EFFECT OF LONG-TERM CROP ROTATION ON PRODUCTIVITY, GREENHOUSE GAS EMISSION, AND SOIL PROPERTIES

By

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Dissertation Abstract

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Under the supervision of Professor Joseph G. Lauer

At the University of Wisconsin – Madison

To deal with climate change, agricultural practices that ensure continued productivity with a minimal impact on the environment are currently being evaluated. Crop rotation is often neglected due to economic influences, but it has a high potential to maximize resiliency of the corn-based system of the Midwestern region of the United States under uncertain weather patterns.

Each study contained in this dissertation serve individually to answer specific questions concerning the impact of crop rotation on crop productivity, greenhouse gas emission and soil quality, but collectively serve to integrate these areas in order to better understand how crop rotation management affects the whole system. This dissertation is a transdisciplinary study grouped in five chapters where continuous corn (CC), 2-yr corn-soybean [*Glycine max* (L.) Merr.] (CS), and 3-yr corn-soybean-wheat (*Triticum aestivum* L.) (CSW) rotations were studied in a multi-site and multi-year experiment in Wisconsin in order to evaluate their impact on: (i) crop productivity, accumulation and partitioning of carbon and nitrogen, within corn plant components; (ii) greenhouse gas emission to identify the main sources of emission and to assess potential opportunities for emission reduction; and iii) key soil physical and chemical properties to determine any changes that may impact soil health. The last chapter integrated these impacts to: (iv) test the biogeochemical DAYCENT model against field collected data to estimate emission of nitrous oxide (N_2O) during the non-vegetative period when field measurements were not collected, and (v) to simulate future rotation effects on N_2O and crop yield responses under different climate change scenarios.

This research provides valuable information on how, through proper decision-making, certain environmental challenges can be successfully resolved. These results highlight that long-term high productivity can be achieved and environmental concerns satisfied when crop rotations are implemented.

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General Abstract

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Climate change projections suggest an increased frequency of extreme climate conditions which highlight a systematical need to address agricultural vulnerability to these events. When dealing with climate change and developing management strategies we must not only think of building resiliency towards maximization of production but also towards minimization of costs with efforts leading to mitigation of greenhouse gases emission and proper maintenance of soil health to assure long-term productivity. The Midwestern region of the U.S. is based on heavily fertilized corn (*Zea mays* L.) production where continuously grown corn, that has often negative impact on the environment, is commonly seen, especially when grain prices are high. Crop rotation, which increases the crop diversity of a system, is often neglected due to economic influences, but it has a high potential to solve many environmental problems associated with growing crops in monoculture and still maintain productivity.

This dissertation is a composite of transdisciplinary studies grouped in four main chapters (chapters 1-4) where three long-term corn-based crop rotations in multi-site and multi-year experiments in Wisconsin were selected to evaluate and assess potential benefits for implementation. The studied crop rotation systems were: continuous corn; 2-yr corn-soybean [*Glycine max* (L.) Merr.] and 3-yr corn-soybean-wheat (*Triticum aestivum* L.). Sufficient time (5-10 years) has passed to allow these extended crop rotations experiments to equilibrate differences within treatments.

This dissertation starts with the 1st chapter, designed to evaluate the contribution of corn plant components (grain, stover, cob) to final biomass production, and carbon and nitrogen accumulation and

partitioning within the plant. Therefore, this study helped to better understand how crop rotation performs across a range of typically practiced field management strategies in the Midwest for grain production and helped to quantify differences in residue abundance after harvest which is so essential to protects soils. Only a few studies have been conducted to address similar research questions and even fewer attempted to determine the interaction across different environments in a multi-year structure.

Agricultural soils contribute to GHG emissions and most distinctively to potent, soil-born, nitrous oxide (N_2O) emissions that is often stimulated by the addition of nitrogen fertilizers. The research included in the 2nd chapter is the first attempt performed in Wisconsin that investigates the impacts of the long-term crop rotations on the intensity of the key GHG emissions from a range of differently managed environments. This study was designed to assess increasing rotation diversity effects on the emissions of N_2O, CO_2, and CH_4. It identified influential factors that drive emissions that are specific to each environment, and also compared the agricultural land use efficiency among rotations by considering yield-scaled N_2O emissions.

Soil is the essence of life and needs to be protected in order to satisfy continuously increasing global food demand due to population growth. The effect of crop rotations on soil is not consistent, but in general is positive and often depends upon the quantity and quality of plant residues produced by rotated crops. Practices that supply carbon to the soil are of particular interest since it influences many other properties such as water retention, which is particularly important under prolonged dry conditions. Thus, the principal objective of 3rd chapter was to evaluate the effect of the long-crop rotation on selected soil physical and chemical properties across unique sites in Wisconsin.

A precise in-field estimation of N_2O emissions from cropping systems is challenging. It requires continuous large-scale monitoring which is often discontinued during the non-vegetated season. This period may lead to a significant underestimation of the emissions. Moreover, it requires specialized human personnel and equipment which makes it costly. The widely recognized biogeochemical model, DAYCENT, is capable of simulating many different environmental processes including GHG emission and crop productivity. The goals of the 4th chapter were to test the ability of the DAYCENT model to simulate N_2O emissions and grain yields of investigated crop rotations during the vegetated period when the field data were collected and to estimate N_2O emissions during periods when the field measurements were not collected to assess their impact on the total annual emissions. This chapter was concluded with simulations of future crop rotation effects on GHG emissions and crop yield responses across different moderate sensitivity climate change scenarios.

In summary, this dissertation was a transdisciplinary study where each chapter serves individually to answer specific questions concerning the impact of crop rotation on crop productivity, greenhouse gas emission and soil properties, but collectively serve to integrate these areas in order to better understand how crop rotation management affects the system in the long-run. In most research, the emphasis is often placed on comparing yields among different cropping systems; however, in the current era, climate change environmental concerns should be equally considered. This dissertation contributes to gaps in our knowledge and will provide valuable assets to the decision-making process in corn-based systems not only in Wisconsin but in the Midwest Corn Belt Region of the U.S.

Chapter 1. *The Influence of Crop Rotation on Corn Total Biomass Production*

1.1 Abstract

Agriculture in the Midwest region of the United States is based on intensive corn (*Zea Mays* L.) production that provides food, feed and fuel. Three rotation systems: continuous corn (CC), corn-soybean [*Glycine max* (L.) Merr.] (CS), and corn-soybean-wheat (*Triticum aestivum* L.) (CSW) were selected to study their effects on grain yields and carbon (C) and nitrogen (N) accumulation and partitioning within corn grain, stover and cob plant components. The experiment was conducted at three pre-established crop rotation experiments located at three sites in Wisconsin. Biomass sampling was performed in four consecutive years (2011-2014). Analysis of variance showed differences in location for most variables, an effect of crop rotation on stover biomass and stover C, and an interaction effect between location and rotation on soybean grain yield. Averaged across years and locations, final corn and soybean grain yield increased with rotation complexity where corn in the CSW rotation had 15%, and 8% greater yield than CC and CS rotation, respectively. Overall, the biomass distribution among corn plant parts was 52%, 41%, and 7% for grain, stover, and cob, respectively. Stover and cobs harvested from corn grown in monoculture produced approximately 11% (0.54 Mg C ha^{-1}) less C than corn grown in either CS or CSW rotation. Across rotations, the accumulation of N in plant tissues was not significantly different. These results show that growing corn in rotation with additional crops in the rotation can increase grain yields and biomass C in plant tissue.

Abbreviations: CC, continuous corn; CS, corn-soybean rotation; CSW, corn-soybean-wheat rotation; C, carbon; N, nitrogen.

1.2 Introduction

Concerns about climate change have led to a search for management practices that are more sustainable. It is predicted that agriculture will experience in the near future more extreme events such prolonged droughts and intensive precipitation events (IPCC, 2007; IPCC, 2013). Sustainable practices that economically provide basic food and fiber needs for humans and animals, should also sustain or enhance environmental quality in such way that the long-term productivity of the system is secured (Delgado et al., 2011; Tilman, 1999).

Crop rotation is a management practice where two or more crops are grown in a sequential order. This well-known management practice often leads to a yield increase compared to the same crops grown in monoculture (Boyer et al., 2015; Crookston et al., 1991; Pedersen and Lauer, 2003; Stanger and Lauer, 2008). There seems to be no single mechanism that is responsible for the rotation effect that leads to the yield increase. This naturally occurring phenomenon is often referred to as the “rotation effect” (Bullock, 1992).

Multiple reasons have been reported as influential in the rotation effect. Some examples are improved soil physical properties; reduced pressure from weeds, pests and diseases; or improved microbial biodiversity (Bullock, 1992; Karlen et al., 1994a). Crop rotations may also improve environmental quality by lowering N fertilizer inputs, especially when a legume crop is included in the rotation (Pedersen and Lauer, 2003; Stanger and Lauer, 2008). This has also been linked with a significant reduction of the greenhouse gas nitrous oxide (N_2O) (Bayer et al., 2015; Drury et al., 2008; Omonode et al., 2011), which has approximately 300 times the global warming potential of carbon dioxide (CO_2) (IPCC, 2013). Moreover, legume crops as a N source should be taken into a consideration with unstable fertilizer prices which change from year to year (USDA-ERS, 2011).

For many reasons the use of crop rotation other than the 2-yr CS rotation has been reduced (Karlen, 2004). And, still 16% of corn and 6% of soybean were being grown in monoculture for at least 3 consecutive years in 2010 (USDA-ERS, 2013). However, while the “rotation effect” under 2-yr CS rotation may exist, it may not be maximized. Crookston et al. (1991) reported that a 2-yr rotation of corn and soybean increased yields of both crops when managed for maximum production, where corn had 10% and soybean 8% yield advantage over a monoculture of each crop. In the same study, the authors found that the yield of first year soybean increased by 17% after growing continuous corn for 5 consecutive years, and likewise the yield of first year corn yield increased by 15% after growing continuous soybean for 5 consecutive years, compared to continuously grown. This agrees with the findings of Pedersen and Lauer (2003) and Meese et al. (1991). Therefore, yields of long term 2-yr CS rotation can be somehow limited which may suggest that an increase in number of crops in a rotation could further improve yields. With the expected crop grain yield increase, the corresponding increase of crop residue production must exist, however, the majority of these studies have focused on assessing the grain fluctuations among different crop rotations.

Abundance of high C in crop residues on the field after harvest in conjunction with other conservation practices has been proposed or reported to promote a wide spectrum of soil property changes (Al-Kaisi and Yin, 2005; Aziz et al., 2011; Karlen et al., 1994b; Lal, 2004; Mann et al., 2002). However, currently there is a great deal of interest to use corn residues for biofuel (Wilhelm et al., 2007). Such removal may reduce C inputs and lower soil quality. Promoting cropping systems that produce high amounts of biomass would compensate for its partial removal. In a few studies it has been proposed that removing corn cobs may provide an inexpensive way to support biofuel production and not harm soil organic carbon by leaving stover on the ground (Avila-Segura et al., 2011).

In recent years more focus has been placed on improving methods to grow crops in a more environmental friendly manner. The fear of climate change and its effects on humanity has raised more concerns on how we can either maintain or increase food production. Crop rotation has a potential to solve many environmental problems associated with growing crops in monoculture and still maintain and ensure productivity. The objective of this study was to determine the effect CC, CS and CSW rotation on whole corn plant yield, and C and N accumulation and partitioning within the plant.

1.3 Materials and Methods

1.3.1 Sampling Locations

This study was conducted at the University of Wisconsin’s Agricultural Research Station in Arlington (43°18’N, 89°20’W), Lancaster (42°50’ N, 90°47’ W), and Marshfield (44°76’ N, 90°09’ W). At each location three rotation treatments, continuous corn (CC), corn-soybean (CS) and corn-soybean-winter wheat (CSW) were used to evaluate crop productivity and carbon (C) and nitrogen (N) allocation within corn plants at maturity. These were long-term trials established in a randomized complete block arranged with three replications at Arlington and Marshfield and two replications at Lancaster to account for field variability. For this study, we collected data from 2011 to 2014. The experimental plots at Arlington were initiated in 2002, at Marshfield in 2007 and at Lancaster in 2005. Therefore, sufficient time has passed at each location to allow these extended crop rotation experiments to equilibrate differences within rotation treatments. The study at Lancaster is among one of the oldest rotation studies in U.S. and was initiated to evaluate response of crop rotations on productivity and N balance by varying the N fertilization rates (Vanotti and Bundy, 1994). The mean annual temperature and precipitation at Arlington are 7.7°C and 854 mm, at Lancaster 7.8 °C and 880 mm, and at Marshfield 6.8 °C and 820 mm, respectively (Appendix A and B). Detailed information regarding soil type differences among locations that influenced chosen crop management practices is outlined in section 3.3.1 (Sampling Locations) of 3rd Chapter.

Applied crop management practices were slightly different at each location but all were typical practices in the Midwestern region of the United States. Crop hybrids used in these experiments differed across years but were chosen based upon their performance in the previous year at each location separately. Soil fertility samples were collected and analyzed every year at Arlington and every 3 years at Lancaster and Marshfield, and uniform rates of phosphorus (P) and potassium (K) fertilizers were applied as recommended amounts using soil nutrient information from soil tests. Soil fertility, hybrids used, and dates of key management operations for each crop at each location during the data collection period are presented in Table 1.2. The summary of applied chemicals to the crops is presented in Appendix C.

Arlington

At Arlington, individual plots were 3 m wide x 9 m long. All plots were managed as no-till systems with all residue left on-field. None of the crops received starter fertilizer. All corn plots were fertilized after planting with 28% urea ammonium nitrate ($CH_4N_2O + NH_4NO_3$) at a rate of 224 kg N ha^{-1} and winter wheat with urea at the rate of 113 kg N ha^{-1} in 2011-2012 and 134.4 kg N ha^{-1} in 2013-2014. Seeds were planted into the undisturbed residue of the previous crop using a Kinze 2000 Interplant Planter (Kinze Manufacturing, Williamsburg, IA) mounted with a 13-wave coulter, trash whippers (Yetter, Location) and double disk seed openers. Corn seed was treated with 0.25 mg a.i. $seed^{-1}$ clothianidin (Poncho 250) [(E)-l-(2-chloro-l,3-thiazol-5-ylmethyl)-3-methyl-2-nitroguanidine]. Corn seeds were planted in 76-cm rows at 3.8-cm depth seeding rate 86,450 seeds ha^{-1}. The two middle rows of each corn plot were harvested with a Kincaid 8XP Plot Combine (Kincaid Equipment Manufacturing, Haven, KS). Using the same planter, soybean was planted in 76-cm rows at 444,600 seeds ha^{-1} at a depth of 2.5-cm. Soybean seed was treated with 0.0076 mg a.i. $seed^{-1}$ fludioxonil (Maxim) [4-(2,2-difluoro-l,3-benzodioxol-4-yl)-l/-pyrrole-3-carbonitrile] fungicide and 0.0756 mg a.i. $seed^{-1}$ thiamethoxam (Cruiser 5FS) [3-[(2-Chloro-1,3-thiazol-5-yl)methyl]-5-methyl-N-nitro-1,3,5-oxadiazinan-4-imine] insecticide. The two middle rows of each soybean plots were harvested using an Almaco Plot Combine (Allen Machine Co., Nevada, IA). Winter wheat was planted in 19-cm rows at 2.54-cm depth seeding rate 4.199 million seeds ha^{-1} using JD750 no-till drill (John Deere, Moline, IL). Wheat seed was treated with 118 mL per 45.4 kg $seeds^{-1}$ of difenoconazole + mefenoxam (Dividend Extreme) [1-[2-[2-chloro-4-(4-chloro-phenoxy)-phenyl]-4- methyl[1,3]dioxolan-2-ylmethyl]-1H-1,2,4-triazole] + [(R)-2-[(2,6-dimethylphenyl) methoxyacetylamino]propionic acid methyl ester]. Winter wheat was fertilized in spring with urea at a rate of 113 kg N ha^{-1} in 2011-2012 and 134.4 kg N ha^{-1} in 2013-2014. Using the same harvester used for soybean, the middle eight rows of winter wheat plots were harvested. In 2011, preplant weed control was done with 0.75 kg a.i. ha^{-1} glyphosate (PowerMax) [N-(phosphonomethyl)glycine] and 1.39 kg a.i. ha^{-1} s-metolachlor (Dual II Magnum) [2-chloro-N-(2-ethyl-6-methylphenyl)-N-[(1S)-2-methoxy-1-methylethyl]acetamide] in corn and soybean plots. Glyphosate was applied once after emergence at the same rate. Weed control in wheat was done with 0.11 + 0.03 kg a.i. ha^{-1} pinoxaden + cloquintocet-mexyl (Axial) [8-(2,6-Diethyl-p-tolyl)-1,2,4,5-tetrahydro-7-oxo-7H-pyrazolo[1,2-d][1,4,5]oxadiazepin-9-yl-2,2-dimethylpropanoate] + [1-methylhexyl 2-[(5-chloro-8-quinolinyl)oxy]acetate] and 0.25 kg a.i. ha^{-1} octanoic acid ester of bromoxynil (Buctril) [3,5-dibromo-4-hydroxybenzonitrile]. No fungicide control was applied to corn and soybean in either year. Fungicide control in wheat was done at the Feeks 10.5.1 growth stage (Large, 1954) with 0.15 kg a.i. ha^{-1} pyraclostrobin (Headline) [carbamic acid, [2-[[[1-(4-chlorophenyl)-1H-pyrazol-3- yl]oxy]methyl\phenyl]methoxy-, methyl ester)] and with 0.09 + 0.09 a.i. ha^{-1} propiconazole + tebuconazole (Prosaro) [2-[2-(1-Chlorocyclopropyl)-3-(2-chlorophenyl)- 2-hydroxypropyl]-1, 2-dihydro-3H-1, 2, 4-triazole-3-thione] + [alpha-[2-(4-chlorophenyl) ethyl]-alpha-(1, 1-dimethylethyl)-1H-1, 2, 4-triazole-1-ethanol]. In 2012, to control weeds corn and soybean received preplant 0.52 kg a.i. ha^{-1} of 2,4-D [2,4(dichlorophenoxy)acetic acid] and 1.43 kg a.i. ha^{-1} glyphosate and postplant 1.39 kg a.i. ha^{-1} s-metolachlor and 0.75 kg a.i. ha^{-1} glyphosate. The same chemical types and rates as in 2011 were applied to wheat crop in 2012. Insecticide control was done only in 2012 in corn plots with 0.56 kg a.i. ha^{-1} dimethoate (Dimethoate 400) [(O,O-dimethyl-S-[methylcabamoyl) methyl]phosphorodithioate)]. In 2013, to control weeds, corn and soybean received preplant 1.39 kg a.i. ha^{-1} s-metolachlor and 0.82 kg a.i. ha^{-1} glyphosate, where 0.82 kg a.i. ha^{-1} glyphosate was also applied postplant. Weed control in wheat was done with 0.03 + 0.12 kg a.i. ha^{-1} pyrasulfotole + bromoxynil octanoate (Huskie) [5-hydroxy-1,3-dimethyl-1*H*-pyrazol-4-yl)[2-(methylsulfonyl)-4-(trifluoromethyl)phenyl]methanone, (5-Hydroxy-1,3-dimethylpyrazol-4-yl)(α,α,α-trifluoro-2-mesyl-p-tolyl)methanone] + [3,5-dibromo-4-hydroxybenzonitrile]. Fungicide control in wheat was done with 0.15 kg a.i. ha^{-1} pyraclostrobin. In 2014, to control weeds corn and soybean received preplant 1.39 kg a.i. ha^{-1} s-metolachlor and 0.75 kg a.i. ha^{-1} acid equivalent glyphosate (Roundup Weathermax) [isopropylamine salt of N-(phosphonomethyl)glycine) of glyphosate]. Glyphosate was applied once after emergence and once after harvest at 0.96 and 0.83 kg a.i. ha^{-1}, respectively, to control weeds in corn. Weed control in wheat was done with 0.03 + 0.12 kg a.i. ha^{-1} pyrasulfotole + bromoxynil octanoate. Fungicide control in wheat was done with 0.08 + 0.16 kg a.i. ha^{-1} fluxapyroxad + pyraclostrobin (Priaxor) [1H-Pyrazole-4-carboxamide, 3-(difuoromethyl)-1 methyl-N-(3',4',5'-trifuoro[1,1'-biphenyl]-2-yl)] + [(carbamic acid, [2-[[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester)].

Lancaster

At Lancaster, individual seeded plots were 6.1 m wide x 15.2 m long. Harvested plot size was 1.5 m wide and 15.2 long. Tillage varied among rotations. Both, CS and CSW rotations were no-tilled and CC was fall chiseled using Case-870 Ecolo-tiger disk ripper, spring disked and cultimulched using Case-IH 34’ turbo till (Case Corporation, Racine, WI). Starter fertilizer was applied to corn and its rate varied over the years. Typically, corn plots received 9.2 kg N ha^{-1}, 42.2 kg P_2O_5 ha^{-1}, and 55.0 kg K_2O ha^{-1} as row applied granular starter fertilizer at planting. Corn and winter wheat plots were fertilized after planting with 34% ammonium nitrate (NH_4NO_3) at a rate of 224 kg N ha^{-1} and 33.6 kg N ha^{-1}, respectively. Additionally, both soybean and winter wheat received 17.3 kg P_2O_5 ha^{-1} and 34.7 kg K_2O ha^{-1} after planting. Corn was planted in 76-cm rows at 3.8-cm depth seeding rate 82,745 seeds ha^{-1} using 4-row White 6100 Planter (AGCO Corporation, Duluth, GA). Corn plots were harvested with Kincaid 8XP Plot Combine (Kincaid Equipment Manufacturing, Haven, KS). Soybean was planted with a Krause no-till drill (Kuhn Krause, Hutchinson, KS) into corn residue in 38-cm rows at 370,500 seeds ha^{-1} seeding rate at 1.75 cm depth. With the same planter, winter wheat was planted no-till into soybean residue in 19-cm rows at 2.2 kg ha^{-1} seeding rate and 2.54 cm planting depth. In 2011, postplant weed control in corn was done with 1.42 kg a.i. ha^{-1} s-metolachlor + 1.9 kg a.i. ha-1 glyphosate + 0.15 kg a.i. ha^{-1} mesotrione (Callisto) [2-[4-(Methylsulfonyl)-2-nitrobenzoyl]cyclohexane-1,3-dione]. Postplant weed control in soybean was done with 3.09 kg a.i. ha^{-1} glyphosate. In 2012, postplant weed control in corn was done with 0.75 kg a.i. ha^{-1} glyphosate and 2.25 + 0.84 + 0.23 kg a.i. ha^{-1} s-metolachlor + atrazine + mesotrione (Lumax) [atrazine: [2-chloro-4-(ethylamine)-6-(isopropylamino)-s-triazine]]. Weed control in soybean was done twice with 0.75 kg a.i. ha^{-1} glyphosate pre- and postplant at the same rate. In 2013, postplant weed control in corn was done with 1.81 kg a.i. ha^{-1} s-metolachlor, 0.15 kg a.i. ha^{-1} mesotrione, and 0.96 kg a.i. ha^{-1} glyphosate. In 2014, weed control in corn was done at planting with 0.02 + 0.18 kg a.i. ha^{-1} rimsulfuron + mesotrione (Instigate) [rimsulfuron: N-((4,6-dimethoxypyrimidin-2-yl)aminocarbonyl)-3-(ethylsulfonyl)-2-pyridinesulfonamide] and postplant with 1.17 + 1.63 + 0.12 kg a.i. ha^{-1} s-metolachlor + glyphosate + mesotrione (Halex GT). Weed control in soybean was done at planting with 0.9 kg a.i. ha^{-1} dimethenamid-P (Outlook) [(S)-2-chloro-*N*-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide] and 0.04 kg a.i. ha^{-1} cloransulam-methyl (FirstRate) [N-(2-carbomethoxy- 6-chlorophenyl)-5-ethoxy-7- fluoro(1,2,4)triazolo-[1,5-c]pyrimidine- 2-sulfonamide] and postplant with 0.94 + 1.26 kg a.i. ha-1 glyphosate + s-metolachlor (Sequence). Postplant weed control in wheat was done with thifensulfuron-methyl 0.02 kg a.i. ha^{-1} (Harmony SG) [Methyl 3-[[[[(4-methoxy-6-methyl-1,3,5- triazin-2-yl) amino]carbonyl]amino] sulfonyl]-2-]. No insecticides or fungicides were applied at Lancaster during the experiment period.

Marshfield

At Marshfield, individual plots were 18.3 m wide x 18.3 m long. Harvested plot size was 3 m wide x 18.3 m long for corn and 4 m wide x 18.3 m long for soybean and wheat. Tillage operations in all rotations included, fall tillage using Brillion chisel plow (Landoll Corporation, Marysville, KS), followed with a finishing tillage operation in spring using Lely Roterra Harrow (Lely Holding, Maassluis, Netherlands). A Brillion row cultivator (Brillion, WI) was used after planting to suppress any competition coming from weeds by uprooting them. Starter fertilizer was applied to every crop with the corn planter at the time of planting. All plots received 15.1 kg N ha^{-1}, 18.5 kg P_2O_5 ha^{-1}, and 50.4 kg K_2O ha^{-1}, 10.1 kg S ha^{-1}. After planting, corn was fertilized with 28% urea ammonium nitrate at a rate of 134.5 kg N ha^{-1} and 90 kg N ha^{-1} in CC and two other rotations, respectively. Winter wheat was fertilized with urea at the rate of 97.4 kg N ha^{-1} in 2012 and 72.8 kg N ha^{-1} in all other years. Corn was planted in 76-cm rows at 3.8-cm depth seeding rate 86,450 seeds ha^{-1} using JD1750 (John Deere, Moline, IL). No additional seed treatments were applied to any seeds. Soybean was planted in 19-cm rows at 370,500 seeds ha^{-1} seeding rate at 2.54 cm depth using Great Plains 1206NT (Great Plains Manufacturing, Inc., Salina, KS). With the same planter, winter wheat was planted at the same depth and row width as soybean with a target seeding rate of 4.9 million seeds ha^{-1}. All crops were harvested with Massey Ferguson 550 combine (AGCO Corporation, Duluth, GA). In 2011, weed control in corn and soybean was done with 1.87 kg a.i. ha^{-1} metolachlor (Paraller) [2-chloro-N-(2-ethyl-6-methylphenyl) -N-(2-methoxy-1-methylethyl) acetamide] and 1.09 kg a.i. ha^{-1} acid equivalent glyphosate. Weed control in wheat was done with 0.018 + 0.018 kg a.i. ha^{-1} thifensulfuron-methyl + tribenuron-methyl (Affinity Brodspec) [methyl 3-[[[[(4-methoxy-6-methyl-1,3,5- triazin-2-yl) amino]carbonyl]amino] sulfonyl]-2-] + [methyl 2-[[[[N-(4-methoxy-6-methyl-1,3,5- triazin-2-yl)methylamino]carbonyl] amino]sulfonyl]benzoate]. In 2012, weed control in corn and soybean was done with 1.87 kg a.i. ha^{-1} metolachlor, 1.09 kg a.i. ha^{-1} acid equivalent glyphosate, and soybean additionally received 0.14 kg a.i. ha^{-1} sethoxydim (Poast Plus) [2-[1-(ethoxyimino)butyl]-5-[2-thylthio) propyl]-3-hydroxy-2-cyclohexen-1-one]. Weed control in wheat was done with 0.009 + 0.009 kg a.i. ha^{-1} thifensulfuron-methyl + tribenuron-methyl. In 2013, weed control in corn and soybean was done with 1.79 kg a.i. ha^{-1} s-metolachlor (Brawl II) and 1.09 kg a.i. ha^{-1} acid equivalent glyphosate. Weed control in wheat was done with 0.53 kg a.i. ha^{-1} (2,4-D). In 2014, weed control in corn was done with 1.79 kg a.i. ha^{-1} s-metolachlor, 1.09 kg a.i. ha^{-1} acid equivalent glyphosate, and 0.04 + 0.111.79 kg a.i. ha^{-1} flumetsulam + clopyralid (Hornet WDG) [*N*-(2,6-difluorophenyl)-5-methyl-1,2,4-triazolo-[1,5a]-pyrimidine-2-sulfonamide] + [3,6-dichloro-2-pyridinecarboxylic acid, potassium salt]. Weed control in soybean was done with 1.09 kg a.i. ha^{-1} acid equivalent glyphosate and in wheat with 0.53 kg a.i. ha^{-1} (2,4-D). No fungicide was applied to any crops in Marshfield in any year. Insecticide control in corn and soybean was done only in 2012 with 0.03 kg a.i. ha^{-1} cyfluthrin (Baythroid 2) [Cyano(4-fluoro-3-phenoxyphenyl)methyl-3-(2,2-dichloroethenyl)-2,2-dimethyl-cyclopropanecarboxylate].

1.3.2 Data Collection

Six random representative corn plants per plot were harvested at the ground level from CC, CS, and CSW rotations after black layer formation at physiological maturity (R6) (Abendroth et al., 2011) at all locations in four consecutive years 2011-2014, except at Marshfield in 2012 when no samples were collected. The R6 stage of corn development was chosen to measure the proportion of the stover component of corn biomass. Ears were removed from plants, while keeping the ear shank and husks intact and hand shelled. All plant components (stover, ears and cobs) were weighed separately fresh. Subsequently, stover was chopped with a Troy Built Tomahawk Pro chipper (Troy, NY), mixed, and an approximate 500 g subsample was collected for moisture determination. Samples were oven-dried at 60 °C for seven days and weighed to determine moisture content at harvest and their proportions to the total biomass on a dry matter basis. The dried samples were ground in a laboratory Wiley mill (Thomas Scientific, NJ) to pass through a 1.0-mm screen. Finely ground subsamples of each plant component were packed into 5 x 9 mm tin capsules and analyzed for total nitrogen (N) and total carbon (C) concentration by dry combustion using a using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy).

At the final harvest, data collected from the same corn plots included grain yield and grain moisture. Grain yields were adjusted to moisture content of 155 g kg^{-1}, 130 g kg^{-1}, and 135 g kg^{-1}, for corn, soybean, and wheat, respectively.

1.3.3 Statistical Analysis

All data were subjected to an analysis of variance using the PROC MIXED procedure of SAS Institute version 9.3 (2011). For determining the expected mean squares, appropriate *F*-tests and *T*-tests in the analysis with random effects of year, rep(location x year) and fixed effects of location, rotation and location x rotation interaction were used. Least square means of the fixed effects were computed, and the PDIFF option of the LSMEANS statement was used to display the differences among least square means for comparison. This option uses Fisher’s protected LSD, and comparisons were conducted at $P \leq 0.05$.The residuals were tested for normality using the Shapiro-Wilk test using the PROC UNIVERATE procedure.

1.4 Results and Discussion

Weather conditions substantially differed across seasons (Appendix A and B). Air temperatures were closest to the 30-yr mean in 2011. At all locations, abnormally high air temperatures occurred during winter and mid-summer in 2012 and abnormally cold conditions occurred in a majority of months in 2013 and 2014. Precipitation totals in 2011 were below the 30-yr average only at Arlington, which was the result of low rainfall in May to August. In 2012, across all locations, drought conditions in winter and from June through mid-July resulted in the highest deficit of rain across the study period. Unusually wet conditions were present in the beginning of the 2013 growing season which caused planting delays; however, subsequent monthly precipitation totals in 2013 were below the 30-yr average. In 2014, differences in precipitation among locations was the highest, with -128 mm below the 30-yr mean at Lancaster, and 18, and 173 mm above the average at Arlington and Marshfield, respectively.

1.4.1 Grain Yield

The analysis of variance revealed that there was an effect of location and rotation on corn and soybean yield, and there was a significant location x rotation interaction for soybean yield (Table 1.3). Generally, grain yield of corn, soybean, and wheat were similar at Arlington and Lancaster and lower at Marshfield (Table 1.4). Corn grain yield responded to crop rotation. When pooled over locations, corn grain yield from the 3-yr CSW rotation had the highest yield (11.8 Mg ha^{-1}) and yielded 1.5 Mg ha^{-1} (15%) more than CC and 0.9 Mg ha^{-1} (8%) more than the 2-yr CS rotation (Table 1.4). Grain yield comparisons of CC with corn grown in rotations with various crops have confirmed the monoculture com yield penalty (Crookston et al., 1991; Lund et al., 1993; Pedersen and Lauer, 2003; Stanger and Lauer, 2008). Locations differed in terms of tillage management. Generally, studies have also demonstrated conflicting evidence for the effects of tillage and rotation upon crop yields. Some studies report that tillage has no effect on corn yield, regardless of rotation sequence (Pedersen and Lauer, 2002). In contrast, Meese et al. (1991) found greater corn yield in a conventionally tilled system versus no-till when averaged across rotations in two out of three study years. Yields were equal in one particularly dry year

(1988), which may have been due to improved season-long resource use as a result of delayed germination in no-till corn.

Soybean grain yield differed across locations. At Lancaster, soybean in CSW yielded 3.7 Mg ha^{-1} and it was 0.8 Mg ha^{-1} (22%) more than in the CS rotation; whereas at Arlington soybean in CSW yielded 4.2 Mg ha^{-1} which was 0.6 Mg ha^{-1} (14%) more than the CS rotation. At Marshfield no difference was observed between rotations and both soybean rotations yielded 2.3 Mg ha^{-1} which caused a significant location x rotation interaction (Table 1.4).

This study did not include a continuous soybean rotation, but there is agreement in the literature that soybean grain yield is improved with the 2-yr CS rotation (Lund et al., 1993; Pedersen and Lauer, 2002). The results of this study indicate that in most situations soybean yield can be improved if a third crop was added to the rotation. Similarly, some studies suggest soybean yield improvement in more complex rotations than 2-yr CS (Katsvairo and Cox, 2000) while some studies suggest no difference when adding a third crop (Lund et al., 1993).

1.4.2 Corn Plant Components

P-values from analysis of variance of yield, C, and N, of each plant component (grain, stover, cob, and total stover) are shown in Table 1.3 and main effects (location, rotation and their interaction) means separation in Table 1.5. No significant location x rotation interaction was found in any of the studied variables. When pooled over locations, crop rotations where not different in corn grain biomass and its C and N content (Table 1.4). However, the rotation effect on crop grain biomass was almost significant (P=0.0848). Continuous corn tended to have lower corn grain biomass and C and N content than other rotations, which was confirmed by orthogonal contrasts when CS and CSW rotations were pooled together and compared to the CC (Table 1.4).

Corn plant biomass was collected earlier than the final grain harvest. In the period between soft dough stage and maturity, Center at al. (1970) found that the weight of corn stover (stem+leaf) was 2 Mg ha^{-1} lower and ear weight (with cob included) 2 Mg ha^{-1} higher than at final harvest. This was due to the translocation of minerals and nutrients such as N within the plant. In this study, for two out of three locations (Arlington and Lancaster) the final corn grain yields were higher than corn grain biomass collected at R6 for components determination. However, the opposite was true at Marshfield. These differences could be attributed to differences in the environments. Soils at Marshfield are described as poorly drained (Soil Survey Staff, 2015) and occasionally for extensive periods of time experience prolonged water saturation, which has an impact on timing of management practices. As an example, in 2013, wet conditions delayed timely planting and additionally severe lodging issues occurred causing final grain yield reductions.

Crop rotation had an effect on stover biomass and stover C, but not on cob biomass when cobs were separated from the stover (Table 1.3). Cobs were an important component of the total stover, and accounted for 11 to16% of biomass and 8 to 13% of N (Table 1.5). Corn in CS rotation produced 10% and in CSW 11% more total stover biomass than CC. For stover, C, CS and CSW rotation yielded 0.59 and 0.48 Mg C ha^{-1} more, respectively, than CC. When pooled over rotations, generally, Lancaster had higher total stover biomass, C and N than Arlington and Marshfield which were similar. Pordesimo et al. (2004), in a one year study performed in Tennessee, reported that when corn reached physiological maturity the grain biomass accounted for 46% of the total dry matter distribution. When pooled over locations and rotations, in our study corn grain accounted for 52% of the total biomass. Avila-Seguira et al. (2011) reported that grain at the final harvest accounted on average 57% of the total biomass in a 6-yr study. In their study N amount accumulated in corn grain at the final harvest was 2.9 times greater than in stover, where in our study it was greater by 1.7 to 2.0 times prior to grain harvest across location when rotations were averaged.

There was no effect of crop rotations and location x rotation interaction on C/N ratio of plant components, and on average across locations the ratios were 33 and 59, for grain and total stover, respectively (Table 1.3 and 2.5). Small differences existed in grain C/N ratio across locations, but higher average values in Arlington stover versus the other study sites.

1.5 Conclusions

Rotations had similar response across locations on all tested crop production parameters, except there was a significant rotation x location interaction on final soybean grain yield. When pooled over locations, the CSW rotation had 15%, and 8% greater final corn grain yield than CC and CS rotation, respectively. Smaller differences were noticed in corn grain biomass samples collected at physiological maturity, CS and CSW rotations were similarly greater that CC. Corn grown in monoculture produced 11% less total stover biomass (with cobs included) than corn grown in either CS or CSW rotation, which on average equaled to 0.54 Mg ha^{-1} of C. The biomass distribution among corn plant components collected between physiological maturity and final harvest was 52%, 41%, and 7% for grain, stover, and cob, respectively. Rotations were not different ($P > 0.05$) in relation to N accumulation in corn plant stover or C/N ratios of either grain or total stover. It is important to emphasize that cobs represented a significant proportion of stover biomass which could serve as an inexpensive biofuel source. These results suggest that rotating corn can increase crop grain and stover production compared to the CC system on an annual basis. In the long-term, this increase might partially offset the differences in soil C which are expected to be greater under the CC system that produces more residue. Additionally, increases of biodiversity make long-term crop rotations more sustainable and can increase resiliency to the predicted increases of weather anomalies.

1.6 References

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Table 1.1. Rotation phases of corn (C), soybean (S), and wheat (W) at Arlington, Lancaster and Marshfield Research Stations, WI during the 2011 to 2014 growing seasons.

	Year			
Crop rotation phase	2011	2012	2013	2014
1. Continuous corn	C	C	C	C
2. C-S	C	S	C	S
3. S-C	S	C	S	C
4. C-S-W	C	S	W	C
5. S-W-C	S	W	C	S
6. W-C-S	W	C	S	W

Table 1.2. Soil fertility, varieties used, and dates of field operations for each crop during the 2011 to 2014 growing seasons at the Arlington, Lancaster and Marshfield Research Stations, WI.

	Arlington				Lancaster				Marshfield			
	Year				Year				Year			
	2011	2012	2013	2014	2011	2012	2013	2014	2011	2012	2013	2014
Soil fertility												
P (mg kg^{-1})	19	19	28	22	17	--†	19	--	49	--	--	--
K (mg kg^{-1})	127	104	132	105	102	--	118	--	162	--	--	--
pH	6.9	6.9	6.8	6.6	7.0	--	6.4	--	7.0	--	--	--
OM (g kg^{-1})	3.1	2.9	3.5	2.6	2.6	--	2.6	--	3.3	--	--	--
Varieties used												
Corn	Pioneer 37N68	Pioneer 9917AM1	Pioneer 9917AM1	Pioneer 9917AMX	Legacy 3000GT (CRW)	Dekalb C53-98 (CRW)	Pioneer 832 AMX	Legacy L5522-VT3	Pioneer P8906HR	Pioneer P8906HR	Pioneer P8906HR	Pioneer 8906AM1
Soybean	Pioneer 92Y30	Pioneer 92Y30	Pioneer 92Y51	Pioneer P16T04R	FS Hisoy 24R91	Trelay 21RR37	NuTech G2-7250	O'Soy 245NR2y	Croplan R2T0860	Croplan R2T0860	Croplan R2T0860	Asgrow 1431
Wheat	Excel 234	Excel 234	Pioneer 25R40	Pioneer P2540	Pioneer 729	Pioneer 729	Pioneer 25R40	Pioneer 25R47	Pioneer 25R47	Pioneer 25R47	Pioneer 25R47	Pioneer 25R47
Field management												
Corn												
Planting	11-May	11-May	21-May	20-May	12-May	8-May	8-May	22-May	3-Nov	2-Oct	28-Oct	20-Nov
Harvest	12-Oct	25-Sep	29-Oct	3-Nov	28-Oct	8-Nov	5-Dec	4-Nov	20-May	17-May	3-Jun	30-May
Soybean												
Planting	4-May	11-May	9-May	21-May	13-May	9-May	16-May	28-May	20-May	6-Jun	3-Jun	30-May
Harvest	6-Oct	3-Oct	10-Oct	1-Oct	20-Oct	28-Sep	25-Oct	27-Oct	6-Oct	27-Sep	9-Oct	10-Oct
Wheat												
Planting	10-Oct (2010)	7-Oct (2011)	9-Oct (2012)	7-Oct (2013)	14-Oct (2010)	21-Oct (2011)	24-Oct (2012)	25-Oct (2013)	8-Oct (2010)	7-Oct (2011)	3-Jun (2013)	11-Oct (2013)
Harvest	26-Jul	2-Jul	29-Jul	2-Oct	20-Jul	3-Jul	24-Jul	30-Jul	15-Aug	24-Jul	10-Sep	14-Aug

† Dash (-), indicates that no data is available.

Table 1.3. Analysis of variance *P*-values for the main effects of location, rotation, and their interactions on combine harvested grain yield of all rotated crops, corn plant components (grain, stover, cob, total stover) yield, carbon (C), nitrogen (N), and C/N ratio for grain and total stover, in experiment performed at Arlington, Lancaster, and Marshfield, WI (2011-2014).

	Combine Harvested Grain Yield			Plant Component†												C/N ratio	
				Grain			Stover			Cob			Total Stover‡				
Factor	Corn	Soybean	Wheat	Yield	C	N	Yield	C	N	Yield	C	N	Yield	C	N	Grain	Total Stover‡
Location (L)	<0.001	<0.001	<0.001	0.072	0.080	0.001	0.001	0.001	0.003	0.050	0.035	0.112	0.001	0.001	0.005	0.021	0.002
Rotation (R)	<0.001	0.001		0.085	0.165	0.380	0.022	0.012	0.292	0.693	0.818	0.925	0.035	0.018	0.350	0.507	0.364
L x R	0.235	0.019		0.316	0.389	0.736	0.146	0.259	0.104	0.818	0.741	0.961	0.253	0.361	0.138	0.905	0.103

† Biomass, total carbon and nitrogen of corn components (grain, stover, and cob) were measured close after crops achieved R6 (black layer) stage of development.

‡Total stover represents combined stover and cob components.

Table 1.4. Harvested grain yield of each crop of continues corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotation at Arlington, Lancaster, and Marshfield in Wisconsin, 2011-2014. Values are model estimates rather than mathematical means to account for differences in number of blokes per location.

Factor	Corn	Soybean	Wheat
		Mg ha^{-1}	
Rotation by location			
Arlington			
CC	11.5		
CS	11.5	3.6	
CSW	13.0	4.2	4.1
Lancaster			
CC	11.7		
CS	12.2	2.9	
CSW	13.5	3.7	4.7
Marshfield			
CC	7.7		
CS	9.1	2.3	
CSW	9.0	2.3	2.6
LSD(0.05)	NS†	0.8	-
Location mean			
Arlington	12.0	3.9	4.1
Lancaster	12.5	3.3	4.7
Marshfield	8.6	2.3	2.6
LSD(0.05)	1.3	0.8	0.9
Rotation mean			
CC	10.3		
CS	10.9	3.0	
CSW	11.8	3.4	3.8
LSD(0.05)	0.7	0.3	
Contrasts			
CC vs. CS + CSW	**	-	-
CS vs. CSW	NS	**	-

*, **, and *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† NS, not significant.

Table 1.5. Contribution of corn plant components (grain, stover, cob, total stover) in biomass, carbon (C) and nitrogen (N) accumulation, and carbon to nitrogen ratios of grain and total stover from continues corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotations at Arlington, Lancaster, and Marshfield in Wisconsin, 2011-2014. Values are model estimates rather than mathematical means to account for differences in number of blokes per location.

	Plant Component†												C/N ratio	
	Grain			Stover			Cob			Total Stover‡				
Main Effect	Biomass	C	N	Biomass	C	N	Biomass	C	N	Biomass	C	N	Grain	Total Stover‡
	kg ha^{-1}													
Rotation by location														
Arlington														
CC	9750	4290	128	7310	3290	63	1310	615	8	8630	3900	71	34	60
CS	10250	4510	133	7720	3830	59	1440	671	9	9160	4500	68	34	68
CSW	11130	4920	143	7760	3510	55	1430	674	8	9190	4180	63	35	69
Lancaster														
CC	11310	5020	160	9580	4280	79	1450	691	9	11030	4970	88	31	57
CS	11410	5020	162	9710	4370	78	1430	676	8	11140	5040	86	31	59
CSW	11550	5180	161	10680	4770	89	1380	651	8	12070	5420	97	32	56
Marshfield														
CC	8430	3860	113	5960	2670	53	1120	523	7	7080	3190	60	34	57
CS	10300	4570	132	8380	3750	71	1180	532	7	9560	4280	77	34	57
CSW	9400	4140	122	7450	3330	74	1200	560	7	8650	3890	82	34	52
LSD(0.05)	NS§	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Location mean														
Arlington	10380	4570	135	7600	3540	59	1400	653	8	8990	4190	68	34	66
Lancaster	11420	5080	161	9990	4470	82	1420	673	8	11410	5140	90	31	57
Marshfield	9370	4190	123	7270	3250	66	1170	538	7	8430	3790	73	34	55
LSD(0.05)	NS	NS	17	1370	581	13	NS	103	NS	1443	615	13	2	6
Rotation mean														
CC	9830	4390	134	7620	3410	65	1290	610	8	8910	4020	73	33	58
CS	10650	4700	143	8610	3980	69	1350	626	8	9950	4610	77	33	61
CSW	10690	4750	142	8630	3870	73	1340	629	8	9970	4500	81	34	59
LSD(0.05)	NS	NS	NS	812	391	NS	NS	NS	NS	910	425	NS	NS	NS
Contrasts														
CC vs. CS + CSW	*	NS	NS	**	**	NS	NS	NS	NS	**	**	NS	NS	NS
CS vs. CSW	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, and *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Biomass, total carbon and nitrogen of corn components (grain, stover, and cob) were measured close after crops achieved R6 (black layer) stage of development.

‡Total stover represents combined stover and cob components.

§ NS, not significant.

Chapter 2. *Greenhouse Gases Emissions from Wisconsin Soils in Corn-Based Cropping Systems (2012-2014)*

2.1 Abstract

Crop rotation is a management practice of high GHG mitigating potential, but due to recent economic influences is often neglected. Three corn-based long-term rotation studies at different locations in Wisconsin were selected to assess potential opportunities in mitigating greenhouse gas emissions by comparing temporal and spatial variability of emissions from continuous corn (*Zea mays* L.) (CC), corn-soybean [*Glycine max* (L.) Merr.] (CS), and corn-soybean-wheat (*Triticum aestivum* L.) (CSW). Each phase of each rotation was always present in a given year. Sampling was done during three growing seasons (2012-2014) on weekly or biweekly schedule using a static chamber method. Greenhouse gas emission was influenced by weather conditions and peaks of nitrous oxide (N_2O) following nitrogen (N) application. On average across years, at Arlington and Lancaster, in the high N input environments, N_2O emissions in CC were 5.80 and 4.40 kg N ha^{-1}, respectively, which was much higher than the emissions from 2-yr CS and 3-yr CSW rotations that ranged from 1.52 to 3.33 kg N ha^{-1}. At Marshfield, in the low N input environment, N_2O emissions were not statistically different among rotations (1.20 to 1.66 kg N ha^{-1}). Despite apparent differences described above, the yield-scaled N_2O emissions appeared to be no different among crop rotations and on average ranged from 0.43 to 0.50 kg N Mg^{-1} yield. When pooled over locations, CO_2 emissions were highest in CC (4.16 Mg C ha^{-1}) and were similar in CS and CSW (3.71 and 3.5 Mg C ha^{-1}, respectively). Overall, soils either emit or absorb small amounts of CH_4 and ranged from 0.09 to -0.32 kg C ha^{-1} across locations and rotations. Generally, across locations and rotations, CO_2 and N_2O emissions from corn phases were usually highest among crops. These results provide important insights as to how weather conditions and differences among environments affect GHG emissions. Furthermore, the results indicate that application of either 2-yr CS or 3-yr CSW rotation can be equally effective in reducing N_2O emissions, especially with high N applications.

Abbreviations: CC, continuous corn rotation; CS, corn-soybean rotation; CSW, corn-soybean-wheat rotation; GHG, greenhouse gas; N, nitrogen.

2.2 Introduction

Agriculture plays a significant role in the emission of three major greenhouse gasses N_2O, CO_2, and CH_4 capable of trapping and holding infrared radiation which warm the Earth (IPCC, 2013; USDA, 2011; USEPA, 2011). Since the Pre-Industrial Revolution, all of these gases have increased their concentrations in the atmosphere compared to 2005, CO_2 by 39%, CH_4 by 157%, and N_2O by 19%. As a result of these increases the global temperature increased by 0.8 ^{o}C over the 20th century and is predicted to increase by another 1.4-5.8 ^{o}C by the end of 21st century (IPCC, 2007). In 2010, GHG emissions from agriculture accounted for 6.3% of the total emissions in the USA with CH_4 and N_2O most prominent (USEPA, 2012). Climate change projections suggest an increased frequency of extreme climate conditions, such as sustained drought or prolonged precipitation raising even more concerns about the intensity of greenhouse gas emissions (IPCC, 2007; IPCC, 2013). A large amount of GHG emissions are thought to be derived from soil through crop intensification (Snyder et al., 2009). There is an urgent need to search for agriculture management practices that would satisfy the world's food demand that is expected to double by 2050 (Karp and Richter, 2011) but also limit GHG emissions. Agricultural soils properly managed have a high potential to keep GHG emissions at a minimum level (Adviento-Borbe et al., 2007; Dobermann et al., 2007; Grace et al., 2011; Smith et al., 2008). Crop rotation is a management practice of high mitigating potential, but due to recent economic influences its use has been minimized in the U.S. The effect of crop rotations versus monocultures on GHG emissions has been often described as a positive in terms of mitigation (Adviento-Borbe et al., 2007; Drury et al., 2008).

Agriculture is a major source of N_2O emission. In the U.S., cropped and grazed soils accounted for almost 70% of the total N_2O emissions in 2009 (USEPA, 2012). Other significant anthropogenic sources of N_2O production are combustion of fuels and nitric acid, the compound used to make synthetic fertilizers (USEPA, 2012). Nitrous oxide is a by-product of two microbial soil processes: nitrification and denitrification. Both processes are controlled by many environmental conditions and their interactions (Robertson and Groffman, 2007). Nitrification mostly occurs in well-aerated dry soils. Denitrification, on the other hand, occurs in poorly aerated soils, often saturated after heavy rain storms or when a frozen soil starts to thaw. Denitrification takes place when soil pore space is filled with a minimum 60% of water (Robertson and Groffman, 2007). Daily N_2O emissions under corn increase as the soil begins to warm in late May and are low in late fall (Omonode et al., 2007). High peaks of N_2O emissions have been also reported at the transition of winter to spring when freezing and thawing processes take place and create so called "hot sports" for N_2O emissions (Groffman et al., 2009). In season, emissions of N_2O are closely related to N fertilizer management (Burzaco et al., 2013; Drury et al., 2006; USEPA, 2015) and its rate, form and placement play a large role in contributing to conditions conducive to the production of N_2O (Halvorson and Del Grosso, 2012; Halvorson and Del Grosso, 2013).

The Midwestern region of U.S. is based on intensive corn production. In 2010, corn in the U.S. on average received 157 kg ha^{-1} of N fertilizer (USDA-ERS, 2011), where higher rates exceeding 200 hg ha^{-1} in high productive corn systems are often seen. The annual N_2O emissions from corn have been reported five times higher than from soybean (Parkin, 2008). Other results confirm that N_2O emissions are greater from CC than from soybean or from the wheat phase in a 3-yr CSW rotation (Omonode et al., 2007). For example, corn grown in rotation with other crops can lower N_2O emissions by 20% relative to continuous corn and further reductions may be achieved by reducing N application rates below recommended levels (Omonode et al., 2007). Averaged N_2O emitted from the 2-yr CS rotation and from the 3-yr CSW rotation was 61% lower than emissions from CC (Drury et al., 2008). In the same study, annual N_2O emissions were up to five times greater in CC than from continuous soybean or continuous winter wheat. The N_2O emissions have been seen in smaller amounts in-rows than between-rows where inorganic N fertilizer is applied (Parkin, 2008). Previous crop can also influence the amount of N_2O emissions in corn after corn, the average N_2O emissions were about doubled compared to corn following soybean and about 60% higher than corn following winter wheat (Drury et al., 2008). However, Adviento-Borbe et al. (2007) found that CC due to increased soil carbon sequestration had lower overall global warming potential than CS rotation systems and additional intensive management did not always cause a significant increase in global warming potential. In Southern Ontario, perennial crops such as alfalfa (*Medicago sativa* L.) or bluegrass (*Poa pratensis* L.) had lower annual N_2O emissions than annual cereal crops. This has been associated with lower nitrate levels that are observed in early spring in perennial treatments (Wagner-Riddle et al., 1997). Thus, providing a permanent cover in soils during winter by planting cover crops or by adding a third crop such as winter wheat to the most common 2-yr CS rotation might have a greater potential in reducing the negative spring thaw effect on N_2O emissions.

Some studies have also used yield-scaled emissions (kg N_2O Mg^{-1} grain) as a method for describing the greenhouse gas efficiency of agricultural systems, where greenhouse gases are reported per unit yield (Mg grain) rather than per unit area (ha) (Osterholz et al., 2014; Venterea et al., 2011). Therefore, it often shows that highly productive systems of high N_2O emissions equalize yield-scaled emissions with lower productive systems (Johnson et al., 2012; Osterholz et al., 2014).

Soils have already lost up to more than one third of their original soil organic carbon (SOC) mainly due to human activity (Lal, 2001) which has significantly contributed to CO_2 increases in the atmosphere (IPCC, 2007; IPCC, 2013). Restoring soil organic carbon is necessary in order to improve soil, provide clean water and mitigate GHG emissions (Lal, 2004). Decomposition and soil respiration have been identified as main processes leading to CO_2 emission which are controlled by many agricultural practices (Lal, 2003). In soils, CO_2 concentration increases with depth and it has been reported to stabilize below 60 cm suggesting strong respiration by soil bacteria in upper layers (Wang et al., 2013). Carbon dioxide emissions follow the peak of soil temperature, precipitation and appear to be linked to plant root respiration. And the emissions reach their peak in the middle of growing season (Almaraz et al., 2009). It is believed that reduced tillage and an increase in biodiversity through crop rotation can sequester more organic carbon to soils which would decrease accumulated global warming potential of a system even though it might result in higher N_2O emissions (Johnson et al., 2010). Total annual CO_2 emissions was seen to be 22% higher in CC than in CS rotation, in a complete 2-yr cycle (Adviento-Borbe et al., 2007). Carbon dioxide emissions have been reported low in early spring and increase with increasing temperature and progressing growth of corn, reaching a maximum around the silking stage (Almaraz et al., 2009). Corn CO_2 emissions have been found higher from winter wheat when wheat was growing under colder conditions in China (Wang et al., 2013) and by 45% lower when averaged over 3-yr period in Southwestern Ontario, Canada, where they occurred early in season (Drury et al., 2008). Both, a current crop as well as a previous crop must be considered when calculating CO_2 emissions. For example, when corn followed winter wheat, the CO_2 emissions were 20% greater from emissions when corn followed soybean and 29% greater when corn followed corn (Drury et al., 2008). Drury et al. (2006), in a different study, reported no effect of tillage, depth of N fertilizer application, on CO_2 emissions form soils under CSW rotation.

After CO_2, CH_4 is the second most important human caused GHG (IPCC, 2007). More than 30% of CH_4 is derived from natural wetlands where under flooded and anaerobic conditions organic compounds are broken-down by soil microorganisms (Smith and Conen, 2004). Methane emissions from agriculture soils have been reported having negligible contribution to overall GHG emissions compared to CO_2 or N_2O (Jin et al., 2014; USEPA, 2011). In soils CH_4 is emitted from organic matter decay under oxygen limited conditions, mainly from rice plantations growing on saturated soils (Mosier et al., 1998). Generally, agricultural soils have been found to uptake small CH_4 amounts through methanotrophic bacteria consumption or give off small CH_4 emissions (Johnson et al., 2010; Venterea et al., 2005). However, higher CH_4 emissions under wet conditions have been seen (Lehman and Osborne, 2013). Most CH_4 has been reported to be located in topsoil and decreases with depth without any distinguished seasonal patterns (Wang et al., 2013).

Although, the Midwestern region of the United States is one of the major country’s agricultural production area little information exists about the long-term effects of crop rotation practices on GHG emissions from the soil surface. This study is the first attempt performed in Wisconsin to investigate the impacts of long-term (>6 years) crop rotations on intensity of the key GHG emissions from a range of differently managed environments. Therefore, three corn-based long-term rotations, namely, CC, 2-yr CS, and a 3-yr CSW were selected (i) to assess potential opportunities in mitigating N_2O, CO_2, and CH_4 emissions when crop rotation complexity increases (ii) to characterize spatial (across three locations) and temporal (2012-2014) effects on GHG emissions and identify influential factors that drive the emissions, and (iii) to compare the agricultural land use efficiency among rotations by considering yield-scaled N_2O emissions metric.

2.3 Materials and Methods

2.3.1 Sampling Locations and Field Management

This 3-yr (2012-2014) study was conducted at the University of Wisconsin’s Agricultural Research Station at Arlington (43°18’N, 89°20’W) on Plano silt loam (fine-silty, mixed, superactive, mesic Typic Argiudolls), at Lancaster (42°50’ N, 90°47’ W) on Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs), and at Marshfield (44°76’ N, 90°09’ W) on Marshfield silt loam (Fine-loamy, mixed, superactive, frigid Mollic Epiaqualfs). The Plano soil series consists of deep and well drained silty soils formed in loess or similar silty materials on outwash plains or stream terraces under prairie grasses. Permeability is moderate, and slopes range from 0 to 12%. The Fayette soil series consists of deep well drained soils formed in loess on convex crests and side slopes on uplands as well as on treads and risers on high stream terraces. Slopes range from 0 to 60% and the surface runoff potential varies from negligible to high. The Marshfield soil series are deep and poorly drained with moderate permeability formed in loess or silty alluvium under deciduous water-tolerant trees. Slopes range from 0 to 2%. Marshfield soils form a drainage sequence with Loyal soils (Soil Survey Staff, 2015). The mean annual temperature and precipitation at Arlington are 7.7°C and 854 mm, at Lancaster 7.8 °C and 880 mm, and at Marshfield 6.8 °C and 820 mm, respectively. Monthly precipitation and temperature with departure from 30-yr normals at all locations are presented in the Appendix A and B.

Experiments were arranged in a randomized complete block design, with three replications at Arlington and Marshfield and two replications at Lancaster. Main plots consisted of three rotations: continuous-corn (CC), corn-soybean (CS), corn-soybean-winter wheat (CSW), where each phase of each rotation was always present resulting in 6 rotation sequences studied each year (Table 1.1 – 1st Chapter). Applied management practices were slightly different at each location but they all are being practiced in rainfed agriculture at the Midwestern region of the United States. Detailed information regarding locations management, including tillage, fertilizer application forms and rates as well as other agronomic management practices, is outlined in section 1.3.2 (Site Management) of 1st Chapter.

2.3.2 GHG Data Collection

The data collection procedure used in this study has been previously described (Jackson et al., 2015; Oates et al., 2015; Osterholz et al., 2014). Greenhouse gas (CO_2, N_2O, and CH_4) emissions were measured at 1- to 3-week sampling intervals during three growing seasons (2012-2014) with additional measurements to capture emission pulses following fertilizer application or rainfall events. Such events are known to contribute significantly to annual GHG emissions (Groffman et al., 2009). The measurement period differed among years and locations depending on the weather. Arlington and Lancaster had an earlier sampling initiation time compared to Marshfield, the northern station. The rule of thumb was to measure emissions when the soil temperature was >0 °C during the snow-free period. Sampling was always made between 8:00 and 14:00 local time using white cylindrical HDPE chambers (U.S. Plastic Corp., Lima, OH) installed in all plots at ~5 cm depth. The chamber diameter was 21 cm and height 16 cm. Chamber installment involved a minor disturbance of soil, therefore, they were deployed at least 24 h before sampling allowing the soil to equilibrate and minimize error. During the sampling period, each chamber was installed with a lid equipped with a rubber gasket along the contact edge, a septum for sample extraction, and a 2 mm diameter and 17 cm long cooper vent tube for chamber overpressure suppression. To minimize spatial variability and to capture peak emissions where the N fertilizer was band applied; two chambers were installed in each experimental unit (plot). One chamber was installed between crop rows and the other was installed in the middle crop row which resulted in a total of 12 chambers per replicate. Any vegetation present within the chambers was trimmed off up to the chamber height. In addition to gas samples, soil temperature was measured at 10 cm depth with a digital thermometer (HANNA Instruments, Woonsocket, RI) and volumetric moisture content was measured as an average of 5 cm depth with a TH300 equipped with a time-domain reflectometer probe (Dynamax Inc., Houston, TX) within 0.5 m of each chamber.

Greenhouse gases emissions were measured at four 20-minute sampling intervals over a 1 h period. Samples were collected by extracting accumulated headspace soil air by inserting 30 ml syringe equipped with a 23-gauge needle through the rubber septa. About 20 ml of the 30 ml collected sample was used to flush a 5.9 ml glass vial (Labco Limited, Buckinghamshire, UK) and the remaining 10 ml of the sample was inserted into the vial resulting with overpressure to facilitate further analysis and assure tight vial closure. A gas chromatograph technique was used to determine the amount of each individual greenhouse gas by using a Shimadzu GC-14B gas analyzer (Shimadzu Analytical and Measuring Instruments Division, Kyoto, Japan). An infrared gas analyzer (IRGA, LiCor 820, Lincoln, NE, USA), electron capture detector (micro-ECD, Agilent 7890A GC System, Santa Clara, CA, USA), and flame ionization detector (FID, Agilent 7890A) were used to determine CO_2, N_2O, and CH_4 concentrations, respectively.

2.3.3 GHG Estimation and Data Analysis

In a case were CO_2 emissions were negative or had an unnatural pattern, a sample was considered having lost pressure or other sample handling problems. About 4% of total collected samples were discarded from further analysis. Greenhouse gases were calculated with a method developed by Pedersen et al. (2010) in the R statistical environment (R Core Team, 2014). This approach accounts for possible nonlinear greenhouse gas emissions by automatically choosing among either the revised Hutchinson and Mosier (1981) nonlinear model (HM), simple linear model, or null flux based on root mean squared error minimization. In R, the package is called HMR. The nonlinear estimate was only used when 95% of its confidence interval excluded the corresponding linear estimate. The chosen final estimate was used to calculate the daily emissions by assuming the estimate represented the average emission for a particular day. Linear interpolation of the daily emissions was used to calculate cumulative growing season emissions, between beginning and the end of data collection each year. Yield-scaled emissions were calculated by dividing cumulative growing season N_2O emissions (kg N_2O ha^{-1}) by grain yield (Mg grain ha^{-1}) of corresponding crop grain yield.

For GHG measurements and yield scaled emissions, the experimental design was a randomized complete block. Analysis of variance for the fixed effects of location, rotation, phase within rotation, location x rotation, and location x phase within rotation and for random effects of year and rep(location x year) was performed using the PROC MIXED procedure of SAS Institute (2011). Dependent variables measured each year were analyzed using a repeated measures approach with the first-order autoregressive variance structure (AR1) (Littel et al., 2006). The auto-regressor was plot and was used in the SUBJECT statement. Treatment means were compared using Fisher's protected least significant difference (LSD) at $P \leq 0.05$ and each for dependent variable the PDIFF option of the LSMEANS statement was used to display the differences among computed means for comparison. The residuals of each greenhouse gas and yield scaled emissions were tested for normality using the Shapiro-Wilk test using the PROC UNIVERATE procedure of SAS Institute (2011). Only the N_2O emissions were found to be non-normal where the residuals appeared to have a slight positive skewness (Shapiro-Wilk W=0.92; Skewness=1.15). Logarithmic transformation of N_2O emission data did not change any significance among main effects; therefore; we decided not to apply any transformation to analyze the N_2O emission data given that it was nearly symmetric.

2.4 Results

2.4.1 Weather

Weather conditions varied considerably during 3-yr period of this study (Appendix A and B). Year 2012 opened with a much warmer winter which resulted in above normal mean air temperature across locations. Soil moisture is one of the key factors influencing N_2O emissions. The growing season 2012 was one of the driest ever recorded in Wisconsin. In 2012, total growing season precipitation was 184, 197, and 79 mm below normal across all locations which resulted in lower soil moisture content. The 2013 season was an extremely wet and unusually cold spring across locations with the total year precipitation from 62 to 124 mm above normal across locations. The growing season 2014 had the most contrasting precipitation across locations with 18 and 173 mm above- and with 128 below-normal at Arlington, Marshfield, and Lancaster, respectively.

2.4.2 Corn Rotation Effect on N_2O Emissions

Averaged over the three growing seasons, N_2O emissions were highest at Arlington (3.99 kg N ha^{-1}) followed by Lancaster (2.59 kg N ha^{-1}) and lowest at Marshfield (1.36 kg N ha^{-1}). There was a significant location x rotation interaction, but the general patterns of N_2O emissions were similar across locations (Table 2.1 and 2.2). Continuous corn rotation resulted having N_2O emissions 2.4 and 2.9 times higher at Lancaster and 1.7 and 2.0 at Arlington times higher than CS and CSW rotation, respectively. At Marshfield, CC (1.66 kg N ha^{-1}) had noticeably higher N_2O emissions from CS (1.23 kg N ha^{-1}) and CSW (1.2 kg N ha^{-1}), but due to the fact that all rotations presented much lower emissions at this location these were not statistically different. Orthogonal contrasts indicated that no difference exist in terms of N_2O emissions between CS and CSW and both were equally effective in reducing the emissions compared to CC across locations. Also, there was a location x phase within rotation interaction detected (Table 2.3). At Arlington, all corn phases were higher for N_2O either from soybean or wheat phases. At Lancaster only CC phase was statistically higher for N_2O and at Marshfield all phases were the same. No significant difference was detected between soybean and wheat phase across rotations and locations for N_2O. Generally, CC phase presented the highest N_2O emissions among all corn phases across locations, but only at Lancaster was it significant.

2.4.3 Corn Rotation Effect on CO_2 Emissions

Averaged over the three growing seasons, CO_2 emissions were the highest at Lancaster (4.32 Mg C ha^{-1}) fallowed by Arlington (3.98 Mg C ha^{-1}) and these were not statistically different, however; they were significantly higher than CO_2 emissions at Marshfield (3.16 Mg C ha^{-1}), the most northern location (Table 2.2). We found no interaction between location and rotation. Continuous corn had significantly higher CO_2 emissions than either CS or CSW, which were not significantly different across locations. There was a significant interaction between location and phase (Table 2.3). No significant difference between crop phases within rotations was detected at Marshfield. At two other stations (Arlington and Lancaster), the wheat phase had the lowest CO_2 emissions and corn phase highest among all phases except soybean the CSW rotation at Arlington. Continuous corn at Lancaster had the highest CO_2 emissions among all corn phases.

2.4.4 Corn Rotation Effect on CH_4 Emissions

Overall, soils appeared to be a small methane sink. Averaged over the three growing seasons, locations were significantly different but the actual numerical differences were small (Table 2.2). The soils at Lancaster showed the highest CH_4 uptake (-0.24 kg C ha^{-1}), followed by Arlington (-0.16 kg C ha^{-1}), soils at Marshfield were neutral (0.01 kg C ha^{-1}). There was a significant location x rotation interaction. At Arlington and Lancaster, all rotations were the same except CSW at Lancaster which had higher CH_4 uptake. At Marshfield, positive CH_4 emissions occurred in CC and CSW rotations and they both were significantly different from CS rotation which had a small amount of CH_4 uptake. There was no location x phase within rotation interaction and averaged phase differences across locations were small for CH_4, with the range from -0.07 to -0.21 kg C ha^{-1} (Table 2.3).

2.4.5 Yield Scaled N_2O Emissions

The results of the statistical analysis for yield scaled N_2O emissions across growing seasons show that crop rotations did not differ across location and there was no rotation x location interaction or location x crop phase within rotation interaction (Table 2.2). There was a significant effect of crop phase with rotations. Averaged across locations, corn phases of 2-yr CS and 3-yr CSW rotation had the lowest yield scaled emissions and soybean phases the highest yield scaled emissions, while no difference existed among other phases (Table 2.3).

2.4.6 Factors Influencing GHG Emissions

Locations differed in terms of N_2O emissions which could be associated with differences in fertilizer application rates, tillage operations and the timing of precipitation events across the years at each location. Generally, the corn phase within each rotation accounted for majority of the N_2O emissions across seasons and locations. Most of the daily N_2O emissions occurred in-season after N fertilizer application, especially under wet conditions, except those at Marshfield station where no clear response to N fertilization was observed (Fig. 2.1). Averaged across crop phases within each rotation daily N_2O emissions, precipitation and measured volumetric water content in each year at each location are presented in Fig. 2.1, and growing season cumulative N_2O emissions among crop phases are presented in Fig. 2 .2.

In 2012 season N_2O emissions under unusually dry soil moisture conditions were the lowest compared to other years across the locations. At Arlington, N fertilizer in corn was applied into dry soils and more than a month later the first >10 mm rainfall event occurred resulting in low N_2O emissions. In short period of time (8 days) soils at Arlington received 102 mm of rainfall which activated biological processes leading to noticeable high N_2O emissions which accounted for 23-53% (0.16-1.47 kg N ha^{-1}) of the total seasonal emissions during a three-week period across all crop phases. At Lancaster, N fertilizer in corn was applied one week after a heavy 67 mm and a day before smaller 11 mm rainfall events.

Similarly, in a short period of time (3 weeks), N_2O emissions across all phases ranged from 34-74% (0.2-1.24 kg N ha $^{-1}$) of the total seasonal emissions. Where, among all phases, at both locations the corn phases had the highest emissions. At Marshfield, CC received 40% and corn in other phases 60% less N-fertilizer relative to corresponding corn at other locations. Small differences in terms of Marshfield N_2O emissions were noticed among phases across all seasons and N-fertilization and rainfalls were less influential compared to other locations with the single exception in CC in 2013 where the emissions were somehow related these events.

Contrary to the previous year, soils in 2013 were wet especially up to mid-season. At Arlington, N-fertilizer in corn was applied into moderately moist soil conditions followed by heavy rainfall events over the next 10 days (131 mm). These led to the highest N_2O emissions recorded across the research period where corn phases during the three-week period accumulated 45-57% (3.49-4.49 kg N ha^{-1}) of the total seasonal emissions. In comparison, soybean and wheat phases emitted only 5.9-7.8% (0.13-0.47 kg N ha^{-1}) of the total seasonal emissions. At Lancaster, CC had the highest N_2O emissions among all phases prior to N-fertilizer application in early June and was the only one that responded to heavy rainfall events that occurred over the last 10 days (163mm) of the month. Other corn phases had similar N_2O emissions to other crops through the season. One high N_2O emissions event that affected all phases occurred toward the last week of July when the soils were dry (VWC<10%).

During the 2014 season, the growing conditions were the most favorable. Similar N_2O emission patterns were observed at Arlington and Lancaster. At both locations, following N-fertilizer application, the second half of June was exposed to multiple heavy rainfall events >30 mm and up to the first week of July most of the emissions in corn phases occurred. Where, in a three-week period of time, CC phase had the highest peaks of the N_2O emissions which resulted in 59% (3.97 kg N ha^{-1}) and 72% (4.61 kg N ha^{-1}) of the total seasonal emissions at Arlington and Lancaster, respectively. In these locations, in the same short period of time high peaks of N_2O emissions occurred also in other corn phases 43-62% (0.85-2 kg N ha^{-1}) as well as in crops that did not receive N-fertilizer: 10-27% (0.19-0.33 kg N ha^{-1}) and

24-51% (0.38-0.93 kg N ha^{-1}) across soybean and wheat phases, respectively. Linear regression of daily N_2O, CO_2 and CH_4 measurements against VWC and soil temperature showed significant probability values. However, the predictive power for both variables to explain either of the greenhouse gas emission was low ($R^2<0.05$), except temperature on CO_2 ($R^2=0.48$).

2.5 Discussion

These were long-term rotations that allowed the treatments differences to equilibrate. Other studies have derived similar conclusions that time is needed to reach equilibrium among rotations (Drury et al., 1998; Six et al., 2004). Results from this study indicated that crop rotation practices can impact all measured greenhouse gases and can be used to reduce N_2O emissions. Even though significant effects were found in emissions of either CO_2 or CH_4 these were relatively small among rotations and were mostly the result of naturally occurring environmental processes rather than management choices. In the United States agricultural soils contribute 70% of the total annual N_2O emissions (USEPA, 2015). Therefore, there is currently a great deal of interest in developing management practices that might lead to N_2O emission reduction since on a molecular basis it possesses almost 300 times stronger radiative force then CO_2 on the 100-yr timescale (IPCC, 2007). It is important to emphasize that in this study, emissions underestimate the total annual emissions due to lack of measurements during winter which can contribute to the total annual emissions (Butterbach-Bahl et al., 2013).

Nitrogen fertilizer has been identified as the main management factor stimulating N_2O emission (USEPA, 2015). This study also confirmed that N fertilizer application rates that varied across crops and locations as well as the timing of the application were the most influential. Therefore, its placement, amount and timing of application play a significant role in minimizing residual soil nitrate, which helps lower the risk of increased N_2O emissions (Parkin, 2008). Under saturated soil conditions and with an excess of plant available N, denitrification of N is favored and, in this case, may have accounted for more than 50% of total cumulative seasonal emissions which were observed within three weeks of N-fertilization. Similar findings were reported in other studies (Drury et al., 2006; Drury et al., 2008; Omonode et al., 2011). For example, Omonode et al. (2011) reported that nine days following urea application half of the total N_2O emissions occurred regardless of tillage or rotation practices and after that N_2O emission declined rapidly for the rest of the season. In our study, the contrasting patterns of N_2O emissions between fertilized corn and winter wheat showed how timing of N application may increase emissions. Winter wheat was typically fertilized early in the growing season into still cold soils, corn usually in June into warm soils where large amounts of rainfall occurred, therefore much smaller N_2O emissions peaks were observes in winter wheat. As expected, the highest N_2O emissions were observed in corn phases which were directly related to higher N rates; however, CC had generally higher emissions from other corn phases but only those at Lancaster differed statistically. This indicates that rotating crops may have an additional positive effect on lowering N_2O emission. A similar conclusion was reported in a Canadian study where N_2O emissions of CC were about doubled compared to corn when followed soybean and 60% higher from corn following wheat (Drury et al., 2008).

Strong temporal and spatial differences were observed in N_2O emissions among crops. Extremely dry conditions of 2012 growing season reduced N_2O emissions by suppressing emissions coming from denitrification processes across locations. These conditions partially may have led to increased residual soil N, which may explain unusually high N_2O emissions in the subsequent soybean crop. In 2013, soybean phases had 4.4 and 1.9 times higher N_2O emissions compared to soybean emissions in the drought year 2012, at Arlington and Lancaster, respectively. High emissions of soybean following corn grown under dry conditions was also reported by other studies (Iqbal et al., 2015). Averaged across growing seasons, Marshfield emissions were the lowest and Arlington the highest. Even though a similar pattern of the emission was observed at Marshfield where corn phases had the highest emissions, these were not statistically different from other crops. The main reason why corn phases had lower emissions at Marshfield was due to the fact that CC received 40% and corn in CSW rotation 60% less N then at other locations. Application of fertilizers according to plant needs or banding fertilizer instead of broadcasting it, or dividing the total desired N application into two smaller amounts have been effective in reducing N_2O emissions (Gregorich et al., 2005).

Crop rotation resulted in similar yield-scaled emissions but crop phases where different when pooled over locations. Differences among crop phases were most influenced by N_2O emissions. Soybean and wheat, lower yielding crops than corn, had the highest yield scaled emissions. However, corn in CC had much higher grain yield but produced a similar yield scaled emission to soybean and wheat. On average among locations over the three-year period of the study, corn in 2-yr CS rotation had 12% and 3-yr CSW rotation 14% greater grain yield than continuously rotated corn, and on average 28% lower N_2O emissions (Table 2.2). This resulted in significantly lower yield scaled emissions of rotated corn across all crop phases. Crop rotation is a known practice that improves yield of all rotated crops under the same N fertilizer rates as compared to corresponding continuously grown crops (Pedersen and Lauer, 2003; Stanger and Lauer, 2008). Improved N use efficiency of rotated corn can explain its lower yield scaled emissions; therefore, crop rotations have potential to further reduce yield scaled emissions of highly productive crops. Overall, the yield-scaled N_2O emissions metric is interesting to consider when describing the system's land use efficiency but less useful in its N_2O emissions contribution in the atmosphere.

As expected the highest CO_2 emissions where observed in CC which was related to larger root biomass of previously grown corn, but these differences were relatively small - less than 10% at two out of three locations. At Lancaster, much higher emissions of CO_2 in CC rotations related to other rotations >20% was due to the fact that this rotation was chiseled plowed where no tillage operations were performed in any other rotations. Intensive tillage has been identified as one of the main triggers leading to loss of up to 70% of their original SOC (Lal, 2001). Almaraz et al. (2009) reported that CO_2 emissions often follow the peak of soil temperatures, precipitation and are also linked to plant root respiration where it can occur in the middle of growing season under dry conditions.

Both positive and negative CH_4 emission was recorded, but the measurements tended to oscillate around zero. Soils, generally, showed small CH_4 uptake in most of the seasons across rotations with one exception at Marshfield where under CC small amounts of positive CH_4 emissions where observed, which is related to differences in soil properties. Contrary to other locations, soils at Marshfield are poorly drained which during wet years such as 2013 led to higher CH_4 emissions under saturated soil conditions. Under dry conditions usually all treatments in all locations appeared to be a small methane sink.

Generally, agricultural soils have been identified as a minor CH_4 sink through methanotrophic bacteria consumption (Johnson et al., 2010; Venterea et al., 2005). Mineral N status plays a key role in CH_4 uptake by soil. With few exceptions (Venterea et al., 2005; Wang et al., 2013), N fertilizer application tends to lower CH_4 consumption by soil microbial communities and through rapid methanotrophic bacteria inhibition (Drury et al., 2008). Therefore, through better N management there is a potential to control CH_4 emissions.

2.6 Conclusions

Crop rotation and crop phase significantly influenced N_2O emissions in a majority of the studied environments. The differences among location in cumulative N_2O emissions depended upon the difference among environments themselves and total N fertilizer input. In high N input environments, at Arlington and Lancaster, cumulative N_2O emissions averaged over the three years were highest from CC and the emissions from CS and CSW rotation were similar. Therefore, there was no difference in reducing N_2O when adding winter wheat into rotations which means that CS and CSW are equally efficient at reducing N_2O compared to CC., At Marshfield in a low N input environment, all studied rotations had similar low N_2O emissions. Highest peaks of N_2O emissions were often recorded in corn plots when large amount of precipitation coupled with N fertilization and in some situations the peaks exceeded even 70% of the total cumulative seasonal emissions in just three weeks after N was applied. However, there was not evident difference in yield-scaled emissions among rotations across all locations which favors high productive CC which is in agreement with other work (Osterholz et al., 2014). Carbon dioxide emissions increased as air temperature increased and crop growth progressed. On average, CC had significantly higher CO_2 emissions than CS and CSW rotations which can be explained with higher biomass inputs provided by corn. At Lancaster, the differences of CO_2 emissions were the highest for chisel plough managed CC compared to no-till for other rotations. Positive and negative emissions were recorded for CH_4, but generally soils acted as a minor CH_4 sink and actual differences among crop rotations were small.

These results suggest that crop rotations can be successfully used when reduction of GHG emissions is the target. To reduce the emissions of both CO_2 and N_2O, in the high N input environment, the 2-yr CS rotation and the 3-yr CSW rotation are better than CC and equally effective. In contrast to difficult to control emissions of carbon based CO_2 and CH_4, opportunities exist in reducing in-season N_2O emissions. As evident in this study, the highest peaks occurred when high precipitation events occurred around the time when N fertilizer was applied to corn. Since it is impossible to control the weather patterns, actions should be taken towards adaptation of practices that reduce N losses such as split-applications of N, N-stabilizers/additives (urease inhibitors, nitrification inhibitors, or poly-coated N products), or “green-seeker” sensing technologies which address field variability by applying N fertilizer amount that match crop need.

2.7 References

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Table 2.1. Significance of analysis of variance for the effects of location, crop rotation, crop phase nested within rotation and their interactions on nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), grain yield, and yield-scaled N_2O emissions at experiments conducted in Arlington, Lancaster, and Marshfield, WI in 2012-2014.

	Growing season emission			Grain	Yield-scaled
Source	N_2O	CO_2	CH_4	yield	N_2O emissions †
Location (L)	<0.001	<0.001	<0.001	<0.001	0.264
Rotation (R)	<0.001	<0.001	0.037	0.044	0.706
L x R	0.007	0.201	0.001	<0.001	0.707
Phase within rotation (P)	<0.001	0.001	0.003	<0.001	0.004
L x P	<0.001	0.012	0.064	<0.001	0.227

† Calculated as Mg of grain yield / kg of N_2O-N ha^{-1} $season^{-1}$.

Table 2.2. Growing season emission of nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), grain yield, and yield-scaled N_2O emission in three corn-based rotations at Arlington, Lancaster, and Marshfield, WI (2012-2014).

Factor	Growing season emission N_2O	CO_2	CH_4	Grain yield	Yield-scaled N_2O emissions †
	kg N ha^{-1}	Mg C ha^{-1}	kg C ha^{-1}	Mg ha^{-1}	kg N Mg^{-1} yield
Rotation within location‡					
Arlington					
C	5.80	4.34	-0.12	11.39	0.57
CS	3.33	3.91	-0.19	8.15	0.52
CSW	2.85	3.70	-0.16	6.92	0.63
Lancaster					
C	4.40	5.01	-0.20	12.66	0.52
CS	1.84	4.14	-0.19	9.02	0.35
CSW	1.52	3.82	-0.32	7.89	0.30
Marshfield					
C	1.66	3.15	0.09	6.78	0.35
CS	1.23	3.06	-0.09	5.43	0.41
CSW	1.20	2.97	0.02	3.81	0.56
LSD (0.05)	1.19	NS§	0.10	1.2	NS
Rotation across location					
C	3.95	4.16	-0.07	10.3	0.48
CS	2.13	3.71	-0.16	7.5	0.43
CSW	1.86	3.50	-0.15	6.2	0.50
LSD (0.05)	0.58	0.28	0.06	0.6	NS
Location					
Arlington	3.99	3.98	-0.16	8.82	0.57
Lancaster	2.59	4.32	-0.24	9.86	0.39
Marshfield	1.36	3.06	0.01	5.34	0.44
LSD (0.05)	1.01	0.46	0.07	0.89	NS
Contrasts					
CC vs. CS and CSW	***	**	*	***	NS
CS vs. CSW	NS	*	NS	***	NS

*, **, and *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† Calculated as Mg of grain yield / kg of N_2O-N ha^{-1} $season^{-1}$.

‡ CC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat.

§ NS, no significant difference at $P \leq 0.05$.

Table 2.3. Growing season emission of nitrous oxide (N_2O), carbon dioxide (CO_2), methane (CH_4), grain yield, and yield-scaled N_2O emission in every phase of three corn-based rotations at Arlington, Lancaster, and Marshfield, WI (2012-2014).

	Growing season emission			Grain	Yield-scaled
Factor	N_2O	CO_2	CH_4	yield	N_2O emissions †
	kg N ha^{-1}	Mg C ha^{-1}	kg C ha^{-1}	Mg ha^{-1}	kg N Mg^{-1} yield
Phase within location‡					
Arlington					
CC	5.80	4.34	-0.12	11.39	0.57
CS-corn	4.97	4.20	-0.24	12.16	0.51
CS-soybean	1.69	3.61	-0.14	4.14	0.53
CSW-corn	4.91	3.93	-0.19	13.37	0.44
CSW-soybean	2.15	3.89	-0.11	4.89	0.58
CSW-wheat	1.50	3.28	-0.17	2.51	0.87
Lancaster					
CC	4.40	5.01	-0.20	12.66	0.52
CS-corn	2.13	4.40	-0.17	13.95	0.13
CS-soybean	1.55	3.89	-0.20	4.10	0.57
CSW-corn	2.20	4.21	-0.46	14.29	0.21
CSW-soybean	1.28	3.97	-0.27	4.95	0.33
CSW-wheat	1.10	3.29	-0.24	4.42	0.37
Marshfield					
CC	1.66	3.15	0.09	6.78	0.35
CS-corn	1.48	3.13	-0.14	8.79	0.19
CS-soybean	0.98	3.00	-0.05	2.08	0.63
CSW-corn	1.36	2.95	0.01	8.03	0.15
CSW-soybean	1.21	2.83	0.08	1.86	0.85
CSW-wheat	1.03	3.12	-0.03	1.56	0.67
LSD (0.05)	1.46	0.60	NS§	1.54	NS
Across Locations					
CC	3.95	4.16	-0.07	10.28	0.48
CS-corn	2.86	3.91	-0.18	11.63	0.28
CS-soybean	1.41	3.50	-0.13	3.44	0.58
CSW-corn	2.82	3.70	-0.21	11.90	0.27
CSW-soybean	1.55	3.57	-0.10	3.90	0.59
CSW-wheat	1.21	3.23	-0.14	2.83	0.64
LSD (0.05)	0.76	0.30	0.07	0.85	0.27

† Calculated as Mg of grain yield / kg of N_2O-N ha^{-1} season^{-1}.

‡ CC, continuous corn; CS, corn-soybean followed by phase; CSW, corn-soybean-wheat followed by phase.

§ NS, no significant difference at $P \leq 0.05$.

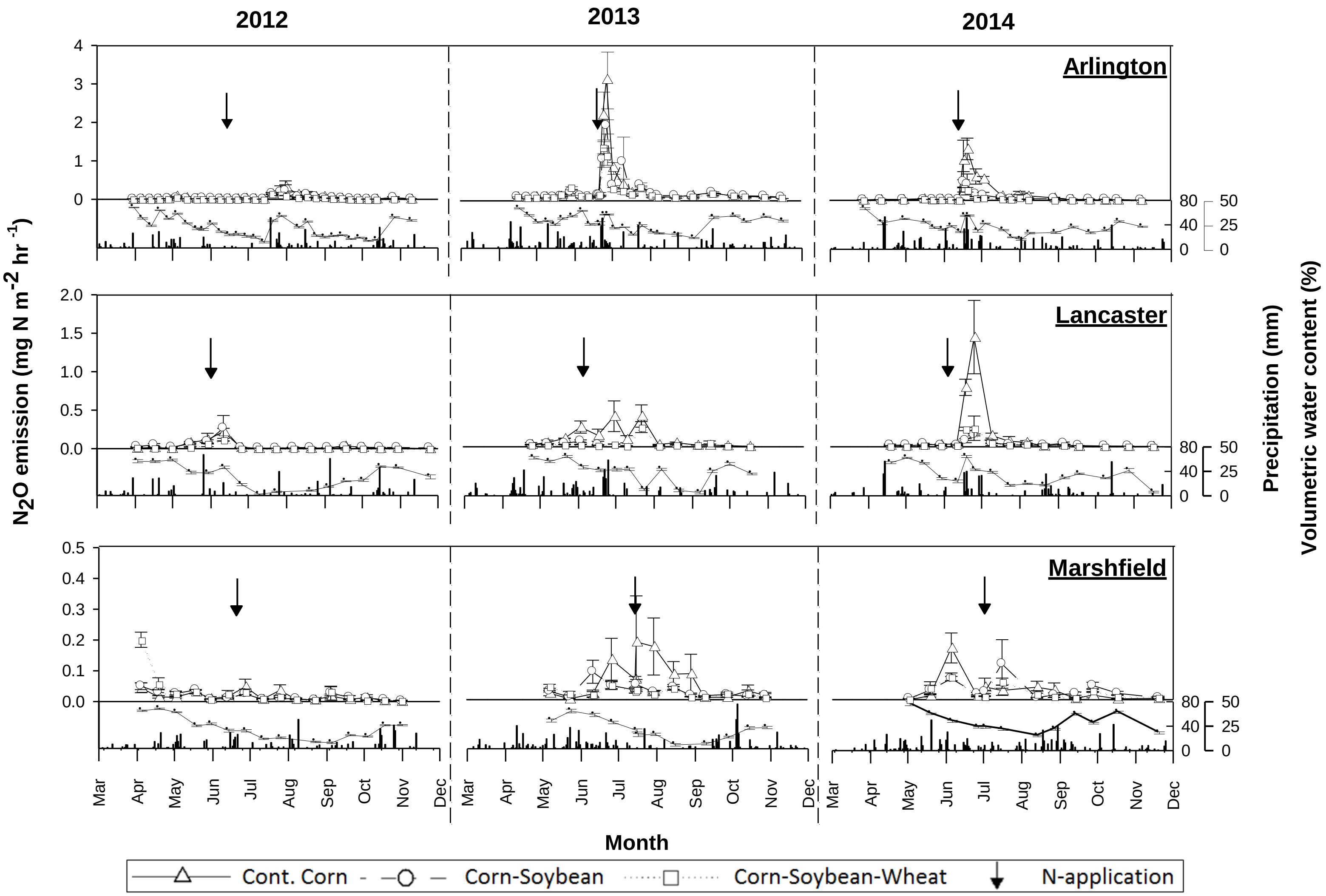

Figure 2.1. Daily nitrous oxide (N_2O) emission, volumetric water content of continuous corn, corn-soybean, and corn-soybean-wheat rotation at Arlington, Lancaster, and Marshfield, WI (2012-2014). Data present averaged N_2O emission across crop phases within each rotation. Black arrows indicate a date of N fertilizer application in corn.

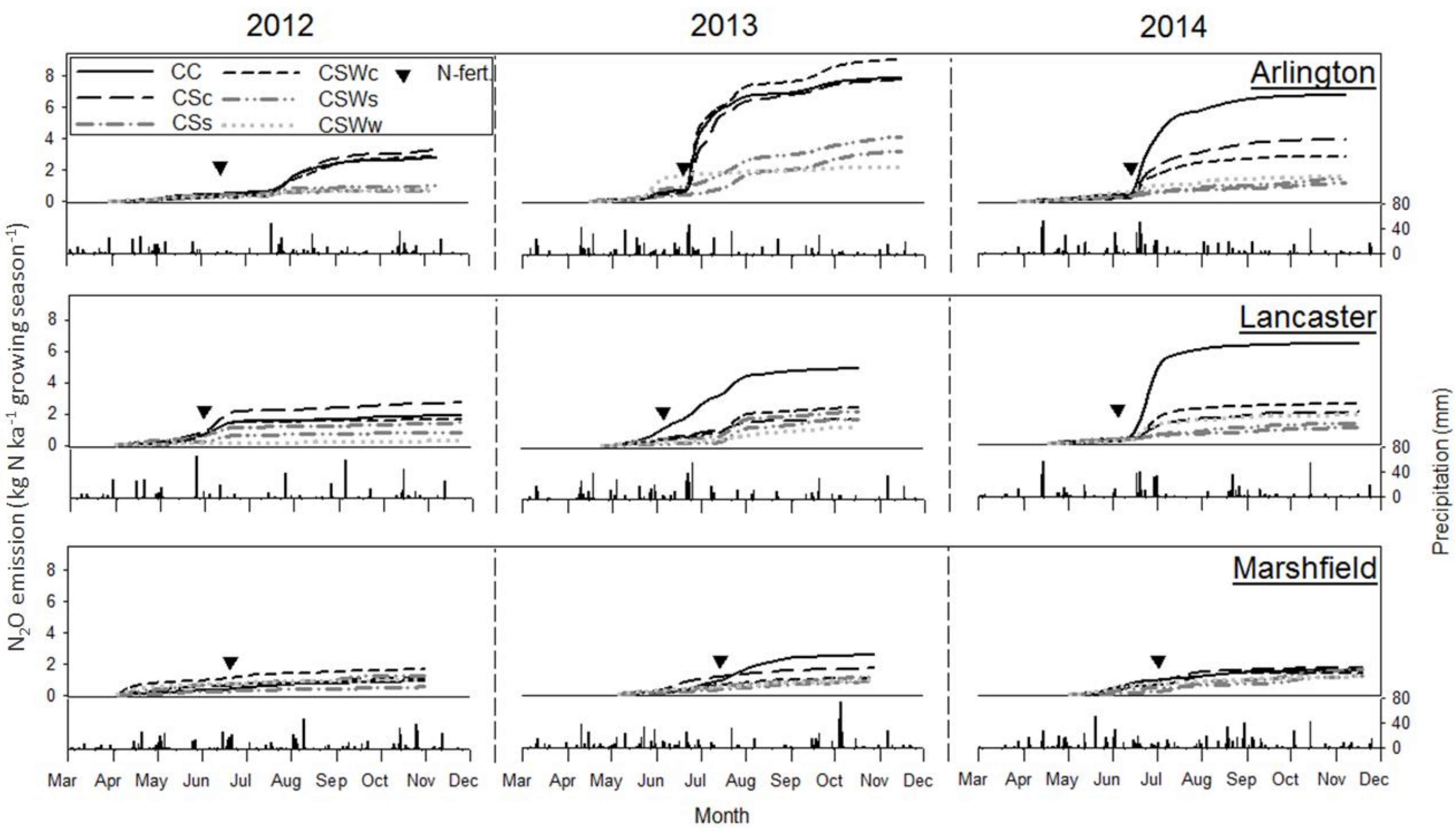

Figure 2.2. Growing season cumulative nitrous oxide (N_2O) emission of continuous corn (CC), corn (CSc) and soybean (CSs) phase of corn-soybean rotation and corn (CSWc), soybean (CSWs), and wheat (CSWw) phase of corn-soybean-wheat rotation, at Arlington, Lancaster, and Marshfield, WI (2012-2014). Black arrows indicate a date of nitrogen fertilizer application in corn.

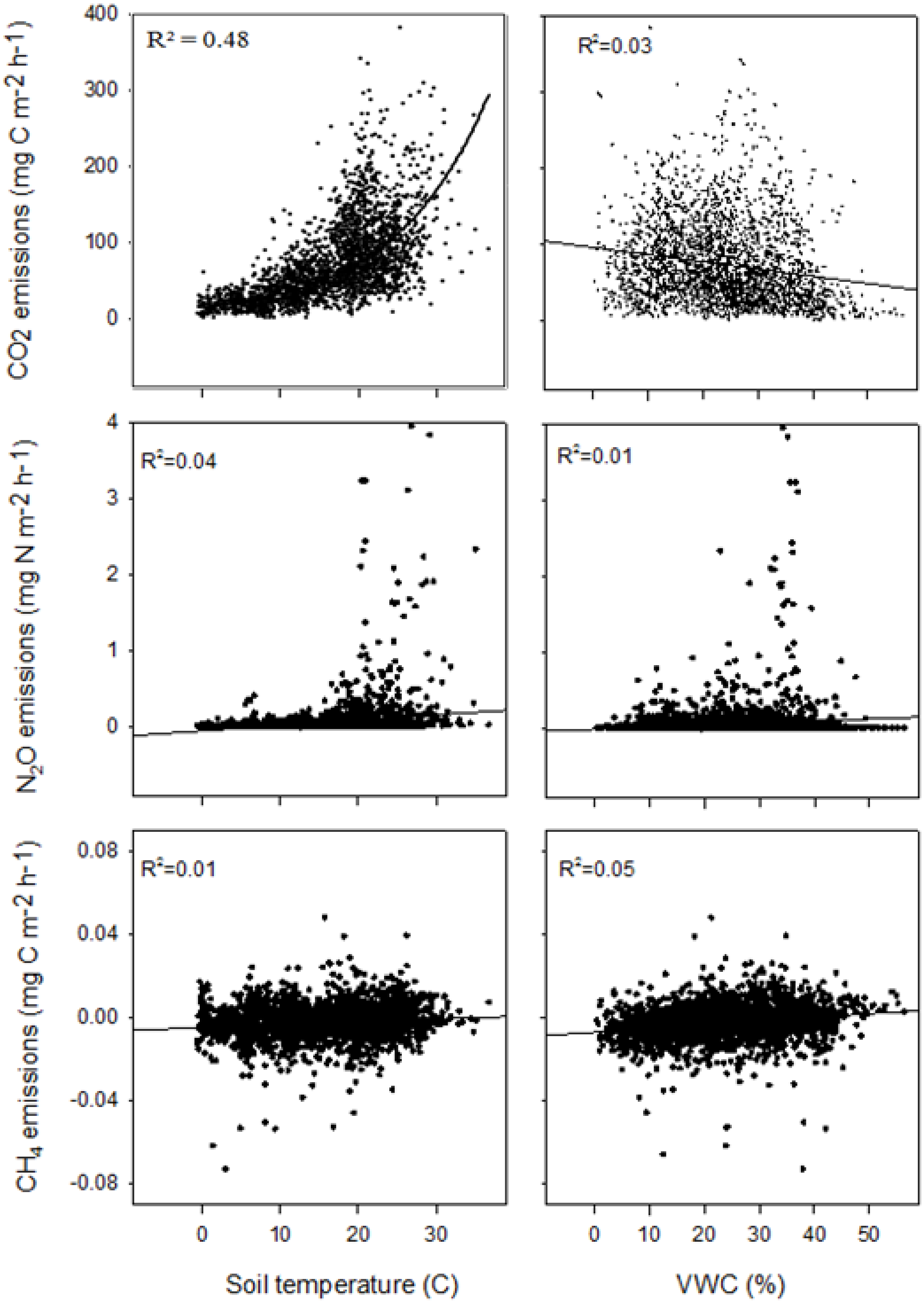

Figure 2.3. Simple linear regression of CO_2, N_2O, and CH_4 versus soil temperature measured at 10 cm depth and volumetric water content measured as an average of 0-5 cm depth. All regressions had a significant probability values ($P<0.001$) of F test; therefore, only coefficient of correlation (R^2) values are shown in each figure.

Chapter 3. *Soil Property Changes during Corn Rotations*

3.1 Abstract

In response to climate change, agriculture may need to adopt more resilient cropping systems. In this study, three corn-based rotations: continuous corn (*Zea mays* L.) (CC), corn-soybean [*Glycine max* (L.) Merr.] (CS), and corn-soybean-wheat (*Triticum aestivum* L.) (CSW) where all residues were retained on the field after harvest were selected to study their effects on soil properties at three managed sites in Wisconsin. Soil core samples were collected at four depths 0-10, 10-20, 20-40 and 40-60 cm in 2011, in 2013 at the two top depths, and in 2015 also at the top two depths at one location. Soil water retention (WR), plant available water (PAW), bulk density (BD), soil carbon (C), soil nitrogen (N), C/N ratio, and soil texture were evaluated. Water retention was determined from the top two depths at five different matric potentials (Ψ=0, −5, −10, −33 and −1500 kPa). There was a significant location x depth interaction across soil properties which could be associated with differences in management among locations. Averaged across location, CC and CSW rotations had greater water content and PAW across WR tensions than CS rotation at 0-10 cm depth, while rotations equalized at 10-20 cm depth. Crop rotations had similar BD across locations and depths. A significant 3-way location x depth x rotation interaction for C and N amount was influenced with generally higher C and N amounts in CSW rotation at Lancaster and smaller differences among crop rotations at other locations. Low soil C/N ratio values indicated potential for soil organic matter to provide some N to the crop. Results from this study indicate that long-term CC systems had similar soil properties to those found in the CS and CSW rotations. However, there is a potential for higher WR under CSW rotation which might be important under variable climate patterns.

Abbreviations: CC, continuous corn rotation; CS, corn-soybean rotation; CSW, corn-soybean-wheat rotation; BD, bulk density; WR, water retentions; PAW, plant available water; C, soil carbon; N, soil nitrogen; SOC, soil organic carbon.

3.2 Introduction

Agriculture in the Midwestern region of the USA is based on intensive corn production. Agricultural practices that can help offset emissions of greenhouse gases, improve soil structure, reduce erosion, and increase soil water holding capacity might increase overall soil resilience to climate variability (IPCC, 2007). Conservation practices that have been reported to address some of the above challenges include reduced or no-tillage (Bescansa et al., 2006), crop rotations (Aziz et al., 2011), cover crops (Abdalla et al., 2014) and nutrient management (Coulter et al., 2009).

Crop rotation is a practice of growing different crops on the same land in a particular order over multiple growing seasons (Bullock, 1992; Karlen et al., 1994a). Current U.S agriculture is dominated by two crops, carbohydrate-rich corn and protein-rich soybean. These two crops complement each other, and are usually grown in a 2-yr CS rotation. USDA estimated that 84% of corn and 94% of soybean were grown in some type of a rotational system in 2011. However, current crop prices and profit margins have led to monoculture cropping systems (USDA-ERS, 2013).

The effects of crop rotation on soil properties are not consistent over studies. There is mixed evidence on short- and long-term impact of crop rotations on soil properties. It is often reported that the effects of crop rotation on soil depends on the individual crop grown in a particular rotation since crops within rotation leave different quantity and quality of plant residues on the field (Sanford et al., 2012; Zuber et al., 2015). Leaving residues on the field has a positive effect on soils. In a 10-yr no-till corn study, crop residues reduced water and wind erosion, increased earthworm population and available nutrients, and improved WR (Karlen et al., 1994b). Since corn produces more residue than soybean or wheat, one could assume that SOC in a continuous corn scenario would increase versus corn grown in a rotation. However, Zuber et al. (2015), in a 15-yr study in Illinois reported similar SOC concentrations in CC and corn grown in rotation with other crops and concluded it could be attributed to lower residue production due to a yield penalty after long-term CC production and a greater overall productivity of rotations including corn. In the same study, corn-based rotations lowered BD and SOC compared to continuously grown soybean which leaves low quantities of residues.

Conservation tillage is an intensively studied management practice for soil improvement (Al-Kaisi and Yin, 2005; Ogle et al., 2012; Olson and Al-Kaisi, 2015). With technological improvements such as development of herbicide resistant crops it is easier now than in the past to control weeds leading to an increase in conservation tillage management. It has been estimated that the use of conservation tillage will increase 40% by 2020 compared to 1995 (Lal, 2001). This is a positive trend since conventional tillage is a practice that impacts soil structure and modifies soil pore distribution leading to significant soil, air and water relationship changes (Hubbard et al., 2013). Practices such as no-tillage, strip tillage, deep rip or chisel plow have proved to sequester more carbon and emit less carbon dioxide compared to moldboard under CS rotation (Al-Kaisi and Yin, 2005). However, some studies reported higher SOC stocks in moldboard plow systems compared to no-tillage systems. Higher SOC in the lower depths of moldboard systems can destabilize aggregates and translocate carbon-rich upper horizon materials to lower levels (Olson and Al-Kaisi, 2015). Ogle et al. (2012) in an analyses performed on a national scale estimated that no-tillage has a potential to increase SOC only when the yield penalty of residues production is less than 15%.

Several studies have investigated an interaction of crop rotations and tillage and their influence on many soil properties (Aziz et al., 2015; Havlin et al., 1990; Katsvairo et al., 2002; West and Marland, 2002; Zuber et al., 2015). In an analysis of 67 long-term agriculture experiments with 267 paired treatments, West and Post (2002) concluded that the transition from conventional tillage to no-tillage in long-term CS rotation results in high carbon sequestration rates. These authors estimated that if both practices are applied, then an increase in SOC would have two phases: short-term of 15- to 20-years driven by changes in tillage and long-term of 40- to 60-years due to rotation enhancement and stabilization in residue amounts. However, the majority of experiments included by West and Post (2002) had a maximum sampling depth of 20 cm and less and none of them exceeded 30 cm depth. Baker et al.

(2007) in their work provided a scientific evidence of no-difference between conventional and conservational tillage methods on C sequestration when studies consider deeper sampling depths. Also, different studies found that significant effects of both tillage and rotations on SOC can be detectable in shorter periods of time when high residue producing crops were used (Havlin et al., 1990). Havlin et al. (1990) studied nitrogen fertilizer rates in conjunction with tillage and rotations and found that SOC was increased under high nitrogen fertilizer rates. Evaluating different soil properties, Katsvairo et al. (2002) found that different corn rotations did not interact with tillage and had no effect either on BD or air-filled porosity during vegetative stages of corn development at the 15 cm soil depth. However, in the same study, the extended soybean – wheat/clover (*Trifolium pretense* L.) – corn rotation had greater earthworm density and greater water infiltration compared to other rotations which contributed to higher yields.

Water scarcity is a major environmental challenge for agriculture. It is predicted that extreme weather conditions such as prolonged droughts are going to be more common in the future (IPCC, 2014). In fact, since the beginning of global surface temperature recordkeeping in 1880, nine out of the ten warmest years have been recorded in the last thirteen years with 2014 the warmest ever recorded (NOAA, 2015). There is a high risk that these events would reduce water availability for plants, thus reducing yields. Water retention is the ability of soil to retain water, which is then available for plant production (Gupta and Larson, 1979). It is important to keep SOC at the highest possible level since it often promotes greater WR (Arriaga and Lowery, 2003; Bescansa et al., 2006). Therefore, management practices that supply carbon into the soil are of particular interest. A strong correlation has been detected between SOC and water content at saturation and 20 kPa of suction in the top 7.6 cm of soil (Arriaga and Lowery, 2003). Also, there is a strong relationship between water retention and soil pore-size allocation. Bescansa et al., (2006) found that under a no-tillage system, small pores (0.2-6 μm) occupied around 60% of the total pore volume in the top 15 cm of soil, and the opposite was true under reduced and moldboard tillage where large pores (>9 μm) occupied the majority of the pore space. This difference in pore size distribution is attributed to the higher water holding capacity under no-tillage. Erodible soils tend to have less soil aggregates due to reduced carbon input from the soil surface, and it might also lead to increase in BD and lower WR (Arriaga and Lowery, 2003). The advantage of conservation tillage over traditional tillage to store more water has been well documented under prolonged dry conditions. In Argentina, higher WR in no-till was advantageous during critical corn growing stages in summer; moreover, no-till corn yields were similar to conventionally tilled treatments with the same N rate, which provided an advantageous management alternative for Argentinian farmers (Fabrizzi et al., 2005).

Application of long-term crop rotations and changing from conventional tillage to conservation tillage without removing crop residues changes soil properties. Often the effect is positive which in the long-run which can improve the resiliency of cropping systems to climate change. Thus, it is necessary to understand how different rotations will affect soil properties. No studies to our knowledge have examined the effects of the same long-term crop rotations on a wide array of soil physical and chemical properties across different environments and management practices. Also, there is little information available on how the addition of winter wheat with fine and dense roots affect soil changes to the common 2-yr CS rotation. Therefore, our objectives were to compare BD, C, N, C/N ratio, WR, PAW, and soil texture following long-term use of CC, CS, and CSW rotations in three unique sites in Wisconsin. We hypothesized that regardless of the environment increased rotation complexity would improve these soil properties.

3.3 Materials and Methods

3.3.1 Sampling Locations

This study was conducted at the University of Wisconsin's Agricultural Research Station at Arlington (43°18'N, 89°20'W), Lancaster (42°50' N, 90°47' W), and at Marshfield (44°76' N, 90°09' W). At each location continuous corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotations were selected to study their effects on soil physical properties and soil C and N after long-term use. The experimental design was a randomized complete block with three replications at Arlington and Marshfield and two replications at Lancaster. Only those phases with corn grown during the sampling year were sampled in the CC, CS and CSW rotations. Soil samples were collected and evaluated twice, in 2011 and 2013, at four different depths. All experiments were established prior to sample collection. The study at Arlington was established in 2002 on Plano silt loam (fine-silty, mixed, superactive, Mesic Typic Argiudolls) with slopes range from 2 to 6%. The Plano series consists of deep and well drained silty soils formed in loess or similar silty materials on uplands under tall prairie grasses. They are characterized as having moderate permeability with slopes ranging from 0 to 12%. The study at Lancaster was established in 2005 on Fayette silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). The Fayette series consists of deep, well drained soils formed in loess on convex crests and side slopes on uplands and on treads and risers on high stream terraces. With the slopes ranging from 0 to 60% the surface runoff potential varies from negligible to high. The study at Marshfield was established in 2007 on Marshfield silt loam (Fine-loamy, mixed, superactive, frigid Mollic Epiaqualfs) with 0 to 2% slope. Marshfield soils form a drainage sequence with Loyal silt loam (Fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs). These soils are deep and poorly drained with moderate permeability formed in loess or silty alluvium under deciduous water-tolerant trees (Soil Survey Staff, 2015). In Wisconsin, the large scale conversion of prairies into agricultural lands began in the 1840s. For many years, continuous wheat and then forage systems based on corn, wheat, oat

(*Avena sativa* L.) and alfalfa (*Medicago sativa* L.) used to support the fast growing dairy industry were dominant (Posner et al., 1995).

3.3.2 Field Management

Applied management practices were different at each location, with tillage practices varying among locations and rotations. All plots at Arlington were no-tillage. At Lancaster, both, CS and CSW rotations were no-tilled and CC was fall chisel plow, spring disking and cultimulching. Tillage operations at Marshfield in all rotations included fall chisel plow, spring disking and field cultivating. Crop hybrids used in this experiment were adapted high-performing hybrids based upon previous research at each location. Corn and soybean were planted in April or May each year. Corn was seeded in 76-cm rows at all locations and soybean in 76- 38- and 19-cm rows at Arlington, Lancaster and Marshfield, respectively. Winter wheat was drilled in 19-cm rows after soybean harvest in late September to early October. The seeding rates were 82,745 to 86,450 seeds ha^{-1} of corn, 370,500 to 444,600 seeds ha^{-1} of soybean, and 4.2 to 4.9 million seeds ha^{-1} of wheat. Nitrogen fertilization of corn occurred after planting as 28% urea ammonium nitrate at a rate of 224 kg N ha^{-1} at Arlington, 34% ammonium nitrate (NH_4NO_3) and the same rate at Lancaster. At Marshfield, 28% urea ammonium nitrate was applied to corn as a nitrogen source at a rate of 134.5 kg N ha^{-1} in CC and 90 kg N ha^{-1} in CS and CSW rotations. Winter wheat was fertilized with nitrogen fertilizer in the form of urea at a rate of 113 kg N ha^{-1} in 2011-2012 and 134 kg N ha^{-1} in 2013-2014 at Arlington and at a rate of 97 kg N ha^{-1} in 2012 and 73 kg N ha^{-1} in all other years at Marshfield. Winter wheat at Lancaster was fertilized with ammonium nitrate at a rate of 34 kg N ha^{-1}. No nitrogen fertilizer was applied to soybean. Weeds were controlled using pre- and/or post- emerge herbicides following best recommended practices at each environment (Appendix C). If needed, crops were also treated with insecticides also following best recommended practices. Soil fertility samples were collected and analyzed annually at Arlington and every three years at Lancaster and Marshfield. Phosphorus and K fertilizers were applied as recommended using soil nutrient information from soil tests.

3.3.3 Soil Sampling and Analysis

In the spring 2011, and 2013 soil samples were collected from corn plots of CC, CS, and CSW rotations at four depths (0 to 10, 10 to 20, 20 to 40, and 40 to 60 cm) from every plot in the approximate center of each depth interval from the quarter row position free of wheel tracks. At Arlington soil samples were also collected in 2015, only from the top two depths. But, soil sampling frequency, sampling depths and sampling methods differed across studied soil properties.

Three soil cores (3.1 cm in diameter and 6 cm long) were collected for WR measurements from each plot. Water retention was measured for the two top depths. Immediately after collection, soil cores were sealed and transported to the laboratory and stored at 4 °C. Water retention was measured at the following matric potentials: 0, −5, −10, −33 and −1500 kPa. The first three points characterize the so called "wet end" of the WR curve up to the field capacity (-33 kPa). The last point (-1500 kPa), the so called "dry end" determines the permanent wilting point, the point at which water is no longer available for plants and plants start to die. Prior to WR analysis, samples were saturated with tap water. A fine nylon screen was installed on the bottom of each core with a rubber band to prevent soil losses. Cores were placed in a tub which was then filled with tap water to about half of the core height and allowed to equilibrate for at least 8 hours. Afterwards, more water was added to the top edge of the cores but water was not allowed to flow over the soil surface. Samples were allowed to equilibrate again for at least 8 hours. Saturated weights were recorded and WR analysis followed. Different methods were applied between years to measure the "wet end" of WR curve. A hanging water column apparatus designed by McGuire and Lowery (1992) was used on samples collected in 2011 and a water tension apparatus (Dane and Hopmans, 2002) was used on samples collected in 2013. Both methods were based on similar assumptions and procedures. After completing "wet end" suction points, the samples were dried at 105 °C for least 24 h and the last point of the WR curve at -1500 kPa "dry end" was measured with WP4 dew point potentiometer (Decagon Devices, Pullman, WA, USA). This method required a fine size material; therefore, dried samples were passed through a 2 mm screen of a mill design to grind soil. The method included placing 3 to 4 g of finely ground soil from each core into four separate cups (2 cm diameter). Deionized water was poured into the cups at 100, 200, 300, and 400 μL increment rates. Prepared samples were covered and allowed to equilibrate for 24 h and then analyzed. Plant available water (cm) was calculated by subtracting the water content at the “dry end” from the water content at the “wet end” and multiplied by the length of the measured depth.

The same core samples were used for BD. For BD calculations, undisturbed oven dried core weights were recorded and divided by the core’s volume (Blake and Hartge, 1986). In 2011, BD was measured at four depths and in 2013 on the top two depths. In 2015, BD was measured on the top two depths, only at Arlington. Core samples collected in 2011 from 20-40 and 40-60 depths were used for BD determination without WR measurement.

Each year a minimum of 12 push-probe (1.9 cm diameter) samples from all four depths (0 to 10, 10 to 20, 20 to 40, and 40-to 60-cm) were collected and composited into one bag per depth for standard soil fertility analysis including phosphorus (P), potassium (K), cation exchange capacity (CEC), and pH . The composites were collected from the same plots where the core samples were collected. These soil samples were also used for particle size analysis using the hydrometer method to determine sand, silt and clay fractions (Gee and Bauder, 1986). Particle size analyses were performed on samples collected in 2011.

Carbon and N concentration analyses were performed with the composite samples after drying and grinding. Approximately 8 to 10 mg of soil were packed into 5 x 9 mm tin capsules and the concentrations were determined with a dry combustion method using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy). These data served to calculate C/N ratio as well as C and N amounts expressed in mass units (kg ha^{-1}) at each depth and accounting for differences in BD.

3.3.4 Data Analysis

Linear mixed effects models were developed using the MIXED procedure of SAS software version 9.3 (2011) to analyze soil chemical (pH, P, K, and CEC) as well as physical (BD, soil C and N concentration and mass data, C/N ratio, WR, PAW) properties as a function of year (2011-2015), location (Arlington, Lancaster, Marshfield), rotation (CC, CS, CSW), depth (0-10, 10-20, 20-40, and 40-60 cm) and WR (0, -5, 10, -33, and -1500 kPa). Location, rotation, depth and tension, and their interactions were treated as fixed effects while year, rep(year*location), and rep*rotation(year*location) were treated as random effects. Least square means were separated using the PDIFF option of LSMEANS. This option uses Fisher's protected *F*-test at $P \leq 0.05$. The Kolmogorov-Smirnov test was applied to check for normality assumption but no transformations were needed. Differences in management across locations may influence soil properties. However since, crop rotations were the main focus in this study we allowed for this known source of variability in order to compare the responses of long-term crop rotations on soil properties across typically practiced management practices in Wisconsin.

3.4 Results and Discussion

3.4.1 Chemical Analysis

Locations had significantly different pH, P and CEC, and not significantly different K concentrations across rotations and depth (Table 3.1). The model main effects of rotation and location similarly affected all variables. There was no significant difference among rotations and in any interaction that included rotation. However, the analysis of variance revealed significant effects of depth and location x depth interaction.

Small differences in pH were observed in all depths across locations that oscillated near neutral (pH ranged from 6.7 to 7.2), except in the acidic conditions of the 40-60 cm depth in Marshfield (pH=5.7) (Table 3.3). Potassium concentrations were the highest at the 0-10 cm depth (127-169 ppm) and decreased with the depth ranging from 60-101 ppm across locations; with the greatest decreases at Lancaster at 61-67 ppm across depths. Phosphorus concentrations varied across locations and ranged from 8.3-19.6, 10.3-24.5, and 16.2 -51.6 ppm at Arlington, Lancaster and Marshfield, respectively. Cation exchanged capacity increased with the depth at Arlington and Lancaster and decreased at Marshfield.

3.4.2 Soil Carbon and Nitrogen

There were significant effects of location, depth and their interaction on soil C and N expressed either in concentration (%) or mass (kg ha^{-1}) units as well as C/N ratio calculated from measured concentration data (Table 3.1). In addition, a significant location x rotation and location x rotation x depth interactions were observed in C and N expressed in mass units. Separation of the means that highlights the above *F*-test results is presented in Table 3.5, and the significant 3-way interaction is presented in Table 3.6.

Soil C and N concentrations decreased with depth and when averaged across depths were the lowest at Lancaster (Table 3.5). The significant location x depth interaction was influenced with no difference in C and N concentration at the two lowest depths at Lancaster. Soil C and N expressed in mass at each depth had different patterns across locations. Soil C at Arlington contained significantly more C (2224 kg ha^{-1}) than either Marshfield (1989 kg ha^{-1}) or Lancaster (1346 kg ha^{-1}). However, the averaged N masses were equal at Arlington (236 kg ha^{-1}) and Marshfield (229 kg ha^{-1}) and lower at Lancaster (170 kg ha^{-1}). At Lancaster, the CSW rotation had more C than other rotations at all three top depths and rotations equalized at 40-60 cm depth. The Fayette soil series at Lancaster are located on slope surfaces and are prone to surface runoff, and this may partially explain much lower C concentrations.

Crop rotation did not affect BD, N, and C when averaged across locations but some differences were found for C and N mass units among crop rotations within a location (Table 3.5). Arlington CC soils had higher C mass at 20-40 cm depth than the Arlington CSW rotation. Soils at Arlington had the highest C mass at 40-60 cm depth across locations. Marshfield had C mass similar to Arlington at the top three depths, with the exception of the 20-40 cm depth in CC, which was much lower. At Lancaster, CSW rotation generally had higher C mass at all three top depths, however all Lancaster rotations had similar C mass at 40-60 cm and were similar to 40-60 cm C mass at Marshfield. Sanford at al. (2012), during a 20-yr period of study, compared various cropping systems and reported that the greatest C losses were under intense CC (-2 Mg ha^{-1} yr^{-1}) in 0 to 90 cm depth and that this was more than half of C loses from CS or CSW rotations. The only C increase in the same study was found under a rotational pasture system (6.5 Mg ha^{-1} yr^{-1}), but only up to 15 cm depth. The authors concluded that this was mainly attributed to the differences of the estimated belowground biomass inputs since the majority of fine perennial grass root biomass is located close to the surface. Much lower variation in C was recorded in our study among crop rotations. In this experiment, at Arlington all rotations were under no-till management whereas CC in Sanford at al. (2012) study was chisel ploughed which would greatly offset the C contribution from corn aboveground residues. This may also be reflected in our results, where the chisel-plowed CC at

Lancaster had lower mean soil C in the upper layers than the other rotations. However, the difference between the rotations was not significant.

The pattern of soil N mass was more equally distributed through the soil profile across locations than that of C. At Arlington, across rotations, soils had similar N mass at the two top depths but rotations showed some difference deeper in the soil profile where at the 20-40 cm depth CC had much higher and the CSW rotation at 40-60 cm much lower N mass compared to CS (Table 3.6). At Lancaster, across depths, rotations had similar N amounts except the CSW rotation at 20-40 cm depth which were significantly higher compared to the other rotations. At Marshfield, CC at 20-40 cm depth had lower N amount than other crop rotations.

Differences in soil C contributed to observed differences in BD, WR or PAW. Also, it has been observed that clay particles interact more with soil organic matter than larger soil particles (Arriaga and Lowery, 2003). Generally, soils at Arlington had more clay particles to 20 cm depths and Marshfield more sand particles at all depths (Table 3.7). Differences in texture could in addition to higher surface runoff potential explain lower C amounts at Lancaster, but were poor in explaining high C level in Marshfield. Soils at Marshfield were subjected to intense chisel plough management and contained as much C at the two top depths as the full depth of no-till soils at Arlington. This may be related to the land history of the two sites where the transition of native prairies into highly cultivated grain crops at Arlington has contributed to significant losses of C and may yet to have reached soil C equilibrium (Posner et al., 1995; Sanford et al., 2012). Moreover, part of the reason why Marshfield had more C can be attributed to lower drainage capacity and slightly cooler temperatures in Marshfield relative to Lancaster and Arlington.

Carbon to N ratio decreased with depth at Lancaster and Marshfield and was relatively stable in the top three depths at Arlington. This difference across locations contributed to a significant location x depth interaction (Table 3.5). Carbon to N ratio varied slightly across rotations, but there was no significant main effect of rotation on soil C/N ratios. In general, low soil C/N ratio values across locations indicated a potential for the soil organic matter in these systems to provide some N to the crop.

3.4.3 Bulk Density

Crop rotations showed a similar BD across locations and depths. However, depths were found to have different BD across locations due to the significant location x depth interaction (Table 3.1 and Fig. 3.1). At Arlington, no differences were found across depths for BD which ranged from 1.35-1.40 g cm^{-3}, where surprisingly BD values at the top and the deepest depths were almost identical. At two other locations, BD was the lowest and not different at the first depth and ranged from 1.23-1.27 g cm^{-3}. At the 10-20 cm depth BD increased more at Lancaster (1.39 g cm^{-3}) then at Marshfield (1.30 g cm^{-3}) and then continued to increase at the 40-60 depth.

Organic matter promotes aggregation which often leads to BD reduction (Arriaga and Lowery, 2003; Jordahl and Karlen, 1993). Therefore, practices that supply carbon into the soil are of particular interest. Arriaga and Lowery (2003) reported that continuously repeated manure application significantly decreased BD from eroded soil up to 23 cm soil depth; and, these BD changes were negatively correlated with total soil C increases. There are a couple of factors that may explain the lack of differences in BD among crop rotations within locations (Table 3.1). First, even though corn out-competes soybean and wheat in residue abundance after harvest, the long-term CC practice reduces the residue inputs compared to rotated corn due to total yield decline which might offset to a certain extent the differences (Zuber et al., 2015).There is a large body of literature that confirm yield depression under continuously grown crops compared to rotated crops (Crookston et al., 1991; Pedersen and Lauer, 2002; Pedersen and Lauer, 2003; Stanger and Lauer, 2008). Also, West and Post (2002) in a large meta-analysis comparison concluded that it could take >40-years to stabilize and detect differences in SOC under different crop residues. These experiments had 5-10 years when the first soil samples were collected which may suggest that more time would have to pass to detect any differences since C buildup is a slow process. Significant differences that occurred among depths across locations could be attributed to differences in soils as well as management. Soils at Arlington and Marshfield had a similar C amount at 0-10 and 10-20 cm depths (Table 3.5). However, the tillage operations at Marshfield may additionally explain lower BD at the top two depths because the two lowest depths had the highest BD among all locations possibly due to relatively lower C amounts and soil series type which is described as poorly drained. No-tilled and carbon rich soils at Arlington resulted in consistent BD across all depths.

3.4.4 Water Retention, Water Content and Plant Available Water

There was no difference in averaged water content across locations and crop rotations and their interaction; however, besides significant effects of depth and tension, a significant rotation x depth, location x tension, depth x tension and a 3-way location x depth x tension interactions were observed (Table 3.2).

Water retention curves of each rotation at each location are presented for depth 0-10 cm in Fig 3.2 and for 10-20 cm depth in Fig 3.3. Crop rotations influenced WR in a similar manner at each location regardless of management methods. The 2-yr CS rotation had noticeably lower water contents at the field capacity tension point (-33 kPa) at each location in the first depth (0-10 cm) while at the second depth all rotations had similar lower water content. Extending the CS rotation with winter wheat that has a dense and fine root system might explain this tendency of improved WR at the first depth. These differences were too small to be captured statistically, however, they were large enough to influence the differences in PAW calculated as a difference of the field capacity (-33 kPa) and permanent wilting point (-1500) (Table 3.2). Averaged across locations, at the 0-10 cm depth, CC and CSW rotation had greater PAW than the CS rotation (Fig 3.2). Where, at the 10-20 cm depth all rotations equalized PAW (Table 3.2).

Water retention decreased with depth but the differences were small (Table 3.4). WR at the top depth was only different from the second depth at the first tension point which represented the saturation water content (0 kPa), except at Arlington where it was also higher at -5 kPa tension point. Also soils at

Marshfield had consistently the highest WR at the 0 bar at both depths and Arlington generally had the highest WR at the -1500 kPa tension point representing permanent wilting point.

The decrease of WR across tensions and PAW with depth can be mainly attributed to higher carbon content at the top depth since it promotes soil aggregate formation (Arriaga and Lowery, 2003; Bescansa et al., 2006). However, the differences in carbon content among rotations were relatively small and inconsistent across rotations and depths to explain why WR and PAW were the lowest in CS rotation regardless of tillage management method across location. Therefore, there must be other significant factors contributing to those differences. One potential explanation may lay in the differences of root systems between crops. Corn and wheat have denser root systems than soybean promoting sites for aggregate formation capable of retaining more water. Blanco-Canqui et al. (2010) reported reduced BD, increased water infiltration, higher SOC at all studied depths. Their study indicated that the presence of winter wheat in a system may improve water retention at certain tensions.

3.5 Conclusions

The negative effects of climate change such as more frequent and persistent droughts, flooding or extreme rainfall events highlight a systematical need to address agricultural vulnerability to those events and a search for better adaptation strategies. In this study, a long-term CC and CSW rotation showed a slight trend of increasing soil WR and PAW only at 0-10 cm compared to a CS rotation. Therefore, adding wheat to the 2-yr CS rotation has a potential to retain more water. Generally, differences in the soil properties measured were small among crop rotations but were high among locations due to differences in management and the environments. As an example no-tilled soils at Arlington had the most stable C amounts and BD, while prone to erosion soils at Lancaster had lowest C amounts. However, at Lancaster CSW rotation resulted in a slight trend of retaining more C. There is an indication that the changes in the microbial communities as well as in emission of greenhouse gases, that drive climate change, might be more sensitive to crop rotations than the soil properties evaluated in this study. There is a potential that with extending growing season length, growing conditions are becoming more suitable for implementing cover crops which could provide additional benefits to the soils. Here, the application of either long-term 2-yr CS or 3-yr CSW rotation affects in similar way most soil properties compared to higher residue production in CC across a range of management practices in Wisconsin.

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Table 3.1. Significance of analysis of variance for the effects of location, depth, and their interactions on bulk density, soil concentration and mass of carbon (C) and nitrogen (N), and the key chemical analysis at long-term crop rotation experiments conducted in Arlington, Lancaster, and Marshfield, WI.

		Soil					Chemical Analysis			
Source	Bulk density	N, %	C, %	C, kg ha^{-1}	N, kg ha^{-1}	C/N	pH	K	P	CEC
Location(L)	0.612	<0.001	<0.001	<0.001	<0.001	0.004	0.002	0.105	<0.001	<0.001
Rotation(R)	0.842	0.895	0.633	0.756	0.998	0.437	0.178	0.269	0.309	0.577
L x R	0.892	0.157	0.229	0.019	<0.001	0.044	0.559	0.151	0.348	0.903
Depth(D)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
L x D	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
R x D	0.118	0.318	0.602	0.061	0.246	0.983	0.931	0.742	0.684	0.239
L x R x D	0.690	0.598	0.393	0.014	0.018	0.091	0.302	0.516	0.723	0.319

Table 3.2. Significance of analysis of variance for the effects of location, rotation, depth, tension, and their interactions on water retention and plant available water at long-term crop rotation experiments conducted in Arlington, Lancaster, and Marshfield, WI.

Source	Water retention	Plant Available Water
Location(L)	0.235	0.334
Rotation(R)	0.191	0.030
L x R	0.839	0.852
Depth (D)	<0.001	<0.001
L x D	0.084	0.749
R x D	0.003	0.038
L x R x D	0.525	0.463
Tension (T)	<0.001	-
L x T	<0.001	-
R x T	0.498	-
D x T	<0.001	-
L x R x T	0.824	-
L x D x T	0.040	-
R x D x T	0.614	-
L x R x D x T	0.993	-

Table 3.3. Interaction effect of location and depth on soil pH, potassium (K), phosphorus (P), and cation exchanged capacity (CEC) at four different soil depths at Arlington, Lancaster, and Marshfield , WI (2011-2015).

	Chemical Analysis			
Effect	pH	K	P	CEC
		— ppm —		cmol kg^{-1}
Location by depth				
Arlington				
0-10	7.0	140.6	19.6	12.1
10-20	7.1	87.8	14.6	12.8
20-40	7.0	65.9	8.3	13.6
40-60	7.0	72.1	15.4	15.0
Lancaster				
0-10	6.7	126.7	24.5	8.5
10-20	7.0	67.4	10.3	9.1
20-40	7.2	60.9	12.1	13.0
40-60	6.9	66.6	23.8	15.3
Marshfield				
0-10	7.1	169.2	51.6	11.3
10-20	7.0	101.1	45.1	10.5
20-40	6.7	59.6	20.0	8.3
40-60	5.7	64.4	16.2	9.8
LSD(0.05)	0.3	19.1	6.7	1.4
Location means				
Arlington	7.0	91.6	14.5	13.4
Lancaster	6.9	80.4	17.6	11.5
Marshfield	6.6	98.6	33.2	10.0
LSD(0.05)	0.2	NS†	6.4	1.4

† NS, not significant.

Table 3.4. Interaction effects of rotation x depth and location x depth x tension at Arlington, Lancaster, and Marshfield. WI (2011-2015).

Effect	Water content 0-10 cm	Water content 10-20 cm
	—$m^3 m^{-3}$—	
Rotation x depth		
CC	0.350	0.333
CS	0.341	0.335
CSW	0.351	0.337
LSD (0.05)	0.007	
Location x depth x tension		
Arlington		
0 kPa	0.492	0.470
-5 kPa	0.392	0.375
-10 kPa	0.379	0.365
-33 kPa	0.352	0.342
-1500 kPa	0.107	0.108
Lancaster		
0 kPa	0.515	0.467
-5 kPa	0.403	0.389
-10 kPa	0.382	0.372
-33 kPa	0.337	0.332
-1500 kPa	0.082	0.078
Marshfield		
0 kPa	0.536	0.508
-5 kPa	0.400	0.392
-10 kPa	0.384	0.381
-33 kPa	0.364	0.354
-1500 kPa	0.088	0.093
LSD (0.05)	0.016	

Table 3.5. Bulk density, soil C and N expressed in concentration and mass units, and C/N ratio calculated from soil concentration data.

				Soil§				
Location†	Rotation‡	Depth	Bulk density§¶	Carbon	Nitrogen	C/N	Carbon	Nitrogen
		cm	g cm^{-3}	—— % ——			— kg ha^{-1} —	
ARL			1.37	1.28	0.13	9.41	2224	236
LAN			1.39	0.84	0.10	8.12	1346	170
MAR			1.39	1.24	0.14	8.12	1989	229
LSD(0.05)			NS#	0.12	0.01	0.81	224	24
	CC		1.39	1.11	0.12	8.56	1844	211
	CS		1.38	1.10	0.12	8.37	1825	212
	CSW		1.38	1.15	0.12	8.73	1890	212
	LSD(0.05)		NS	NS	NS	NS	NS	NS
		0-10	1.28	1.83	0.18	10.00	2343	234
		10-20	1.36	1.51	0.16	9.38	2036	216
		20-40	1.45	0.70	0.09	7.98	1923	232
		40-60	1.45	0.43	0.06	6.85	1110	163
		LSD(0.05)	0.02	0.06	0.01	0.42	115	15
ARL	CC		1.37	1.33	0.14	9.00	2412	265
	CS		1.38	1.21	0.13	9.23	2177	235
	CSW		1.37	1.29	0.13	10.01	2083	207
LAN	CC		1.40	0.81	0.09	8.33	1319	162
	CS		1.39	0.76	0.09	7.52	1202	162
	CSW		1.39	0.94	0.11	8.52	1517	184
MAR	CC		1.41	1.18	0.13	8.34	1800	206
	CS		1.38	1.32	0.14	8.35	2097	238
	CSW		1.39	1.21	0.14	7.66	2070	244
	LSD(0.05)		NS	NS	NS	1.07	323	32
ARL		0-10	1.35	1.84	0.18	10.32	2473	241
		10-20	1.39	1.63	0.16	10.18	2262	225
		20-40	1.40	1.01	0.11	9.35	2561	277
		40-60	1.36	0.64	0.08	7.81	1601	200
LAN		0-10	1.27	1.52	0.16	9.76	1947	199
		10-20	1.39	1.02	0.12	8.48	1413	167
		20-40	1.46	0.44	0.06	7.06	1153	174
		40-60	1.45	0.37	0.05	7.19	871	139
MAR		0-10	1.23	2.13	0.21	9.92	2610	263
		10-20	1.30	1.88	0.20	9.48	2433	257
		20-40	1.50	0.66	0.09	7.52	2054	247
		40-60	1.54	0.28	0.05	5.55	859	150
		LSD(0.05)	0.05	0.14	0.01	0.91	247	30

† Arlington (ARL), Lancaster (LAN), and Marshfield (MAR).

‡ CC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat.

§ The first two depths were measured in 2011 and 2013 at all stations, where Arlington had additional measurement taken in 2015.

¶ Depths 20-40 and 20-60 cm measured only in 2011, since it is not expected to change over short period of time.

Table 3.6. Soil C and N concentration and mass by rotation and depth within rotation at Arlingron, Lancaster and Marshfield.

		Carbon†			Nitrogen†		
Effect	Depth	ARL	LAN	MAR	ARL	LAN	MAR
Rotation x depth	cm			kg ha^{-1}			
CC							
	0-10	2582	1790	2564	250	183	261
	10-20	2395	1470	2327	252	165	253
	20-40	2824	1074	1405	322	157	177
	40-60	1848	943	904	235	144	135
CS							
	0-10	2431	1926	2631	243	199	269
	10-20	2156	1141	2514	214	150	256
	20-40	2593	923	2396	277	152	278
	40-60	1528	816	848	205	148	147
CSW							
	0-10	2407	2123	2636	229	214	260
	10-20	2234	1628	2458	209	185	261
	20-40	2264	1462	2363	230	212	285
	40-60	1426	854	823	161	126	167
LSD(0.05)			420			48	

† Collected in 2011 and 2013 at all locations. At Arlington, the two top depths where additionally sampled in 2015.

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Table 3.7. Soil texture at different depths at Arlington, Lancaster, and Marshfield, WI (2011).

Location	Depth	Sand		Silt		Clay	
	cm			%			
Arlington	0-10	7.9	(±0.4†)	70.4	(±0.6)	21.7	(±0.5)
	10-20	7.2	(±0.6)	69.4	(±0.7)	23.3	(±1.0)
	20-40	4.1	(±0.4)	66.6	(±1.1)	29.3	(±1.2)
	40-60	3.9	(±0.5)	64.0	(±0.9)	32.1	(±1.2)
Lancaster	0-10	9.2	(±0.7)	79.0	(±0.5)	11.8	(±0.7)
	10-20	7.3	(±0.7)	76.7	(±1.5)	16.0	(±1.3)
	20-40	5.5	(±0.3)	67.3	(±0.8)	27.2	(±0.9)
	40-60	4.2	(±0.3)	64.2	(±0.3)	31.7	(±0.4)
Marshfield	0-10	16.1	(±0.8)	69.1	(±0.5)	14.8	(±0.5)
	10-20	16.2	(±1.0)	69.4	(±0.7)	14.3	(±0.7)
	20-40	16.2	(±1.3)	66.6	(±0.9)	17.2	(±0.8)
	40-60	20.1	(±1.6)	54.2	(±3.0)	25.7	(±2.1)

† Standard error.

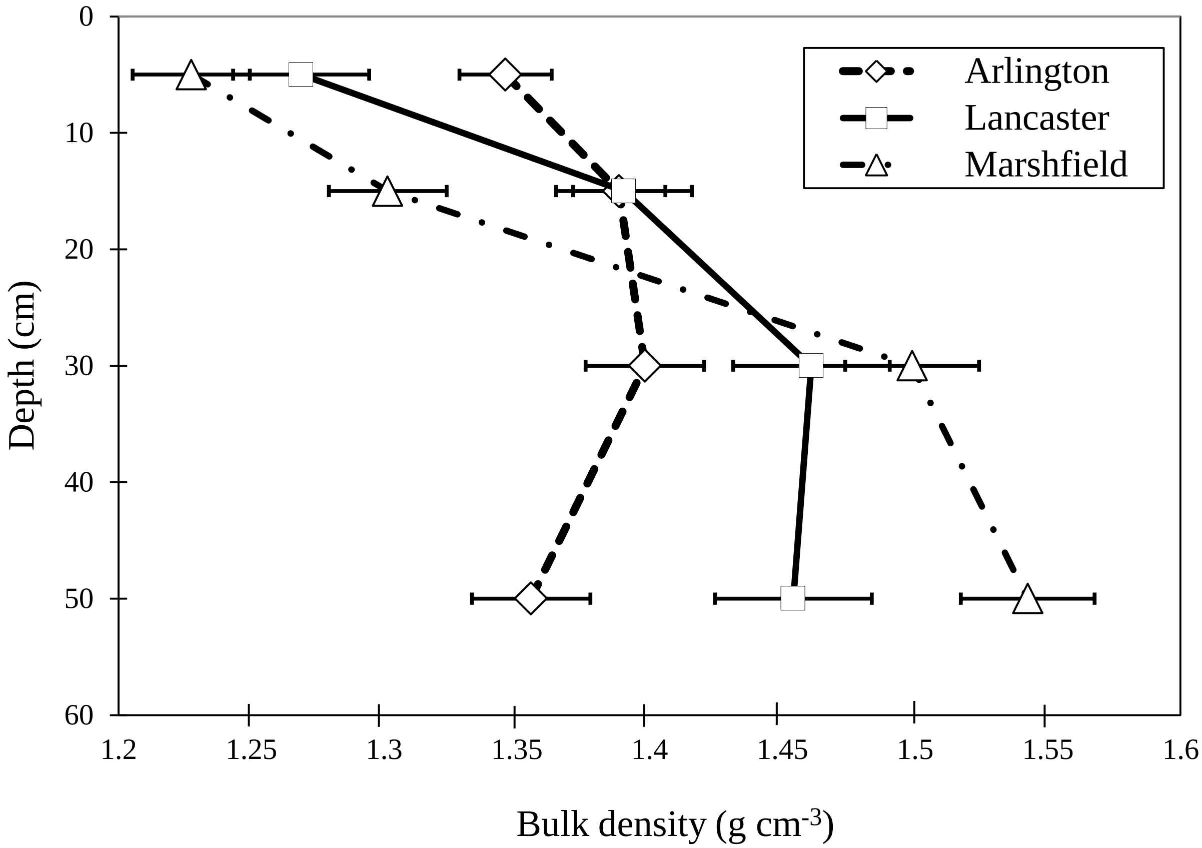

Figure 3.1. Bulk density at four soil depth 0-10, 10-20, 20-40, and 40-60 cm presented in the middle of each depth range at Arlington, Lancaster, and Marshfield, WI. Data represent average across years and crop rotation within locations. The first two depths were measured in 2011 and 2013 at all stations, where Arlington had additional measurement taken in 2015. Depths 20-40 and 20-60 cm had bulk density measured only in 2011.

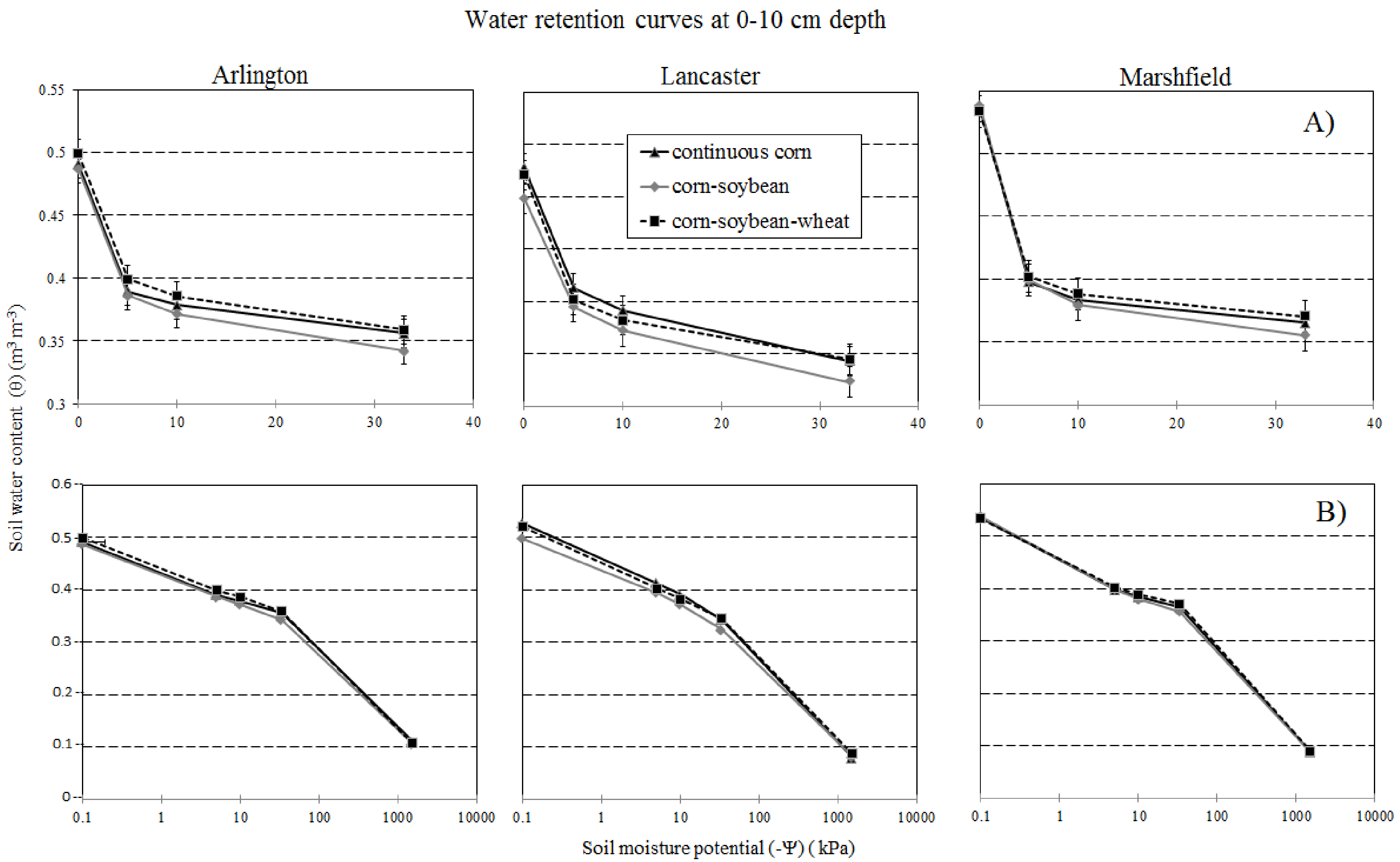

Figure 3.2. Water retention curves at 0-10 cm depth of continuous corn, corn-soybean, and corn-soybean wheat rotation at three locations in Wisconsin, where A) shows the “wet end” of the curve up to the field capacity (-33 kPa), and B) shows the complete curve up to the permanent wilting point (-1500 kPa) presented on log scale.

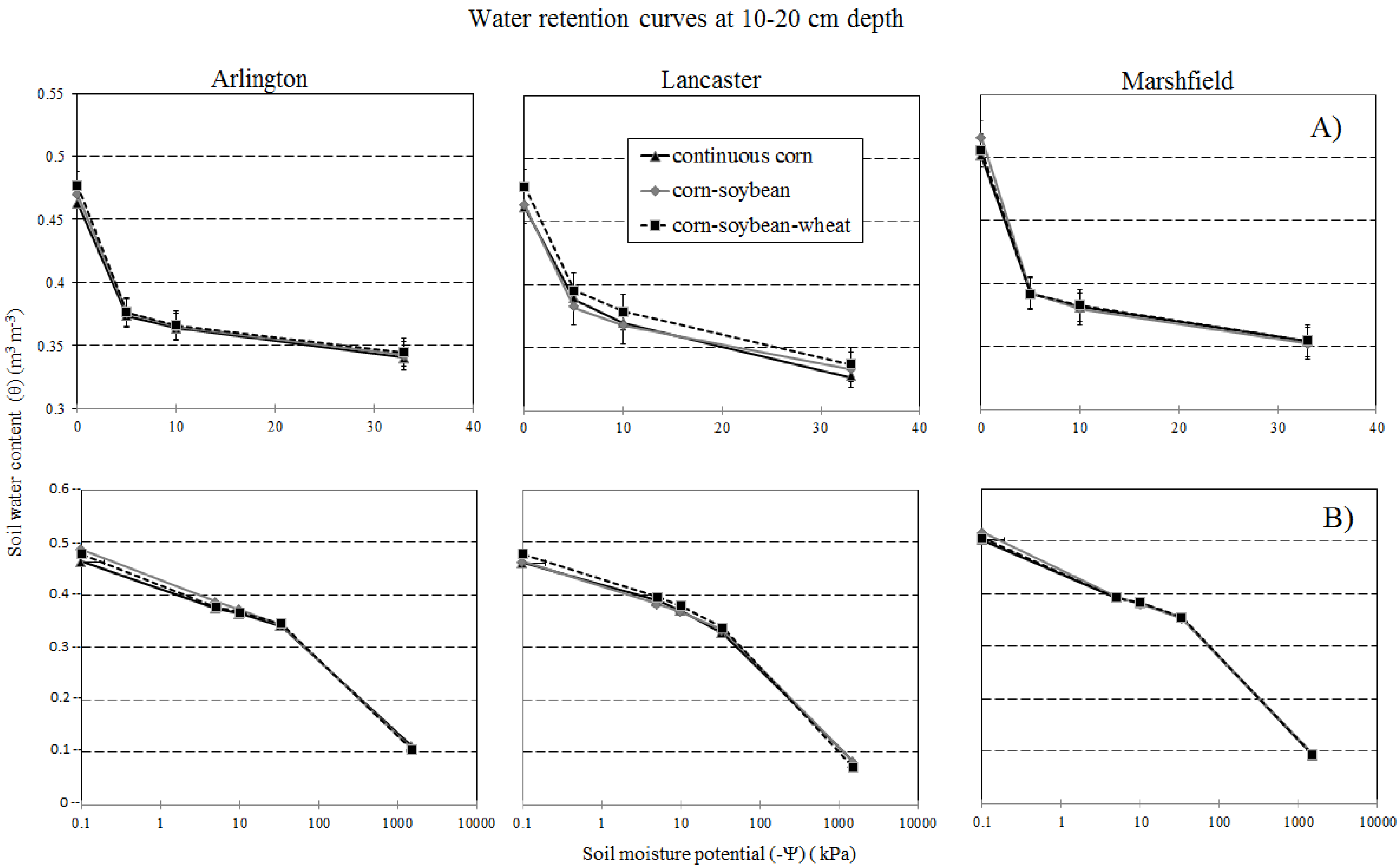

Figure 3.3. Water retention curves at 10-20 cm depth of continuous corn, corn-soybean, and corn-soybean wheat rotation at three locations in Wisconsin, where A) shows the “wet end” of the curve up to the field capacity (-33 kPa), and B) shows the complete curve up to the permanent wilting point (-1500 kPa) presented on log scale.

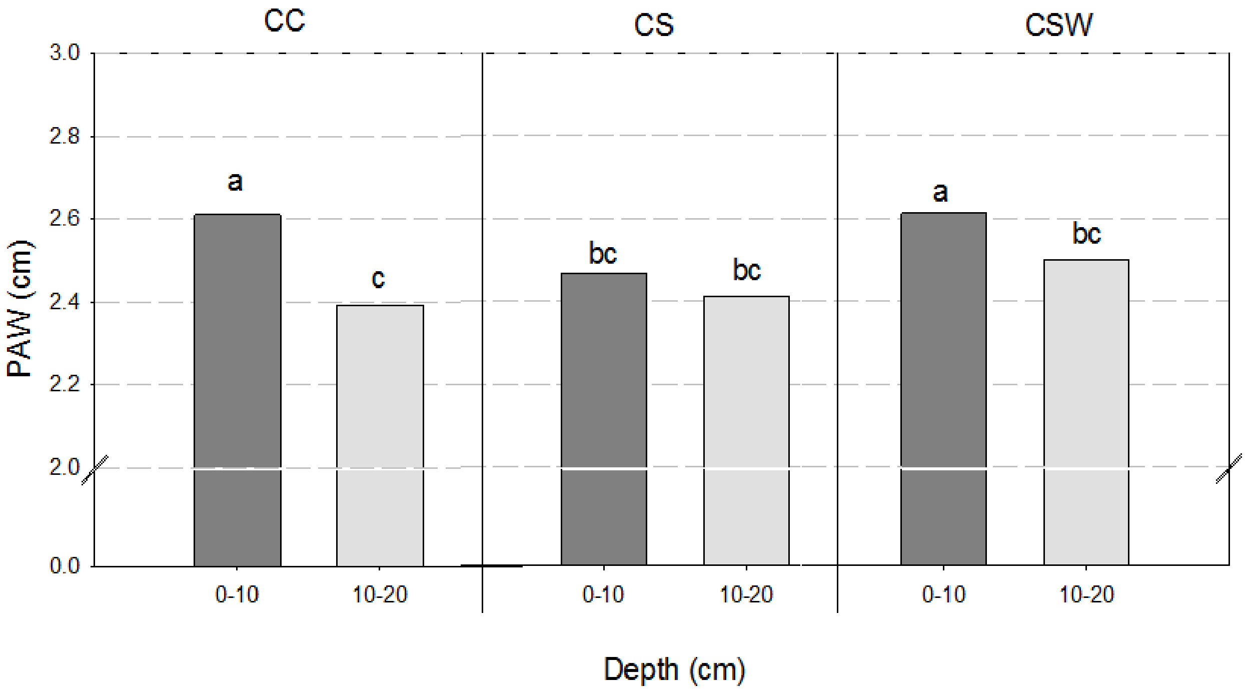

Figure 3.4. Comparison of plant available water among continuous-corn (CC), corn-soybean, and corn soybean wheat (CSW) measured at two soil depths. Data are averages across three locations and years (2011-2015).

Chapter 4. *Calibration of DAYCENT to Estimate N_2O Emissions during the Non-Vegetated Season and Response to Future Climate from Three Corn-Based Rotations in Wisconsin*

4.1 Abstract

Crop rotations if properly managed have a high potential to increase resilience to climate change, and modeling approaches provide a way to test phenomena/effects that are often overlooked or hard to physically measure. The main aims of this study were to use the DAYCENT biogeochemical model to estimate N_2O emissions when field measurements were not collected (from mid-November to late-March/early-April) to correct for total annual emissions and to simulate future crop rotation effects on crop productivity and GHG emissions using 7 climate change scenarios. First, the model was tested and calibrated as needed for observed grain yield, nitrous oxide (N_2O), and other data from three corn- (*Zea Mays* L.) based rotations in three differently managed sites in Wisconsin. Overall, the model was able to estimate field collected grain yield and N_2O emissions data but the precision depended upon complexity of the system. Non-vegetated soil contributions of N_2O emissions to the total emission ranged from 8 to 44% of total annual emissions across crop rotations and locations. The highest emission of N_2O-N coming from the non-vegetated period accounted for 2.2 kg ha^{-1} in continuous corn (CC) in Lancaster and the emissions from all other rotations across locations were much smaller and did not exceed more than 1 kg N_2O-N ha^{-1}. Generally, corn and soybean [*Glycine max* (L.) Merr.] are expected to have small grain yield increases and then stabilize towards the end of the 21st century while wheat (*Triticum aestivum* L.) yield remains stable. Compared to CC, corn in rotations under high nitrogen (N) input regimes have a high potential to reduce N_2O driven global warming potential (GWP) by 41% for 2-yr corn-soybean (CS) rotation and 48% for 3-yr corn-soybean-wheat (CSW) rotation.

Abbreviations: CC, continuous corn rotation; CS, corn-soybean rotation; CSW, corn-soybean-wheat rotation; GWP, global warming potential; GHGi, greenhouse gas intensity

4.2 Introduction

The cropping systems of the Midwestern region of the U.S. is based on intensive corn (*Zea mays* L.) production. Agriculture is a major source of N_2O emission and in the U.S. 70% of N_2O annual emissions come from agricultural soils (USEPA, 2012). Although the amount of N_2O emitted to the atmosphere is low compared to carbon dioxide (CO_2), it has been described as having 263-310 times greater GWP (IPCC, 2007; IPCC, 2013b; Snyder et al., 2009). Nitrogen fertilizer has been identified as the main management factor stimulating agricultural N_2O emissions (USEPA, 2015). On average, U.S. corn receives 157 kg ha^{-1} of inorganic nitrogen fertilizer (USDA-ERS, 2011). It has been estimated that 1.25% of the total applied nitrogen is biologically converted to N_2O which subsequently is emitted to the atmosphere (IPCC, 2007). Climate change projections suggest an increased variability of extreme climate conditions, such as sustained drought or prolonged precipitation (IPCC, 2013a). These events have a negative effect on crop production but have also created many questions and concerns regarding the intensity of GHG emissions. High N demand and large acreage on which corn is grown leads to high N_2O emissions where improved management practices could be developed to promote GHG mitigation. Crop rotation is a management practice often reported as having a positive mitigation potential (Adviento-Borbe et al., 2007; Drury et al., 2008), but due to recent economic influences is often neglected.

Progressive development of process-based models provides a way to simulate various environmental processes over time and across environments. Such models can be used to simulate temporal and spatial greenhouse gas variability from diverse cropping systems over a whole year period. The DAYCENT biogeochemical model (Del Grosso et al., 2011; Parton et al., 1998) is one of the most prominent and widely used process-based models. The model has been used to simulate greenhouse gas production from typical croplands either at the field scale (Fitton et al., 2014; Jarecki et al., 2008), regional scale (De Gryze et al., 2011), national scale (Del Grosso et al., 2006) or global scale levels (Stehfest et al., 2007). It has also been used in a range of bioenergy cropping systems (Adler et al., 2007; Chamberlain et al., 2011; Hudiburg et al., 2015). Also, the model has been found to be useful in predicting methane production from rice paddies in China (Cheng et al., 2013) and future effects of climate change on various crop productivity levels (Lee et al., 2011) and greenhouse gas emissions (Abdalla et al., 2010). Currently, DAYCENT is used by the USEPA to estimate annual N_2O emissions from agricultural lands in the U.S. and to provide an informative tool for public and policy decision making (Del Grosso et al., 2006).

Although there has been a considerable increase in the number of experiments that measure in-field N_2O, there is still high uncertainty for accuracy of N_2O emission estimation due to large spatial and temporal variability (Goodroad et al., 1984; Groffman et al., 2009). Nitrous oxide is a by-product of microbiological processes that are controlled by many environmental conditions and their interactions (Del Grosso et al., 2000; Parton et al., 1996; Parton et al., 2001; Robertson and Groffman, 2015). Precise estimation of N_2O emissions from soils is difficult to obtain because it requires continuous and large-scale monitoring that is usually discontinued in winter with winter emissions often considered negligible or are estimated with linear interpolation methods that can greatly reduce precision. However, when soils are exposed to freezing and thawing processes, released N_2O that was stored under the frozen layer can significantly contribute to annual emissions (Cates and Keeney, 1987; De Bruijn et al., 2009; Wagner-Riddle et al., 1997).

Most research reports only in-season N_2O emissions and often lack late-winter and early-spring emissions that may be a result of freezing and thawing processes (Drury et al., 2006; Omonode et al., 2011; Osterholz et al., 2014). Also, only a few report annual N_2O measurements (Halvorson and Del Grosso, 2012; Lehman and Osborne, 2013). There are many potential pathways of N_2O emissions when soil temperature oscillates near 0 ^{o}C. De Bruijn et al. (2009), evaluated multiple hypothesis that explain high winter N_2O emissions and highlighted that reduction of oxygen diffusion occurring under freezing and thawing processes may have a major influence on increased denitrification rates.

The overall effects of climate change on crop productivity will depend upon location specific conditions but also chosen management practices. Changes in weather have been shown to cause either beneficial or negative effects upon crops depending on global geographic location (Peiris et al., 1996). Crop rotation, which increases the crop diversity of a system, has a high potential to solve many environmental problems and still maintain productivity. Many studies have used a range of crop models to project the effects of climate change on cropping systems around the world (IPCC, 2007; IPCC, 2013b). However, limited work has been done to describe the effects of long-term use of corn-based rotations as a potential strategy to increase resiliency to climate change in the Midwest. There is also sufficient evidence of high pre-growing season N_2O emissions before planting when soils are mostly inaccessible. These events can account for a substantial portion of the total annual emissions and reduce the accuracy of growing season-only estimates of N_2O emissions. The goals of this study were: (i) test the ability of the DAYCENT biogeochemical model to simulate N_2O emissions and grain yields from CC, CS, and CSW rotations in three different Wisconsin environments; (ii) estimate N_2O emissions when N_2O measurements were not collected (usually: mid-November – late-March/early-April) to correct for total annual emissions; and (iii) use a suite of 7 climate change projections to simulate future agronomic and environmental performance of three corn-based crop rotations.

4.3 Materials and Methods

4.3.1 Experimental Locations and Field Management

This study was conducted at the University of Wisconsin’s Agricultural Research Stations in Arlington (43°18’N, 89°20’W), Lancaster (42°50’ N, 90°47’ W), and Marshfield (44°76’ N, 90°09’ W). Experiments were arranged in a randomized complete block design in a split-plot arrangement, with three replications at Arlington and Marshfield and two replications at Lancaster. Main plots consisted of three rotations: continuous-corn (CC), corn-soybean (CS), corn-soybean-winter wheat (CSW), where each phase of each rotation was always present resulting in six rotation phases studied each year. Sufficient time (5 to 10 years) has passed since plot establishment to allow these extended crop rotation experiments to equilibrate differences within treatments

Applied management practices were different at each location, but they all are being practiced by farmers in rainfed agriculture at the Midwestern region of the United States. Tillage practices varied among locations and rotations. All plots at Arlington were no-till. At Lancaster, both CS and CSW rotations were no-tilled and CC was fall chiseled, spring disked and cultimulched. Tillage operations at Marshfield in all rotations included, fall chisel plow, spring disk, and field cultivator. Crop hybrids used in this experiment were adapted high-performing hybrids based upon previous performance at each location. Soil fertility samples were collected and analyzed every year at Arlington and every 3 years at Lancaster and Marshfield, and uniform rates of P and K fertilizers were applied at recommended rates using soil nutrient information from soil tests. Weeds were controlled using pre- and/or post-emerge herbicides following best practice recommendations for each environment. If needed, crops were also treated with insecticides also following best recommendation practices (Appendix C). The detailed information about site managements is described in the material and methods section of the 1st chapter.

4.3.2 DAYCENT Model Overview

DAYCENT is a daily time-step version of the Century model which simulates the exchanges of carbon, nutrients, and trace gases between the atmosphere, soil and vegetation (Del Grosso et al., 2011; Parton et al., 1998). The key sub-models in DAYCENT include plant growth with dynamic carbon allocation among the above- and below-ground biomass pools, decomposition of dead plant material, and three SOM pools that have three distinct decomposition rates which influence C and nutrient exchange. There are also sub-models for simulating soil water and temperature dynamics, and nitrogen gas emissions (Del Grosso et al., 2011). DAYCENT is a biogeochemical model that has been tested for the modeling of N_2O emissions from cropping systems (Abdalla et al., 2010; Del Grosso et al., 2005; Fitton et al., 2014). The model simulates the short term effects of environmental variables on the production of nitrogen gases in ecosystems. Within the N-gas submodel, total rates of nitrification and denitrification are calculated and a ratio function of NOx to N_2O is used to calculate individual gas species emissions from denitrification. The rates of N_2O emissions are controlled by soil water content, temperature, respiration, soil NH_4^+ and NO_3^- concentrations, gas diffusivity and labile C availability (Parton et al., 1998; Parton et al., 2001).

DAYCENT is controlled by scheduling events files for specific days and can include crop type, dates of plating, harvest, fertilization, cultivation, month of first growth and senescence, fertilizer type and application rates, organic matter addition, irrigation, grazing, erosion, and fire. DAYCENT is capable of simulating annual, perennial, forest, and savannah ecosystems. Due to differences in climate, soil, and historic land management, each modeled site must be parameterized. Input variables used to drive the DAYCENT model are soil physical and chemical properties, weather, latitude, longitude, and management. The model requires information on soil bulk density, pH, and percentages of sand, silt, and clay. DAYCENT can be run using weather data consisting of daily minimum temperature, maximum temperature, and total precipitation. Latitude and longitude are used to calculate day length and the accumulation of growing degree-days used to simulate plant development and growth.

4.3.3 DAYCENT Model Calibration

As recommended by DAYCENT model developers, our model validation exercise first required an initialization and spin-up procedure for 1000 years prior to the initiation of experiments that represented historical land cover and land use change. This procedure was necessary to allow soil carbon and nitrogen pools to reach an equilibrium state. The same spin-up procedure was used at each location. For years -1000 to 1830, prairie grass was grown to simulate native vegetation and then starting in 1830, a 3-yr rotation of wheat-wheat-fallow was simulated until year 1860. In 1861, land was converted to pasture and grazed continuously under low intensity through 1969. In 1970, the pasture was converted to a 4-yr dairy cropping rotation of corn-alfalfa-alfalfa-alfalfa, which was simulated until the initiation of the experiments.

Yields Calibration Procedure

We calibrated DAYCENT for the prediction of yield by adjusting two model parameters which affect simulated crop physiology. The first parameter is designated, in DAYCENT, as PRDX(1) and is a coefficient used to calculate maximum potential aboveground production. This parameter affects the overall productivity of a simulated plant and increasing its value can increase aboveground productivity. This parameter can be used for simulating improvements in productivity due to advances in plant breeding and genetics. PRDX(1) also has indirect effects on nutrient cycling, where increased above ground production results in increased plant uptake of nitrogen. Additionally, increased aboveground production can return more carbon to the soil as post-harvest residue. We limited our calibration of PRDX(1) to ± 50% of the default value (1.00) for corn, soybean, and wheat (1.0, 0.7, and 0.8, respectively). The DAYCENT documentation does not provide an acceptable range for calibration of the PRDX(1) parameter, and so we limited the calibration of yields to +- 50% of default values to avoid over-calibration of the model.

We used observed mean yields for corn, soybean, and wheat for the years 2012-2014 as a target for calibration. Each rotation was calibrated individually for each site. While yield data was available for several years at each site, we calibrated the model using only data from 2012-2014, the years during which N_2O emission data was collected. We considered the model as calibrated if simulated mean yields were within the standard error for observed yields and attempted to reduce the difference between observed and simulated mean yields. We also monitored the R^2 value for the regression of simulated yield against observed yield. Calibrations were made such that the R^2 value either improved or did not significantly worsen. In the event that our calibration of PRDX(1) was insufficient to simulate observed yields, we adjusted a second parameter, WSCOEFF(1,2), which is a coefficient defined as ‘4 times the slope at relative water content required for 50% of maximum production’ and limits plant productivity as a function of soil relative water content. In preliminary calibrations, we observed that increases in productivity due to calibration of PRDX(1) led to over-predictions of yield during years of below average precipitation and apparent water stress. We used the calibration of WSCOEFF(1,2) to mediate our calibrations for productive potential and simulate the response of yield to apparent water stress observed in our field data. Increases of the default value (9.0) for WSCOEFF(1,2) had the effect of reducing the effect of water stress where decreasing the value simulated a more sensitive response of yield to relative soil water content. We placed no limitations on our adjustments of WSCOEFF(1,2). The calibrated parameter values for each crop, in each rotation, and at each site are reported in Table 4.1.

N_2O Calibration Procedure

After calibrating the DAYCENT model for yield, we used the same period (2012-2014) to calibrate the model for N_2O emission. The detailed information about N_2O field data collection is outlined in the materials and methods section of the 2nd chapter. Several parameters in DAYCENT can be adjusted to directly affect the processes of N cycling in the soil. However, unlike the crop parameters described above, these “site” parameters pertain to entire simulation runs and are unable to be adjusted for specific years. Our objective was to best simulate N dynamics in the years 2012-2014, such that our winter simulated N_2O emissions were most reliable. So, calibrating crops individually by rotation, we felt, was the best way to mimic system performance, specifically with regard to plant N uptake as a function of yield. This resulted in slightly different calibrations for simulated corn crops that were, in fact, the same seed sown across all rotations. While the performance of corn within each rotation was different and likely due to the rotation effect, we captured this apparent effect by changing the biological properties of corn itself. As a result, calibrations were conducted by field site (Arlington, Lancaster, Marshfield) and crop rotation (continuous corn, corn-soybean, corn-soybean-wheat), which resulted in 9 separate calibrations for N_2O emissions.

We used a suite of 5 parameters directly affecting nitrogen cycling to calibrate DAYCENT for the simulation of N_2O emissions (Table 4.2). These parameters were grouped as directly affecting either the processes of nitrification or denitrification. Nitrification process parameters were manipulated to adjust mean N_2O emissions within rotations. The nitrification process provides two primary limits on emissions of N_2O by producing a base quantity of N_2O as a result of nitrification and by regulating the transformation of soil NH_4-N to NO_3-N for eventual denitrification. We adjusted these limits in order to simulate the observed mean N_2O emissions from each rotation by manipulating three parameters. The first nitrification parameter limited the maximum fraction of N_2O produced as a byproduct of nitrification when soils are at field capacity. The default DAYCENT value for this parameter is 0.015, or 1.5% of nitrified nitrogen is assumed to be lost as N_2O. Goreau et al. (1980) have shown that, for some species of nitrifying bacteria (*Nitrosomonas europaea*) found in soils, this fraction can be as high 4.7% when oxygen is limited, which we used as an upper bound on our calibrations. If necessary, a secondary adjustment was made to the limit on N_2O produced by adjusting the limit on maximum daily nitrification (g N m^{-2}). Adjustments to nitrification potential would both increase N_2O emissions directly from nitrification and indirectly by increasing the amount of nitrified NO_3^- made available for denitrification. Limits on adjustments made to this parameter were ± 50% of the default value (0.4 g N m^{-2}). The third calibrated nitrification parameter controlled the fraction of NO_3^- produced by new net mineralization. This parameter was adjusted to mediate the mean contribution of denitrification to mean annual N_2O emissions when adjustments to direct contribution to N_2O nitrification emissions were insufficient to simulate observed mean N_2O emissions. Adjustments of this parameter were limited to ± 50% of the default value (0.02). The parameters for maximum daily nitrification rate and fraction of nitrified N produced as NO_3^- affect the coupling of the denitrification and nitrification processes by controlling the amount of NO_3^- available as substrate for denitrification.

Parameters affecting the process of denitrification were used to calibrate DAYCENT simulations to the inter-annual variability observed in mean growing season emissions from our field sites. Emissions of N_2O produced from denitrification are positively correlated with soil water content and seasonal precipitation (Parkin and Kaspar, 2006), and Gaillard et al. (In revision) have demonstrated that denitrification drives variability in N_2O emissions from similar soils in Wisconsin. We calibrated DAYCENT to simulate variability in growing season N_2O emissions due to changes in N_2O produced from denitrification by adjusting two DAYCENT parameters. The amount of N_2O produced in denitrification is primarily a function of soil water-filled pore space (WFPS) (Parton et al., 1996). This relationship is simulated in DAYCENT and may be manipulated by adjusting the inflection point on the WFPS:denitrification curve (Parton et al., 1996). Increasing the default multiplier to the inflection point (1.0) will move the inflection point to higher values for WFPS and, subsequently, higher WFPS values will be required for denitrification to occur and begin producing N_2O. Conversely, lower values (<1.0) will lower the WFPS required for denitrification. DAYCENT is highly sensitive to adjustments in this parameter, and no calibrations greater than ± 15% of the default value were used.

In the case where calibrations of the WFPS inflection point were unable to improve model simulations, we calibrated a second denitrification parameter, the N_2:N_2O ratio. This parameter is a coefficient that adjusts the response of the denitrification N_2:N_2O ratio to WFPS. As WFPS increases, the ratio of N_2 produced to N_2O increases until it reaches a maximum that approximates the complete reduction of all NO_3^- to N_2. Increases to this adjustment coefficient will increase the rate at which the N_2:N_2O ratio increases. Calibration limits to this parameter were ± 50% of the default value (1.0).

If adjustments to denitrification variables were able to simulate inter-annual variability in seasonal emissions, but increased the mean emissions for the system, then nitrification parameters were adjusted accordingly to bring simulated mean emissions into agreement with observed means. This process of calibrating for means followed by calibrating for inter-annual variability was repeated iteratively until no more improvements could be made. In the events when the N_2O calibration procedure had adverse effects upon simulated grain yields, grain yields were recalibrated using the new N_2O parameters, and the N_2O calibration procedure was repeated. We used accumulated growing season N_2O emissions with standard error terms as a target for calibration by observing model performance with respect to accumulations of growing season N_2O across the years 2012-2014. We also monitored the coefficients of correlations (R^2) values for daily N_2O emissions (data not shown), but as has been reported in the literature (Parton et al., 1998), DAYCENT has predicted accumulations of N_2O more accurately than daily emissions.

4.3.4 Modeling Rotational Response to Future Climate Change

We used calibrations of the DAYCENT model described to simulate the effects of climate change on crop productivity and environmental impact. The calibrated DAYCENT model was run until 2099 for each rotation at each location using 7 different climate projection models taken from Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007) that have been further statistically downscaled as described by Stoner et al. (2013) so that extremes are better represented. CMIP3 is the name of the protocol used to develop the IPCC Fourth Assessment Report (IPCC, 2007). The selected models represented the A1B scenario of the report and are listed in Table 4.3. We used an average management regime derived from management in years 2012-2014 at each location to limit the effects of changes in management on model results. In this approach we limited management changes to isolate the impacts of climate variables on the rotation agronomic and environmental performance. The effects of changes in precipitation and growing degree day (GDD) accumulation may be confounded by the adjustment of management strategies like planting date and hybrid selection. The model was run using daily historic weather, and future weather projections starting from 2015. To simulate the performance of the simplified system over time, we used 1985 as a start date to allow each rotation to fully equilibrate before the data was incorporated into the results. Global warming potential (GWP) was calculated as a sum CO_2 equivalents (kg CO_2-eq. ha^{-1}) of carbon dioxide (GWP=1), N_2O (GWP=298), and CH_4 (GWP=26) according to (IPCC, 2007). Greenhouse gas intensity (GHGi) was calculated as GWP divided by grain yield (Mg grain ha^{-1} yr^{-1}) to compare land use efficiency across the systems.

4.3.5 Statistical Analysis

Statistical differences between DAYCENT estimated and measured crop grain yield were evaluated using two different methods. First, we compared how DAYCENT estimates grain yields in a long-term time frame by comparing standard errors of field measured values with standard errors around the means of DAYCENT estimates averaged over the experiment period . Standard errors were calculated using the PROC MEANS procedure of SAS Institute (2011). Each location had different startup length averages: Arlington used years 2002-2014, Lancaster used years 2005-2014, and Marshfield used years 2007-2014. Secondly, simple regression models were performed using PROC REG procedure of SAS Institute (2011) on DAYCENT estimated and field measured grain yield for individual crop phase or averaged within crop rotation level during the same experimental period. Corresponding R^2 values were calculated to evaluate model performance. The same procedure was performed on soil volumetric water content and temperature data on a daily timescale but the period was limited at each location to 2012-2014 period. Statistical differences in cumulative N_2O emissions were assessed by comparing the DAYCENT estimated values with standard errors of the measured cumulative emission at individual crop phase level or a whole crop rotation level when crop phases were averaged within rotations. The comparisons were performed separately at annual or 3-yr averaged scales.

4.4 Results and Discussion

4.4.1 Grain Yields

Before calibration, simulated Arlington average grain yields were similar to observed values, with only CS-corn and CSW-wheat falling outside of the observed standard error. After calibration, all average grain yields were within the standard error of field measured yields. DAYCENT poorly estimated annual grain yields of crop phases across rotations. The linear regressions between annual collected and DAYCENT calibrated values were only significant for both corn and soybean in CS rotation with R^2=0.57 and R^2=0.46, respectively, and for other phases the R^2 ranged between 0.03 and 0.27. However, when all phases of each rotation were included, the regressions were significant for CS and CSW rotation ($P<0.001$) (R^2=0.96 and R^2=0.85, respectively) and slightly below significance level (P=0.069) for CC (R^2=0.27).

At Lancaster, calibration of DAYCENT improved simulated average grain yield (2005-2014) compared to default values in three out of four instances where simulated values were out of standard error range. The model calibration underestimated by 1.1 Mg ha^{-1} corn grain yield in CSW rotation and underestimated by 1.1 Mg ha^{-1} wheat grain yield in CSW. None of the linear regressions between annual collected and DAYCENT calibrated values were significant at the individual crop phase level of each rotation, R^2 ranged between 0.08 and 0.34 (Fig. 4.2). However, the regressions became significant at the rotation level when all crop phases were included in 2-yr CS (R^2=0.77) and 3-yr CSW (R^2=0.73) rotation but not in CC (R^2=0.14) (Fig 5.3).

At Marshfield, DAYCENT calibration were similar to average (2007-2014) grain yield means; however, standard errors overlapped only in CC and corn in CS rotation, while other grain yield values were relatively close (Fig. 4.1). The DAYCENT default parameters, before calibration, resulted with high overestimation of wheat averaged yield across all locations, especially at Marshfield which was the highest (2.4 times), and the model calibration greatly improved agreement between observed and simulated yields. The linear regressions between annual collected and DAYCENT calibrated values were significant ($P<0.05$) for corn in CC and CS rotation and wheat in CSW rotation with R^2 range between 0.52 and 0.63, compared to R^2 in non-significant regressions range between 0.22 and 0.3 (Fig.5.2). All regressions became significant ($P<0.05$) at the rotation level when all crop phases were included with R^2 range between 0.63 and 0.96 (Fig 5.3).

The capability of DAYCENT to capture long-term grain yields varied by location. Generally, DAYCENT successfully estimated grain yield when averaged over years (Fig. 4.1) and on an annual basis. DAYCENT was more effective in capturing rotations (Fig 5.3) rather than individual phases of each rotation (Fig 5.2). The performance of DAYCENT was comparable with other previous studies, which reported DAYCENT simulated grain yields to be similar to observed yields (Congreves et al., 2015; De Gryze et al., 2011; Del Grosso et al., 2008). Other research also reported higher precision in estimating corn grain yield better that soybean (Gaillard et al., In revision). De Gryze et al. (2011) when comparing grain yield of various crops at a regional scale in the Central Valley of California found better precision of DAYCENT predicted grain yield when all crops where included in the model rather than separated.

4.4.2 Soil Volumetric Water Content and Temperature

DAYCENT accurately simulated soil temperature (0-5 cm) across all locations and rotations (Fig. 4.7a). The linear regressions between field collected and DAYCENT calibrated soil temperatures were all significant and had R^2 values ranged between 0.56 and 0.85. Comparable correlation coefficients using DAYCENT were previously reported (Abdalla et al., 2010).

The strength and significance of correlation between simulated and observed VSWC varies across location and rotation (Fig. 4.7b). The linear regressions between field collected and DAYCENT calibrated water contents were all highly significant at Arlington and Marshfield in all rotations with R^2 ranging from 0.68 to 0.56, and from 0.58 to 0.35, respectively. Similarly high relationships were found for irrigated corn in Colorado (R^2=0.47) (Del Grosso et al., 2008).

At Lancaster, DAYCENT was able to simulate volumetric water contents in CC with R^2=0.69, but the R^2 values in CS and CSW rotations were low, 0.08 and 0.01, respectively.

4.4.3 Soil in-Season N_2O Emissions

Inter-annual Soil and In-Season N_2O Emissions

The growing season of 2012 was dry (Appendix A) and as expected low N_2O emissions were observed. DAYCENT was able to account for dry conditions and also capture differences among locations. Highly fertilized corn phases at the Arlington and Lancaster stations had cumulative N_2O emissions ranging from 1.4 to 3.2 kg N_2O-N ha^{-1} $season^{-1}$ compared to DAYCENT which ranged from 2.0 to 3.4 kg N_2O-N ha^{-1} $season^{-1}$; while, low fertilized corn in Marshfield had field measured emissions ranging from 0.9-1.7 kg N_2O-N ha^{-1} $season^{-1}$ compared to DAYCENT from 1.14 to 1.4 kg N_2O-N ha^{-1} $season^{-1}$. Cumulative field measured seasonal emissions from other crops across locations were always below 1.4 kg N_2O-N ha^{-1} $season^{-1}$, and DAYCENT tended to slightly overestimate these emissions with wheat. DAYCENT was able to capture low cumulative seasonal N_2O at Marshfield across all years and crop phases which generally did not differ. In a few instances DAYCENT tended to overestimate these low N_2O emissions which was most pronounced in the wheat phase.

Soils in 2013 were wet especially up to mid-season. At Arlington, N-fertilizer in corn was applied into moderately moist soil conditions that were enhanced with subsequent heavy rainfall events over the next 10 days (131 mm). These led to the highest N_2O emissions recorded across the whole research period across all locations and years (Fig 5.4). DAYCENT was able to simulate mean N_2O emissions within the standard error of observed means. High field emission of corn was measured in CC (7.8 kg N_2O-N ha^{-1} $season^{-1}$) and CS (7.7 kg N_2O-N ha^{-1} $season^{-1}$) rotation which in DAYCENT was 7 kg N_2O-N ha^{-1} $season^{-1}$ and 6 kg N_2O-N ha^{-1} $season^{-1}$, respectively; but DAYCENT underestimated by 52% the field emissions in

CSW rotation (9 kg N_2O-N ha^{-1} season^{-1}) (Fig.5.4). The model underestimated N_2O emissions of the soybean phase in CSW rotation as 75% lower than the field collected value (4.1 kg N_2O-N ha^{-1} season^{-1}) and overestimated wheat phase of the same rotation which was 1.98 times greater than the corresponding field value (2.2 kg N_2O-N ha^{-1} season^{-1}). At Lancaster, DAYCENT captured high cumulative N_2O seasonal emission for CC (5 kg N_2O-N ha^{-1} season^{-1}) while other crop phases had field measured emission ranging between 1.2 and 2.5 kg N_2O-N ha^{-1} season^{-1}. These were adequately simulated by DAYCENT, except for higher estimation of corn phase in CS rotation and lower estimation of soybean in CSW rotation.

In 2014, DAYCENT was able to capture high cumulative seasonal N_2O emissions of CC at both Arlington and Lancaster locations where field observed values were 6.8 and 6.4 kg N_2O-N ha^{-1} season^{-1}, respectively (Fig. 4.4). Calibrated DAYCENT typically overestimated other crop phases at Arlington, especially the wheat phase of CSW rotation for which the field collected value represented only 25% of the model estimated (5.9 kg N_2O-N ha^{-1} season^{-1}). DAYCENT underestimated the relatively low N_2O emissions (ranging 2.5 to 1 kg N_2O-N ha^{-1} season^{-1}) of all phases in CS and CSW rotation at Lancaster.

DAYCENT was able to capture the difference in magnitude of cumulative N_2O emission among the years and locations but the precision of individual crop phases varied (Fig. 4.4). The growing season in 2012 was dry and low N_2O emissions were observed and simulated. Much higher N_2O emissions occurred in the wetter 2013 year (Appendix A). An excess amount of precipitation has been well documented to increase N_2O emissions due to reduction of available O_2 that stimulates higher denitrification rates (Aulakh et al., 1992; Groffman et al., 2009). In this study, simulated differences in magnitudes of cumulative growing season N_2O emissions compared favorably with measured emissions and was the best represented for corn across locations and rotations- The ability of DAY CENT to provide accurate estimates usually decreased with an increase in the complexity of rotation.

Averaged Over 3-years Soil in-Season N_2O Emissions

DAYCENT estimation of cumulative seasonal N_2O emissions varied by phase and location when averaged over growing seasons. At Arlington, DAYCENT was able to capture corn phases within standard error ranges of field measured values. Calibration of the model resulted in improved cumulative N_2O emission means of soybean phases, however, they were still outside of the standard error of the field measured values and the emissions in wheat were highly overestimated (Fig 5.5a). At Lancaster, DAYCENT successfully captured high N_2O emissions in CC and lower emission of rotated corn phases. Most of model estimated N_2O means were outside of field measured standard error, but appeared to be relatively close and were always within 35% range of the field values. Similarly, in Marshfield, most of DAYCENT estimated N_2O emissions were outside of field measured standard error values. However, DAYCENT was able to simulate the lower N_2O emissions of corn and soybean phases at Marshfield when compared with the other field sites. Field measured N_2O emissions ranged from 0.98 to 1.65 kg N_2O-N ha^{-1} season^{-1} and simulated emissions ranged from 1.5 to 2 kg N_2O-N ha^{-1} season^{-1}. However, the model poorly estimated emissions under the wheat phase of CSW rotation where the estimated value was 2.4 times greater than field measured value (1.0 kg N_2O-N ha^{-1} season^{-1}).

When averaged over years and crop phase within rotations, DAYCENT was able to capture cumulative seasonal N_2O emissions across locations (Fig 5.5b). The model was able to capture high N_2O emissions of CC at Arlington and Lancaster within the standard error of field collected values. CS and CSW rotations were within the standard error at Arlington but slightly outside of the standard error at Lancaster. At, Marshfield, all field measured N_2O emissions were low and ranged from 1.19 to 1.64 kg ha^{-1} N_2O-N season^{-1}, while DAYCENT estimates ranged between 1.6 to 2.0 kg ha^{-1} N_2O-N season^{-1} which was overestimated, but did account for the low nitrogen input environment.

Most of the model estimated cumulative seasonal means were outside of the standard error of field measured emissions, only 28% fell within the range in 2012, 33% in 2013, and 50% in 2014, across locations. DAYCENT was most successful in estimating N_2O emissions from corn followed by soybean and least in wheat, which usually had overestimated emissions. The ability of DAYCENT to simulate cumulative emissions of N_2O similar to field collected data was comparable to previous studies in U.S. (Abdalla et al., 2010; Chamberlain et al., 2011; Del Grosso et al., 2008; Jarecki et al., 2008).

4.4.4 Estimated Non-Vegetated Season N_2O Emissions

DAYCENT estimated non-vegetated N_2O emissions greatly contributed to the total emissions; however, differences were observed across locations, crop rotation, and rotation phase (Fig. 4.6a and 5.6b). At Arlington, the non-vegetated contribution of N_2O emissions to the total yearly emission was smaller than at other locations and increased the total emission from 6 to 24% across crop phases with the smaller increase in corn phases (less than 11%). In two other locations non-vegetated N_2O emission added to the total from 18 to 36% in corn phases, from 30 to 42% in soybean, and the largest addition was in wheat at 42 and 56% at Marshfield and Arlington, respectively.

Different patterns of DAYCENT estimated non-vegetated N_2O emissions were simulated across locations when crop phases were averaged within rotation (Fig 5.6b). The non-vegetated contribution of N_2O emissions to the total yearly emission ranged from 8 to 15% at Arlington and from 27 to 44% across crop rotation at other locations. The highest emissions of N_2O coming from the non-vegetated period was observed at Lancaster in CC where an additional 34% of the already high emissions resulted in 2.2 kg N_2O-N ha^{-1} of additional N_2O emissions. In all other rotations non-vegetated emissions were lower, always no larger than 1 kg ha^{-1} and, importantly, the relative differences among rotations across locations persisted.

A large amount of research reports high N_2O emissions during winter or early spring as a result of freezing and thawing processes from agricultural soils (Cates and Keeney, 1987; De Bruijn et al., 2009; Groffman et al., 2009). Many potential pathways may contribute to high N_2O emission, but a reduction of oxygen diffusion under freezing and thawing processes that increases denitrification rates may be the leading cause De Bruijn et al. (2009). Wagner-Riddle et al. (1997), in a Canadian study, reported that early spring emissions (March-April) can account for 65% of the yearly cumulative N_2O emission and range between 1.5 to 4.3 kg N ha^{-1}. This was much higher than in this study. More research should be performed to evaluate our findings with field collected data. Improved methodology and techniques should be developed to accurately measure and estimate these significant N_2O emission events.

4.4.5 Response of Crop Rotations under Future Climate

All seven future weather projections agree on shifts toward greater accumulated growing degree days in response to expected warmer temperatures; however, the responses, in regard to the future accumulated precipitations at these three locations in Wisconsin were not consistent (Fig. 4.8). Generally, these weather projections suggest stable or increased trends in accumulated precipitations, except one (HadGEM1) which suggest a slight downscaled trend. Change in spring precipitation could impact corn production and N losses and the differences of these patterns among the projections have yet to be determined.

The climate models produced similar responses in future grain yields in the studied cropping systems, across all locations, which are indicated with small standard errors terms (Fig. 4.9). The general pattern indicates yield increases up to 2075 for corn and soybean which is represented with the first three averaged 25-yr blocks (years 2000-2074), and then became stable in the last block (years 2075-2099). Smaller grain yield increases were observed for winter wheat where the three last blocks (2025-2099) presented similar higher yields compared to the first block (2000-2024). For corn, the rotation effect on grain yield increased as rotation complexity increased and was most pronounced at Arlington and followed by Lancaster where only CSW had a higher trend than CC. At Marshfield, DAYCENT simulated lower yields of rotated corn compared to CC. The model is sensitive to N fertilizer inputs, and, at Marshfield, N credit from the legume soybean crop was applied to rotated corn and received 36% less N than CC. The climate models suggest that, in the long-run, this might not be an adequate practice and higher N rates should be applied to corn as weather patterns becoming more suitable to growing this crop in the Northern region of Wisconsin.

The crop rotation effect on GWP, which combines CO_2, N_2O, and CH_4 emissions into single CO_2 equivalent units (kg CO_2 eq. ha^{-1}), was different among studied locations (Fig. 4.10A). In general, across rotations, an increased trend in GWP was observed at Arlington and Marshfield and a stable trend at Lancaster, when GWP was averaged across all 7 climate projections. N_2O contributed to the vast majority of the GWP ranging from 89 to100% in all crop phases across all rotations (Fig. 4.11). In the first two blocks (years 2000-2049), carbon sequestration was present in CC, across all locations and in CS rotation at Arlington and Marshfield, as indicated with the negative CO_2 equivalent values coming from CO_2 greenhouse gas, which reduced GWP. This effect became small (oscillated around zero) or even a positive contribution to GWP from CO_2 was observed in all other blocks across all rotations (Fig 5.11). The contribution of CH_4 to the GWP was negligible.

These results are in the alignment with the conclusions presented in the 2nd chapter. Under high N input environments at Arlington and Lancaster, reduction of N_2O, which affects GWP the most (Fig. 4.11), can be achieved when either 2-yr CS or 3-yr CSW rotation is applied. At Arlington, on average across four blocks of the entire 21st century, CS rotation reduced GWP by 34% and CSW rotation 39%, while at Lancaster CS rotation reduced GWP by 48% and CSW rotation by 57% in relation to GWP of CC that equaled 4011 and 3828 kg CO_2 eq. ha^{-1}, at Arlington and Lancaster, respectively. And, under low N input regimes at Marshfield, no difference among crop rotations was observed in terms of GWP (Fig 4.11). A low GWP potential at Marshfield, especially during 2000-2050, was affected by small positive N_2O and small negative contribution of CO_2, indicating C sequestration.

Greenhouse gas intensity (GHGi), calculated as GWP (kg CO_2 eq. ha^{-1}) divided by grain yield (Mg grain ha^{-1} year^{-1}), showed a similar pattern as previously referred in the 2nd chapter for N_2O yield-scaled emissions. Here, the GHGi was not consistent accross the models as indicated by the relatively high standard error. Generally, highly productive CC at Arlington and Lancaster had similar GHGi to 2-yr CS and 3-yr CSW rotation. At Marshfield, the high yields and low GWP of CC resulted in that rotation having a GHGi 72% lower than the average GHGi (319 kg CO_2 eq. ha^{-1}) of all other rotations across all locations. Overall, this metric is interesting to consider when describing the system's land use efficiency but it can be misleading when describing GWP of a system by favoring systems that are more productive.

This study served as a basis to understand how crop rotations would respond to different climate change scenarios if on adaptive management strategies were employed. Further attempts that will investigate the effects of changes in periodicity and intensity of spring precipitation events on crop rotation responses in regard to productivity and N loses are necessary, as increases in early-season cumulative precipitation have been confirmed in Wisconsin (Kucharik et al., 2010). This work will be further advanced by testing the DAYCENT model response to the same suite of climate scenarios with improved management techniques, such as splitting N application rates, leading to optimization of the rate and timing of N fertilization and have a potential to minimize N losses while protecting crop productivity under less favorable weather conditions. In a similar manner, with the expansion of growing season, the model can test the shifts towards earlier planting and later harvest of crops, choosing crop hybrids of longer maturity or the addition of cover crops into the systems that would provide longer time soil protection. This work provides valuable information about crop rotation effects on the environment and confirms that the use of crop rotation in corn-based systems can successfully promote GHG mitigation and maintain high productivity but also suggest a possibility for applying more N in low N input environments to increase yield as crop demands are expected to increase (at Marshfield). These modeling approaches have the potential to inform many other gaps in our knowledge to help promote best management practices that would increase the resilience of cropping systems to climate change in Wisconsin and nearby areas.

4.5 Conclusions

The default settings of DAYCENT model in some situations failed to sufficiently represent the observed data due to the differences in environments and complexity of the systems. Few studies have reported on the calibration process, which disadvantages those who are unfamiliar with model calibration processes or would like to learn to use models. Described in detail, an optional calibration procedure can serve as a platform for future research and is not limited to further improvements. The calibrated DAYCENT model was able to accurately simulate the effects of location and crop rotation on grain yields and N_2O emissions from agricultural soils in Wisconsin. In our first objective, we found that N_2O emission during non-vegetated season can significantly increase from 8 to 44% across crop rotations and locations, contribute to the whole year emissions, and should be taken into account. Future research should first validate our findings in field by measuring N_2O emission throughout a whole year, and second, study the potential factors that may influence both inter-annual N_2O variability and high emissions during the non-vegetated season. To answer our second objective, the calibrated version of DAYCENT model was used to simulate future long-term rotation behaviors in terms of GHG emissions and crop yield responses under different climate change scenarios over the 21st century. The findings highlighted the importance of the environment and the chosen management strategy. Most crops, across locations, presented increased grain yields in the first three 25-yr blocks of the 21st century and then stabilized, which was most likely associated with improved growing conditions until conditions favored maximum crop productivity. On average in high N input environments, CS rotation reduced GWP by 41% and CSW rotation by 48%, compared to CC and similar response among rotation was under low N input environment.

4.6 References

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Table 4.1. Calibration of yield affecting parameters of DAYCENT model in every crop phase of three different crop rotations at three locations in Wisconsin for 2012-2014 period.

			DAYCENT Parameter	
Location	Rotation	Crop	PRDX(1)†	WSCOEFF(1,2)‡
Arlington	Continuous Corn	Corn	1.10	9.00
	Corn-Soybean	Corn	1.23	7.00
		Soybean	0.70	9.00
	Corn-Soybean-Wheat	Corn	1.13	6.00
		Soybean	0.70	9.00
		Wheat	0.60	9.00
Lancaster	Continuous Corn	Corn	1.03	6.00
	Corn-Soybean	Corn	0.98	6.00
		Soybean	0.42	4.97
	Corn-Soybean-Wheat	Corn	1.10	8.33
		Soybean	0.50	9.00
		Wheat	0.60	9.00
Marshfield	Continuous Corn	Corn	1.30	8.00
	Corn-Soybean	Corn	1.75	9.00
		Soybean	0.70	9.00
	Corn-Soybean-Wheat	Corn	1.75	15.00
		Soybean	0.70	9.00
		Wheat	0.60	0.99

† PRDX(1), coefficient for calculating potential aboveground monthly production as a function of solar radiation outside the atmosphere. The default value for corn, soybean, and wheat is 1.0, 0.7, and 0.8, respectively.

‡ WSCOEFF(1,2), “4 times the slope at relative water content required for 50% of maximum production”. The default value is 9.0.

Table 4.2. Calibration of parameters affecting denitrification and nitrification processes simulated in DAYCENT model of three different crop rotations at three locations in Wisconsin for 2012-2014 period.

		Nitrification Parameters			Denitrification Parameters	
Location	Rotation†	Maximum Nitrification N_2O Fraction	Maximum Daily Nitrification	Fraction to NO_3^-	WFPS‡ Inflection Point	N_2:N_2O adjustment
Arlington	CC	0.050	-§	-	0.95	-
	CS	0.050	-	-	0.95	-
	CSW	-	-	0.03	0.85	-
Lancaster	CC	-	-	-	0.95	-
	CS	0.030	0.45	0.15	1.10	-
	CSW	0.020	-	0.10	-	1.25
Marshfield	CC	-	0.30	0.10	-	-
	CS	-	-	-	-	-
	CSW	-	-	-	-	-
Default Value		0.015	0.40	0.02	1.00	1.00

† CC, continuous corn; CS, corn-soybean; CSW, corn-soybean-wheat.

‡ WFPS, water filled pore space.

§ - (dashes), no calibration performed.

Table 4.3. Seven downscaled climate projections considered in this study.

Model (CMIP3)†	This study I.D.	Center and location
CGCM3.1(T47)	t47	Canadian Centre for Climate Modeling and Analysis (Canada)
CGCM3.1(T63)	t63	
CNRM-CM3	cnrm	Meteo-France, Centre National de Recherches Meteorologiques (France)
ECHAM5–MPI-OM	echa	Max Planck Institute for Meteorology (Germany)
ECHO-G	echo	Meteorological Institute of the University of Bonn, Germany Meteorological Research Institute of KMA, and Model and Data group (Germany and Korea)
PCM	pcm	National Center for Atmospheric Research (United States)
HadGEM1	hadgem	Hadley Centre for Climate Prediction and Research, Met Office (United Kingdom)

† Coupled Model Inter-comparison Project Phase 3 contributing to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) statistically downscaled as described by Stoner et al. (2013).

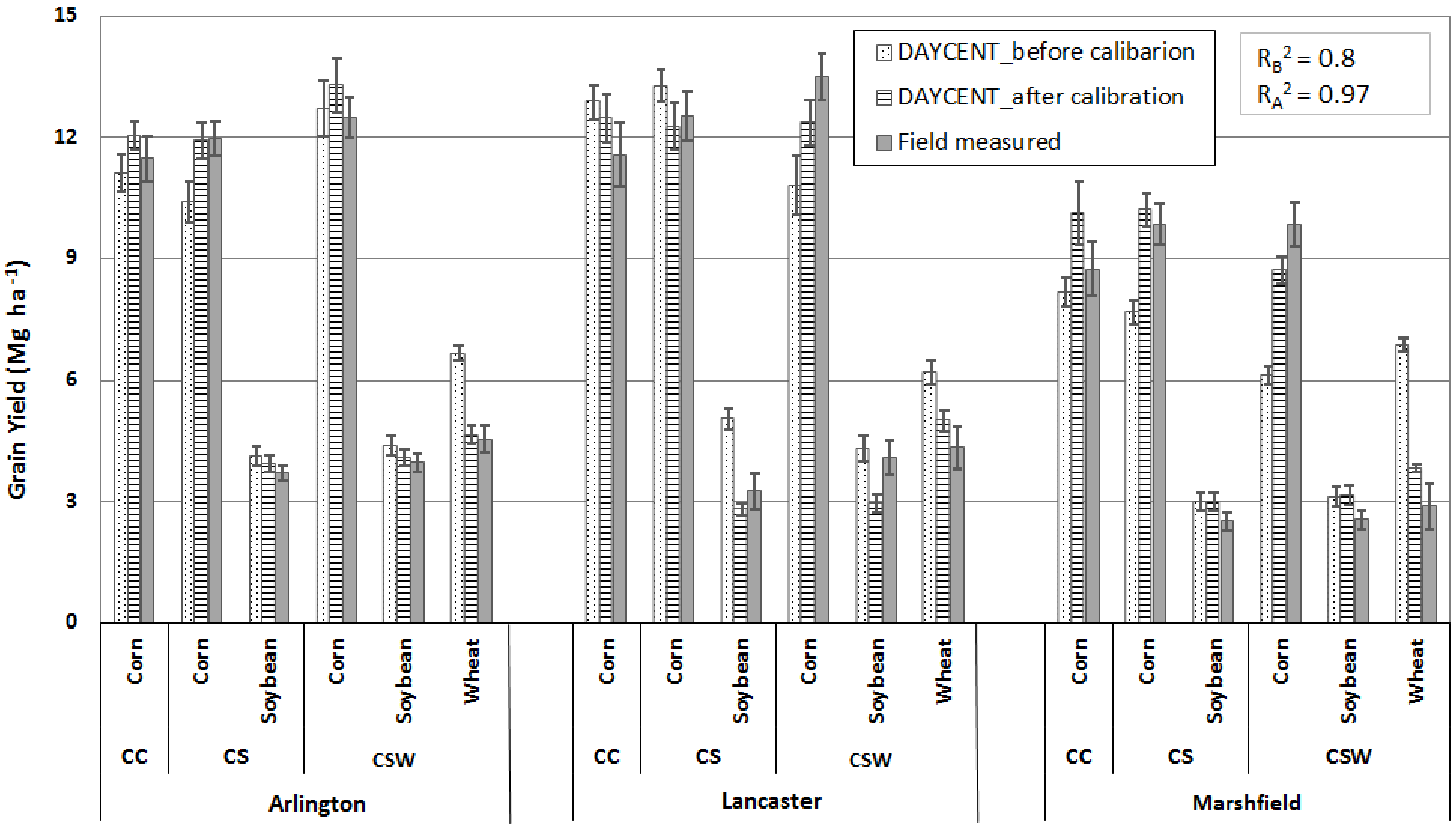


Figure 4.1. Averaged field measured and DAYCENT calibrated and non-calibrated grain yield with standard error bars at Arlington (2002-2014), Lancaster (2005-2014), and Marshfield (2007-2014), WI. Coefficients of determination from simple linear regression across systems and locations are present, where; R_A^2=calibrated model vs. field collected and R_B^2 =non-calibrated model vs. field collected grain yield.

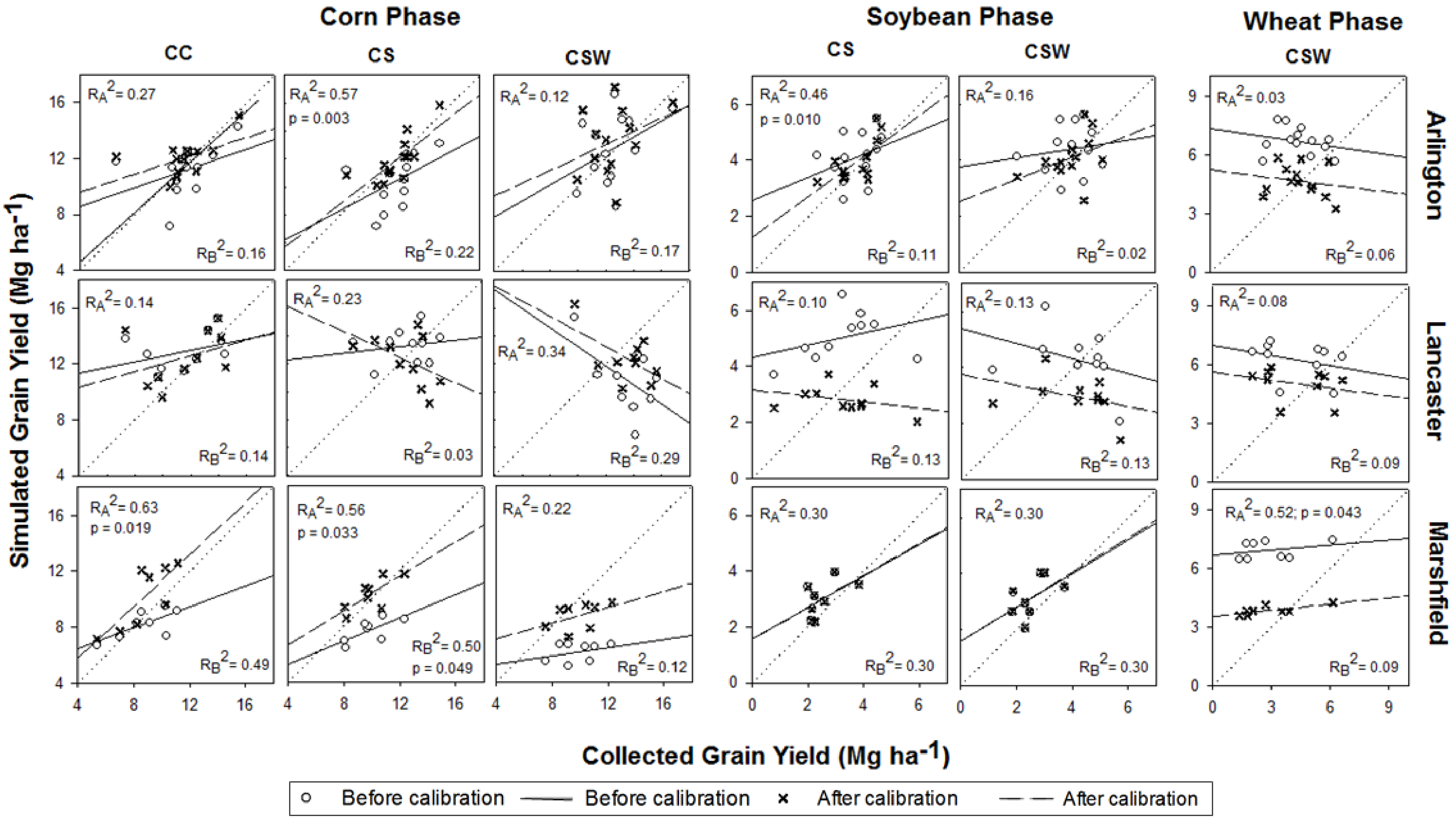


Figure 4.2. Relationship between collected grain yield versus either non-calibrated and calibrated DAYCENT model of every crop phase of continuous corn (CC), corn-soybean (CS) and corn-soybean-wheat (CSW) at Arlington (2002-2014), Lancaster (2005-2014), and at Marshfield (2007-2014), WI. Each figure include 1:1 line and corresponding coefficients of determination; where, R_A^2=calibrated model vs. field collected and R_B^2=non-calibrated model vs. field collected grain yields. Only significant (*P*<0.05) probabilities values are shown.

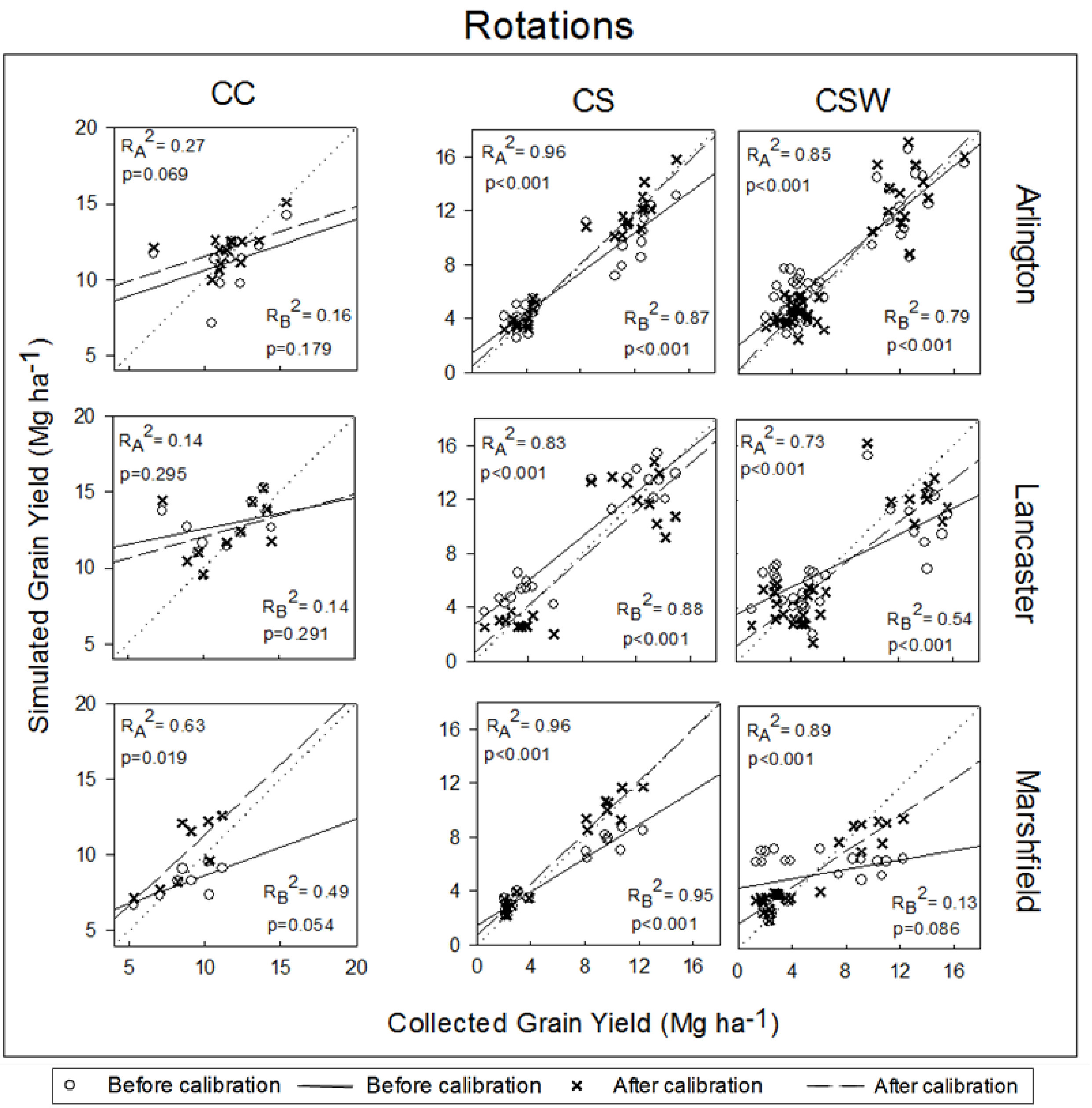


Figure 4.3. Relationship between collected grain yield versus either non-calibrated and calibrated DAYCENT model of continuous corn (CC), corn-soybean (CS) and corn-soybean-wheat (CSW) rotation with every phase included at Arlington (2002-2014), Lancaster (2005-2014), and at Marshfield (2007-2014), WI. Each figure include 1:1 line and corresponding coefficients of determination; where, R_A^2=calibrated model vs. field collected and R_B^2 = non-calibrated model vs. field collected grain yields with corresponding probability values.

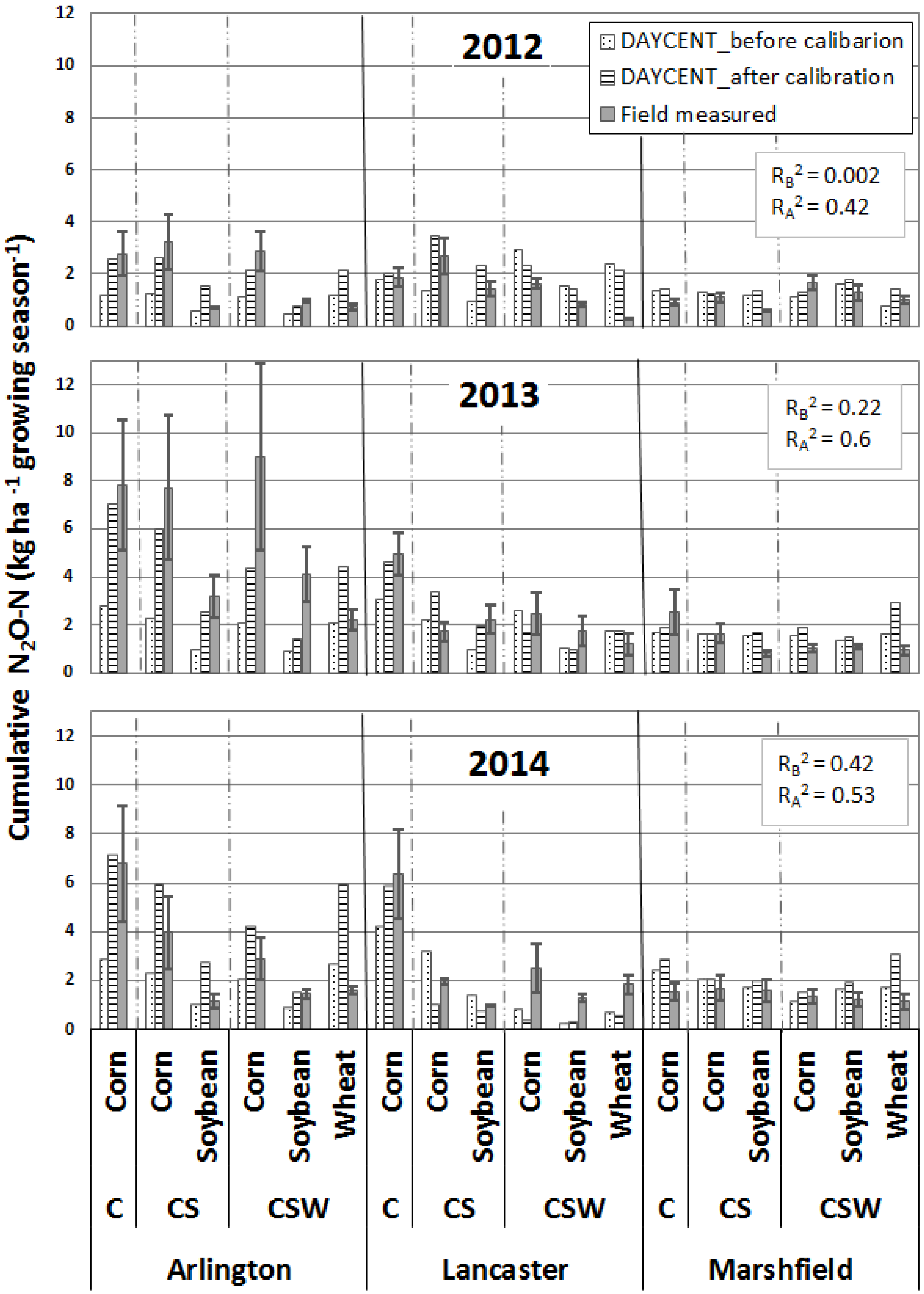


Figure 4.4. Field measured with error bars, DAYCENT calibrated and non-calibrated cumulative N_2O emissions (seasonal) of continuous con (C), corn-soybean (CS), and corn-soybean-wheat (CSW) rotations with all phases present at Arlington, Lancaster and Marshfield, WI (2012-2014). Coefficients of determination from simple linear regression across systems and locations are present, where; R_A^2=calibrated model vs. field collected and R_B^2=non-calibrated model vs. field collected N_2O emissions.

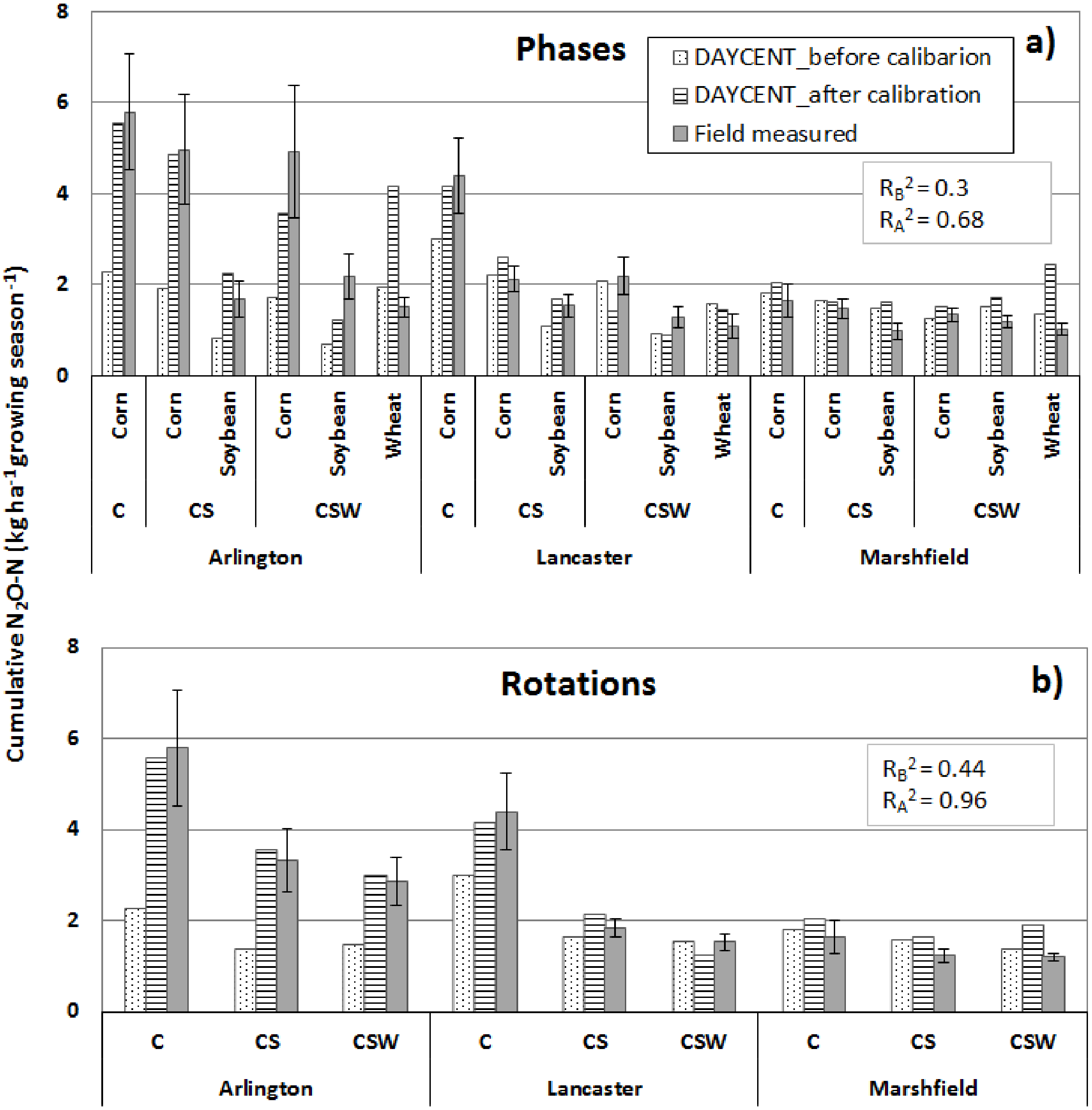


Figure 4.5. Field measured with error bars, DAYCENT calibrated and non-calibrated cumulative 3-yr average (2012-2014) N_2O emissions (seasonal) of continuous con (C), corn-soybean (CS), and corn-soybean-wheat (CSW) rotation where a) phases are present within each rotation and b) phases are averaged within each rotation at Arlington, Lancaster and Marshfield, WI. Coefficients of determination from simple linear regression across systems and locations are present, where; R_A^2=calibrated model vs. field collected and R_B^2=non-calibrated model vs. field collected N_2O emissions.

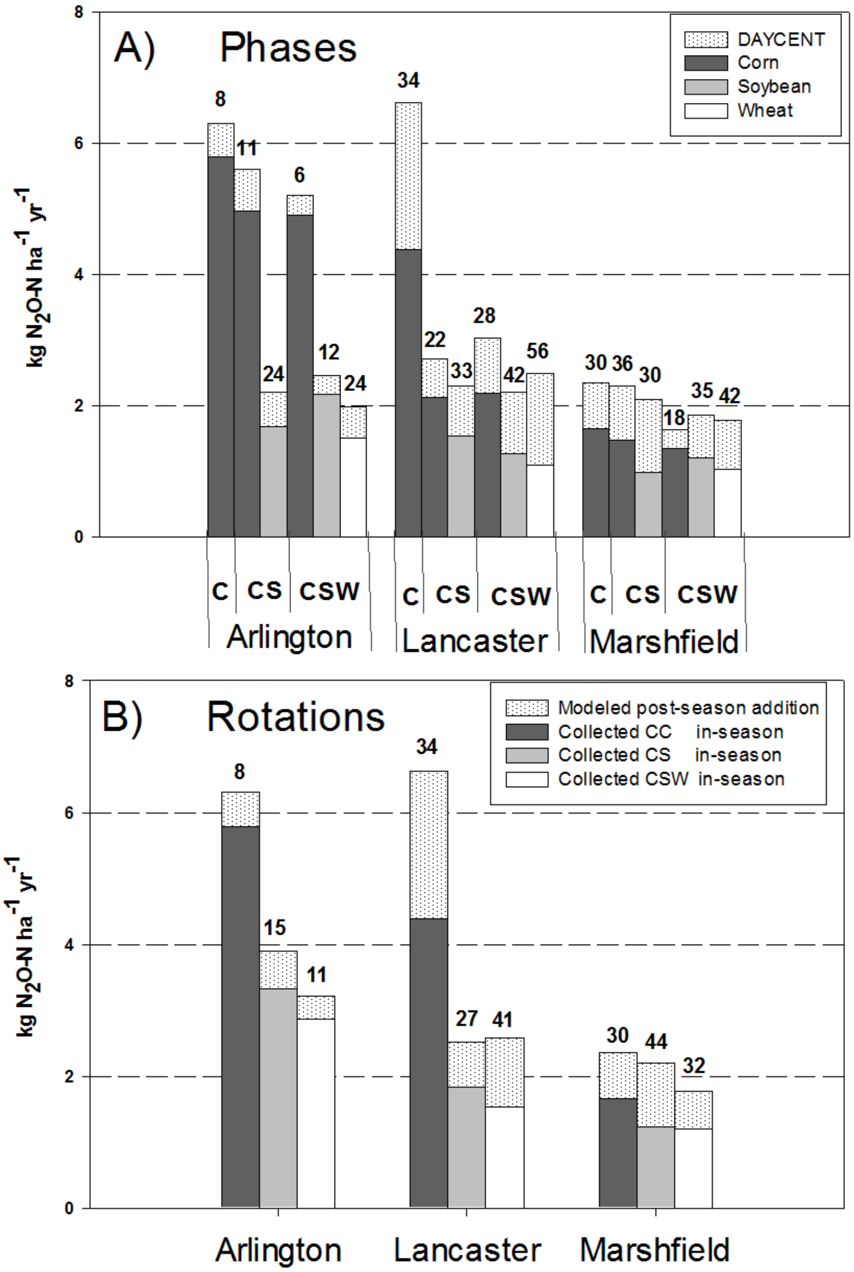


Figure 4.6. DAYCENT estimated non-vegetative N_2O emissions of continuous-corn (CC), corn-soybean (CS, and corn-soybean-wheat rotation each A) crop phase within rotation and B) rotation average across crop phases at Arlington, Lancaster, and Marshfield, WI (2012-2104). Numbers inside bars represent a percent of additional N_2O emissions to the corresponding seasonal emissions collected in-field. The difference of season duration at each location might explain the high variation among them. Where, at Arlington data collection usually began 1-2 weeks earlier and ended 1-2 weeks later; therefore more N_2O emission from thaw-freeze periods potentially was captured compare to the other locations.

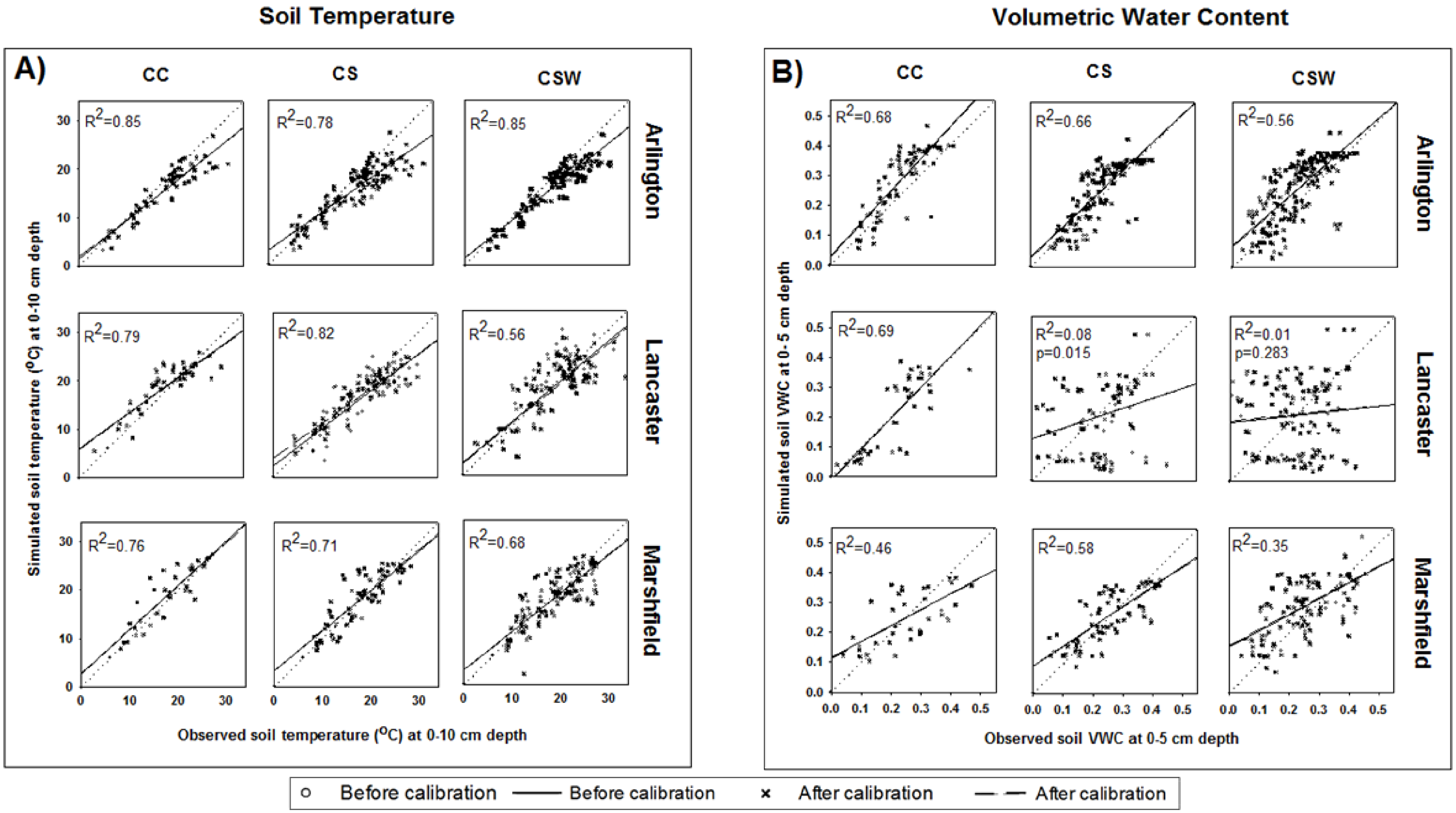


Figure 4.7. Correlation between collected vs. DAYCENT prior to calibration and collected vs. DAYCENT calibrated of A) soil temperature (top 0-10 cm depth) and B) soil volumetric water (VWC) content (top 0-5 cm depth) of continuous corn (CC), corn-soybean (CS) and corn-soybean-wheat (CSW) rotation across crop phases at Arlington, Lancaster, and at Marshfield, WI (2012-2014). Overall calibration for crop grain yield and N_2O did not affect either soil temperature and soil volumetric water content; therefore, only calibrated R^2 values and corresponding probability values when *P*>0.001 are shown.

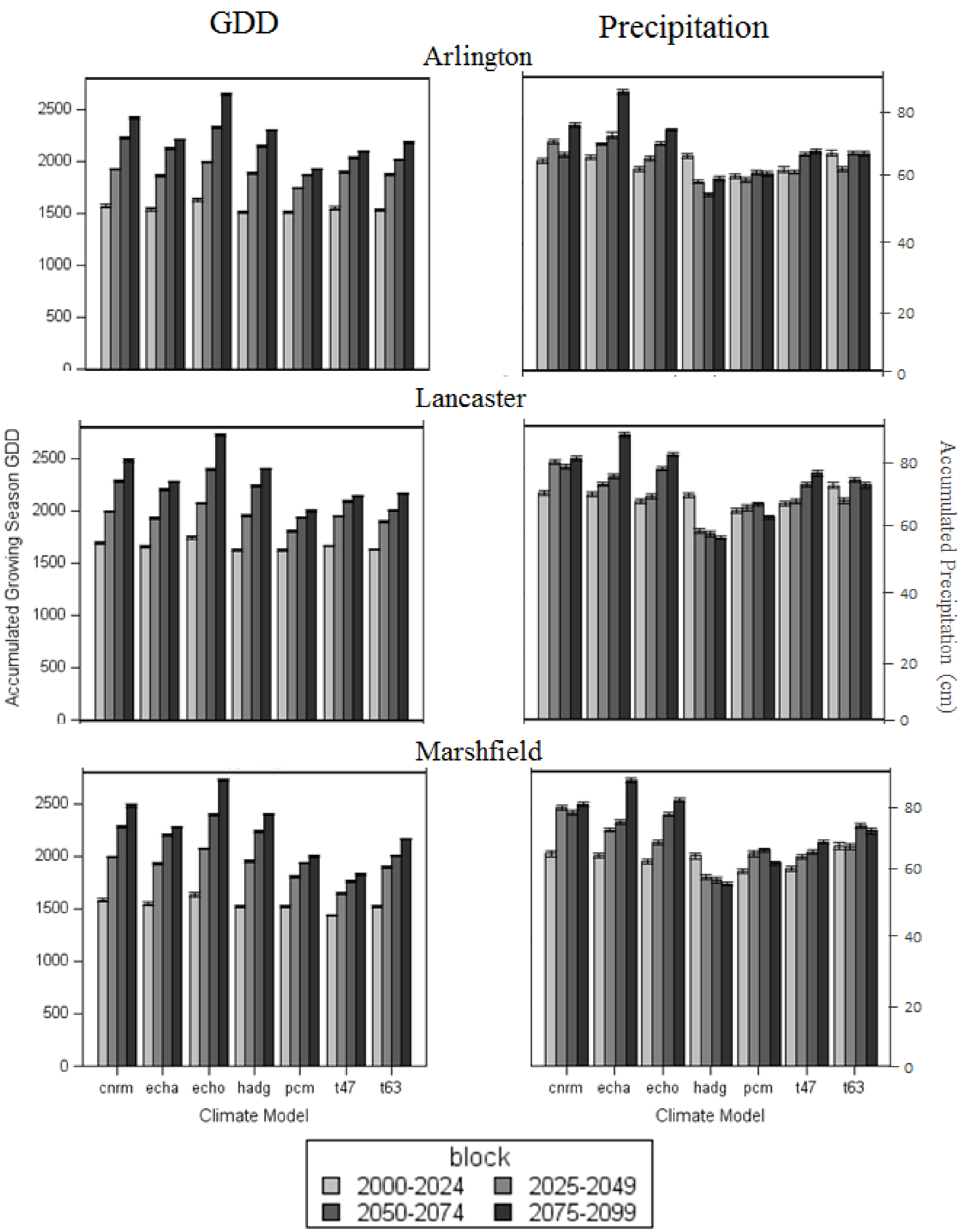


Figure 4.8. Accumulated annual growing degree days [10° C base and 30 °C upper cut off points] (GDD) and annual precipitation (cm) with standard errors at three locations in Wisconsin predicted with seven climate models (described in Table 4.3) in four 25-yr blocks of the 21st century.

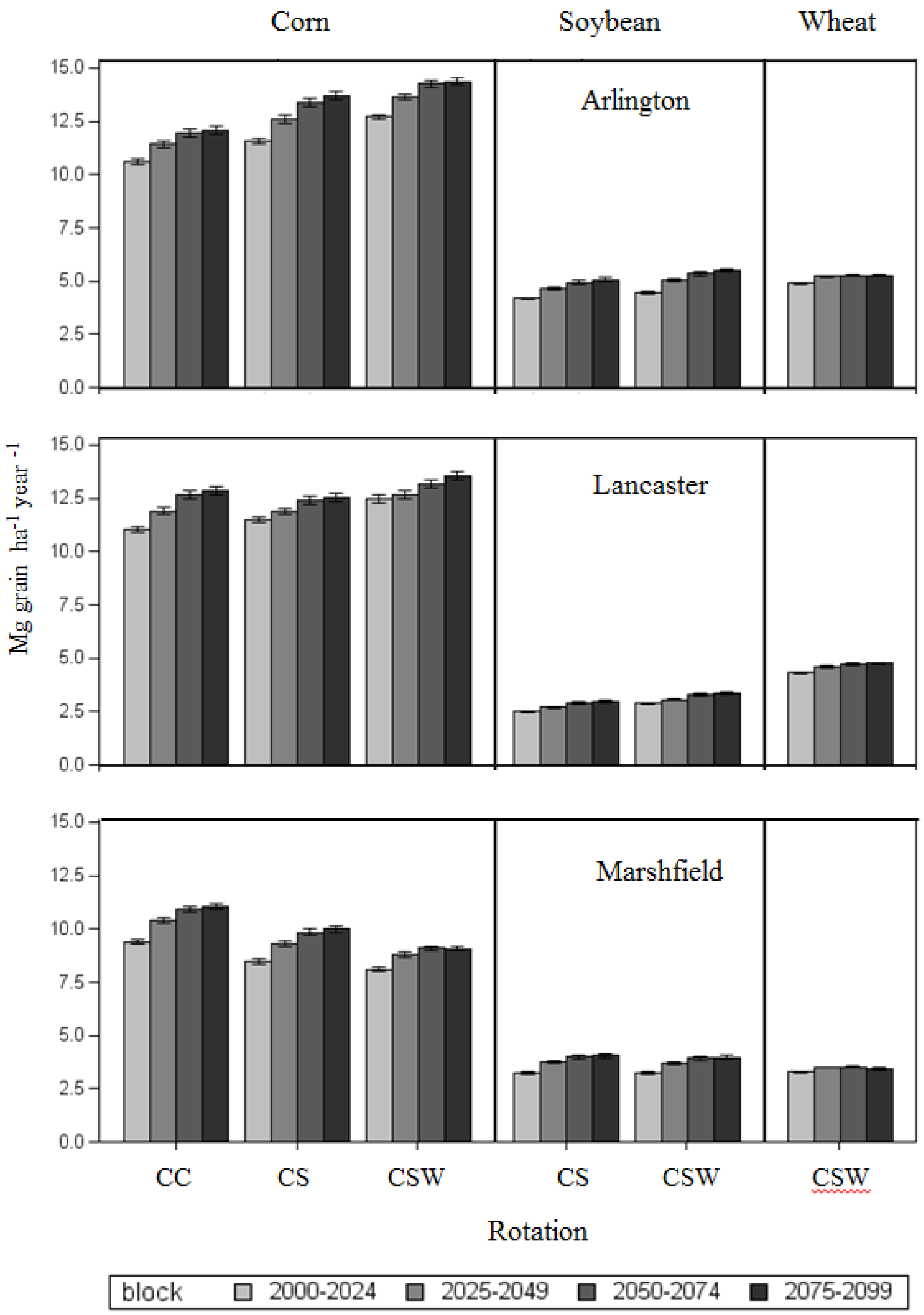


Figure 4.9. Grain yield (Mg grain ha^{-1} year^{-1}) of each crop phase in continuous corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotation across three sites in Wisconsin. Data represent average yield with standard errors averaged across seven climate models (described in table Table 4.3) in four 25-yr blocks of the 21st century.

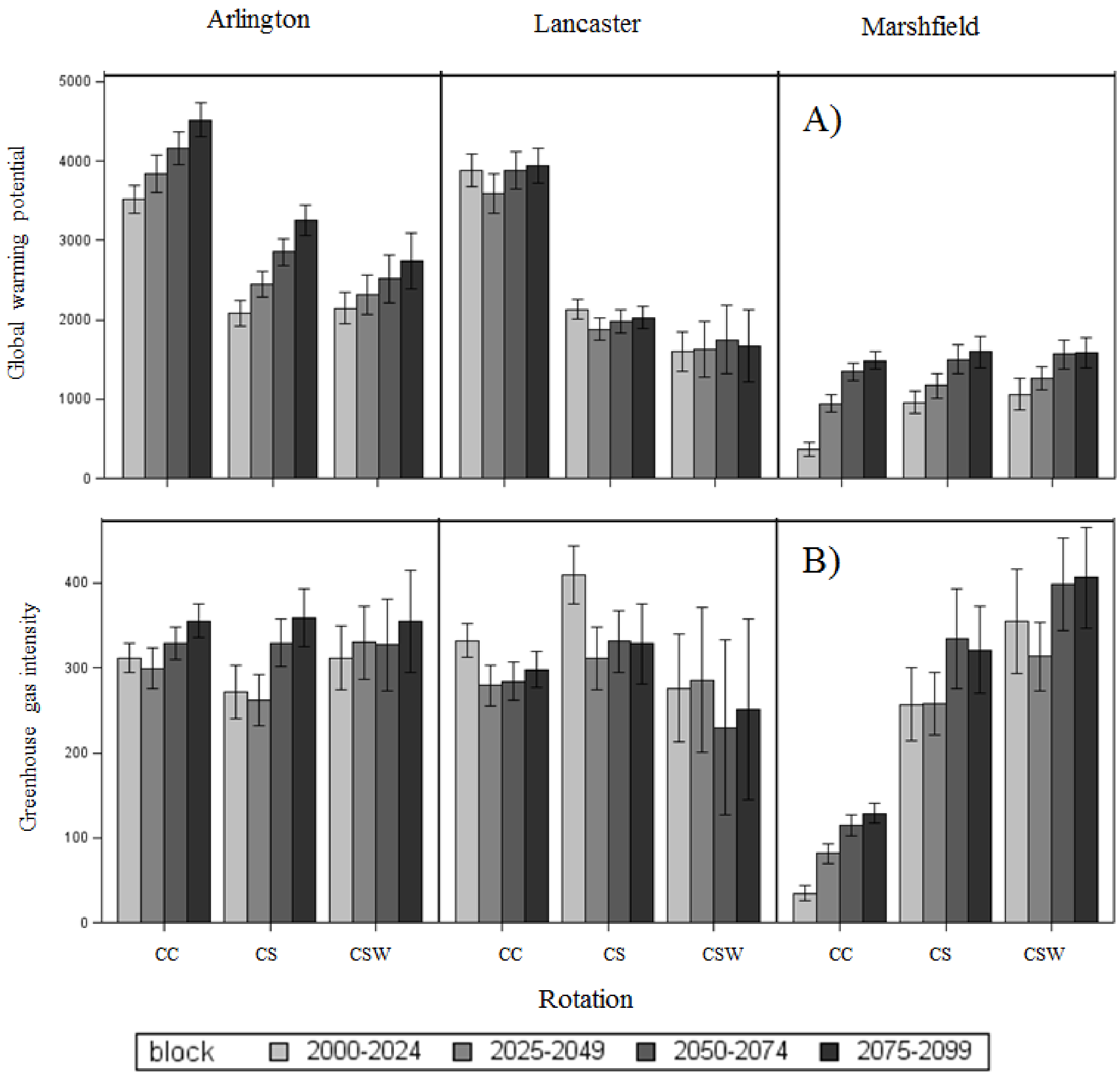


Figure 4.10. Response to climate change of continuous corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotation (across crop phases within rotation) in three sites in Wisconsin on A) global warming potential (GWP) calculated as CO_2 equivalents (kg CO_2-eq. ha^{-1}) and B) greenhouse gas intensity where GWP was divided by grain yield (Mg grain ha^{-1} yr^{-1}) averaged across seven climate models (described in Table 5.3) with standard errors present among four 25-yr blocks of the 21st century. GWP was calculated as CO_2 equivalents of carbon dioxide (GWP=1), N_2O (GWP=298), and CH_4 (GWP=26) according to IPCC (2007b).

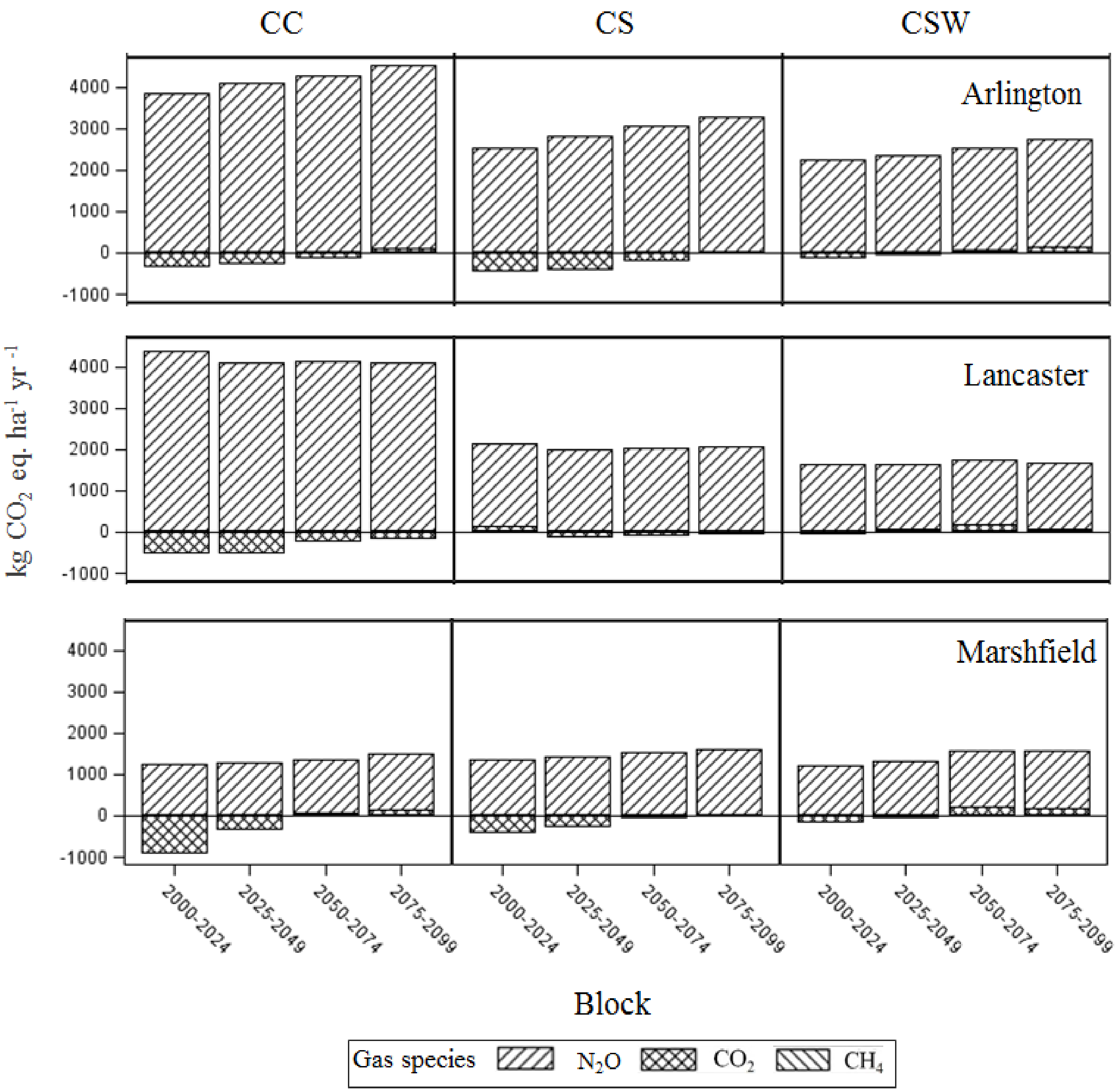


Figure 4.11. Contribution of nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) to global warming potential (GWP) in continuous corn (CC), corn-soybean (CS), and corn-soybean-wheat (CSW) rotation at three sites in Wisconsin. GWP calculated as CO_2 equivalents (kg CO_2 eq. ha^{-1}) of carbon dioxide (GWP=1), N_2O (GWP=298), and CH_4 (GWP=26) according to the IPCC 4th assessment report (2007b). Data represent average values across seven climate models (described in table 4.3) in four 25-yr blocks of the 21st century.

Appendix

Appendix A. Total precipitation at the Arlington. Lancaster, and Marshfield WI, Agricultural Research Stations between 2011-2014 with the departure from 30-yr normals.

Month	2011		2012		2013		2014	
	Total	Dep.	Total	Dep.	Total	Dep.	Total	Dep.
	Precipitation, mm							
	Arlington							
Jan	15	-14	20	-9	57	28	19	-11
Feb	18	-11	24	-5	48	18	26	-3
Mar	86	36	62	12	60	10	24	-25
Apr	90	5	78	-7	138	50	164	74
May	40	-55	75	-19	153	58	71	-23
Jun	104	-15	7	-110	191	70	237	115
Jul	63	-39	109	6	76	-26	48	-54
Aug	37	-60	73	-23	45	-49	94	-2
Sep	98	6	26	-66	75	-17	45	-45
Oct	40	-23	101	35	39	-25	70	9
Nov	83	26	28	-26	67	12	44	-9
Dec	60	21	65	27	29	-8	29	-7
Total	733	-123	668	-184	978	122	872	18
	Lancaster							
Jan	17	-6	20	-3	75	50	24	-3
Feb	45	18	23	-5	37	9	37	9
Mar	54	3	62	11	51	0	34	-17
Apr	91	-1	78	-15	154	58	132	35
May	59	-48	99	-6	144	38	37	-66
Jun	137	4	38	-94	201	65	163	29
Jul	176	66	57	-50	49	-58	46	-60
Aug	66	-33	39	-59	41	-55	99	1
Sep	91	11	82	0	80	-1	56	-25
Oct	37	-27	96	32	28	-35	71	12
Nov	73	10	33	-28	67	7	26	-32
Dec	53	15	58	20	23	-15	26	-11
Total	899	11	685	-197	948	62	752	-128
	Marshfield							
Jan	19	-5	30	7	34	10	35	10
Feb	16	-4	28	7	36	15	38	17
Mar	48	2	33	-12	45	0	21	-25
Apr	75	5	58	-11	108	38	132	61
May	81	-13	97	3	168	72	122	23
Jun	105	-3	91	-18	120	8	131	23
Jul	207	102	34	-65	60	-39	75	-23
Aug	69	-37	104	-3	27	-76	176	69
Sep	92	-8	43	-53	84	-11	79	-17
Oct	59	-6	146	78	182	110	90	19
Nov	22	-34	31	-23	49	-2	55	4
Dec	34	2	43	12	32	1	41	11
Total	826	1	739	-79	946	124	994	173

Appendix B. Average temperature at the Arlington. Lancaster, and Marshfield WI, Agricultural Research Stations between 2011-2014 with the departure from 30-yr normals.

Month	2011		2012		2013		2014	
	Average	Dep.	Average	Dep.	Average	Dep.	Average	Dep.
	Temperature, °C							
	Arlington							
Jan	-10.6	-2.7	-6.3	1.4	-8.7	-0.9	-14.5	-6.6
Feb	-8.0	-2.6	-2.9	2.4	-8.5	-3.0	-13.6	-7.7
Mar	-2.0	-2.6	7.5	6.6	-5.3	-6.0	-5.6	-6.2
Apr	5.2	-2.7	6.4	-1.5	4.1	-3.8	4.9	-2.9
May	12.0	-2.1	15.0	1.0	13.4	-0.7	12.5	-1.5
Jun	18.2	-1.3	19.8	0.3	17.9	-1.6	19.2	-0.3
Jul	22.7	1.1	24.3	2.6	20.4	-1.2	18.1	-3.4
Aug	19.9	-0.6	19.4	-1.1	19.2	-1.2	20.6	0.3
Sep	13.6	-2.5	14.3	-1.9	15.3	-0.8	15.4	-0.6
Oct	9.7	0.2	7.2	-2.2	7.9	-1.4	8.9	-0.3
Nov	2.1	0.2	1.2	-0.7	-0.8	-2.6	-2.2	-3.8
Dec	-2.6	2.8	-3.5	2.0	-10.5	-5.1	-2.5	2.9
Average	6.8	-1.1	8.6	0.7	5.4	-2.4	5.2	-2.6
	Lancaster							
Jan	-9.8	-1.3	-4.1	4.0	-6.9	1.3	-12.7	-4.3
Feb	-6.2	-0.6	-1.4	4.0	-6.8	-1.2	-12.8	-6.8
Mar	0.3	-0.6	10.4	9.1	-3.2	-4.2	-3.6	-4.7
Apr	7.8	-0.5	9.6	1.3	5.6	-2.7	7.2	-1.1
May	14.3	0.0	18.0	3.7	15.2	0.7	14.5	0.0
Jun	20.0	0.5	21.5	1.8	19.6	-0.1	20.8	1.1
Jul	24.6	2.7	26.1	4.1	21.8	-0.1	19.5	-2.4
Aug	21.8	1.1	21.7	0.9	21.3	0.6	21.2	0.5
Sep	15.0	-1.1	16.4	0.2	18.6	2.4	15.8	-0.5
Oct	11.4	2.0	9.2	-0.1	9.8	0.4	8.9	-0.4
Nov	3.9	2.0	2.8	0.8	0.3	-1.5	-2.4	-4.0
Dec	-1.2	4.5	-2.8	3.0	-9.4	-3.8	-2.8	2.9
Average	8.5	0.7	10.8	2.9	7.2	-0.7	6.2	-1.6
	Marshfield							
Jan	-11.1	-1.8	-7.0	2.0	-9.1	-0.1	-14.8	-5.6
Feb	-7.9	-1.1	-3.9	2.7	-9.1	-2.4	-14.8	-7.6
Mar	-2.5	-1.8	7.1	7.5	-4.6	-4.0	-7.7	-7.0
Apr	5.2	-2.1	7.4	0.0	2.6	-4.7	4.3	-2.8
May	12.7	-0.9	15.2	1.6	13.2	-0.5	13.2	-0.5
Jun	18.3	-0.4	19.5	0.6	17.9	-0.9	20.0	1.1
Jul	23.1	1.9	23.7	2.4	20.9	-0.3	19.2	-2.0
Aug	20.9	0.7	19.7	-0.5	20.3	0.1	19.7	-0.4
Sep	14.1	-1.2	14.4	-1.0	16.2	0.8	14.7	-0.7
Oct	10.0	1.4	7.1	-1.5	8.1	-0.5	7.6	-0.9
Nov	2.3	1.4	1.3	0.4	-1.1	-1.9	-4.0	-4.6
Dec	-4.5	2.4	-4.5	2.3	-11.4	-4.6	-4.7	2.1
Average	6.8	-0.1	8.4	1.3	5.4	-1.6	4.5	-2.4

Appendix C. Chemical types applied to crop during 2011 to 2014 growing seasons at the Arlington, Lancaster and Marshfield Research Stations, WI.

				Active ingredient		Application
Location	Crop	Chemical†	Trade name‡	Name	Rate	date
					kg a.i. ha^{-1}	
Arlington						
2011	Corn, Soybean	H	Dual II Magnum	s-metolachlor	1.39	3-May
	Corn, Soybean	H	PowerMax	glyphosate	0.75	3-May
	Corn, Soybean	H	PowerMax	glyphosate	0.75	17-Jun
	Wheat	H	Buctril	bromoxynil	0.25	27-May
	Wheat	H	Axial	pinoxaden	0.11	27-May
				cloquintocet-mexyl	0.03	
	Wheat	F	Headline	pyraclostrobin	0.15	2-Jun
	Wheat	F	Prosaro	propiconazole	0.09	9-Jun
				tebuconazole	0.09	
2012	Corn, Soybean	H	2.4-D	dimethylamine	0.52	6-Apr
	Corn, Soybean	H	PowerMax	glyphosate	1.43	6-Apr
	Corn, Soybean	H	Dual II Magnum	s-metolachlor	1.39	19-May
	Corn, Soybean	H	PowerMax	glyphosate	0.75	19-May
	Wheat	H	Buctril	bromoxynil	0.25	20-May
	Wheat	H	Axial	pinoxaden	0.11	20-May
				cloquintocet-mexyl	0.03	
	Corn	I	Dimethoate 400	dimethoate	0.56	29-Jul
	Wheat	F	Headline	pyraclostrobin	0.15	1-Jun
	Wheat	F	Prosaro	propiconazole	0.09	12-Jun
				tebuconazole	0.09	
2013	Corn, Soybean	H	Dual II Magnum	s-metolachlor	1.39	29-Apr
	Corn, Soybean	H	PowerMax	glyphosate	0.82	29-Apr
	Corn, Soybean	H	PowerMax	glyphosate	0.82	2-Jul
	Wheat	H	Huskie	pyrasulfotole	0.03	27-May
				bomoxynil	0.25	
	Wheat	F	Headline	pyraclostrobin	0.15	13-Jun
2014	Corn, Soybean	H	Dual II Magnum	s-metolachlor	1.39	8-May
	Corn, Soybean	H	WeatherMax	glyphosate	0.75	8-May
	Corn, Soybean	H	PowerMax	glyphosate	0.96	24-Jun
	Corn	H	PowerMax	glyphosate	1.50	20-Oct
	Wheat	H	Huskie	pyrasulfotole	0.03	20-May
				bromoxynil	0.25	
	Wheat	F	Priaxor	fluxapyroxad	0.08	15-Jun
				pyraclostrobin	0.16	
Lancaster						
2011	Corn	H	Dual II Magnum	s-metolachlor	1.42	24-May
	Corn	H	Callisto	mesotrione	0.15	24-May
	Corn	H	Roundup	glyphosate	1.93	24-May
	Soybean	H	Roundup	glyphosate	3.09	16-Jun
	Wheat	N/A				
2012	Corn	H	PowerMax	glyphosate	0.75	10-May
	Corn	H	Lumax	s-metolachlor	2.25	10-May
				atrazine	0.84	
				mesotrione	0.23	
	Soybean	H	PowerMax	glyphosate	0.75	23-Apr/2-Jul
	Wheat	N/A				

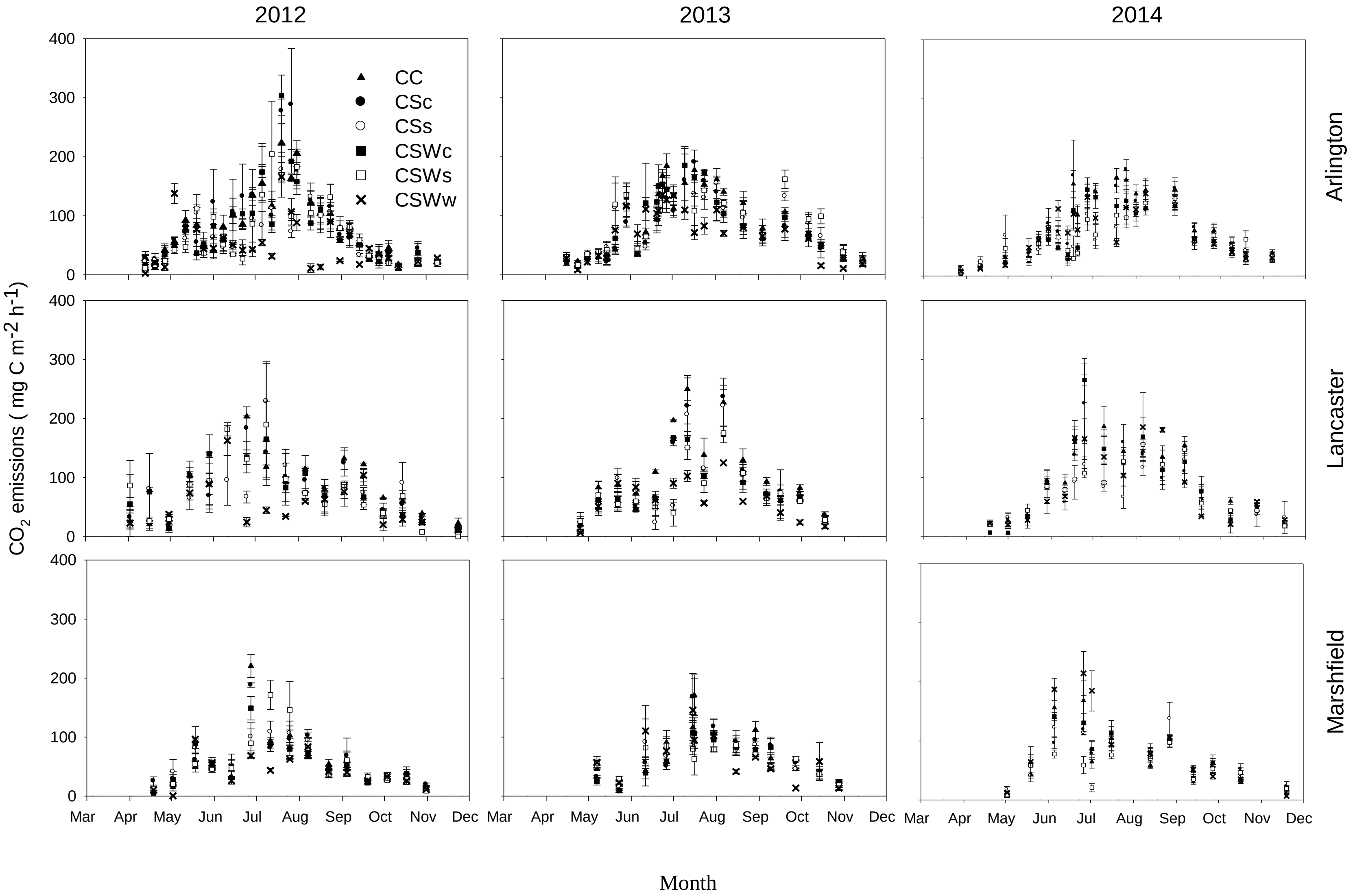
Appendix C. Continued. Chemical types applied to crop during 2011 to 2014 growing seasons at the Arlington, Lancaster and Marshfield Research Stations, WI.

Location	Crop	Chemical†	Trade name	Active ingridient Name	 Rate	Application date
					kg a.i. ha^{-1}	
Lancaster (continued)						
2013	Corn	H	Dual	s-metolachlor	1.81	16-May
		H	Callisto	mesotrione	0.15	16-May
		H	PowerMax	glyphosate	0.96	16-May
	Soybean, Wheat	N/A				
2014	Corn	H	Instigate	rimsulfuron	0.02	22-May
				mesotrione	0.18	22-May
		H	Halex GT	s-metolachlor	1.17	27-Jun
				glyphosate	1.63	
				mesotrione	0.12	
	Soybean	H	Outlook	dimethenamid-P	0.90	28-May
		H	FirstRate	cloransulam	0.04	
		H	Sequence	glyphosate	0.95	25-Jun
				s-metolachlor	1.26	
	Wheat	H	Harmony SG	thifensulfuron-methyl	0.02	9-Jun
Marshfield						
2011	Corn, Soybean	H	Parallel	metolachlor	1.87	27-May
	Corn, Soybean	H	WeatherMax	glyphosate	1.09	29-Jun
	Wheat	H	Affinity Brodspec	thifensulfuron	0.02	27-May
				tribenuron	0.02	
2012	Corn, Soybean	H	Parallel	metolachlor	1.87	19-May
	Corn, Soybean	H	WeatherMax	glyphosate	1.09	21-Jun
	Soybean	H	Poast Plus	sethoxydim	0.14	22-Jun
	Wheat	H	Affinity Brodspec	thifensulfuron	0.01	30-Apr
				tribenuron	0.01	
	Corn, Soybean	I	Baythroid-2	cyfluthrin	0.03	22-Jun
2013	Corn, Soybean	H	Brawl II	s-metolachlor	1.79	3-Jun
	Corn, Soybean	H	WeatherMax	glyphosate	1.09	5-Jul
	Wheat	H	2,4-D	dimethylamine	0.53	5-Jul
2014	Corn	H	Brawl II	s-metolachlor	1.79	5-Jun
	Corn	H	Hornet WDG	flumetsulam	0.04	5-Jun
				clopyralid	0.11	
	Corn, Soybean	H	PowerMax	glyphosate	1.09	10-Jul
	Wheat	H	2,4-D Amine	dimethylamine salt	0.53	10-Jun

† H, herbicide; F, fungicide; I, insecticide; N/A, nothing applied.

‡ Bromoxynil active ingredient in Huskie herbicide as sum of its octanoate and heptanoate form.

Appendix D. Daily Carbon dioxide (CO_2) emission of each phase of continuous corn, corn-soybean, and corn-soybean-wheat rotation at Arlington, Lancaster, and Marshfield, WI (2012-2014).



Appendix E. Daily methane (CH_4) emission of each phase of continuous corn, corn-soybean, and corn-soybean-wheat rotation at Arlington, Lancaster, and Marshfield, WI (2012-2014).