbicides, or pesticides were applied to the pearl millet.

2.3 Soil Electrical Conductivity

Apparent soil electrical conductivity (EC) has been evaluated as a useful and time saving tool for site-specific soil and water management (i.e. precision agriculture) as it can save considerable time and labor by eliminating extensive soil sampling (Farahani et al. 2005). Soil EC is a measure of soil salinity as influenced by a number of physic-chemical properties including soluble salts, mineralogy, bulk density, soil temperature, soil water content, and organic matter (Corwin and Lesch 2005a). Measurements can be applied at field scale to predict spatio-temporal variability in edaphic soil properties including salinity, texture, water content, and organic matter (Corwin and Lesch 2005b). Low EC values generally indicate sandier soils while higher levels indicate greater silt and clay content.

For this study, soil electrical conductivity (EC) was measured prior to planting in spring 2015 using a Veris® 3150 in 18 m transects across the field when soil moisture was approximately at field capacity ($0.2242 \text{ m}^3 \text{ m}^{-3}$ at -10 kPa) (Precision 2012). Thirteen sampling plots were created within the field based on the EC mapping results and topography, using the same methods suggested for precision irrigation applications (Corwin and Lesch 2005a; Farahani et al. 2005). Sampling plots were used to collect additional data on soil texture, plant biomass and net primary productivity, and phenology. Electrical conductivity was delineated by one standard deviation from mean subsoil EC to create four distinct EC zones over the field. Zones less than one ha in size were excluded. Zone one had an average EC value of 2.19 dS m^{-1} . Zones two, three, and four had averages of 2.82, 3.48, and 4.18 dS m^{-1} , respectively (Fig. 1.2; Table 1.3). Topographic variability across the field was accounted for by creating three distinct elevation zones delineated by approximately one standard deviation from the mean. Elevation zones were adjusted to ensure that each of the

four EC zones were present in each elevation zone. Sampling plots were established in high, medium, and low elevation area in each of the four EC zones. Areas characterized as low elevation were below 334.25 m, medium elevations were equal to or greater than 334.25 m and less than 334.81 m, and high elevations were equal to or greater than 334.81 m. This resulted in 12 distinct sampling plots across the field. One additional sampling plot was added to account for the position of a lysimeter in the field. Zones were delineated after the maps were created, but prior to the soils being sampled.

2.4 Soil Carbon and Particle Size Analysis

Soil samples were taken between 5/23/15 and 5/25/15 in each of the 13 sampling plots after tillage and planting of peas. Three samples were taken at two depths in each plot, using a 91.5 cm long metal soil probe with an interior diameter of 1.5 cm, resulting in 6 samples per plot and a total of 78 individual soil samples. The respective sampling depths were 0-30 cm (topsoil, layer 1) and 45-60 cm (subsoil, layer 2). The 30-45 cm soil layer was excluded as this was a transition zone between the A and B horizons. Samples were placed in labeled paper bags and returned to the lab to be prepared for particle size analysis.

In preparation for particle size analysis, a 5-10 g representative subsample from each sample was sieved through a 2 mm sieve to remove any pebbles and gravel present. Samples were placed in pre-weighed ceramic crucibles, weighed, and placed in a 105 °C oven overnight. Hot crucibles were removed from the oven and allowed to cool prior to being weighed again. They were then placed in a 440 °C furnace for 24 hours to determine soil organic carbon loss on ignition. After 24 hours samples were removed from the furnace, cooled at room temperature, and weighed again to determine C content (Hoogsteen et al. 2015). Each sample was then ground with a mortar and pestle to break up any remaining

aggregates. Samples were stored in labeled Whirl-Pak® bags or similar bags after preparation.

Soil particle size was investigated using a Coulter LS230 (Beckman-Coulter Inc., Miami, FL) with fluid sample module connected to a Windows-based computer. The machine uses laser-light diffraction to determine diameter of particles between 2000 and 0.04 μm . Analysis of each sample was carried out using the methods described in Arriaga et al. (2006).

Values for permanent wilting point (PWP), and maximum plant available moisture (PAW) for each soil layer sampled were calculated using the equations developed by Saxton and Rawls (2006). Permanent wilting point at -1500kPa is defined as,

$$\theta_{1500} = \theta_{1500t} + (0.14 \times \theta_{1500t} - 0.02) \quad (1)$$

$$\theta_{1500t} = -0.024S + 0.487C + 0.006OM + 0.005(S \times OM) - 0.013(C \times OM) + 0.068(S \times C) + 0.031 \quad (2)$$

where S = percent sand, C = percent clay, and OM = percent organic matter. Field capacity (FC) at -10 kPa was calculated using the following equations from Saxton et al. 1986,

$$\theta_{10} = \exp \left[\frac{2.302 - \ln A}{B} \right] \quad (3)$$

$$A = \exp \left[-4.396 - 0.0715(\%clay) - 4.880 \times 10^{-4}(\%sand)^2 - 4.285 \times 10^{-5}(\%sand)^2 (\%clay) \right] 100 \quad (4)$$

$$B = -3.140 - 0.00222 (\%clay)^2 - 3.484 \times 10^{-5} (\%sand)^2 (\%clay) \quad (5)$$

Plant available water was determined by subtracting estimated field capacity from the permanent wilting point as shown in the equation below.

$$PAW = \theta_{10} - \theta_{1500} \quad (6)$$

2.5 Net Primary Productivity

2.5.1 Belowground biomass sampling

Ingrowth root cores (Vogt et al. 1998; Steingrobe et al. 2001; von Haden and Dornbush 2014) were used to estimate below ground biomass production of pearl millet. Cores were assembled by sewing a piece of heavy-duty fiberglass window screen onto the end of a 52 cm long, 7.4 cm in diameter rigid plastic mesh core using 9 kg fishing line. This helped retain soil and roots inside the core during and after removal.

Three cores were installed in each of the 13 sampling plots on the field 3-5 days after pearl millet seed was planted. A three-inch hand auger was used to extract soil to a depth of 40 cm and cores were placed inside. Soil removed from each hole was divided into two piles, A and B horizons, then sieved through a 4-mm soil sieve to remove roots and other debris. It was then returned to the inside of the root core in its respective hole. Soil was compacted using a meter stick to mimic field soil bulk density. Cores were monitored for soil settling and added to if necessary.

Root cores were removed on 9/22/15 when it was determined that plants had reached peak biomass (using LAI measurement curves, visual assessments, and changes in seasonal weather). A machete was used to cut around the cores and sever root connections while still in the ground. Cores were then pulled up and transported back to the lab where they were stored in a refrigerator at 5°C until root processing.

To extract soil and roots, the cores were firmly rolled across a table to loosen the soil. Portions of soil were then poured into a 2-mm sieve and sifted through with forceps to remove living roots. Roots were then washed, dried for 48 hours at 60°C, and weighed. It

was assumed that root mass below 40 cm was equal to 14% of total root mass (Gregory and Reddy 1982).

2.5.2 Aboveground biomass sampling

Above ground net primary productivity was estimated through above ground biomass sampling. At peak biomass, approximately 62 days after planting, three 1m² samples were clipped at ground level in each of the 13 sampling plots. Samples were bagged, dried at 60°C for 48 hours, and weighed. Samples were later ground in a Wiley mill to pass through a 1-mm screen and prepared for C and N analysis performed with a FlashEA® 1112 Nitrogen and Carbon Analyzer.

2.6 Leaf Area Index (LAI)

Leaf area index was measured five times in each sampling plot approximately every 7-10 days using a LI-COR 2200 Plant Canopy Analyzer (LI-COR, Inc., Lincoln, NE). Readings were taken on overcast days, at sunset, or when skies were clear/high thin clouds were present with the addition of a light diffuser cap and “4A sequence” to correct for changing light levels. The 4A sequence consists of a set of four measurements taken at the top (above, or A) of the plant canopy prior to each new set of measurements. The first is taken with the diffuser cap on the sensor in full sun, then with the cap shaded, then without the cap shaded, followed by a normal above canopy reading. This sequence allows for light scattering corrections to be made later on using the LI-COR software package FV2200 version 2.0 which follows the model outlined in (Kobayashi et al. 2013).

2.7 Plant physiology

Leaf photosynthetic response to light, temperature, and vapor pressure deficit was assessed using a LI-COR 6400 (LI-COR Inc., Lincoln, NE). Between 8/24/15 and 9/18/15,

leaf gas exchange measurements were made at ambient air temperatures of 15, 20, 25, 30, and 35°C at various locations around the edges of the field. For each measurement, a randomly selected pearl millet leaf was placed into the leaf cuvette of the LI-COR 6400. Flow rate was set to 400 $\mu\text{mol s}^{-1}$ and maintained by the LI-COR 6400 system throughout all measurements. Leaf temperature was set and held close to the respective ambient air temperature and relative humidity was manually maintained within 10% of ambient.

Photosynthetic response to changes in internal CO_2 concentration (C_i) was measured by varying the concentration of external CO_2 (C_a). During A_N/C_i measurements the LI-COR 6400's LED light source was used to illuminate the leaf to a PPFD of 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Reference CO_2 was set to the ambient CO_2 level measured in the field; around 350 $\mu\text{mol mol}^{-1}$. C_a levels were set using the auto program function of the LI-COR 6400. Levels progressed through 15 steps of varying CO_2 concentrations, beginning with a manually logged point at ambient CO_2 ($\sim 350 \mu\text{mol mol}^{-1}$) after stomatal conductance had stabilized. After taking the ambient point the auto program was started and measurements were taken at the following C_a levels: 400, 300, 250, 200, 150, 100, 50, 0, 400, 400, 500, 700, 1000, 1500 $\mu\text{mol mol}^{-1}$.

Photosynthetic response to light (A_N/PPFD (photosynthetic photon flux density) response curve) was measured by varying the PPFD level from 0 to 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Sample CO_2 was set to ambient, (around 350 $\mu\text{mol mol}^{-1}$), and measurements began when stomatal conductance was stabilized. An auto program was run measuring photosynthesis at nine PPFD levels beginning at 2000 $\mu\text{mol m}^{-2} \text{s}^{-1}$ and decreasing to 0 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Flow was maintained to 400 $\mu\text{mol s}^{-1}$ and leaf temperature held within a few degrees of ambient

air temperature by the LI-COR 6400 system during all measurements. Relative humidity was manually maintained within 10% of ambient.

Soil volumetric water content was measured at a depth of 10 cm at the time of each measurement using a TH300 soil moisture probe (Dynamax Inc., Houston, TX).

2.8 Water Use

Weekly ET was calculated for the field site using drainage data from infield passive capillary lysimeters (Drain Gauge G3, Decagon Devices Inc., Pullman, WA) from a companion study. Passive capillary lysimeters allow direct and continuous measurements of drainage and are well suited for use in the irrigated cropping systems of the WCS (Arauzo et al. 2010). They are typically composed of a soil monolith connected to a fiberglass wick that mimics soil suction by forming a hanging water column and imposing a constant boundary condition at the collection depth (Gee et al. 2002; Gee et al. 2003). Four lysimeters were placed across the field into cylindrical 2.2 m deep holes, created by a 0.5 m diameter auger. Drainage estimates were made at five-minute time intervals using a differential pressure transducer connected to a data logger (EM50, Decagon Devices Inc., Pullman, WA). Weekly drainage was also measured manually by pumping water from the collection reservoir through polyurethane tubing. More specific information on installation, methods, and rationale for the lysimetry portion of this study can be found in Nocco (2016).

Weekly water budget data were collected in the field from 7/29/15 to 9/22/15. Evapotranspiration was determined as the remainder of other measured components of the water budget using the equation,

$$P + I - \Delta S - D = ET \quad (9)$$

Integrated water use efficiency (WUE) was determined by dividing average above ground biomass (kg m^{-2} of dry matter) of PM by total evapotranspiration (ET; mm).

$$WUE = \frac{ANPP}{ET} = \frac{ANPP}{P+I-\Delta S-D} \quad (10)$$

where ΔS is change in soil moisture storage to 0.8m, and P, I, and D are weekly precipitation, irrigation, and drainage.

2.9 Statistical Analysis

Analysis of variance (ANOVA) using a JMP 11 statistical package (© SAS Institute Inc., Chicago, IL) was performed for NPP, BNPP, ANPP, soil texture, and SOC to determine if they differed significantly between EC or elevation zones. Relationships between EC, elevation, and EC and elevation combined were determined for above and below ground biomass, soil texture, SOC, and LAI using an analysis of covariance (ANCOVA). Linear regression was performed to assess the relationships between above and belowground biomass, SOC and productivity, and SOC and soil texture. The Tukey HSD test was used to compare means for $P < 0.05$.

3. RESULTS

3.1 Soil Electrical Conductivity

Sand content at depth one (0-30 cm) in EC zone 3 was significantly lower than zones 1 and 2 (Fig. 3.1). Silt content in zone 3 was significantly higher than zone 1. There was no significant difference in clay content between the EC zones. Sand content was significantly lower in the low elevation zone than the medium and high zones, while silt content was significantly higher (Figure 3.2). Clay content was significantly lower in the highest elevation zone than the other two zones. An analysis of covariance showed a significant

relationship between all three soil textural components and EC, elevation, and EC and elevation combined (Table 3.1).

Sand and silt content at depth two did not significantly differ between EC zones, nor were they significantly correlated to EC and/or elevation. Clay content at depth two was significantly related to EC ($F = 2.55$, $df = 7$, $P = 0.0338$). Percent clay increased with EC value ($F = 4.36$, $df = 3$, $P = 0.0113$) and was significantly higher in EC zone 4 than zone 1 ($F = 6.2468$, $df = 3$, $P = 0.0016$). Elevation and soil texture were not significantly related at depth two.

3.2 Soil Organic Carbon

On average, soils at the research site contained 1.38% soil organic carbon (SOC) within the 0-30cm layer (layer one). Soil organic carbon content was higher in EC zone three than zone one ($F = 3.90$, $df = 3$, $P = 0.0166$).

An inverse relationship between SOC and sand content was present at soil layer one ($F = 18.60$, $df = 1$, $P = 0.0001$). Silt ($F = 18.41$, $df = 1$, $P = 0.0001$) and clay ($F = 6.54$, $df = 1$, $P = 0.0148$) content increased with SOC. No significant differences in layer one SOC were found between elevations.

Average SOC content in the 45-60cm layer (layer two) was 0.44%. There were no significant differences in SOC between EC or elevation zones. Clay content increased with SOC ($F = 9.25$, $df = 1$, $P = 0.0043$). There was no significant relationship between productivity and SOC at either layer.

3.3 Leaf Area Index

A mean peak leaf area index (LAI; m² one-sided projected leaf area m⁻² ground area) of 6.24 (SD=0.59, SE=0.16) occurred around 9/16/15, approximately 45 days after planting (Fig. 3.3). The mean standard deviation across all sampling dates was 0.45.

Electrical conductivity (F = 7.58, df = 3, P = 0.0002), elevation (F = 4.66, df = 2, P = 0.0122), and date of measurement (F = 238.7, df = 6, P < 0.0001) all significantly affected LAI. Higher EC values contributed to greater LAI and higher elevation generally contributed to lower LAI. Leaf area index in each sampling plot increased over time as plants progressed through their phenological development. Some variability between sampling plots was observed (Fig. 3.4).

3.4 Photosynthesis

The maximum net CO₂ assimilation Rate (A) measured for PM was 49.1 μmol CO₂ m⁻²s⁻¹ on 9/1/15 with a leaf temperature of 35°C, vapor pressure deficit of 2.40 kPa (relative humidity = 57.6%) and a soil volumetric water content of 0.14m³m⁻³ (Figure 3.5). Pearl millet typically reached a maximum A at an intercellular CO₂ level (C_i) near 200 μmol mol⁻¹. Permanent wilting point (PWP) at -1500 kPa was 0.0574 m³m⁻³ within the 0-30 cm soil layer. Assimilation rates remained high even when soil volumetric water content neared this level (Fig. 3.6). Field capacity (FC) and plant available water (PAW) at -10 kPa were 0.2242 m³m⁻³ and 0.1668 m³m⁻³ respectively. Soil volumetric water content ranged from 0.06 – 0.21 m³m⁻³ across sampling dates. Overall, leaf temperature, radiation, and Ca values had greater affects on photosynthetic rates than soil moisture (Fig. 3.6, 3.7).

3.5 Productivity

3.5.1 Above and belowground biomass accumulation

Mean net primary productivity (NPP; total of above and belowground) across the field was 14.3 Mg dry matter (DM) ha⁻¹ (SE = 0.93). The average aboveground (ANPP) and belowground (BNPP) was 13.1 Mg DM ha⁻¹ (SE = 0.92) and 1.2 Mg DM ha⁻¹ (SE = 0.09) respectively. A linear regression analysis showed no significant relationship between ANPP and BNPP ($R^2 = 0.0017$, $P = 0.8032$). Average above and below ground biomass per sampling plot ranged from 8.3 to 20.1 Mg DM ha⁻¹ and 0.9 to 2.1 Mg DM ha⁻¹ respectively (Figs. 3.8, 3.9) No significant differences were found between EC zones for NPP, ANPP, or BNPP. Elevation and EC had no significant effect on productivity independently, but differences in NPP ($F = 3.58$, $df = 3$, $P = 0.0249$) and ANPP ($F = 3.52$, $df = 3$, $P = 0.0264$) were present at certain combinations of EC and elevation categories. NPP and ANPP tended to increase with elevation in EC zone 2 and decrease with elevation in EC zone 3. There was little variability in productivity among elevation levels in the other two zones.

Overall, soil texture had little affect on NPP, however, there were significant effects in certain zones. Net primary productivity increased with silt content in EC zone 2 ($F = 5.07$, $df = 1$, $P = 0.0481$), but the opposite effect was seen in zones 3 ($F = 4.09$, $df = 1$, $P = 0.0070$) and 4 ($F = 0.2$, $df = 1$, $P = 0.0371$). Additionally, NPP decreased in zone 4 ($F = 5.95$, $df = 1$, $P = 0.0448$) as clay content increased and decreased in zone 2 ($F = 5.72$, $df = 1$, $P = 0.0378$) as sand content increased. Soil organic matter did not significantly affect NPP, ANPP, or BNPP.

3.5.2 *Root:Shoot Ratio*

The average root to shoot ratio for PM was 0.11 (SD=0.08 SE=0.01). Electrical conductivity, elevation, and elevation and EC combined did not significantly affect BNPP or the root to shoot ratio.

3.6 *Plant Carbon and Nitrogen Content*

Our analyses found the carbon to nitrogen ratio of pearl millet dry matter at sampling to be 30.7 (SE±0.75). Pearl millet dry matter was comprised of 41.7% C and 1.41% N. This amounted to an average of 546.9 g C m⁻² and 18.5 g N m⁻² in above ground dry biomass.

3.7 *Water Use Efficiency*

Based on the weekly water budget data, total ET for the course of the growing period for PM was 236.8mm (Nocco 2016). Water use efficiency of mature PM was determined to be 55.35 kg DM ha⁻¹ mm⁻¹ (23.01 kg C ha⁻¹mm⁻¹) based on the ET value and average ANPP.

4. DISCUSSION

4.1 *Pearl millet characterized by rapid growth rate and biomass accumulation*

Pearl millet accumulated high levels of aboveground biomass in a relatively short period of time. Yields were typical of what PM growers in the CS see during a normal growing season (Isherwood per comm.). Pearl Millet's root to shoot ratio was consistent with values reported in the literature; and similar to, though slightly lower than, sorghum and corn (Anderson 1988; Thivierge et al. 2016). Root structure is important for all crops, especially in a region such as the WCS, as plant roots contribute to increased soil organic matter and help reduce soil erosion. Aboveground NPP was comparable to sweet corn biomass measured in the WCS at Hancock Agricultural research station, (13.1 Mg DM ha⁻¹ for PM

versus 13.7 DM Mg ha⁻¹ for sweet corn) (Bundy and Andraski 2005), but higher than other common cover crops such as oats and rye. Oat and rye cover crops can produce up to 9.0 and 11.0 Mg DM ha⁻¹ respectively depending on planting date and environmental factors, but yields for both crops generally range from 1-5 Mg DM ha⁻¹ (Clark 2007; Nielsen et al. 2015).

Pearl Millet's carbon to nitrogen ratio was slightly higher than that of a rye cover crop (26:1 vegetative) but lower than corn stover (57:1) indicating a moderate relative decomposition rate (USDA-NRCS 2011). If knocked down and incorporated into the soil in the fall, its residue will have decomposed enough to allow for drill planting in the spring (Isherwood per comm.). Residue management is an important consideration for growers as it can add additional labor and equipment cost. However, incorporating residue may reduce spring erosion control. Additional research on PM decomposition and the best way to manage residue would benefit growers who would like to add PM to their rotation.

Leaf CO₂ assimilation rates for PM were similar to those of sweet corn, (a representative C₄ species), and potato, (representative C₃ species), grown in the region (Fig. 3.5) and consistent with other PM values found in the literature (Payne et al. 1996; Ashraf et al. 2001; Kering et al. 2009; Ni et al. 2009). Rates generally increased with leaf temperature and soil volumetric water content, however, the crop maintained high assimilation rates when leaf temperature and moisture were low as well. This is indicative of PM's ability to support high levels of productivity across a wide range of environmental conditions, even on sandy soils without continuous irrigation. Pearl Millet's apparent hardiness could make it an excellent choice for producers in the WCS who often face unpredictable changes in weather during a typical Midwestern summer. Additionally, PM's ability to withstand high temperatures and low soil moisture levels may increase its importance as a cover crop in the

region as climate change leads to increasing summertime and fall temperatures and an increased frequency of droughts (WICCI 2011).

4.2. Pearl millet exhibits extremely high WUE

In addition to high biomass accumulation, high water use efficiency was observed for PM. It was comparable to values measured for irrigated maize (corn) in the Western Corn belt that was measured as 18-37 kg ha⁻¹mm⁻¹ (Sadras et al. 2003). Rain fed maize, also grown in the Midwest, during years with normal rainfall had a measured WUE of 40-59 kg DM ha⁻¹mm⁻¹ (Hamilton et al. 2015). In contrast, WUE values of irrigated oat crops grown in the Great Plains were 17.0 – 23.5 kg DM ha⁻¹mm⁻¹ in Akron, CO and 16.9 – 22.9 kg DM ha⁻¹mm⁻¹ in Sidney, NE (Nielsen et al. 2015). The high WUE displayed by PM in this study may make PM a more attractive cover crop option to the water conscious growers of the WCS.

It is evident that variability exists in WUE both between and within plant genotypes. The WUE value reported for PM here is relatively high compared to values from other parts of the Globe. Azam-Ali et al. (1984) reported a WUE value of approximately 25 kg DM ha⁻¹mm⁻¹ based on measurements of PM dry matter production and accumulated water use in Niamey, Niger. Values for PM grown for grain in Niger and Lubbock, TX ranged from 7.6 – 9.7 kg DM ha⁻¹mm⁻¹ and from 4.5 – 6.1 kg DM ha⁻¹mm⁻¹ respectively (Hatfield et al. 2001). These variations could be explained, or partially explained, by differences in soil type, soil nutrient content, climate, and/or specific PM variety. To our knowledge, this is the only water use efficiency value that has been measured for forage PM in the WCS region. Pearl millet's water use efficiency was high in this study but absolute water use was not measured. Additional research is needed to better determine PM's total water demand in the region and how it compares to other crops and cover crops.

4.3 In-field variability had little affect on productivity

Though there were no significant differences in above or belowground NPP between the EC zones, significant variability in above and belowground biomass was observed between the thirteen sampling plots. Electrical conductivity, elevation, and soil texture accounted for some of the variability across the field, but not as much as expected and relationships were counterintuitive in some cases. Residual N from the preceding pea crop may have contributed to the increased NPP in some areas across the site, but more soil testing is needed to confirm this. This raises additional questions about the drivers of variability across the field, as the variables measured here did not appear to adequately explain them.

Overall, the field site did not exhibit a great deal of variability in EC, elevation, or soil texture. The fact that significant differences do exist between zones and/or certain combinations of variables that would otherwise appear homogeneous is worth reporting, but is perhaps not enough to explain the variability in productivity, or to justify different management practices in each zone. Precision agriculture is gaining popularity in the agricultural sector, specifically precision irrigation systems in the WCS. These systems were designed to help reduce over all water use by allowing growers to apply water at varied rates across the field, depending on soil type, so that each area of the field gets exactly the amount of water required. Expensive specialized equipment is needed to create the water management zones and to operate the system. The findings of this study suggest that on certain soil types, such as sands, the variations in soil texture across the field may not be significant enough to warrant implementation of more costly water management systems.

5. CONCLUSION

Cover crops provide innumerable benefits to the land they occupy and continue to be readily utilized in the WCS. This study has demonstrated that Pearl millet could be a viable cover crop option for growers in the WCS and should be further investigated as such. Net primary productivity and photosynthetic rate were comparable to, or greater than, those of other C4 grass species grown in the region. They remained consistently high despite changes in environmental conditions, such as temperature and soil moisture. Furthermore, PM displayed extremely high water use efficiency; an important trait in the sandy, well-drained soils of the WCS. It's productivity was generally higher than that of other more commonly grown cover crops in the region, like oats and rye, implying that it may be a better choice for growers interested in a high yielding cover crop. One caveat of PM is that it is frost sensitive and requires a relatively early planting date. Further research on the impact of planting date on phenological development of PM would be useful to growers who are considering adding it to their rotation.

In addition to the ecosystem services PM provides as a productive and relatively water efficient cover crop, it may also have the potential to become an important nematode management tool. Its effectiveness as a biological control for the RLN has been demonstrated in previous studies, implying that it may be cost effective alternative to fumigation or a useful addition to a rotation. Additional research focused on better understanding PM's RLN suppressing properties may help increase adoption in the region.

Though there was some variability in PM's productivity across the field, it did not appear to be directly related to EC, elevation, soil texture, or organic matter. Some variation was explained by soil texture, and a combination of EC and elevation, but not all. Soil texture

was significantly related to SOC, EC, and elevation to some degree at both soil layers sampled; but these observations did not always correspond with variations in PM's phenological traits. This may indicate that PM is not as sensitive to these variables as other crops may be, however, the overall understanding of PM's relationship to these soil traits would benefit from further research. These findings also suggests that the soil variability at the field site may not be great enough to significantly impact crop production or necessitate different management practices across a field.

TABLES

Map Unit Symbol	Map Unit Name	Acres in Field	Percent of Field
Bt	Billet sandy loam, 0-2% slopes	13.7	20.0
RfA	Richford loamy sand, 0-2% slopes	50.8	74.2
RfB	Richford loamy sand, 2-6% slopes	0.5	0.8
RrA	Rosholt sandy loam, 0-2% slopes	3.4	4.9
Totals for Field		68.5	100.0

Table 1.1 Description and area of soils found at the research site corresponding to Figure 1 (USDA-NRCS 2016).

Season	Temp. °C			Precip. cm Total
	Max	Min	Mean	
Winter	-2.89	-12.61	-7.72	8.84
Spring	12.06	0.67	6.33	21.44
Summer	25.44	14.22	19.83	31.01
		July	21.00	9.96
		Aug.	19.88	9.93
		Sep.	15.06	9.65
Autumn	13.22	2.72	8.00	21.59
Annual Avg	12.06	1.33	6.67	82.88

Table 1.2 Summary of 30-year average temperature and precipitation for Stevens Point, WI, from 1981-2010. Compiled using data from the National Centers for Environmental Information station located in Stevens Point, WI.

ID	Min	Max	Area (ha)
1 (red)	1.72	2.44	4.14
2 (yellow)	2.44	3.17	10.88
3 (light blue)	3.17	3.89	8.41
4 (dark blue)	3.89	4.62	3.00

Table 1.3. Actual EC value range in dS m^{-1} for each EC zone and area in hectares of respective zones. Each zone is denoted by color on the map in Figure 2.2.

Effects	DF	Sum of Squares	F Ratio	P Value
Sand				
EC	3	394.54	11.85	<.0001*
Elevation	2	297.91	13.42	<.0001*
EC*Elevation	6	319.74	4.80	0.0019*
Error	27	299.66	-	-
Total	38	1324.36	-	-
Silt				
EC	3	283.91	9.23	0.0002*
Elevation	2	185.47	9.04	0.0010*
EC*Elevation	6	214.12	3.48	0.0112*
Error	27	276.95	-	-
Total	38	966.68	-	-
Clay				
EC	3	10.45	6.49	0.0019*
Elevation	2	15.18	14.14	<.0001*
EC*Elevation	6	24.47	7.60	<.0001*
Error	27	14.49	-	-
Total	38	65.20	-	-

Table 3.1. Analyses of covariance summarizing the connections between sand, silt, and clay content and EC, and the relationships between elevation, and EC and elevation combined with soil particle size/texture for soil layer 1.

FIGURES



Figure 1.1 Taxonomic classifications of soils found at the research site. Source: National Cooperative Soil Survey Custom Soils Research Report for Portage County, WI.

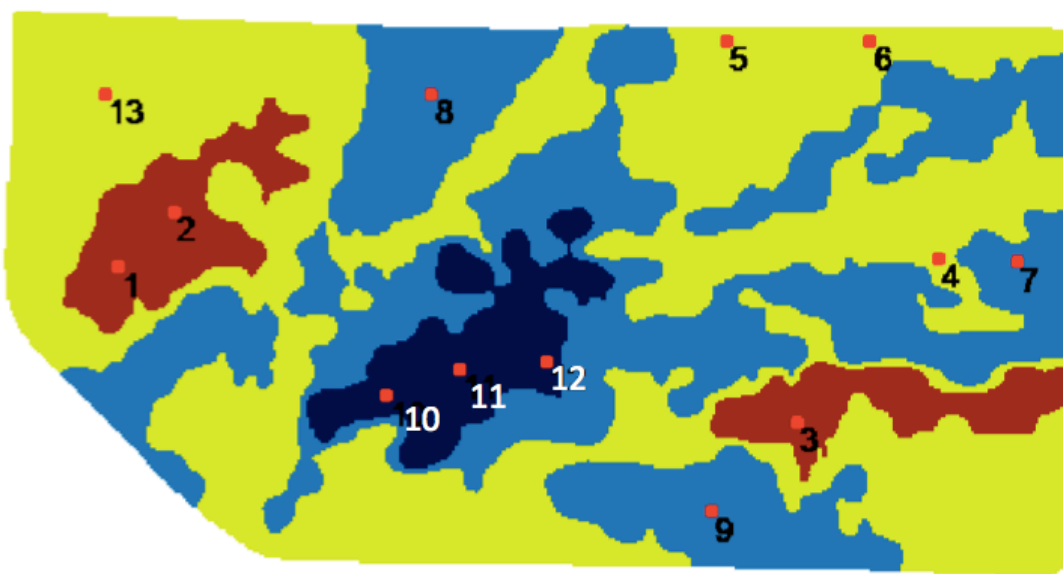


Figure 1.2 Map of research site showing the four EC zones and 13 sample plots. In-field passive capillary lysimeters were located in plots 4, 5, 6, and 7.

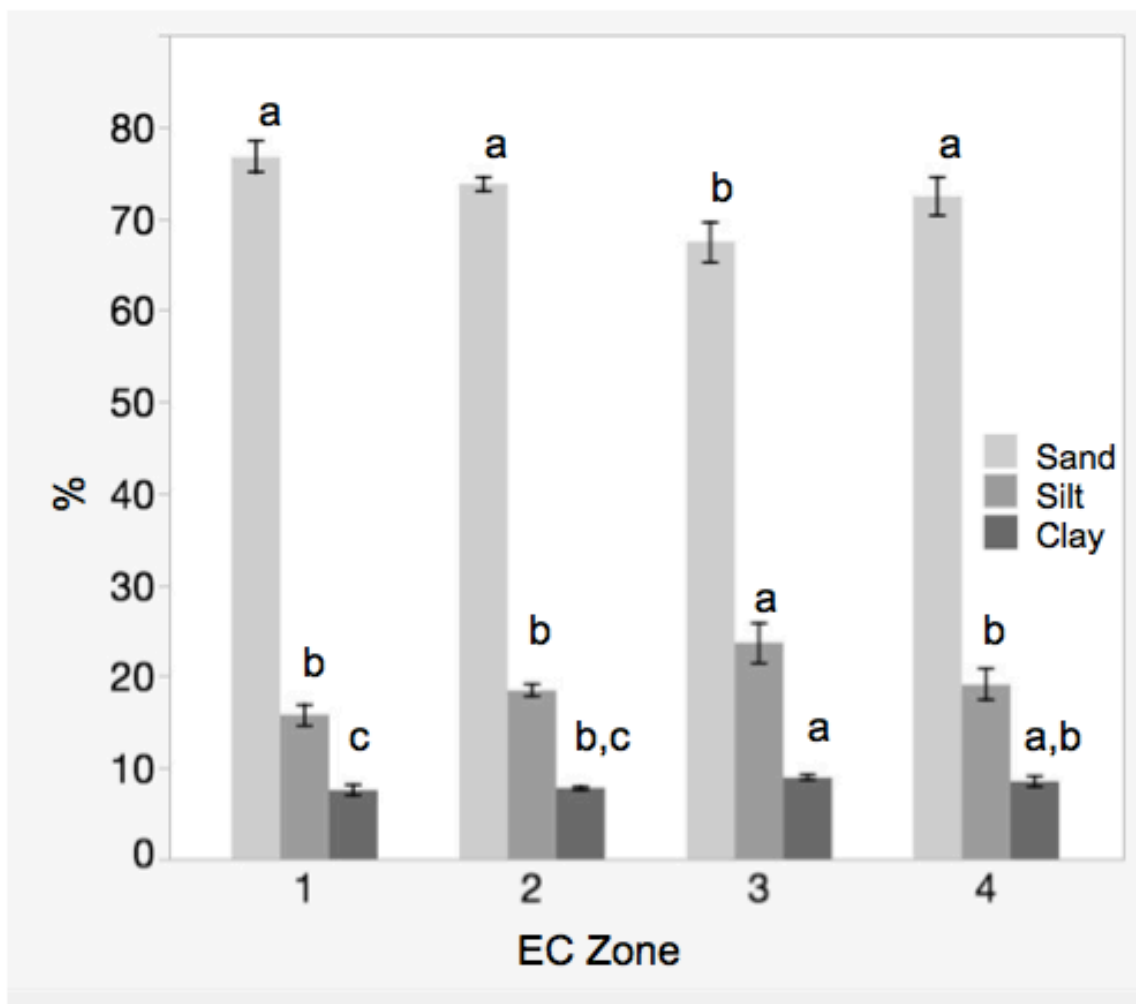


Figure 3.1 Mean percent sand, silt, and clay present at depth 1 in each EC zone (1-4). Error bars denote +/- 1 standard error from the mean. Levels not connected by the same letter are significantly different.

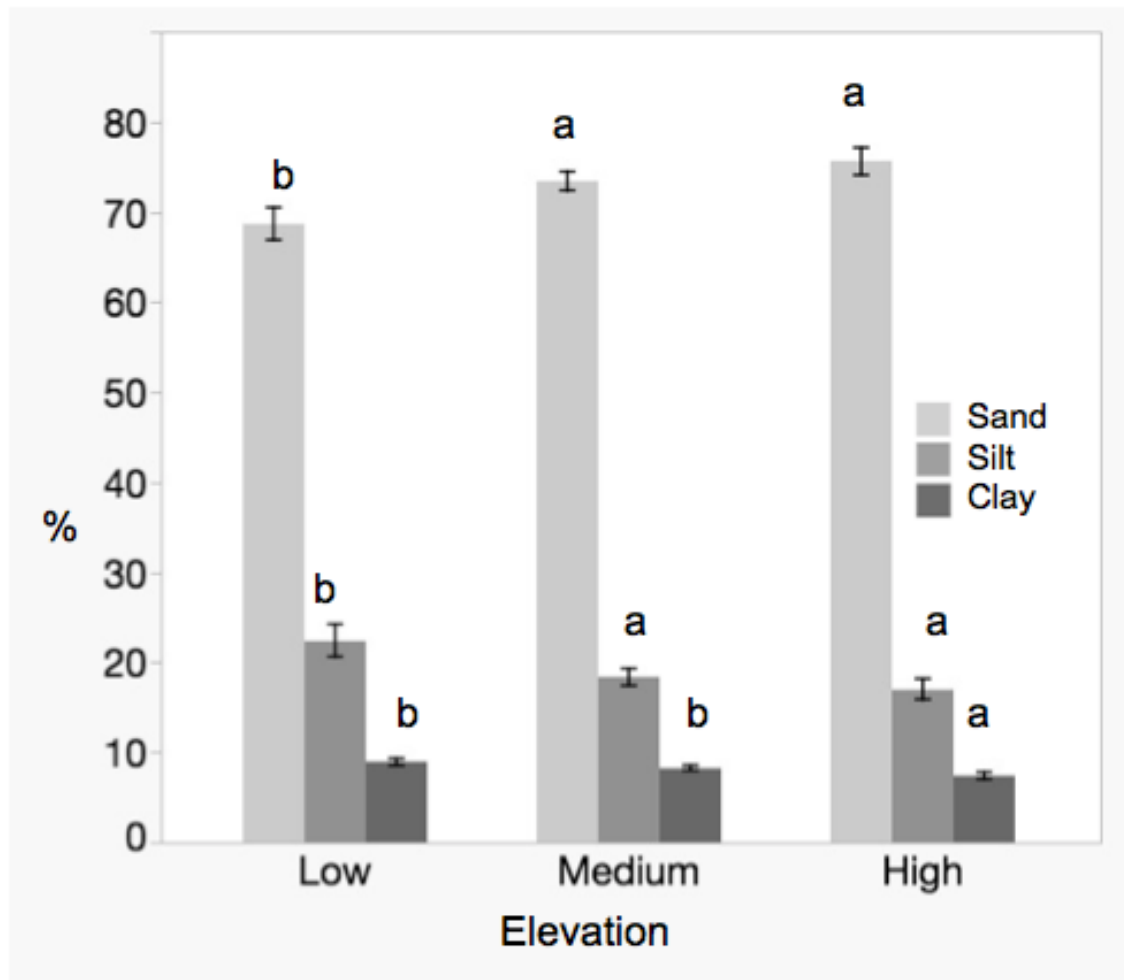


Figure 3.2 Mean percent sand, silt, and clay present at depth one in each elevation zone (high, medium, and low). Error bars denote +/- 1 standard error from the mean. Levels not connected by the same letter are significantly different.

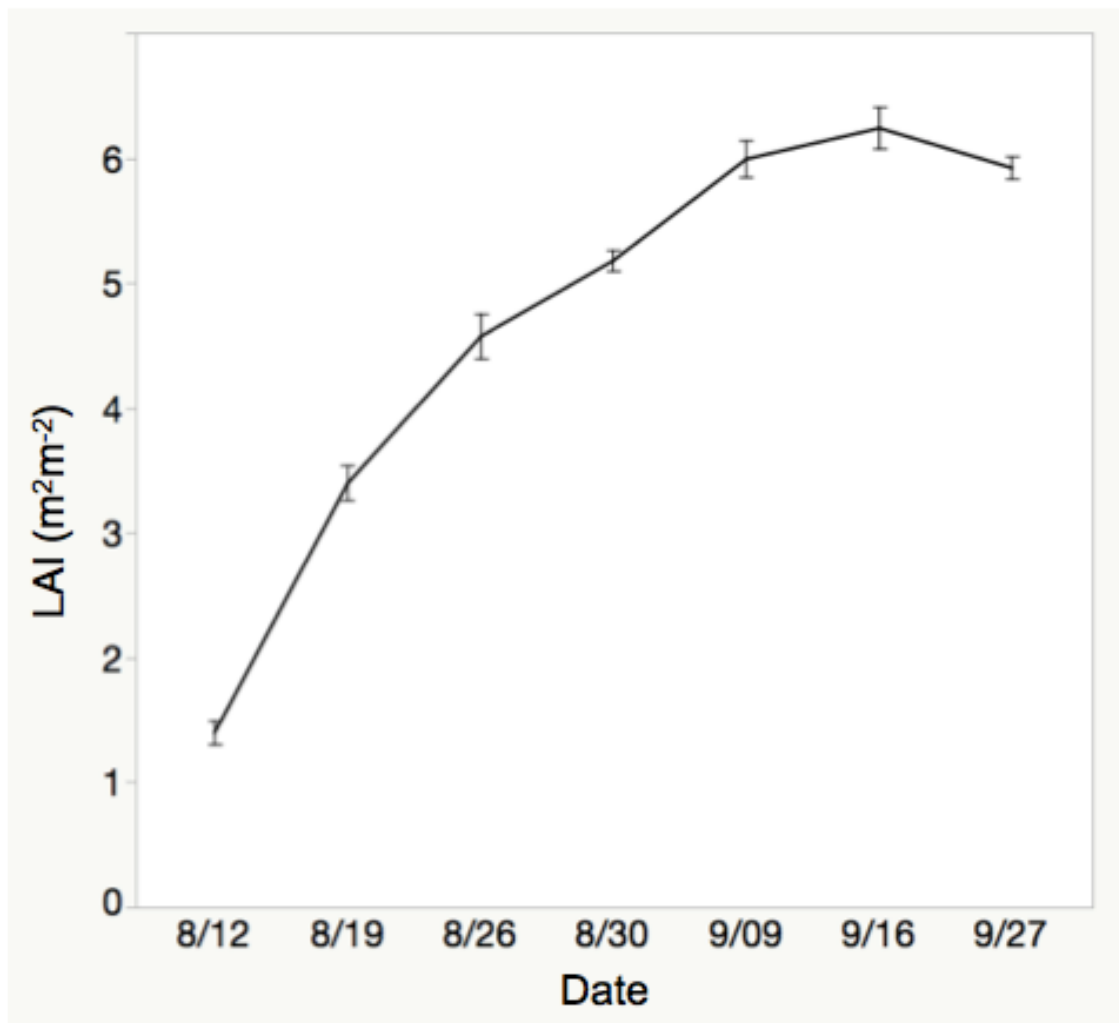


Figure 3.3 Mean LAI across the field by date of measurement. Error bars denote +/- 1 standard error from the mean.



Figure 3.4 Comparison of LAI over the growing season from the presumed driest and wettest sampling plot. Wetter plots were those with low EC and high elevation and drier plots had the higher EC and lower elevation.

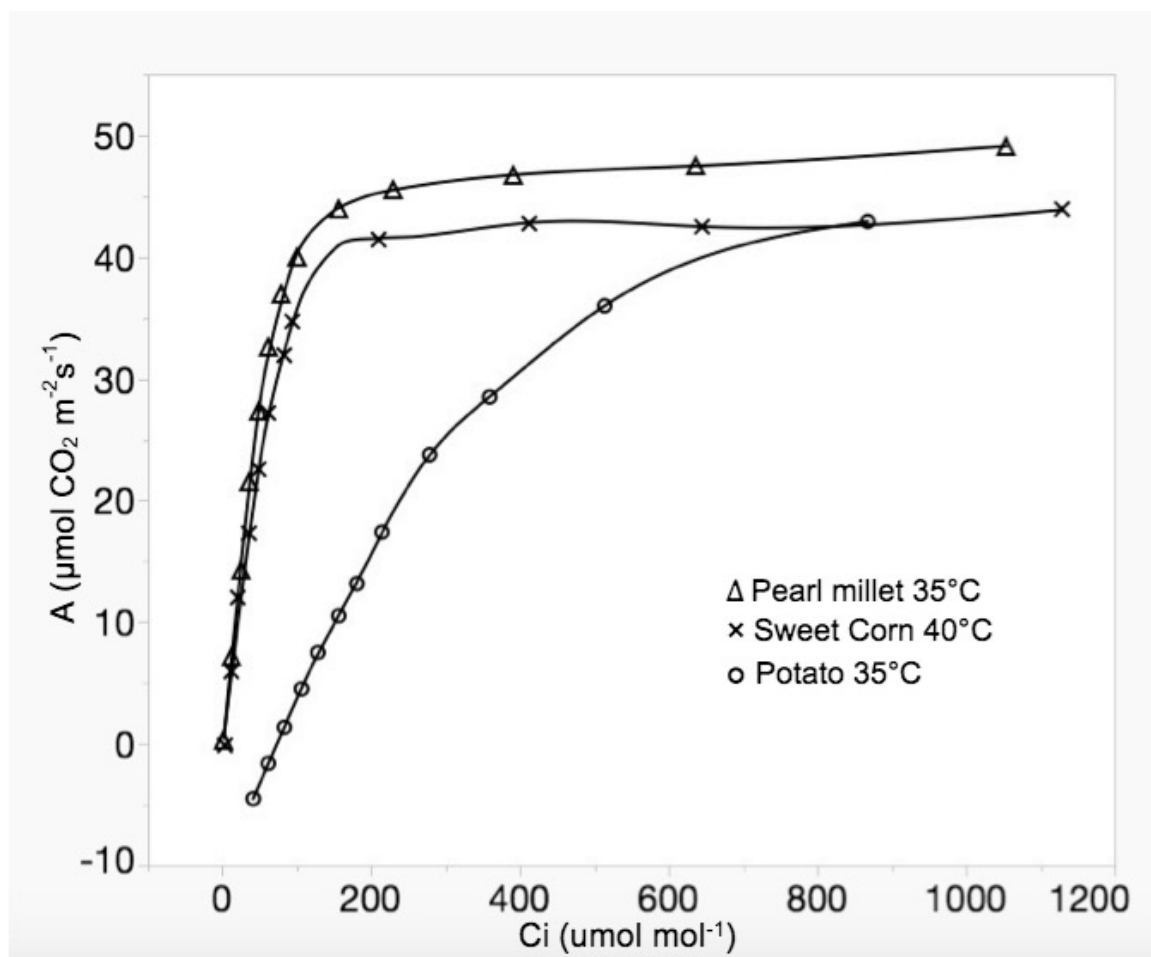


Figure 3.5 Leaf assimilation vs. intercellular CO₂ concentration data (A-C_i) for PM, sweet corn (SC) (representative C₄ plant from the region), and potato (representative C₃ plant from the region) on the same soil type collected when soil volumetric water content was near $0.15 \text{ m}^3 \text{ m}^{-3}$, with leaf temperatures of 35°C and 40°C. Sweet corn and potato data collected by Mallika Nocco for a companion study.

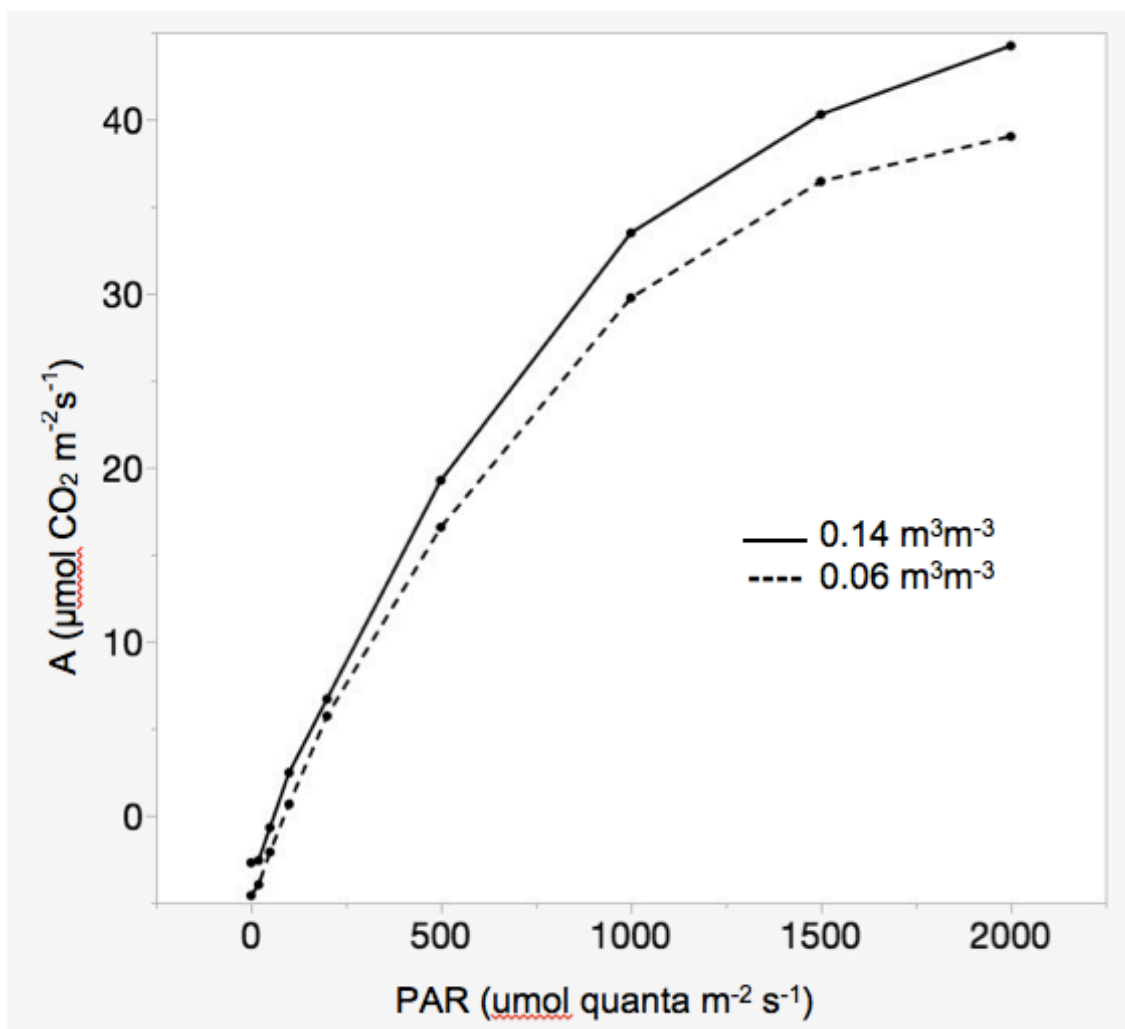


Figure 3.6 Pearl millet photosynthetic response to changes in photosynthetic active radiation (PAR) at two different soil volumetric water contents ($0.14 \text{ m}^3 \text{ m}^{-3}$ and $0.06 \text{ m}^3 \text{ m}^{-3}$). All measurements were collected with leaf temperatures of 35°C .

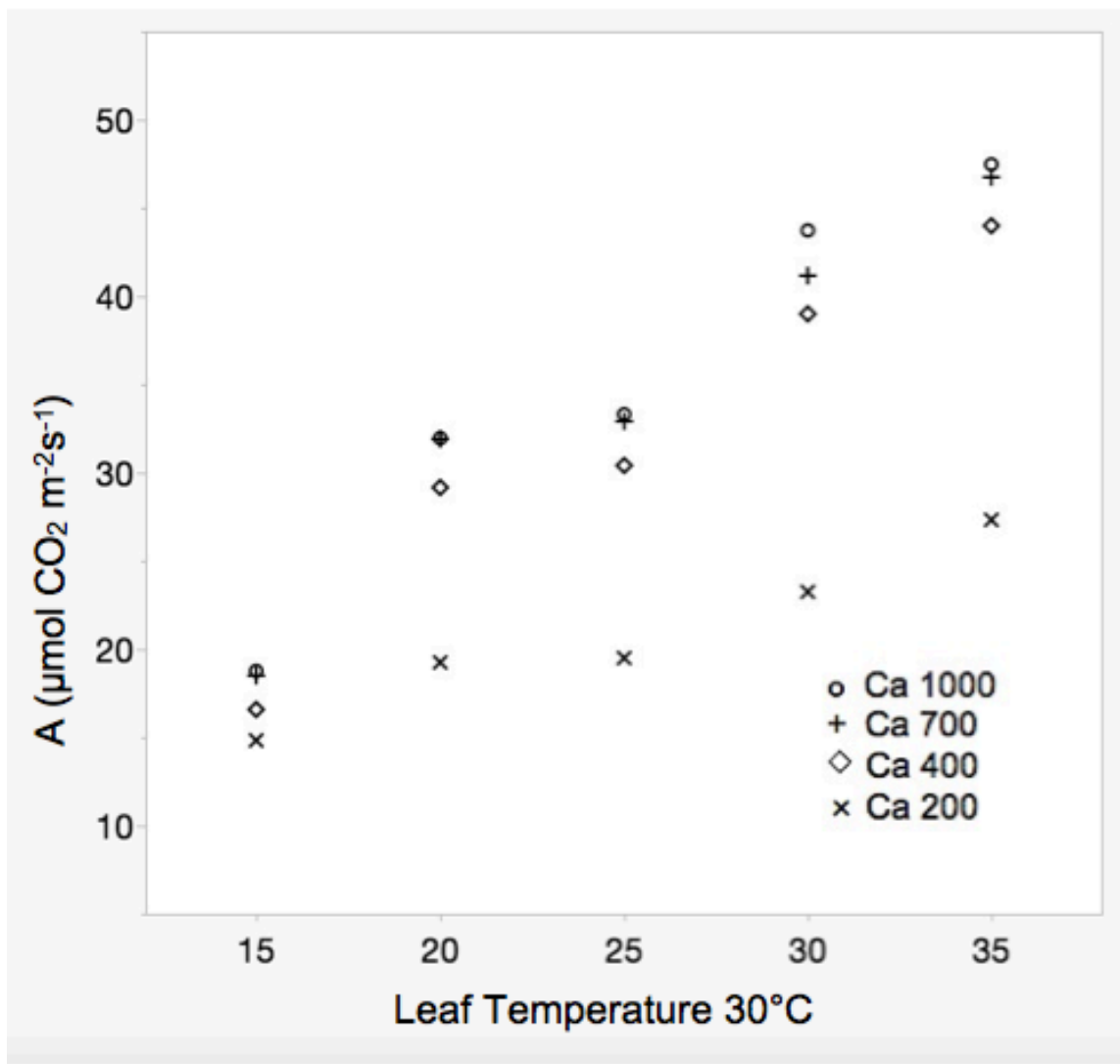


Figure 3.7 Pearl Millet leaf assimilation values ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$) across a range of leaf temperatures ($15^\circ\text{--}30^\circ\text{C}$) and Ca concentrations ($200\text{--}1000 \text{ mmol mol}^{-1}$). Soil volumetric water content was $0.14\text{m}^3\text{m}^{-3}$ to $0.18\text{m}^3\text{m}^{-3}$ across all measurements.

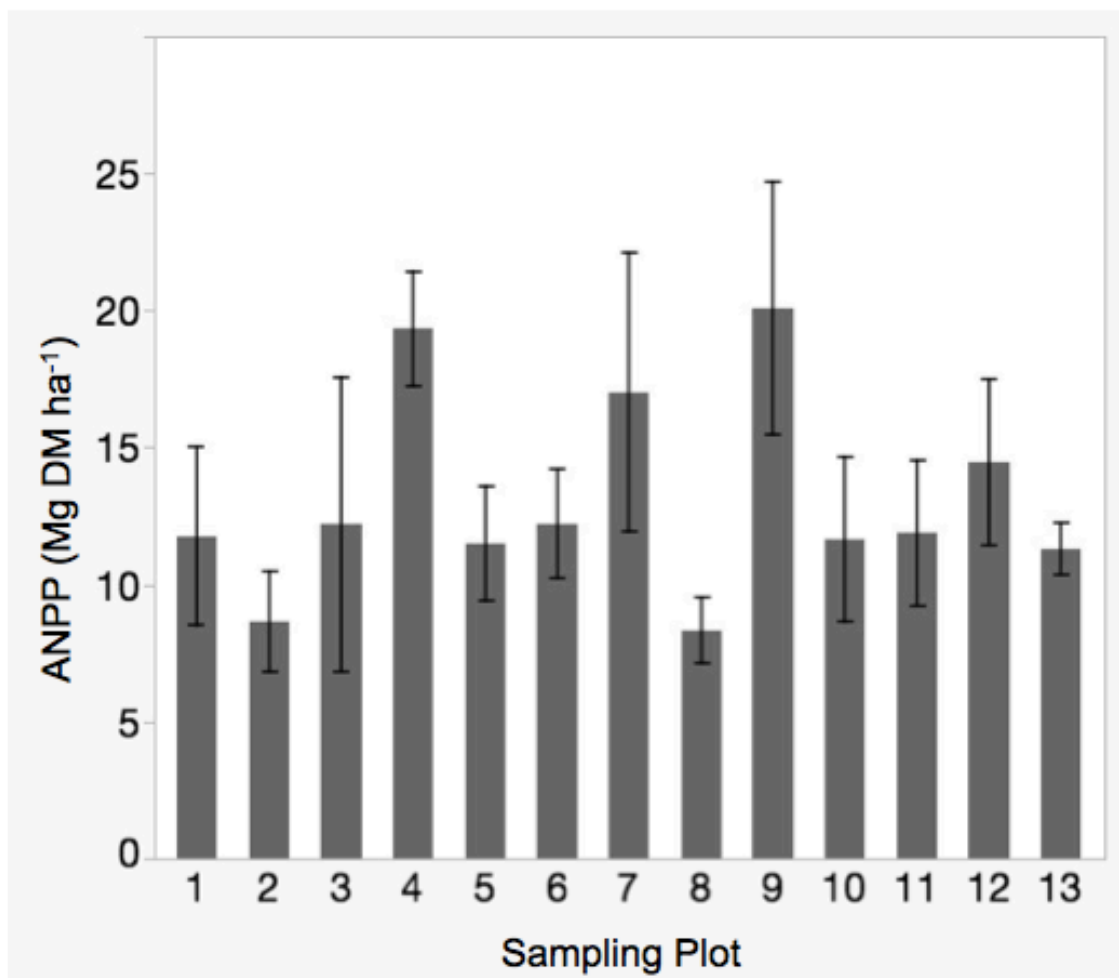


Figure 3.8 Mean aboveground NPP (ANPP) for each of the 13 sampling plots. Error bars were constructed using 1 standard error from the mean. (EC zone 1 = plots 1-3, EC zone 2 = 4-6 and 13, EC zone 3 = 7-9, EC zone 4 = 10-12)

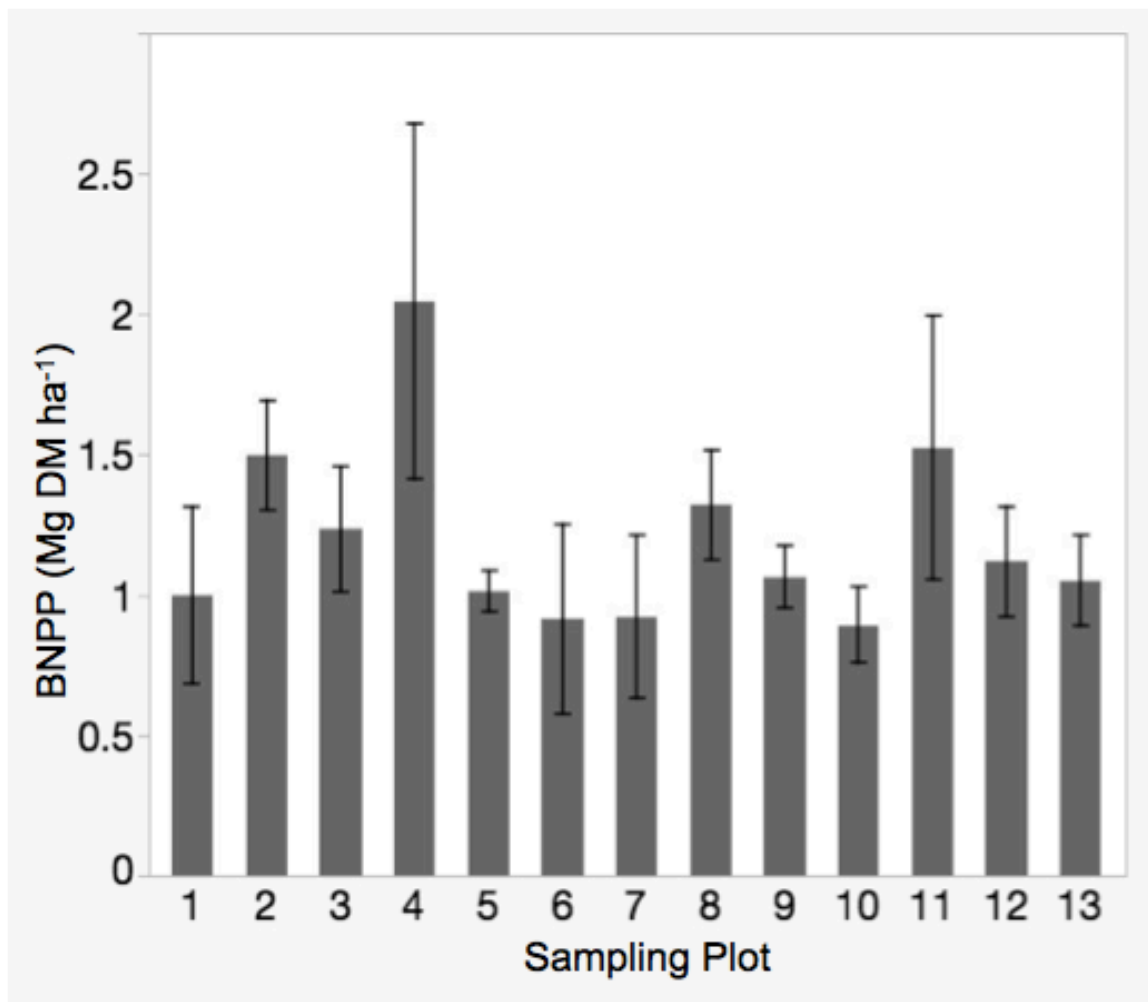


Figure 3.9 Mean belowground NPP (BNPP) for each of the 13 sampling plots. Each error bar is constructed using 1 standard error from the mean. (EC zone 1 = plots 1-3, EC zone 2 = 4-6 and 13, EC zone 3 = 7-9, EC zone 4 = 10-12)

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CHAPTER 3

COVER CROPPING PRACTICES AND DRIVERS IN THE WISCONSIN CENTRAL SANDS

In 2007, 1.73 billion tons of soil was lost from farmland in the US (USDA-NRCS 2010). Practices such as no till, strip till, and cover cropping have helped to decrease soil erosion over the last few decades, but adoption of these practices is still relatively low (Pagliai et al. 2004; Tilman et al. 2006; Mbutia et al. 2015; Wade et al. 2015). While the concept of cover cropping is certainly not new, cover crops (CCs) are still only planted on less than 2% of total cropland in the US (Wade et al. 2015). This percentage is higher or lower depending on the region. The Wisconsin Central Sands (WCS) is one region where CC usage is near universal. It's all but mandatory in the sands; that is unless a grower enjoys watching their soils blow away. Over the years, farmers in the WCS have developed a strategy to support productive agriculture in the region, of which cover cropping plays an integral role. The WCS's unique use of CCs is intriguing and farmers around the country could take a lesson from the growers there. To learn more about specific cover cropping practices and their drivers in the WCS, I interviewed twelve different growers from the region. We discussed what influences the CCs they choose to grow, how willing they are to try new CC varieties, and how they gather information regarding CCs. Though each grower was different, they shared a willingness to learn and try new things, and a commitment to soil conservation.

Cover crop usage is expanding in the Midwest, but the WCS is still ahead of the game when it comes to widespread cover crop use (SARE and CTIC 2014). The sandy, well-drained soils the region is characterized by all but require plant roots to keep the soil in place,

though many hardships were endured before growers discovered this. Learning a little about the region's history is helpful in understanding the current practices and approaches.

Settlement began in the region in the mid 1800's, much later than its surrounding areas, as its soils made it less desirable for agricultural production. Prior to settlement, native prairies, oak savannas, and wetlands dominated the landscape. Within a few decades, the majority of the region was converted for use as agricultural land. Alteration of the native landscape increased soil erosion and intensive crop rotations reduced the nutrient content of the soil, further reducing its fertility (Goc 1990; Lal 2004). The combination of dry weather and bare, extremely sandy soils eventually led to the "Wisconsin Dust Bowl" in the 1930's; a smaller scale, more localized version of the Dust Bowl in the Great Plains. Record low rainfall in combination with the quickly draining soil led to extremely low productivity agriculture, famine, and hardships for the people of the WCS. (Goc 1990) The sands farmers who made it through the disaster had to be innovative and resourceful. Most had abandoned grain farming in the early 20th century and switched to dairying (grazing cattle on hay and alfalfa), much like the rest of Wisconsin. Eventually they began growing cash crops, like potatoes, and harvesting wild crops such as wiregrass, sphagnum moss, berries, and trees for milling to supplement their income. (Goc 1990)

Eventually, modern farming techniques began to take hold. The adoption of irrigation technologies in the 1950s allowed for the return of productive agriculture to the region. Wisconsin is now one of the nation's top producers of canning vegetables (i.e. sweet corn, peas, green beans), and potatoes, a large portion of which are grown in the WCS. Several large food manufacturing and distribution companies, such as Del Monte and Frito Lay, reside and invest in the region, further justifying its economic importance to the state.

Central Sands growers are proud of what they produce, and know it couldn't be done without the use of CCs. The twelve growers I interviewed had farms ranging in size from 750 to 8,500 acres and grew a wide variety of both crops and cover crops. The most common crop grown was sweet corn, followed by green beans, peas, and potatoes. Field corn, soybeans, corn silage, seed corn, cucumbers, dry beans, millet for bird seed, cabbage, carrots, table beets, wheat, pumpkins, seed soy, and alfalfa were also grown by at least one grower interviewed. One would be hard pressed to find this amount of crop diversity elsewhere in the Midwest.

Cover crop diversity was also relatively great, though cereal rye and oats were most common. Eleven of the twelve growers interviewed grew cereal rye and seven grew oats. The third most common CC grown was sorghum sudan grass with five growers. Winter wheat, pearl millet, red clover, annual ryegrass, mustard, radish, barley, and alfalfa were also used by at least one grower. The number of different CCs grown at each operation ranged from 1-6 and averaged at 3.25 (SD=1.49). Growers generally varied which crops they grew each year depending on the previous and subsequent crop, weather, and seed availability.

A number of factors influence which CC a grower plants, (these will be visited later), but the reasons to plant CCs in the first place are relatively straightforward. All twelve growers interviewed plant CCs primarily for erosion control. Considering the soils and history of the region this makes a lot of sense. Central Sands growers are also aware of the multitude of other benefits provided that make the added time and expense associated with CCs more than worth it. The second most common reason growers gave for planting CCs was to improve soil health and fertility. Building soil organic matter and nutrient scavenging tied for third. Growers also listed improving soil tilth, increasing soil microbial activity,

improving water holding capacity, weed suppression, and use as green manure as reasons for planting CCs. In addition, one grower mentioned using a CC as a companion crop to protect small seedlings. Another felt that the crop interlude CCs provide helps spread the disease curve and benefits subsequent cash crops. Other growers mentioned using CCs to improve field condition pre-planting in spring and for harvest preparation in the fall.

It is evident that the many benefits of CCs are well realized by the growers in the WCS, but are some varieties better than others? I inquired as to what growers consider when deciding which CC to plant and received a wide variety of responses. There was one, however, that nearly every grower (ten of twelve) gave: timing. Planting date is just as important for CCs as it is for cash crops, so if the primary crop isn't harvested until later in the season, a grower knows they can't select a CC that needs a lot of time to establish. This is part of the reason cereal rye is so popular. It can be planted late, still provide some fall ground cover, and it will overwinter well to provide coverage in the spring pre-planting. About half the growers interviewed considered overwintering potential a positive CC attribute, but the other half viewed it as a downfall. This is because crops that overwinter, like cereal rye, will need to be terminated in the spring, increasing input costs and labor. Oats, on the other hand, do not overwinter, making them a popular choice for growers if they can be seeded early enough in the fall (it doesn't do well when planted late). Oats do not require termination and the residue left in the spring is generally sufficient to hold the soil down. Other factors that influence what CCs growers choose were seed availability, establishment ease, whether or not the crop has other potential uses (e.g. forage, biofumigant), biomass accumulation, weed suppressing abilities, location in rotation, equipment availability, and what has worked well in the past. Surprisingly, cost was not a big

factor for most growers. They generally agreed that the benefits provided by CCs outweigh the increased cost of some of the pricier varieties. That being said, if a CC gets too expensive it likely won't be planted. Fortunately, growers in the WCS have a lot of options.

I was also interested in learning about grower views on conservation, so I asked how important it was when making decisions on their farm. I quickly learned that conservation means different things to different people, and to the growers in the WCS it refers more specifically to soil conservation. All of them said conservation (i.e. preventing soil erosion) was important to their operation and is one of the primary reasons they plant cover crops. One grower also mentioned the use of windbreaks to limit blowing and ensuring proper nutrient application. Another grower explained why conservation is very important to him: "if we don't take care of the soil, we'll die. The food doesn't just magically appear in the grocery stores". Other growers had similar sentiments; "Well its pretty important, real punch in the gut to watch the field and expensive nutrients blow to the next county". Another recalled thinking there was a fire down the road when really it was just the wind blowing up a lot of dust. Several others described the unchecked blowing sand as a nuisance to neighbors. For all of these reasons, preventing soil erosion is a conservation priority to WCS growers. Water conservation, on the other hand, is a different story.

Another thing that is unique about farmers in the WCS is their willingness to innovate and try new things. I asked the growers if they are ever influenced by what their neighbors are doing, especially with regard to CCs. The answer was yes, and no. For the most part, growers were willing to try something new, like a different cover crop variety, even if no one else around them was using it. A few said they are often the first ones to try a new practice. At the same time, there is communication between growers about what is working and

what's not. Growers said they would be less likely to try something if a neighbor with a comparable system had tried it and it didn't work out.

Central Sands growers also pay close attention to the latest research, especially from the University of Wisconsin-Madison (UW). I asked each of them how they obtain new information regarding cover crops and other management strategies. Most, nine out of twelve said they attend conferences, field days, and tradeshow to learn about new products and techniques. Agronomy journals, farm newspapers, and other farm literature (including internet sources) were cited by eight of the twelve. Growers also value information received from UW Extension and researchers; some even work closely with researchers at their respective operations. Many growers also rely on their own experience when making management decisions. Some even conduct their own on farm research to test out a new practice before applying it more broadly across their operation. A few growers also listed local agricultural agencies and consultants as resources.

I was also interested in asking the growers about a specific cover crop that I have been researching: pearl millet (PM) or *Pennisetum glaucum*, a warm season annual grass that originated in central tropical Africa. I became interested in PM after learning about it through a grower I worked with. This grower used PM as a CC prior to potato in his rotation because of its ability to suppress the root lesion nematode (RLN). The RLN is a common plant parasitic nematode found in the soil that can reduce yields in many crops including potato (Ball-Coelho et al. 2003). It also contributes to potato early dying (PED), a disease that reduces tuber yield and quality through its interactions with the soil pathogen *Verticillium dahliae* (MacGuidwin and Rouse 1990; Saeed et al. 1997). Growers in the WCS are very familiar with the RLN, and *Verticillium*. Many apply synthetic fumigants to control their

populations, but fumigating is expensive and harmful to the soil, humans, and animals (Ibekwe et al. 2001; Collins et al. 2005; Woodrow et al. 2014). Though PM is a relatively lesser known cover crop in the WCS, it's drought and heat tolerance, and potential use as a biological control for the RLN (Ball-Coelho et al. 2003; Dauphinais et al. 2005; Bélair et al. 2005; MacGuidwin and Knuteson 2010) make it a promising cover crop choice for the region.

Nine of twelve growers I interviewed had at least heard of PM from one source or another. Several recalled PM being researched and promoted by members of the UW-Madison Plant Pathology department roughly ten to fifteen years ago. Some even had research plots on their farm. Four currently have PM as a part of their rotation and have had success using it to control RLN populations, likely as a result of that research. Others were hesitant to adopt PM for a number of reasons. For one, it may be harder to fit into a rotation because it requires an early planting date to establish well and accumulate enough biomass for the RLN suppressing properties to be realized. It works after a short season crop, like peas, but some growers in the WCS choose to double crop. I mused to one grower about whether or not he thought planting PM would save enough on fumigation costs to make up for the loss of the second crop. He thought this was an interesting question but was not sure of the answer. I did some checking on the USDA National Agriculture Statistics Service Quick Stats site and found that the price of snap beans (a common double cropping choice in the WCS) in 2015 in Wisconsin was \$202 per ton. The most recent yield data I found for Portage County was an average of 5 tons per acre. So a grower raising snap beans for processing in the WCS could expect roughly \$1000 per acre for their crop. When you factor in fumigation costs of about \$230 per acre (TH Agri-Chemicals, Inc. per comm.), initial seed

and planting cost, irrigation, and other inputs, profit declines rather quickly. Pearl millet on the other hand costs about \$30 an acre to plant (Jay-Mar, Inc. per comm.). There is also the possibility of harvesting and selling PM as forage for around \$100 per acre as it is an excellent forage crop for livestock (Isherwood per comm., Mustafa 2010). It would be interesting to see the results of a more formal cost comparison between PM and a double crop. Perhaps adoption of PM would increase if it was found to be more economical than double cropping?

Growers were also hesitant to plant PM because it does not control *Verticillium* and PED. It may suppress the RLN, but *Verticillium* Wilt and PED could remain risks to potato crops. Fumigation manages both, in addition to many other soil pests and pathogens. However, I learned from one grower that some potato varieties are less susceptible to *Verticillium* than others. He plants Gold Rush potatoes instead of Norkotas, which are highly susceptible to “vert”. Norkotas grade out better and generally yields higher, according to this grower, but he doesn’t think it’s worth it. His perception is; “we don’t need to have higher potato yields. We already raise slightly over what the market needs.” He thinks more people should grow the Gold Rush variety. “It would reduce the amount of potatoes on the market and increase prices. Growers would make more money and not have to use as many chemicals.” A different PM grower had similar sentiments regarding chemical usage. He has never fumigated and feels they have fewer problems on their farm than they would if they did fumigate. “It kills good nematodes too”. He was also proud to tell me that his agronomist said he had the biggest potatoes in the area.

Other barriers to PM adoption cited by growers included worry that PM may become a weed and create too much of a chemical need if not controlled. However, PM varieties used

as cover crops are sterile hybrids so the risk of coming back as a weed is minimal to non-existent. Overall though, most potato growers I spoke with were open to at least trying PM if there was sufficient research, specifically farm scale research.

The last question I asked the growers was; “what it would take to get you to try/adopt a new cover crop?” Growers described the various different things they take into consideration when weighing cover crop options and what attributes an ideal CC would possess. Nearly half said it would need to have the basic conservation benefits, like reducing soil erosion, which the other CCs they plant have. Cost of the seed, planting, and management would need to be reasonable and comparable to other CCs. Whether or not the CC fits into the current crop rotation was also important, as were its management requirements. Does it need to be terminated? Does it require specific equipment to plant? Is it easy to control or could it become a noxious weed? These are all questions growers ask when considering a new CC. Other considerations include whether or not the CC scavenges nutrients, nematode suppression, weed suppression, overwintering potential, growth rate, resistance to soil pathogens, and seed availability and packaging. Three growers also said they would want to see research on a new CC variety before planting it. To quote one individual, “research them like a regular crop”. Growers wanted to know how late a CC could be planted for them to still reap its conservation and soil benefits. They specifically requested more research on biofumigants like mustard and radish. A few growers do their own research by trying a new CC on a few acres first before applying it to a whole field. Clearly a lot of thought and consideration goes into selecting the right CC for ones operation and additional CC research would only make the process easier.

My interviews helped me gain a deeper understanding of cover cropping systems in the WCS and how they are managed. I learned what factors influence the cover crops growers select and what attributes they are looking for in new cover crop varieties. Making the decision to try a new CC variety can be difficult and even risky, but the WCS growers I spoke with were generally willing to take a chance. The WCS is not an easy place to farm, so the farmers who have been successful there have learned to adapt, innovate, and aren't afraid to try new things. This may also help explain why the level of crop diversity is so great in the WCS, at least relative to other parts of the Midwest. Though CCs may be a necessity in the region, growers are well aware of the plethora of other benefits they can provide and utilize them accordingly. Preventing soil erosion, improving soil quality, and building soil organic matter are just the beginning. Ultimately, I believe there is great possibility for positive agricultural change if cover cropping practices are adopted more widely. I hope that this research on CCs can help contribute to a more sustainable, multifunctional form of agriculture across the country by inspiring growers to try planting CCs. These data can also be used to guide future research on specific CC varieties by helping researchers understand what factors are important to growers when considering various CC options.

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APPENDIX A

GROWER INTERVIEW QUESTIONS

Cover Cropping Interview Questions:

Grower interviews over cover cropping practices in the Wisconsin Central Sands will be semi-structured. The following questions will be asked to all growers and responses will be kept within the scope of these questions/topics.

1. What crops do you typically grow? What cover crops do you typically grow?
2. What are your primary reasons for planting cover crops? (i.e. weed suppression, soil building, pest and disease control, erosion control)
3. What factors influence which cover crops you select? (Cost to plant/harvest, benefits to the soil, etc.)
4. How important is conservation when making these decisions? Is it something that you consider? Do you feel like taking care of the environment is embedded in your management decisions?
5. Are decisions ever based on what other farmers are doing? For instance, are you less likely to try a new crop variety if no one else is doing it? If so, why?
6. How do you utilize new scientific knowledge when making on farm decisions? Do you read extension articles? Attend field days? Agronomy journals? How do you get your information related to cover crops?
7. Have you ever heard of Pearl Millet? If so, when/how? Would you consider growing it if it was proven to suppress nematodes and reduce fumigation needs?
8. What would it take to get you to try out a new variety of cover crop?