SOIL CARBON AND NITROGEN AND GREENHOUSE GAS EMISSIONS AFFECTED BY SHEEP GRAZING UNDER DRYLAND CROPPING SYSTEMS

by

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ABSTRACT

Sheep grazing to control weeds during fallow may influence soil C and N and greenhouse gas emissions by consuming crop residue and returning feces and urine to the soil. An experiment was conducted to evaluate the effect of sheep grazing compared to tillage and herbicide application for weed control on soil total C, total N, NH_4-N, and NO_3-N contents at the 0-120 cm depth from 2009 to 2011 and greenhouse gas (CO_2, N_2O, and CH_4) emissions from May to October, 2010 and 2011 under dryland cropping systems in western Montana. Treatments were three fallow management practices (sheep grazing [GRAZ), herbicide application [CHEM], and tillage [MECH]) and three cropping sequences (continuous alfalfa [CA], continuous spring wheat [CSW], and spring wheat-pea/barley hay-fallow [W-P/B-F]). Soil samples were collected with a hydraulic probe after crop harvest and greenhouse gas samples at 3 to 14 d intervals with a static chamber. Soil total C was greater in CSW and W-P/B-F than in CA at 5-30 cm but was greater in CA and CSW than in W-P/B-F at 60-90 cm. Soil total N and NO_3-N contents were greater in CSW and W-P/B-F than in CA at 5-120 cm. Soil NH_4-N content varied with treatments and years. Soil temperature and water content at 0-15 cm were greater in CHEM with W-P/B-F and GRAZ with CA than in other treatments. Greenhouse gas fluxes peaked immediately following substantial precipitation (>12 mm) and/or N fertilization, regardless of treatments. Total CO_2 flux from May to October was greater in GRAZ with CA but N_2O flux was greater in CHEM and GRAZ with CSW than in other treatments in 2010 and 2011. Total CH_4 flux was greater in CA than in CSW and W-P/B-F in 2011. Net global warming potential and greenhouse gas intensity were greater in CHEM with CSW than in other treatments. Continuous spring wheat increased soil C and N storage and available N at subsurface layers compared to other cropping sequences. Because of higher N_2O emissions and lower C sequestration rate, global warming potential and greenhouse gas intensity increased under continuous spring wheat with herbicide application for weed control.

CHAPTER 1

INTRODUCTION

Sheep grazing during fallow periods in wheat-fallow systems or after grain harvest is often used to control weeds and pests, reduce feed cost, and increase nutrient cycling under dryland farming in the northern Great Plains (Johnson et al., 1997; Entz et al., 2002). Fallowing can conserve soil water, release plant nutrients, control weeds, increase subsequent crop yields, and reduce the risk of crop failure (Aase and Pikul, 1995; Jones and Popham, 1997). Tillage and herbicide application to control weeds during fallow have been effective but are expensive, resulting in some of the highest variable costs for small grain production in Montana (Johnson et al., 1997). Other disadvantages of these practices are the exposure of soil to erosion due to tillage and increased risk of contamination of herbicides in soil, water, and air that are hazardous to human and animal health (Fenster, 1997).

Excessive application of commercial fertilizers in the past several decades has increased crop yields but reduced soil and environmental quality by increasing acidity, N leaching, surface runoff of N and P from agricultural lands to streams and lakes causing eutrophication, and greenhouse gases, such as N_2O emissions (Franzluebbers, 2007; Herrero et al., 2010). To reduce such adverse effects, integrated crop-livestock system can be used as an option to improve soil quality and sustain crop yields (Franzluebbers, 2007; Maughan et al., 2009). The system can have many other benefits such as crops, meat, milk, and manure production, use of animals as draft power for tillage

(Franzluebbers, 2007), and weed and pest control (Hatfield et al. 2007a, 2007c; Herrero et al., 2010). Grazing can increase C and N cycling by consuming crop and weed residues and returning C and N inputs into the soil through feces and urine (Abaye et al., 1997; Franzluebbers and Stuedemann, 2008; Sainju et al., 2010b).

As C and N are cycled through sheep grazing and other management practices in the agroecosystem, some byproducts could be the emissions of greenhouse gases (GHG), such as CO_2, N_2O, and CH_4. Root and microbial respirations and mineralization of soil organic matter and crop residue result in CO_2 emissions (Curtin et al., 2000; Sainju et al., 2010a). During photosynthesis, however, CO_2 is absorbed by plants from the atmosphere, which is converted into soil organic matter after the residue is returned to the soil (Lal et al., 1995; Paustian et al., 1995). Soil C level is determined by the balance between the amount of plant residue C added to the soil and rate of C mineralized as CO_2 emissions in unmanured soil (Rasmussen et al., 1980; Peterson et al., 1998). Crop residue and soil organic matter mineralization also emit N_2O but applications of manures and N fertilizer augment the process (Mosier et al., 2006, Sey et al., 2008). Factors, such as substrate availability, available C, and soil temperature, water content, and texture, regulate nitrification and denitrification processes that result in the production of N_2O (Drury et al., 2006; Dusenbury et al., 2008). Agricultural soils under aerobic condition in semiarid regions typically act as small sink for atmospheric CH_4 (Bronson and Mosier, 1994).

Agricultural activities contribute three GHGs: CO_2, N_2O, and CH_4. About 6% of the total GHG emissions are contributed by agricultural practices in U.S.A. (Greenhouse Gas Working Group, 2010). Out of the total anthropogenic emissions, agriculture accounts for 25% of CO_2 and 70% of N_2O emissions (Cole et al., 1997; Smith et al. 2007). Major sources of agricultural CO_2 emissions are fossil fuel consumption, land conversion to cropland, lime application, and N fertilization with associated N_2O emissions are included in soil management practices (USEPA, 2011). Enteric fermentation and manure management account for 96% of the total CH_4 emissions from agriculture (USEPA, 2011). Although emitted in small amounts, N_2O and CH_4 have been considered as potent GHGs. This is due to their greater global warming potential (GWP) (298 and 25 times, respectively, more powerful than CO_2) (IPCC, 2007).

Little information is available about the effect of sheep grazing on soil C and N levels and GHG emissions under dryland cropping systems. It was hypothesized that sheep grazing would increase soil C and N storage and reduce GHG emissions and GWP compared to tillage and herbicide applications for weed control under continuous spring wheat. The objectives of this experiment were to:

1. Examine the amount of spring wheat grain and alfalfa and pea/biomass yields harvested and spring wheat biomass residue returned to the soil in 2010 and 2011 at the study site in western Montana,
2. Determine the effects of fallow management, cropping sequence, and crop species on soil total C, total N, NH_4-N, and NO_3-N content at the 0- to 120-cm depth from 2009 to 2011,
3. Quantify CO_2, N_2O, and CH_4 fluxes as affected by treatments from May to October, 2010 and 2011 and

4. Evaluate GWP and greenhouse gas intensity (GHGI) in various treatments resulting from productions associated with CO_2 emissions and N_2O and CH_4 fluxes.

CHAPTER 2

LITERATURE REVIEW

Integrated Crop-Livestock System

There is a growing interest in integrating crops and livestock as an alternative farming practice due to concerns about degradation of soil, water, and air quality and long-term sustainability. Concerns arise due to excessive applications of inorganic fertilizers, herbicides, and pesticides that contaminate water and air and results in less fertile soil. According to the 2007 Agriculture Census Montana Report, more than 61 million acres of farm and/or production land exist in Montana (NASS, 2007). Out of these, about 65% are in permanent pasture and rangeland and 15% in cropland. Only 3% of cropland is used for animal grazing. In 2007 and 2008, spring wheat was grown in 2,169,600 acres while 3,063,250 acres were under fallow in Montana. With increased demand for food due to rising population in the world, novel management practices are needed to sustain crop yields and maintain soil and environmental quality. Integrated crop-livestock could be an option to increase nutrient cycling, reduce fertilization rates, and sustain crop yields and meat and milk productions without serious alterations in soil and environmental quality.

Other benefits of animal grazing cropland include effective control of weeds and pests and reduced applications of fertilizers, herbicides, and pesticides. Goosey et al. (2005) found no difference in the presence of wheat stem sawfly (*Cephus cinctus* Norton

[Hymenoptera: Cephidae]) in sheep-grazed and non-grazed areas. The wheat stem sawfly has been considered as one of the most destructive pests in Montana's wheat production (Hatfield et al., 2007a). Hatfield et al. (2007c) found that sheep grazing reduced weed density similar to that controlled by tillage in fallow areas, yet it can provide enough residues to control soil erosion. Sheep grazing has minimum impact on soil C and N levels (Sainju et al., 2010b) and variable effect on soil chemical properties (Sainju et al., 2011b) without altering spring and winter wheat yields (Snyder et al., 2007; Sainju et al., 2010b), although more N fertilizer was needed.

Tillage and Fallow Management in the Northern Great Plains

Spring wheat-fallow rotations with conventional tillage have been the traditional farming system over several decades in the northern Great Plains (Haas et al., 1957). This system has resulted in a decline of soil organic matter by 30 to 50% of their original levels in the last 50 to 100 yr (Haas et al., 1957; Mann, 1985; Peterson et al., 1998). Intensive tillage increases the oxidation of soil organic matter (Bowman et al., 1999; Schomberg and Jones, 1999) and fallowing increases its loss by reducing the amount of plant residue returned to the soil (Black and Tanaka, 1997; Campbell et al., 2000). Fallowing is done to conserve water for succeeding crops, release nutrients, and control weeds (Haas et. al., 1974; Eck and Jones, 1992). Precipitation is one of the largest determinants of crop yield in dryland agriculture (Wittwer, 1975; Tanaka and Aase, 1987; Peterson et al., 1998). In the northern Great Plains, the fallow period lasts for 8 months in continuous spring wheat to 14 months in winter wheat-fallow and 21 months in spring wheat-fallow systems. Although extending fallow increases soil water storage and crop yields (Eck and Jones, 1992; Aase and Pikul, 1995; Jones and Popham, 1997; Pikul et al., 1997), increased soil water and temperature during fallow can also accelerate mineralization of soil organic matter due to increased microbial activity (Haas et al., 1974). As a result, the traditional farming system has become inefficient, uneconomical (Aase and Schaefer 1996), and unsustainable (Dhuyvetter et al., 1996).

Several researchers (Eck and Jones, 1992; Jones and Popham, 1997; Lenssen et al., 2007, 2010) have investigated water-use efficiencies of crops under dryland cropping systems. Lenssen et al. (2007) found that pea use less water than spring wheat and barley, thereby resulting in the possibility of continuous cropping compared to crop-fallow. Pea residue also supply N to the soil, thereby reducing N fertilization rates to succeeding crops (Sainju et al., 2009b). Similarly, no-tillage can conserve soil water compared to conventional tillage due to reduced soil disturbance and increased residue accumulation at the soil surface that acts like mulch (Lenssen et al., 2007). Tillage also has little effect on crop grain yields (Jones and Popham, 1997; Lenssen et al., 2007; Sainju et al., 2009b). Therefore, no-tillage with continuous cropping not only increased crop yields but also improved soil quality by increasing organic matter (Aase and Pikul., 1995; Sainju et al. 2007; 2009b).

The risk of crop failure during drought has been apparently buffered by widespread alternate-year tilled-summer fallow adoption in Montana during the 1920's and 1930's, although repercussions became obvious as soil erosion and loss of organic matter increased (Krall and Ford, 1979). Strip farming, where alternate strips of crop and fallow were used, became a more popular mean of controlling soil erosion as early as 1922 (Howard, 1959). Carr et al. (2005) found that both fallowed- and tilled-soils lacking crop residue are susceptible to wind and water erosion. The amount of plant residue left in the soil from previous cropping influences the ability for soil to store water during a summer fallow (Tanaka and Aase, 1987). Tilled-fallow was determined as an unsustainable practice not only for conserving water but also for soil quality due to continuous loss of organic carbon and nitrogen (Janzen et al., 1998; Peterson et al., 2002; Grant et al., 2002; Sainju et al., 2006).

Herbicides and pesticides have become more affordable in recent years to control weeds compared to tillage in dryland cropping systems in the northern Great Plains. Although herbicide and pesticide application have improved crop yields and controlled many weeds and pests, they may not be completely effective, since some weeds have shown resistance to herbicides, such as glyphosate (Prowles and Duke, 2008). Controlling weeds using herbicide can be a substantial variable cost to the farmer (Johnson et al., 1997; Dillion et al., 2002; Young et al., 2004) and environmental quality costs have been researched (McLaughlin 1995; Plantegenest et al., 2010), since increased application of chemicals to crops can contaminate soil, water, and air, thereby resulting in increased health hazard to humans and animals. Sheep grazing can be used an effective tool to control weeds and pests without the need of expensive chemicals (Hatfield et al., 2007a, 2007c).

Soil Nitrogen and Carbon

The primary nitrogen transformations in soil are cycles between inorganic and organic forms involving mineralization and immobilization, and losses to the atmosphere including ammonia volatilization and denitrification as well as losses from water movement by means of erosion and leaching. Soil microorganisms are involved in various transformations of nitrogen including mineralization of N to NH_4-N and nitrification to NO_3^-. Ammonia volatilization is the gaseous loss of N, perhaps of particular interest in pastures and with fertilizers. Denitrification is essentially the reduction of NO3-N to gaseous forms of N such as NO, N_2O and N_2 by bacteria (Pierzynski et al., 2005). Forms of nitrogen, NO_3-N and NH_4-N are available for crop uptake or soil residual N after crop harvest, or may be lost to leaching, volatilization or surface runoff. (Wood et al., 1990; Sainju et al., 2007)

A study on the effect of animal grazing in semiarid regions showed that grazing did not affect soil bulk density and C and N levels of SOM (Hatfield et al., 2007b). Higher C and N contents (from SOM measurements), were found in areas grazed by sheep compared to tillage in Montana (Hatfield, et al., 2007b), Georgia (Franzluebbers and Stuedemann, 2008), and Illinois (Maughan et al., 2009). Animal feces and urine returned to the soil during grazing can enrich nutrients, improve soil quality, and increase crop yields (Tracy and Zhang, 2008; Maughan et al., 2009). The distribution of feces and urine by animals during grazing at the soil surface can be uneven; however, distribution can be more uniform with sheep than with cattle grazing (Abaye et al., 1997). Snyder et al. (2007) reported that sheep grazing during fallow to control weeds did not influence soil organic matter, NO_3-N content, and wheat yields compared with non-grazed treatment in western Montana. Abaye et al. (1997) found that grazing sheep and cattle together increased soil bulk density and organic matter and grass yields compared with grazing sheep or cattle alone.

Sainju et al. (2010b) found that sheep grazing reduced soil organic C and total N at the 0-5 cm depth compared to tillage and herbicide applications for weed control in continuous spring wheat (CSW) system as a result of residue removal following grain harvest, due to consumption by sheep during grazing. They found that greater soil total N in sheep grazing compared to other fallow management practices in CSW was a result of increased biomass residue returned to the soil compared to other cropping sequences. They also observed that higher soil total N content at 30-60 cm in the grazing than in the chemical treatment in continuous spring wheat could be the results of greater sheep urine and feces returned to the soil during grazing. Although grazing did not alter soil NH_4-N and NO_3-N levels compared to other fallow management practices, NO_3-N content was lower in CSW than in other cropping sequences due to greater amount of N removed by wheat grain (Sainju et al., 2010b). Regardless of fallow management practices, soil organic C, total N, and NO_3-N contents decreased from 2004 to 2007 due to continuous tillage (Sainju et al., 2010b).

Tillage and cropping system influence soil N availability. No-tilled continuous cropping system can increase crop yields compared to conventional-tilled crop-fallow by reducing N losses, primarily through leaching (Aase and Pikul, 1995; Halvorson et al., 2000; Sainju et al., 2009a, 2009b). Crop rotations that include forages can sustain yields and increase water-use efficiency (Entz et al., 2002) by improving soil water content and N availability (Pikul and Aase, 2003). Legumes can reduce N fertilization rates for succeeding crops compared to nonlegumes (Sainju and Lenssen, 2011) due to higher turnover rates of plant residue as a result of lower C:N ratios (Franzluebbers et al., 1995; Kuo et al., 1997). Conventional tillage and fallow can increase soil inorganic N level at the cost of organic N due to increased mineralization (Sainju et al., 2009a).

Carbon and nitrogen are directly linked through stochiometry (Vitousek et al., 2002). Conservation tillage practices can increase soil organic carbon and total N compared to conventional tillage by reducing mineralization of soil organic matter (Sainju et al., 2007b, 2009a). By increasing cropping intensity and adoption of more diversified crop rotations, greater amount of residues are returned to the soil, thereby increasing soil organic matter level (Aase and Pikul, 1995; Grant et al., 2002; Halvorson et al., 2002; Sainju et al., 2007b, 2011a). Fallowing decreases organic matter by reducing the amount of plant residue returned to the soil and by increasing microbial activity due to soil temperature and water content during fallow (Haas et al., 1974; Black and Bauer, 1988; Eck and Jones, 1992; Campbell and Zentner, 1993).

Greenhouse Gas Emissions

Anthropogenic emissions of GHGs have been increased substantially in the past 10,000 years (IPCC, 2007). In the past 200 years, CO_2, N_2O, and CH_4 emissions have increased by 36, 18, and 148% respectively. Agricultural activities contribute a substantial proportion of these gases. Although varied among years, atmospheric concentrations of N_2O and CH_4 have increased by 4.9 and 14.9 % between 1990 and 2009 (IPCC, 2007).

Many factors affect GHG emissions from agroecosystems. Abiotic factors include air temperature, precipitation, and soil temperature, water content, and texture. In the global C cycling, CO_2 is emitted from soil due to root and microbial respirations but also fixed in the plant from the atmosphere through photosynthesis and sequestered in the soil as organic matter. For C sequestration to occur, plants and soils need to store more C than they emit (Schlesinger, 1977). More CO_2 is removed from the atmosphere through photosynthesis than is respired by microbes and plant roots (Pierzynski et al., 2005), thereby impeding the growth rate of atmospheric CO_2 concentration (Canadell et al., 2007). It is likely that increased crop biomass productivity in the last century has delayed rising CO_2 emissions (Pierzynski et al., 2005). Carbon dioxide emissions has been known to increase with decreasing clay content due to increased soil organic matter mineralization (Parkin and Kaspar, 2003; Sainju et al., 2012). Soil texture also impacts CH_4 and N_2O fluxes (Mosier et al., 1998). High N_2O emissions may occur in soils after significant rainfall events and/or snow melts (Smith and Tiedje, 1979). Tillage may have variable effect on N_2O emissions (Rochette et al., 1999, Mosier et al., 2006). Nitrogen fertilization, however, is the single largest source of N_2O emissions (Dusenbury et al., 2008; Mosier et al., 2006). High soil temperatures and water content can increase microbial activity and organic matter mineralization, thereby resulting in higher CO_2 and N_2O emissions (Follett, 2001; Parkin and Kaspar, 2003). Both CO_2 and N_2O emissions may be related. (Sey et al., 2008) reported positive correlation between CO_2 and N_2O and suggested similarity in rates of gas accumulation and diffusive flux due to soil moisture.

Farm management practices have various effects on GHG emissions. Reduction in tillage intensity reduces soil disturbance and microbial activity, which in turn, lowers CO_2 and N_2O emissions (Lemke et al., 1999; Drury et al., 2006; Mosier et al., 2006). In contrast, increased tillage intensity increases CO_2 emissions by increasing soil aeration and disrupting soil aggregates (Roberts and Chan, 1990) and by physical degassing of dissolved CO_2 from the soil solution (Jackson et al., 2003). Cropping system can influence CO_2 and N_2O emissions by affecting the quality and quantity of crop residue returned to the soil (Mosier et al., 2006; Sainju et al., 2010a). Nitrogen fertilization typically has a stimulatory effect on N_2O emissions (Mosier et al., 2006; Dusenbury et al., 2008; Robertson and Vitousek, 2009) but a variable effect on CO_2 emissions (Al-Kaisi et al., 2008). Carbon loss as CO_2 emission due to root respiration is estimated to be 48% of the total emissions (Curtin et al., 2000).

Management practices can also indirectly affect GHG emissions by altering soil temperature and water content, since these parameters are directly related with gas emissions (Parkin and Kaspar, 2003; Dusenbury et al., 2008; Liebig et al., 2010). Tillage can dry soil through increased evaporation but no-tillage can conserve soil water and reduce temperature because of decreased soil disturbance and increased residue accumulation at the soil surface (Curtin et al., 2000; Al-Kaisi and Yin, 2005). Similarly, cropping system and crop type can influence soil temperature and water content by affecting shade intensity and evapotranspiration (Curtin et al., 2000; Amos et al., 2005). Irrigation can increase soil water content and reduce soil temperature compared to no irrigation but N fertilization can reduce these parameters compared to no N fertilization by increasing shade intensity and water uptake through increased biomass production (Sainju et al., 2008). Higher water content in no-tilled soils usually results in restricted aeration and greater denitrification rates and N_2O emissions than in conventionally-tilled soils (Doran 1980), since denitrification is stimulated by the lack of oxygen in flooded soils (Smith and Tiedje, 1979). In the northern cornbelt where soil water is more abundant than in other regions due to uniform precipitation throughout the year, Johnson et al. (2010) found no significant effects of tillage and crop rotation on N_2O emissions.

Leguminous crops can be a source of N_2O emissions because of its greater N concentration. Lemke et al. (1999) and Mosier et al. (2006) found greater N_2O emissions with legumes than with nonlegumes due to the presence of rhizobium bacteria related to root nodules. Because of lower C:N ratio and higher N concentration, legumes decompose rapidly compared to nonlegumes, thereby increasing N_2O emissions (Wagner-Riddle and Thurtell, 1998; Huang et al., 2004).

Enteric fermentation from livestock ruminants and manure management can be primary sources of CH_4 emissions in agriculture, though the emissions from animal feces and urine can be insignificant (Flessa et al., 1995; Jarvis et al., 1995). Cultivation in flooded soil, such as rice cultivation, also increases N_2O and CH_4 emissions due to increased denitrification and anaerobic decomposition of soil organic matter but aerobic dryland soils can be a small sink for CH_4 (Bronson and Mosier, 1994; Snyder and Slaton, 2001). Well-aerated soils contain methanotrophic bacteria which gain their energy by oxidizing CH_4 to methanol, thereby reducing the concentration of CH_4 in the atmosphere (Brady and Weil, 2008). Several researchers (Kessavalou et al., 1998, Liebig et al., 2010) have reported negative CH_4 flux under dryland cropping systems. Nitrogen fertilization can reduce soil uptake of CH_4 (Brady and Weil, 2008; Bronson and Mosier, 1994). Several experiments have shown competitive inhibition at the enzyme level (Bronson and Mosier, 1994; Willison et al., 1995), since ammonia can inhibit the enzyme system responsible for methane oxidation by methanotrophs (Dunfield and Knowles, 1995).

Global Warming Potential

Global warming potential (GWP) of GHGs is defined as radiative forcing in the earth's atmosphere (Mosier et al., 2005). Agricultural activities that contribute GHGs play a major role in radiative forcing by increasing the concentration of these gases in the atmosphere (Robertson et al., 2000). By employing novel management practices, such as no-tillage, increased cropping intensity, diversified crop rotation, cover cropping, and reduced rate of N fertilization, GHG emissions can be mitigated by increasing C sequestration, promoting CH_4 oxidation, and reducing N_2O emissions while sustaining crop yields (Robertson et al., 2000; Mosier et al., 2005, 2006). The relationship of soil C changes to N_2O and CH_4 emissions typically regulates net GWP (Robertson et al., 2000). For understanding agriculture's impact on radiative forcing, all sources and sinks of CO_2, N_2O, and CH_4 in the agroecosystem should be considered (Robertson et al., 2000). The initiation of C credit market is one of the attempts to increase soil C sequestration and reduce the concentration of CO_2 in the atmosphere, thereby mitigating the radiative forcing (McCarl and Schneider, 2001; CAST, 2004).

Extensive application of N fertilizer in the past several decades has increased crop yields but also reduced environmental quality by increasing N leaching and N_2O emissions, a major component of GWP (Robertson et al., 2000; Mosier et al., 2005). Management techniques that increase N-use efficiency in crops can reduce N_2O emissions by reducing N fertilization rates and removing residual soil N (Kroeze at al., 1999). Since manufacture and application of N fertilizers to crops also produce CO_2 (Robertson et al., 2000), reduced rate of N fertilization without influencing yields can occur at low environmental cost (Mosier et al., 2005).

Expressing GWP in terms of CO_2 equivalents, N_2O and CH_4 emissions from agricultural activities amount to 7.7 Pg CO_2 equivalents yr^{-1} (Robertson and Grace, 2004), which is close to annual global atmospheric loading rate of 8.4 Pg CO_2 equivalents yr^{-1} (IPCC, 2001). In USA, GWP from farming activities amounts to 450 Tg CO_2 equivalents yr^{-1}. A system becomes a source of net GWP if the value is positive and sink if it is negative. Management techniques that increase soil organic matter and reduce N_2O emissions can reduce GWP (Follett, 2001).

Global warming potential has also been measured in terms of greenhouse gas intensity (GHGI) by relating it with crop yield (Mosier et al., 2006). The GHGI is calculated by dividing GWP by grain or hay biomass yield. Like GWP, a system becomes a net source of CO_2 if GHGI is positive and a sink if it is negative. Little is known about the effect of sheep grazing on GWP and GHGI in dryland cropping systems.

CHAPTER 3

MATERIALS AND METHODS

Site and Treatment Description

The experiment was conducted from 2009 to 2011 at the Fort Ellis Research and Extension Center, Montana State University (45˚40'N, 111˚2'W; altitude 1468 m), approximately 8 km east of Bozeman, MT. The farm is situated in a region that is considered productive (SSS/NRCS, 2010). Total annual precipitation (113-yr average) is 465 mm and mean monthly air temperature ranges from -5.6 ˚C in January to 19 ˚C in July (Table 1) (WRCC, 2011).

Table 1. Monthly total precipitation and average air temperature at the experimental site in 2010 and 2011.

Month	Precipitation			Temperature		
	2010	2011	113-yr average	2010	2011	113-yr average
	mm			°C		
January	25.8	20.4	22.4	-4.0	-3.8	-5.6
February	15.7	19.3	18.5	-2.9	-5.9	-3.7
March	39.7	29.5	33.8	2.9	1.9	0.0
April	59.3	48.6	46.2	5.6	3.4	5.6
May	93.9	90.8	72.6	7.7	8.7	10.4
June	123.3	87.3	73.7	13.8	13.9	14.6
July	10.8	31.3	34.5	18.2	19.6	19.0
August	69.1	22.9	31.5	17.5	19.6	18.3
September	55.8	17.5	43.9	13.8	15.7	12.9
October	23.1	43.8	38.1	9.9	8.9	7.4
November	63.3	29.4	27.7	-2.4	-0.3	0.1
December	26.6	19.2	21.8	-4.8	-3.1	-4.4
May-October	376.0	293.6	294.3	13.5	14.4	13.8
January-December	606.4	460.0	464.8	6.3	6.9	6.2

The soil is Blackmore silt loam (fine-silty, mixed, superactive, frigid Typic Argiustolls) derived from calcareous loess with 0 to 4% slope and contains 250 g kg^{-1} sand, 500 g kg^{-1} silt, and 250 g kg^{-1} clay at the 0-15 cm depth. Soil organic C concentrations measured in the spring of 2004 at 0-15 cm and 15-30 cm were 33.2 and 17.5g C kg^{-1}, respectively. Previous treatments (2004-2008) at the site consisted of three fallow management practices (sheep grazing, tillage or mechanical, and herbicide application or chemical) as the main plot and three cropping sequences (continuous spring wheat [CSW], spring wheat-fallow, and winter wheat-fallow) as the sub-plot variable.

For this study, same main plot fallow management treatments from previous experiment (herbicide application [CHEM], sheep grazing [GRAZ], and conventional tillage [MECH]) were continued. Similarly, in the split-plot treatment, CSW from previous experiment was continued in the same plots but spring wheat-fallow and winter wheat-fallow were replaced by continuous alfalfa (CA) and spring wheat-pea/barley hay-fallow (W-P/B-F). The GRAZ treatment consisted of grazing with a group of western white-faced sheep at a stocking rate of 29 to 153 sheep day ha^{-1}. Sheep were grazed before planting in the early spring and after crop harvest in the fall in CSW and W-P/B-F, and during summer fallow in W-P/B-F. In CA, grazing occurred once each year near the time of first cutting in late summer. Grazing ended when about 47 kg ha^{-1} or less of crop residue and weeds remained in the plot.

All fallow management treatments consisted of applications of post emergence herbicide (glyphosate [*N*-(phosphonomethyl)-glycin]) and dimethylamine salt of dicamba (3, 6-dichloro-o-anisic acid) before planting and after crop harvest for weed control, however the CHEM treatment had further use of the herbicide during summer fallow. The MECH treatment consisted of tilling the plots with Flexicoil harrow (John Deere 100, Kennedy, MN) to a depth of 15 cm during fallow to control weeds as needed and for seedbed preparation. Treatments were arranged in a randomized complete block with three replications (Fig. 1). Each phase of the cropping sequence was present in every year. Individual plot size was 91.4 m × 15.2 m.

Crop Management

Nitrogen fertilizer as urea (45% N) was broadcast in spring wheat and pea/barley hay plots immediately prior to or following planting in May, 2009 to 2011. While N fertilizer was left at the soil surface in GRAZ and CHEM treatments, it was incorporated to a depth of 15 cm using tillage in the MECH treatment. Nitrogen fertilization rates to spring wheat were 202 kg N ha^{-1} in CSW and 252 kg N ha^{-1} in W-P/B-F, based on soil tests completed the previous fall. Similarly, N rate to pea/barley hay was 134 kg N ha^{-1}. The rates depended on yield goals which were 3.9 Mg ha^{-1} for spring wheat grain in CSW and 4.8 Mg ha^{-1} in W-P/B-F and 8.9 Mg ha^{-1} for pea/ barley hay. Soil NO_3-N content to a depth of 60 cm measured after grain and hay harvest in the fall every year was used to adjust N rates before N fertilizer was applied to spring wheat and pea/barley hay. No N

Fig. 1. Plot map of treatments in the experimental site. Fallow management was considered as the main plot and cropping sequence as the split-plot treatment in randomized complete block design with three replications. Black circles denote locations of chambers for greenhouse gas flux measurement (two chambers/plot).

fertilizer was applied to alfalfa. Since the soil contained higher levels of extractable P and K (Sainju, 2011b), no P and K fertilizers were applied.

Immediately after fertilization in mid-May, 2009 to 2011, spring wheat (cv. McNeal, Foundation Seed, Montana State Univ., Bozeman, MT) was planted at 90 kg ha^{-1} in CSW and W-P/B-F using a drill equipped with double disc openers with a row spacing of 30 cm. Using the same equipment, barley hay (cultivar Haybet, Montana State Univ. Stock, Bozeman, MT) was planted at 1.6 million seeds ha^{-1} and Austrian winter pea hay (cultivar Common, Circle S Seed, Logan, UT) planted at 0.8 million seeds ha^{-1} in W-P/B-F. Similarly, alfalfa (cultivar HayGrazer, Browning Brothers Seed, Mosby, MT) was planted at 9 kg ha^{-1} with a JD 750 drill at a row spacing of 20 cm.

In September, total crop biomass (containing grains, stems, and leaves in spring wheat and stems and leaves in pea/barley hay and alfalfa) was collected 2 d before grain and hay harvest from two 0.5 m^2 areas, except for alfalfa biomass in 2010 which was not collected. Biomass samples were oven dried at 60˚C for at 3-4 d for dry matter yield determination. Spring wheat grain yield (within 12-13% moisture content) was determined from an area of 1389 m^2 using a combine harvester. Spring wheat biomass (stems and leaves) was determined by deducting grain yield from total biomass. After grain harvest, spring wheat biomass residue was returned to the soil. In CHEM and MECH treatments, biomass of forages was harvested for hay with a self-propelled swather and round baler. In the GRAZ treatment, sheep were allowed to graze over spring wheat residue, swathed pea/barley hay, and alfalfa biomass. Subsamples of spring wheat grain and biomass and pea/barley and alfalfa biomass were ground to 1 mm for C and N analysis. Total C and N concentrations in plant samples were determined by using the dry combustion C and N analyzer (LECO TruSpec, LECO Corp., St. Joseph, MI). Carbon and N contents in grain and biomass were calculated by multiplying their yields by C and N concentrations.

Soil Sampling and Analysis

A month after crop harvest in October, 2009 to 2011, soil samples were collected from all plots at the 0-120 cm depth from five places in the central rows using a hydraulic probe (5 cm i.d.). Soil cores were divided into 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm depth intervals. A portion of the sample was used to determine bulk density by dividing the weight of the oven-dried soil at 105^{o}C by the volume of the core. The other samples were mixed, air-dried and ground to pass a 2-mm sieve. Total C and N concentrations in soil samples were determined by using the high combustion C and N analyzer (VarioMAX CN, ELEMENTAR Americas Inc., Mt. Laurel, NJ), after grinding the sample to pass a 0.5 mm sieve. The NH_4-N and NO_3-N concentrations in the soil samples were determined by extracting samples with 2*M* KCl for 1 h and analyzing the extract with an autoanalyzer using Cd reduction (Lachat QuikChem 8000, Lachat Instruments, Loveland, CO).

The contents (Mg or kg C ha^{-1}) of soil total C and N, NH_4-N, and NO_3-N at various depths were calculated by multiplying their concentrations (g or mg C kg^{-1}) by bulk density and thickness of the soil layer. Since bulk density was not significantly influenced by treatments and years (data not shown), bulk density values of 1.20, 1.34, 1.61, 1.61, 1.53, and 1.46 Mg m^{-3} at 0-5, 5-15, 15-30, 30-60, 60-90, and 90-120 cm, respectively, averaged across treatments and years, were used to convert concentrations of soil C and N into contents. Total contents at 0-120 cm were determined by summing the contents from individual depths.

Greenhouse Gas Sampling and Analysis

Greenhouse gas sampling and analysis procedures followed USDA-ARS GRACEnet Project Protocol (Parkin and Venterea, 2010). Vented, static chambers were constructed according to specifications recommended by Hutchinson and Mosier (1981). The chamber was made from a non-reactive polyvinyl chloride pipe (1 cm thick) and plexi-glass material (1 cm thick) and consisted of two parts: an anchor (15 cm tall by 20 cm diameter) and a lid (10 cm tall by 20 cm diameter) (Fig. 2). The anchor was inserted to a depth of 10 cm into the soil, leaving 5 cm above the surface. One end of the lid was sealed with plexi-glass using permanent glue and tape and contained ports for ventilation and gas sampling. The outer edge of the other end of the lid was attached with a soft rubber sheet that was lowered to seal the anchor during gas sampling so that no exchange of gases occurs between the inside and the outside of the chamber. Anchors were removed during planting and fertilization and reinstalled near the original place in leveled areas covering crop rows and inter-rows in each treatment and year. A carpenter's level was used at the top to level the anchor in the north-south and east-west directions. A 24 h equilibration period of anchor installation was allowed before gas sampling to avoid error due to soil disturbance. Two chambers were installed at both ends of a plot to reduce

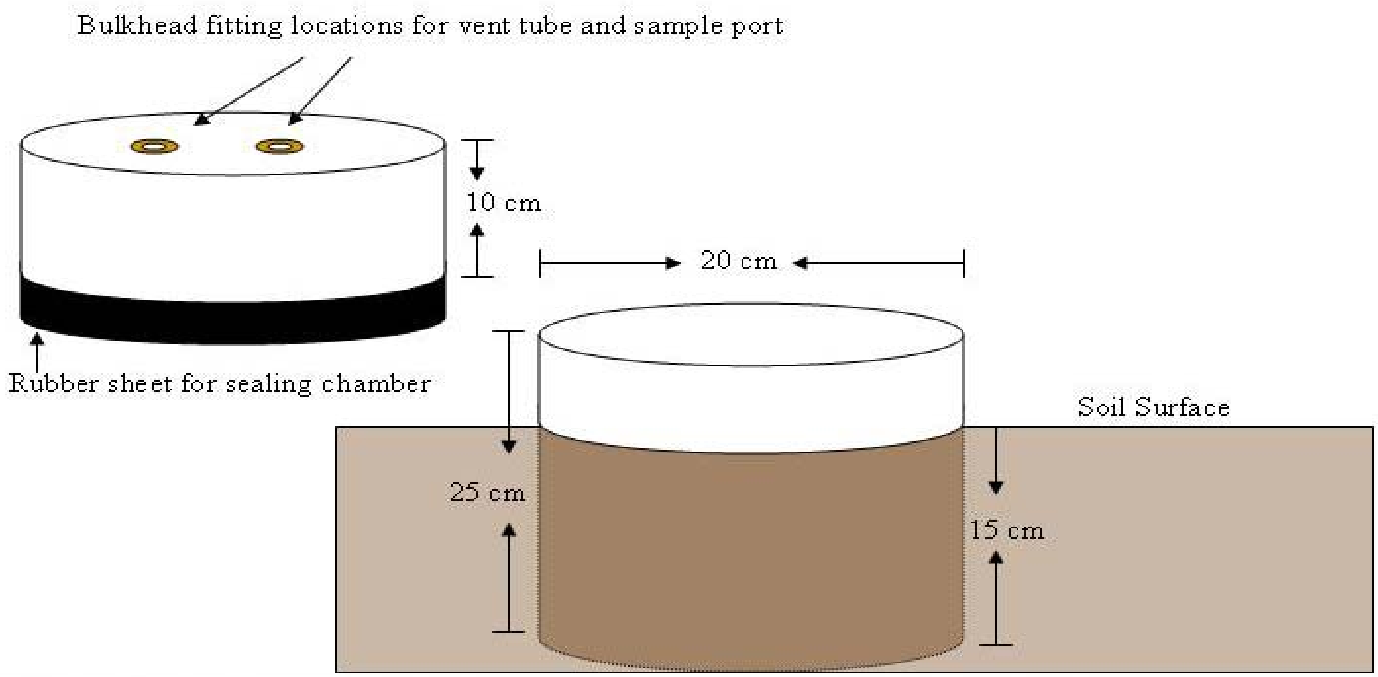

Figure 2. Chamber used for greenhouse gas sampling. Chamber is made of 2 parts PVC: top portion with ports for ventilation and gas sampling and bottom portion as anchor inserted to a depth of 15cm into the soil. Rubber sheet attached to the top portion is lowered to the bottom portion to seal the chamber during sampling.

spatial variability for GHG measurement and mean value was used for data analysis. Total headspace volume of the chamber was determined by adding inside volumes of the anchor above the soil surface and the lid. For this experiment, GHG measurements were made only in CHEM and GRAZ treatments.

Soil surface CO_2, N_2O, and CH_4 fluxes were measured from 8 A.M. to 12 A.M. at 3 to 14 d intervals, depending on crop growth, from May to October, 2010 and 2011. Samplings were collected during the same period in each day to reduce diurnal effect of temperature on GHG fluxes (Parkin and Kaspar, 2003). During gas sampling, the lid was placed on the top of the anchor and the rubber sheet from the lid was lowered to seal the anchor. Gas samples were collected from the port by inserting a needle attached to a 20 ml syringe and transferred to pre-evacuated 12 ml vials sealed with butyl rubber septa (Labco Ltd., High Wycombe, UK). Samples were collected at 0, 20, and 40 min to calculate the flux. Concentrations of CO_2, N_2O, and CH_4 in gas samples inside the vials were determined with a gas chromatograph (Model 3800 Varian, Palo Alto, CA) in a laboratory. The gas chromatograph was fully automated with thermal conductivity, flame ionization, and electron capture detectors for analysis of CO_2, CH_4, and N_2O concentrations, respectively, in one gas sample. Gas flux was calculated as change in either linear or curvilinear concentration gradient over time (Hutchinson and Mosier, 1981; Liebig et al., 2010). Total fluxes during the measurement period from May to October in each year were calculated by linearly interpolating data points and integrating the underlying area (Gilbert, 1987). At the time of gas sampling, soil temperature at the 15 cm depth was measured with a temperature probe and soil water content was determined gravimetrically by collecting field-moist soil sample with a hand probe (2 cm i.d.) near the chamber and oven drying at 105^{o}C. Volumetric soil water content was determined by multiplying gravimetric water content by bulk density measured at the time of soil sampling. Because soils were frozen to more than 1 m depth and insignificant fluxes generally occur from November to April, except N_2O flux (Dusenbury et al., 2008; Liebig et al., 2010), GHG fluxes and soil temperature and water content were not measured during this period.

Statistical Analysis of Data

Data for grain and biomass yields, soil C, N, temperature, and water contents, and greenhouse gas fluxes were analyzed using the MIXED procedure of SAS (Littell et al., 1996). Fallow management was considered as the main-plot treatment and fixed effect. Cropping sequence was considered as the split-plot treatment and another fixed effect. Gas and soil sampling dates and/or year were considered as repeated measure variables. Random effects were replication and replication × fallow management interaction. For a crop rotation, data were averaged across cropping phases and average value was used for the analysis. To determine the effect of crop species within a rotation, data were also analyzed by cropping phases. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al. 2000). Statistical significance was evaluated at $P \leq 0.05$, unless otherwise stated.

CHAPTER 4

RESULTS AND DISCUSSION

Precipitation and Air Temperature

Daily total precipitation varied during the crop growing season (May to October), with most of it occurring in May and June (Fig. 3). Monthly total precipitation in May and June, the active crop growing season, was greater in 2010 and 2011 than the 113-yr average (Table 1). Similarly, total precipitation in August and September was greater in 2010 but lower in 2011 than the long term average. Growing season precipitation accounted for 62 to 64% of the total annual precipitation. Both growing season and total annual precipitation were greater in 2010 than in 2011 and the long term average.

Mean daily air temperature increased from May to August and then declined in 2010 and 2011 (Fig. 3). Monthly average air temperature from May to August was lower in 2010 but greater in 2011 than the 113-yr average, except in May 2011 (Table 1). Air temperature in September and October was, however, greater in 2010 and 2011 than the normal. Growing season average temperature was greater in 2011 than in 2010 and the normal but annual average temperature was similar in all years. Variations in precipitation and air temperature may influence crop yields, soil C and N levels, and GHG emissions among years, as described below.

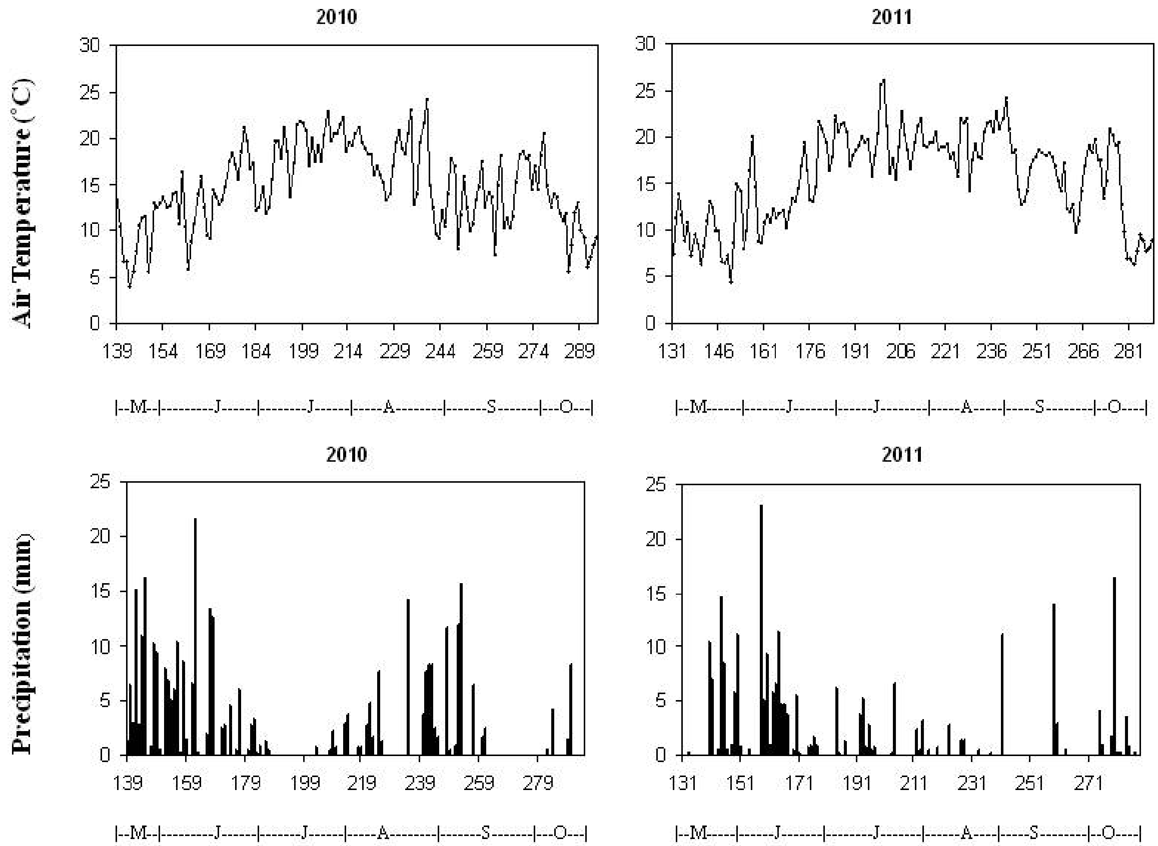

Fig. 3. Daily air temperature and total precipitation from May to October, 2010 and 2011, in the experimental site. Capital letters below the X-axis denote month.

Crop Yields

Spring wheat grain and biomass yields and C and N contents varied among cropping sequences and years (Table 2). Grain and biomass yields and C and N contents were greater in W-P/B-F than in CSW. Conservation of soil water during fallow and lower water requirement for pea/barley hay than for spring wheat as a result of early harvest probably increased spring wheat grain and biomass yields and C and N contents in W-P/B-F compared to CSW. Several researchers (Aase and Pikul, 1995; Lenssen et al., 2007, 2010; Sainju et al., 2009b) have found greater spring wheat grain and biomass yields following fallow than following spring wheat due to higher soil water accumulations during fallow. Lenssen et al. (2010) reported that soil water and NO_3-N contents were greater in durum following fallow and pea/barley hay than in durum following durum. Spring wheat grain and biomass yields and C and N contents were also greater in 2010 than in 2011, likely due to higher growing season precipitation (Table 1).

Table 2. Effects of fallow management and cropping sequence on spring wheat grain and biomass yields from 2010 to 2011.

Cropping sequence†	Year	Grain yield	Biomass yield	C content		N content	
				Grain	Biomass	Grain	Biomass
		-------Mg ha^{-1}------		----Mg C ha^{-1}---		-----kg N ha^{-1}-----	
CSW		2.31b‡	5.06b	0.98b	2.15b	31.6b	68.5b
W-P/B-F		3.55a	7.37a	1.51a	3.14a	48.2a	100.2a
	2010	3.71a	6.87a	1.58a	2.94a	52.8a	98.3a
	2011	2.14b	5.56b	0.91b	2.36b	27.1b	70.4b
Significance							
Fallow management (FM)		NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		**	**	*	**	*	**
FM × CS		NS	NS	NS	NS	NS	NS
Year (Y)		*	*	*	*	**	**
FM × Y		NS	NS	NS	NS	NS	NS
CS × Y		NS	NS	NS	NS	NS	NS
FM × CS × Y		NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$ and 0.01, respectively; NS, not significant.

† Cropping sequence are CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

‡ Numbers followed by different letters within a column in a set are significantly Different at $P \leq 0.05$ by the least square means test.

Fallow management and its interaction with cropping sequence and year were not significant on spring wheat grain and biomass yields and C and N contents. Several researchers (Snyder et al, 2007; Sainju et al., 2011b) also reported no difference in spring wheat grain and biomass yields in sheep-grazed and non-grazed treatments, although more N fertilizers were required.

Alfalfa biomass was not measured in 2010 due to hailstorm damage. In 2011, alfalfa biomass and C content in CA was similar to pea/barley hay biomass in W-P/B-F but N content was greater in alfalfa than in pea/barley hay (Table 3). Because of higher N concentrations associated with a legume, alfalfa may have higher N content than pea/barley hay (Sainju and Lenssen, 2011). Pea/barley hay biomass and C content were also similar in 2010 and 2011 but biomass N content was greater in 2010 than in 2011 due to higher yield.

Table 3. Effects of fallow management and cropping sequence on alfalfa and pea/barley hay in 2010 and 2011.

Cropping sequence†	Biomass yield		Biomass C content		Biomass N content	
	2010	2011	2010	2011	2010	2011
CA (alfalfa)	---‡	7.07a§	---	3.1a	---	182.1a
W-P/B-F (pea/barley hay)	6.56	7.01a	2.8a	2.9a	100.8	86.8b
<u>Significance</u>						
Fallow management (FM)	NS	NS	NS	NS	NS	NS
Cropping sequence (CS)	---	***	---	***	---	***
FM × CS	NS	NS	NS	NS	NS	NS

*** Significant at $P \leq 0.001$; NS, not significant.
† Cropping sequence are CA, continuous alfalfa; and W-P/B-F, spring wheat-pea/barley hay-fallow.
‡ Not measured
§ Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

Since spring wheat grain and hay biomass were removed, only wheat biomass after grain harvest was returned to the soil. Although spring wheat grain and biomass yields were greater in W-P/B-F than in CSW (Table 2), annualized yields will be much lower. This is because spring wheat was grown every year in CSW, but only one in three years in W-P/B-F. Because of the differences in the annualized amount of C and N returned to the soil through wheat residue and its placement in the soil due to tillage and consumption due to sheep grazing, soil C and N levels and GHG emissions differ among treatments, as described below.

Soil Carbon and Nitrogen

Soil Total Carbon and Nitrogen

Soil total C and N contents at various depths varied significantly with cropping sequence and year (Tables 4 and 5). Fallow management and its interactions with cropping sequence and year on soil total C and N were not significant. Soil total C, averaged across fallow management practices and years, was greater in CSW and W-P/B-F than in CA at 5-15, 15-30, 0-15, and 0-30 cm depths but was greater in CA and CSW than in W-P/B-F at 60-90 cm (Table 4). Similarly, soil total N was greater in CSW and W-P/B-F than in CA at 5-15, 15-30, 30-60, 60-90, 0-15, 0-30, 0-60, 0-90, and 0-120 cm but was greater in CSW than in CA and W-P/B-F at 90-120 cm (Table 5). Averaged across treatments, soil total C declined from 2009 to 2011 at all depths, except at 0-5 and 60-90 cm. In contrast, soil total N increased from 2009 to 2011 at 0-5 cm but decreased at

Table 4. Effects of fallow management and cropping sequence on soil total C content at the 0-120 cm depth from 2009 to 2011.

Cropping sequence†	Year	Soil total C content										
		0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
		Mg C ha^{-1}										
CA		16.6a‡	31.9b	33.9b	42.8a	84.1a	73.2a	48.5b	82.4b	125.2a	209.3a	282.5a
CSW		17.6a	35.5a	38.6a	42.1a	79.4a	80.4a	53.1a	91.7a	133.8a	213.2a	293.1a
W-P/B-F		17.5a	35.4a	41.5a	43.3a	71.1b	75.9a	53.0a	94.5a	137.8a	208.8a	284.7a
	2009	17.6a	37.8a	45.6a	48.2a	76.5a	82.8a	55.4a	101.0a	149.2a	225.7a	308.5a
	2010	17.4a	34.4b	37.1b	41.0b	76.3a	72.8b	51.8ab	88.9b	130.0b	206.2b	279.0b
	2011	17.2a	33.2b	37.9b	40.7b	71.7a	75.0b	50.5b	88.4b	129.1b	200.8b	275.8b
Significance												
Cropping sequence (CS)		NS	*	*	NS	**	NS	*	*	NS	NS	NS
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)		NS	*	***	***	NS	*	*	***	***	***	***
CS × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS ×FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Table 5. Effects of fallow management and cropping sequence on soil total N content at the 0-120 cm depth from 2009 to 2011.

Cropping sequence†	Year	Soil total N content 0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
		Mg N ha^{-1}										
CA		12.9a‡	8.7b	8.9b	10.3b	8.7b	7.3b	21.6b	30.5b	40.9b	49.6 b	56.9b
CSW		12.3a	21.2a	29.0a	18.6a	19.0a	33.5a	33.4a	62.4a	81.0a	100.0a	133.5a
W-P/B-F		12.7a	21.7a	26.3a	18.5a	19.9a	26.5b	34.5a	60.7a	79.2a	99.1 a	125.6a
	2009	6.9b	24.5a	37.6a	21.2a	22.6a	36.1a	31.4a	69.0a	90.2a	112.8a	148.9a
	2010	9.6b	23.0a	25.9b	20.2a	16.0 a	17.9 b	32.6 a	58.5ab	78.7ab	94.7a	112.7ab
	2011	20.3a	12.7b	12.3c	11.4b	16.6 a	23.9 a	33.0 a	45.3b	56.7b	73.3a	97.2b
<u>Significance</u>												
Cropping sequence (CS)		NS	***	**	NS	*	***	*	**	**	**	***
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)		***	**	***	**	NS	***	NS	NS	*	NS	*
CS × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow. ‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

all other depths, except at 0-15 cm. Soil total C increased with depth because of higher inorganic C content but soil total N varied.

The greater soil total C at 5-30 cm and total N at 5-90 cm in CSW and W-P/B-F than in CA was probably a result of greater amount of biomass residue C and N returned to the soil. Since spring wheat biomass residue was returned to the soil every year in CSW and one in three years in W-P/B-F while pea/biomass and alfalfa were removed for hay, it could be possible that greater amount of C and N added in residue increased soil total C and N at these subsoil layers. Although soil total C and N at 0-5 cm were also greater in CSW and W-P/B-F than in CA, differences among cropping sequences were not significant. Greater amount of biomass residue returned to the soil can increase soil organic C and total N (Halvorson et al., 2002; Ortega et al., 2002; Sainju et al., 2006). While increased amount of residue C and N returned to the soil likely increased soil total C at 60-90 cm and total N at 90-120 cm in CSW, greater soil total C at 60-90 cm in CA than in W-P/B-F was probably due to increased root biomass. Sainju and Lenssen (2011) have reported greater root biomass and C and N contents in alfalfa than in durum and pea/barley hay. The nonsignificant effect of fallow management suggests that sheep grazing had no influence on soil C and N storage compared to tillage and herbicide application for weed control. This was similar to that observed by Hatfield et al. (2007b) who reported that soil organic matter was not different among sheep-grazed, non-grazed, and tilled treatments in dryland cropping systems in northwestern Montana.

Both soil total C and N continued to decline from 2009 to 2011, especially at the subsurface layers, regardless of treatments. This is probably because the amount of residue C and N returned to the soil also declined from 2010 to 2011, although no crop yields were measured in 2009 (Tables 2 and 3). Similar decline in soil organic C from 2004 to 2007 at the site was previously noted by Sainju et al. (2010b). They suggested that soil organic C declined probably because conversion of pastureland at the initiation of the experiment to cropland due to continuous tillage for wheat planting mineralized soil organic matter. Although plots were not tilled during fallow periods in the CHEM and GRAZ treatments, all treatments were tilled in the spring prior to spring wheat planting, in the fall for winter wheat planting, and during fallow in the MECH treatment to control weeds. Franzluebbers and Stuedemann (2008) reported that tilling pastureland for planting crops significantly reduced soil organic C after 1 yr and reduction further increased as tillage continued over time. Sainju et al. (2010b) further suggested that removal of wheat biomass for hay in 2004, reduced biomass residue returned to the soil from 2005 to 2007, and consumption of residue by sheep during grazing may also have accelerated the reduction in soil organic C.

Soil Ammonium and Nitrate-Nitrogen

Soil NH_4-N content at 0-5, 5-15, 0-15, 0-30, and 0-60 cm depths varied among years (Table 6). Interactions were significant for cropping sequence × fallow management at 90-120 cm, cropping sequence × year at 0-5 cm, fallow management × year at 5-15, 0-15, and 0-30 cm, and cropping sequence × fallow management × year at 0-15, 0-60, and 0-120 cm. The NH_4-N content at 0-15 cm was greater in MECH with CSW than in other treatments in 2009 (Table 7). In 2010, NH_4-N content at 0-15, 0-60,

Table 6. Effects of fallow management and cropping sequence on soil NH_4-N content at the 0-120 cm depth from 2009 to 2011.

Year	Soil NH_4-N content										
	0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
	---kg N ha^{-1}---										
2009	3.1b†	7.5b	11.6a	21.6a	18.7a	19.0a	10.6b	22.2b	43.8a	62.4a	81.5a
2010	4.6a	9.1a	12.3a	20.8a	19.0a	20.0a	13.7a	25.9a	46.7a	65.7a	85.7a
2011	3.2b	5.6c	10.3a	18.7a	17.6a	18.9a	8.8c	19.1c	37.8b	55.4b	74.3a
<u>Significance</u>											
Cropping sequence (CS)	NS¶	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Fallow management (FM)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS
Year (Y)	**	***	NS	NS	NS	NS	***	**	*	NS	NS
CS × Y	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y	NS	*	NS	NS	NS	NS	*	*	NS	NS	NS
CS × FM × Y	NS	NS	NS	NS	NS	NS	*	NS	*	NS	*

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

Table 7. Interaction effects of fallow management, cropping sequence, and year on soil NH4-N content at the 0-120 cm depth from 2009 to 2011.

Year	Fallow management‡	Cropping sequence‡	Soil NH_4-N content 0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
			kg N ha^{-1}										
2009	CHEM	CA	ND§	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	5.5	5.6	9.3	17.4	15.7	22.8	8.3	17.5	35.0	50.7	73.5
		W-P/B-F	3.2	6.3	11.6	19.8	17.0	15.7	9.6	21.2	40.9	58.0	73.7
	GRAZ	CA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	3.4	6.9	10.6	22.9	19.5	18.5	10.1	20.7	43.5	63.1	81.6
		W-P/B-F	3.1	6.5	12.4	22.4	21.3	20.8	9.6	22.0	44.4	65.8	86.6
	MECH	CA	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
		CSW	7.5	16.4	10.6	18.4	17.6	16.3	18.9	29.5	47.9	65.5	81.8
		W-P/B-F	3.2	7.6	12.2	24.6	18.7	20.4	10.8	23.0	47.6	66.3	86.7
2010	CHEM	CA	3.6	9.6	12.0	23.1	17.3	25.0	13.2	25.2	48.3	65.6	90.7
		CSW	2.6	6.1	9.5	14.4	15.5	22.2	9.4	18.9	33.3	48.8	71.0
		W-P/B-F	2.9	10.1	10.7	18.6	12.0	13.7	13.1	23.8	42.4	54.4	68.1
	GRAZ	CA	6.8	12.6	19.1	36.2	43.5	39.4	19.4	38.6	74.7	118.2	157.6
		CSW	3.3	11.3	9.0	15.4	15.8	10.7	18.8	27.8	43.2	59.0	69.7
		W-P/B-F	3.4	7.5	13.8	16.2	18.7	18.5	10.9	24.7	40.8	59.6	78.1
	MECH	CA	2.7	8.3	10.3	16.8	12.7	15.4	13.9	24.2	41.0	53.7	69.1
		CSW	2.5	7.9	13.7	25.9	17.5	16.9	12.5	26.2	52.1	69.6	86.5
		W-P/B-F	3.2	8.5	12.1	21.1	17.6	18.4	11.7	23.8	44.9	62.5	80.9
2011	CHEM	CA	3.7	7.6	19.3	35.8	16.5	16.4	11.3	30.6	66.3	82.8	99.3
		CSW	2.7	5.9	10.3	19.8	15.7	32.0	9.2	19.5	39.3	55.1	87.1
		W-P/B-F	2.6	6.1	9.8	15.2	14.5	17.8	8.7	18.5	33.7	48.2	66.0
	GRAZ	CA	3.5	5.6	8.2	14.1	16.0	16.3	9.1	17.3	31.4	47.4	63.8
		CSW	3.1	5.6	11.2	19.3	22.6	21.0	8.3	19.4	38.7	61.4	82.3
		W-P/B-F	5.8	5.8	9.9	19.9	19.3	16.8	11.6	21.5	41.4	60.8	77.6
	MECH	CA	4.6	5.0	8.3	15.8	21.3	15.9	7.6	15.9	31.7	53.0	68.9
		CSW	2.1	4.3	7.9	13.3	14.8	13.4	6.4	14.3	27.6	42.3	55.7
		W-P/B-F	2.3	4.7	7.9	15.4	17.2	20.5	7.0	15.0	30.3	47.5	68.0
	LSD (0.05)		NS	NS	NS	NS	NS	NS	6.1	NS	27.6	NS	44.8

† Fallow management are CHEM, weed controlled by herbicide application; GRAZ, weed controlled by sheep grazing; and MECH, weed controlled with by tillage

‡Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.§ Not determined.

and 0-120 cm was greater in GRAZ with CA than in most other treatments. In 2011, NH_4-N content at 0-60 and 0-120 cm was greater in CHEM with CA than in most other treatments. Averaged across treatments, NH_4-N content at 0-5, 5-15, 0-15, 0-30, and 0-60 cm was in the order: 2010>2009>2011 (Table 6).

Soil NO_3-N content at 5-15, 15-30, 60-90, 90-120, 0-15, 0-30, 0-60, 0-90, and 0-120 cm varied with cropping sequence and at 0-5, 5-15, 15-30, 30-60, 0-30, and 0-120 cm varied with year (Table 8). Averaged across fallow management practices and years, NO_3-N content at 5-15, 15-30, 60-90, 90-120, 0-15, 0-30, 0-60, 0-90, and 0-120 cm was greater in CSW and W-P/B-F than in CA. Averaged across treatments, NO_3-N content at 0-5 cm was greater in 2011 than in 2009 and 2010 but at 5-15, 15-30, and 30-60 cm was greater in 2009 and 2010 than in 2011. At 90-120, 0-30, and 0-120 cm, NO_3-N content was greater in 2009 than in 2010 and 2011.

Increased amount of crop residue and its incorporation into soil in MECH with CSW probably increased NH_4-N content at 0-15 cm in 2009. Although crop biomass yield was not measured in 2009, annualized biomass residue returned to the soil was greater in CSW than in CA and W-P/B-F due to continuous wheat grown in CSW as opposed to one in three years in W-P/B-F and hay removal in CA. Sainju and Lenssen (2011) reported that greater amount of residue returned to the soil increased NH_4-N content in durum-barley hay than in durum-fallow. In contrast, greater amount of N contributed by alfalfa root biomass and undisturbed soil condition likely increased NH_4-N content at 0-15, 0-60, and 0-120 cm in GRAZ with CA in 2010 and in CHEM with CA in 2011. Sainju and Lenssen (2011) reported that root biomass N was greater in alfalfa

Table 8. Effects of fallow management and cropping sequence on soil NO_3-N content at the 0-120 cm depth from 2009 to 2011.

Cropping sequence†	Year	Soil NO_3-N content										
		0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
		-----kg N ha^{-1}-----										
CA		12.8a‡	8.7b	8.9b	10.3a	8.7b	7.3b	21.6b	30.5b	40.8b	49.6b	57.0 b
CSW		12.2a	21.2a	29.0a	18.6a	19.0a	33.5a	33.4a	62.4a	81.0a	100.0a	133.5a
W-P/B-F		12.7a	21.8a	26.3a	18.5a	19.9a	26.5a	34.5a	60.7a	79.2a	99.1a	125.6a
	2009	6.8b	24.5a	37.6a	21.2a	22.6a	36.1a	31.4a	69.8a	90.2a	112.7a	148.9a
	2010	9.6b	23.0a	25.8b	20.2a	16.0a	17.9b	32.6a	58.5ab	78.7a	94.7a	112.7b
	2011	20.3a	12.7b	12.3c	11.4b	16.6a	23.9a	33.0a	45.3b	56.7a	73.3a	97.2 b
Significance												
Cropping sequence (CS)		NS	***	**	NS	*	***	*	**	**	**	***
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Year (Y)		***	**	***	**	NS	***	NS	*	NS	NS	*
CS × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CS × FM × Y		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

‡ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

than in durum-annual forage sequences. Greater NH_4-N content in 2010 than in 2009 and 2011 was likely a result of greater precipitation (Table 1) (598 mm annual precipitation in 2009) that probably increased N mineralization.

Greater amount of NO_3-N content at most depths in CSW and W-P/B-F than in CA was clearly a result of N fertilization to spring wheat and pea/barley hay but not to alfalfa. Nitrogen fertilizer was applied to spring wheat every year in CSW and to spring wheat and pea/barley hay in two out of three years in W-P/B-F. Although alfalfa can fix N from the atmosphere, most of N is released only after the residue is returned to the soil (Rasse et al., 1999; Kavdir et al., 2005). However, leaf loss during harvest activities may contribute up to 35% of the total aboveground biomass for alfalfa (Tomm et al, 1995). In contrast, alfalfa can remove NO_3-N from the soil during its growth due its higher root biomass compare to durum-annual forage sequences, thereby reducing the potential for N leaching (Sainju and Lenssen, 2011). Alfalfa can reduce soil NO_3-N content during its growth due to N uptake but increase the potential for N leaching after the plant is terminated, since its residue can supply large amounts of N in the soil (Rasse et al., 1999; Kavdir et al., 2005). As with NH_4-N content, greater NO_3-N content at most depths in 2009 and 2010 than in 2011 was probably due to increased precipitation that resulted in increased N mineralization.

Soil Temperature and Water Content

Soil temperature and water content at 0-15 cm varied with cropping sequence and year, with significant interactions for fallow management × cropping sequence and cropping sequence × date of measurement in 2010 and 2011 (Table 9). Fallow management and its interaction with date of measurement on soil temperature and water content were not significant.

Table 9. Effects of fallow management and cropping sequence on soil temperature and water content at the 0-15 cm depth averaged across measurement dates from May to October, 2010 and 2011.

Fallow management†	Cropping sequence‡	Soil water content			Soil temperature		
		2010	2011	Mean	2010	2011	Mean
		---------- cm^3 cm^{-3} -------------			-------------- ^oC ---------------		
CHEM	CA	0.230b§	0.227ab	0.229a	14.5b	13.9b	14.2a
	CSW	0.235b	0.223bc	0.229a	15.1ab	14.8a	14.9a
	W-P/B-F	0.242a	0.224b	0.233a	15.4a	14.9a	15.1a
GRAZ	CA	0.229b	0.236a	0.232a	14.8b	13.4b	14.1a
	CSW	0.230b	0.210c	0.220a	16.0a	14.8a	15.1a
	W-P/B-F	0.232b	0.215c	0.224a	15.4a	14.8a	15.1a
<u>Means</u>							
CHEM		0.236a	0.220a	0.230a	15.0a	14.5a	14.8a
GRAZ		0.230a	0.225a	0.225a	15.2a	14.4a	14. 8a
	CA	0.230b	0.232a	0.231a	14.7b	13.7b	14.2b
	CSW	0.232b	0.217b	0.225a	15.3a	14.8a	15.0a
	W-P/B-F	0.237a	0.219b	0.228a	15.4a	14.8a	15.1a
<u>Significance</u>							
Fallow management (FM)		NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		***	***	NS	***	***	***
FM × CS		*	**	NS	*	***	NS
Date of measurement (D)		***	***	NS	***	***	NS
FM × D		NS	NS	NS	NS	NS	NS
CS × D		***	***	*	***	***	NS
FM × CS × D		NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Fallow managements are CHEM, weed controlled by herbicide application; and GRAZ, weed controlled by sheep grazing.

‡Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Soil temperature increased from May to August and then declined, regardless of treatments. Soil temperature was greater in CSW and W-P/B-F than in CA in July 2010 and June to August 2011 (Fig. 4). Averaged across measurement dates, soil temperature was greater in W-P/B-F than in CA in CHEM and greater in CSW and W-P/B-F than in CA in GRAZ in 2010 (Table 9). In 2011, soil temperature was greater in CSW and W-P/B-F than in CA in CHEM and GRAZ in 2011. Lower biomass yield (Tables 2 and 3), followed by increased exposure to the soil during the fallow period likely reduced shade intensity and increased soil temperature in CSW and W-P/B-F than in CA. Sainju et al. (2010b) have reported that lower crop biomass yield reduces shade intensity and increases soil temperature.

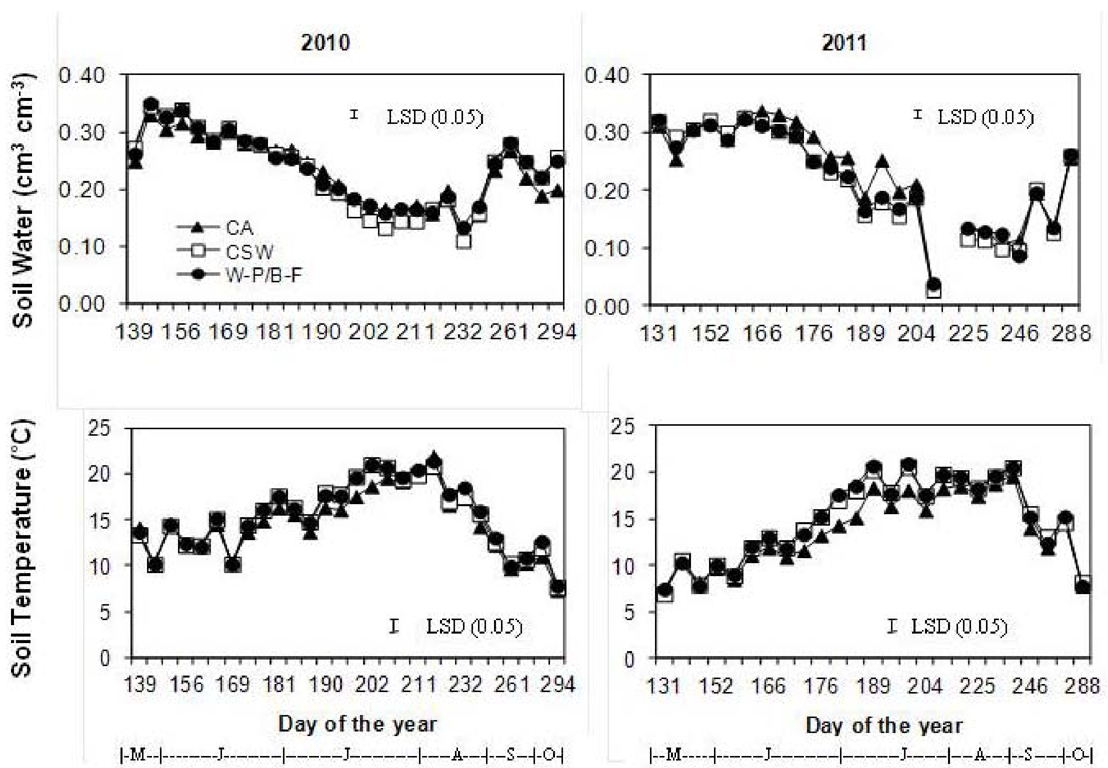

Fig. 4. Soil temperature and water content at the 0- to 15-cm depth as influenced by cropping sequence from May to October, 2010 and 2011. Cropping sequences were CA, continuous alfalfa; CSW, continuous spring wheat, and W-P/B-F, spring wheat-pea/barley hay-fallow. LSD (0.05) is the least significant difference between treatments at P = 0.05. Capital letters below the X-axis denote month.

Soil water content varied with measurement dates and responded to precipitation (Table 9, Figs. 3 and 4). Water content was greater in CSW and W-P/B-F than in CA in June, September, and October but greater in CA and W-P/B-F than in CSW in July and August in 2010 (Fig. 4). In 2011, water content was greater in CA than in CSW and W-P/B-F in June and July. Compared to other treatments, water content, averaged across measurement dates, was greater in CHEM with W-P/B-F in 2010 and in GRAZ with CA in 2011 (Table 9). Averaged across fallow management and measurement dates, water content was greater in W-P/B-F than in CA and CSW in 2010 but was greater in CA than in CSW and W-P/B-F in 2011.

The greater soil water content in CHEM with W-P/B-F in 2010 was probably a result of lower water use by pea/barley hay and increased water conservation during fallow. Pea/barley hay uses less water than durum because of early harvest and absence of plants during fallow which increases soil water content (Lenssen et al., 2010). Although sheep grazing is effective in controlling weeds, it may not be as effective as herbicide application, since some weed roots and plants may survive for a longer period (Hatfield et al., 2007c). As a result, surviving plants may use some soil water until they are completely controlled in the grazing treatment. This probably resulted in lower water content in all cropping sequences in the grazing treatment in 2010. In contrast, hail damaged plant stands and the removal of alfalfa forage by sheep grazing probably reduced water uptake and increased soil water content in GRAZ with CA in 2011. Differences in soil temperature and water content among treatments may influence greenhouse gas emissions, as described below.

Greenhouse Gas Emissions

Carbon Dioxide

Carbon dioxide flux varied with cropping sequence and date of sampling in 2010 and 2011 (Table 10). Significant interactions were observed for fallow management × cropping sequence and fallow management × date of sampling in 2010 and 2011 and cropping sequence × date of sampling in 2011. Fallow management did not influence CO_2 flux.

The flux ranged from 4 kg C ha^{-1} d^{-1} in October to 28 kg C ha^{-1} d^{-1} in July 2011 (Figs. 5 and 6). The peak value of CO_2 flux in this experiment was lower than the values of 80 to 160 kg C ha^{-1} d^{-1} under spring wheat in western Canada (Curtin et al., 2000) and 57 kg C ha^{-1} d^{-1} under malt barley in eastern Montana (Sainju et al., 2010a), both measured by the dynamic chamber method, but greater than 16 kg C ha^{-1} d^{-1} under fallow in North Dakota measured by the static chamber method (Liebig et al., 2010). Differences in soil and environmental conditions and management practices among locations and measurement methods can influence CO_2 emissions (Sainju et al., 2012).

Carbon dioxide flux was greater in CHEM than in GRAZ in mid-June and September but was greater in GRAZ than in CHEM in May, late June and August in 2010 (Fig. 5). In 2011, CO_2 flux was greater in GRAZ than in CHEM in May and July. Increased C substrate availability from sheep feces and urine probably increased microbial activity during periods of elevated soil temperature and water content, thereby increasing CO_2.

Table 10. Effects of fallow management and cropping sequence on total greenhouse gas fluxes from May to October, 2010 and 2011

Fallow management†	Cropping sequence‡	Total CO_2 flux			Total N_2O flux			Total CH_4 flux		
		2010	2011	Mean	2010	2011	Mean	2010	2011	Mean
		-------------Mg C ha^{-1}---------			-----------kg N ha^{-1}-----------			-----------kg C ha^{-1}-----------		
CHEM	CA	2.33ab§	1.67ab	2.00ab	0.84d	0.42c	0.63d	0.21a	0.10a	0.16a
	CSW	2.03b	1.51b	1.77b	4.11a	0.79b	2.35a	0.13a	0.04a	0.08a
	W-P/B-F	1.64c	1.22c	1.43c	1.62c	0.51c	1.03d	0.15a	0.03a	0.09a
GRAZ	CA	2.47a	1.86a	2.17a	3.14b	0.39c	1.76b	0.24a	0.01a	0.17a
	CSW	1.77bc	1.24c	1.51bc	3.92a	1.35a	2.58a	0.22a	-0.04a	0.09a
	W-P/B-F	1.87bc	1.40bc	1.63bc	1.92c	0.74b	1.33bc	0.14a	-0.10a	0.07a
<u>Means</u>										
CHEM		2.00a	1.47a	1.73a	2.19a	0.57a	1.33a	0.16a	0.02a	0.11a
GRAZ		2.04a	1.50a	1.77a	2.99a	0.83a	1.89a	0.20a	0.02a	0.11a
	CA	2.40a	1.77a	2.08a	1.99b	0.40c	1.20b	0.22a	0.03a	0.16a
	CSW	1.90b	1.37b	1.64b	4.02a	1.07a	2.46a	0.18ab	0.02b	0.09b
	W-P/B-F	1.75b	1.31b	1.53c	1.77b	0.62b	1.18b	0.15b	0.02b	0.08b
<u>Significance</u>										
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		***	***	***	***	***	***	*	*	*
FM × CS		***	***	***	***	***	**	NS	NS	NS
Date of Sampling (D)		***	***	***	***	***	***	***	***	***
FM × D		**	*	NS	*	**	NS	***	***	NS
CS × D		NS	***	NS	***	***	***	NS	NS	NS
FM × CS × D		NS	NS	NS	NS	NS	***	NS	NS	NS

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively; NS, not significant.

† Fallow managements are CHEM, weed controlled by herbicide application; and GRAZ, weed controlled by sheep grazing.

‡Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

flux in GRAZ during this time. Total CO_2 flux from May to October, however, was not influenced by fallow management (Table 10). Carbon dioxide flux was greater in CA than in CSW and W-P/B-F in June, July, and August 2010 and in June and July 2011 (Fig. 6). Total CO_2 flux from May to October was greater in GRAZ with CA in than in other treatments, except in CHEM with CA in 2010 and 2011 (Table 10). Averaged across fallow management and sampling dates, total CO_2 flux was greater in CA than in CSW and W-P/B-F. Averaged across treatments, total CO_2 flux was greater in 2010 than in 2011.

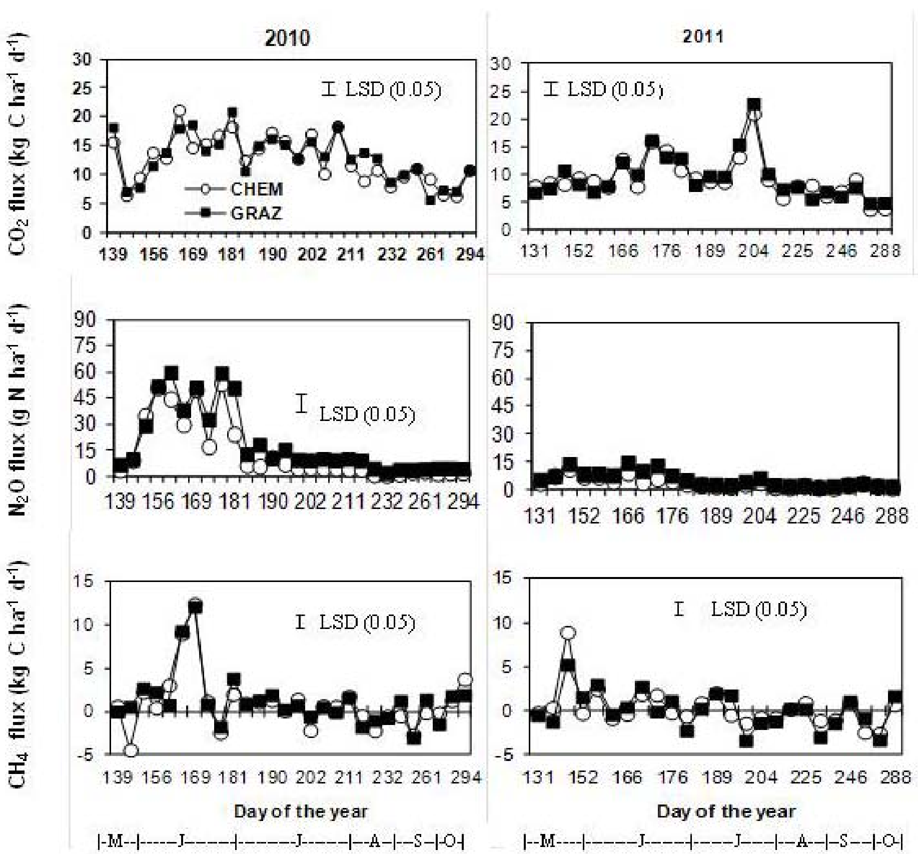

Fig. 5. Effect of fallow management on soil greenhouse gas fluxes from March to October, 2010 and 2011. Fallow management practices were CHEM, weeds controlled by herbicide application; and GRAZ, weeds controlled by sheep grazing. LSD (0.05) is the least significant difference between treatments at $P = 0.05$. Capital letters below the X-axis denote month.

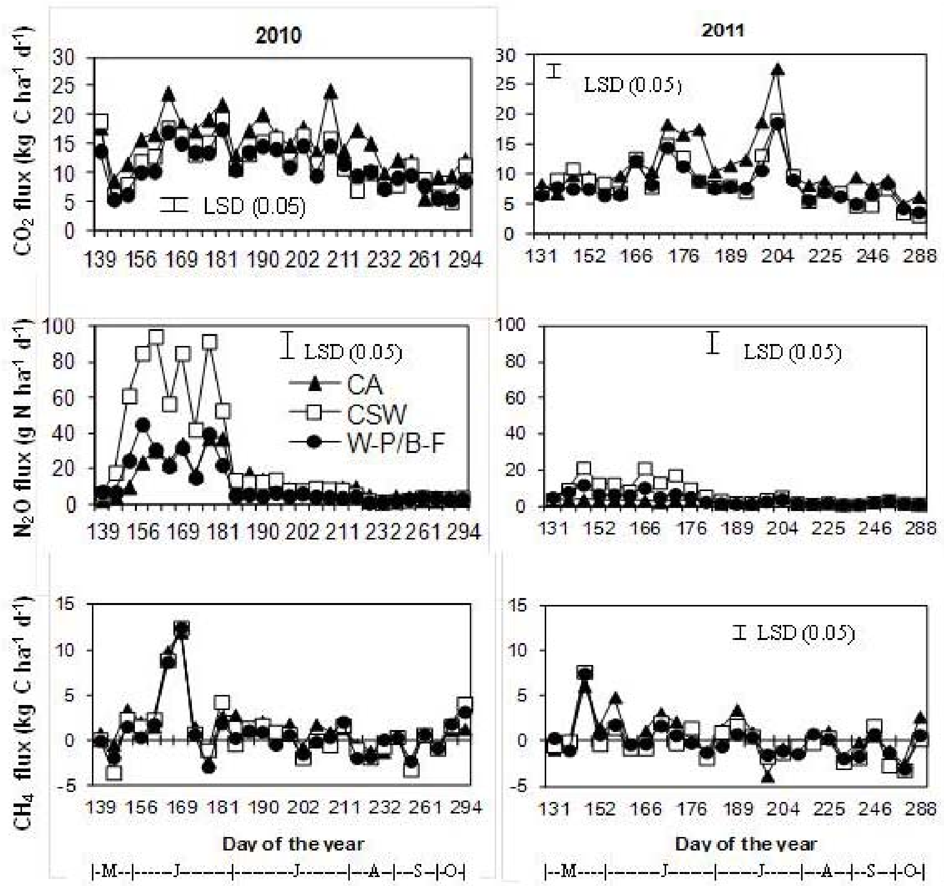

Fig. 6. Effect of cropping sequence on soil greenhouse gas fluxes from May to October, 2010 and 2011. Cropping sequence were CA, continuous alfalfa; CSW, continuous spring wheat; and W-P/B-F, spring wheat-pea/barley hay-fallow. LSD (0.05) is the least significant difference between treatments at P = 0.05. Capital letters below the X-axis denote month.

The greater CO_2 flux in CA than in CSW and W-P/B-F in CHEM and GRAZ treatments was probably a result of greater root respiration due to higher belowground biomass in the perennial alfalfa system compared to annual cropping systems. It has been reported that alfalfa has higher root biomass than durum and annual forages (Sainju and Lenssen, 2011) and CO_2 flux is higher under grasses containing a mixture of alfalfa and other grasses than under annual crops (Sainju et al., 2008). Similarly, greater CO_2 flux in CSW than in W-P/B-F in CHEM (Table 10) was likely a result of greater amount of spring wheat biomass residue returned to the soil, since wheat residue was returned annually in CSW compared to one in three years in W-P/B-F. Several researchers (Curtin et al., 2000, Amos et al., 2005) have also reported greater CO_2 flux in cropping systems with increased amount of crop residue returned to the soil. Absence of plants during fallow also may have reduced root respiration and therefore CO_2 flux in W-P/B-F. In the GRAZ treatment, consumption of residue by sheep during grazing may have resulted in similar CO_2 fluxes between CSW and W-P/B-F. Greater CO_2 flux in 2010 than in 2011 was likely a result of greater precipitation and soil water content during the measurement period (Tables 1, 9, and 10).

To evaluate the effect of crop species on CO_2 flux, data have been analyzed by cropping phases in W-P/B-F. Carbon dioxide flux was greater under pea/barley hay than under spring wheat and fallow from May to July 2010 but was greater under spring wheat than under pea/barley hay and fallow in May and August 2011 (Fig. 7). Averaged across measurement dates, soil temperature and water content were greater under fallow than under spring wheat and pea/barley hay in 2010 and 2011 (Table 11). Total CO_2 flux from May to October was greater under pea/barley hay than under spring wheat and fallow in 2010 but not different among crop species in 2011.

Greater CO_2 flux under pea/barley hay than under spring wheat and fallow in 2010 could be a result of higher soil total C content. Soil total C was greater in pea/barley hay than in spring wheat at 0-5 and 0-30 cm and greater than fallow at 0-90 and 0-120 cm (Table 12). Probably, greater C substrate availability increased CO_2 flux in pea/barley hay compared to spring wheat and fallow. Although soil temperature and water content were greater in fallow (Fig. 8, Table 11), they had minimum effect on CO_2 flux. This shows that substrate availability is probably equally important as soil temperature and water content for CO_2 emissions under dryland cropping systems.

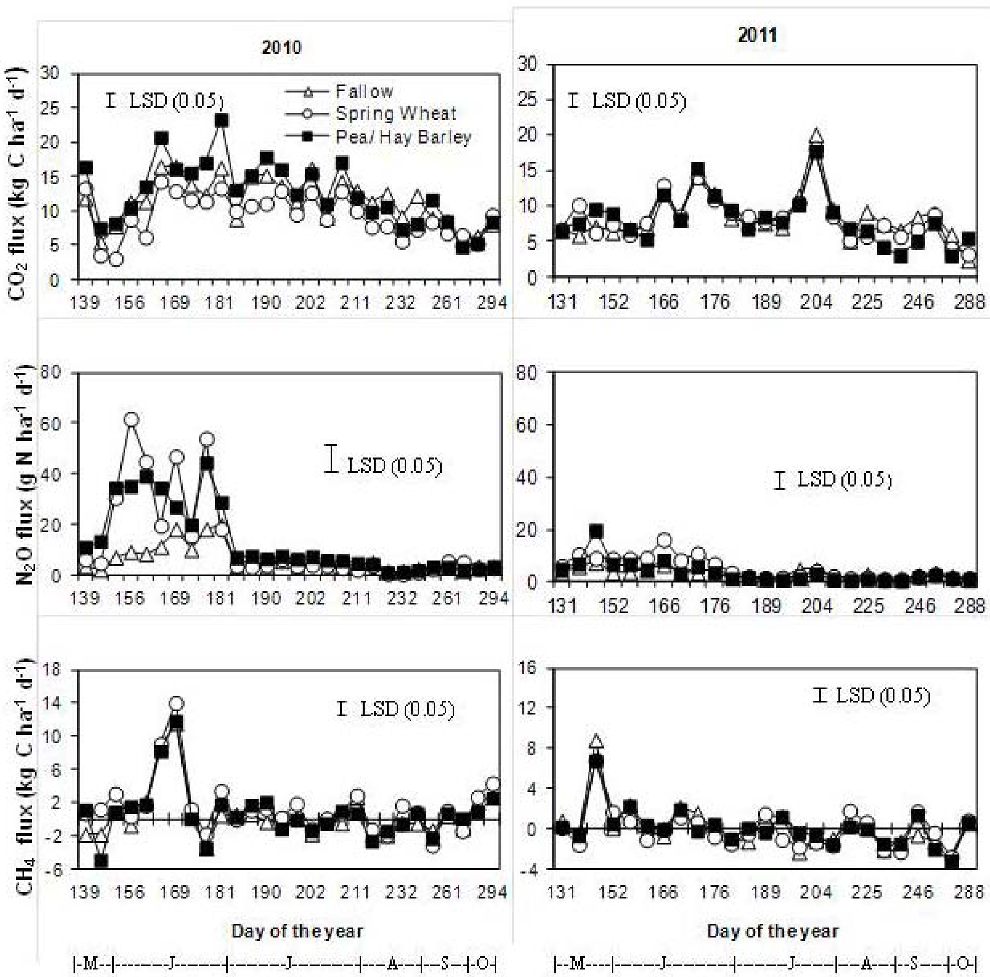

Fig. 7. Effect of cropping phase on soil greenhouse gas fluxes in spring wheat-pea/barley hay-fallow rotation from May to October, 2010 and 2011. LSD (0.05) is the least significant difference between treatments at P = 0.05. Capital letters below the X-axis denote month.

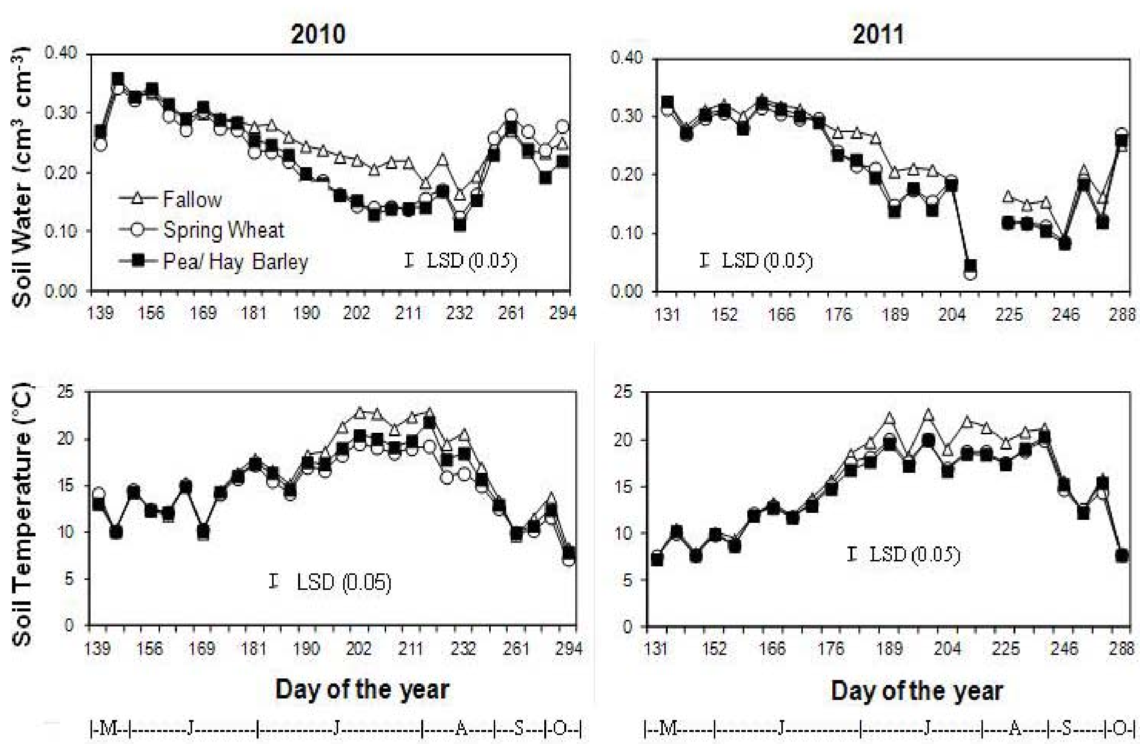

Fig. 8. Effect of cropping phase on soil temperature and water content at the 0- to 15-cm depth in the spring wheat-pea/barley hay-fallow rotation from May to October, 2010 and 2011. LSD (0.05) is the least significant difference between treatments at P = 0.05. Capital letters below the X-axis denote month.

Nitrous Oxide

Similar to CO_2 flux, N_2O flux varied with cropping sequence and date of sampling but not with fallow management in 2010 and 2011 (Table 10). Interactions were significant for cropping sequence × fallow management, fallow management × date of sampling, and cropping sequence × date of sampling in both years.

Table 11. Effect of crop species on average soil temperature and soil water content and total greenhouse gas fluxes in spring wheat-pea/barely hay-fallow rotation from May to October, 2010 and 2011.

	Soil water content		Soil temperature		Total CO_2 flux		Total N_2O flux		Total CH_4 flux	
Crop species	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	------cm^3cm^{-3}-------		--------°C----------		----Mg C ha^{-1}---		----kg N ha^{-1}----		----kg C ha^{-1}------	
Fallow	0.255a†	0.236a	16.2a	15.6a	1.81b	1.34a	0.98b	0.52b	0.09b	0.01a
Spring wheat	0.229b	0.212b	14.7c	14.5b	1.47c	1.31a	2.03a	0.79a	0.24a	-0.01a
Pea/barley	0.227b	0.211b	15.3b	14.4b	1.98a	1.27a	2.08a	0.57a	0.11b	0.02a

† Numbers followed by the different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

Table 12. Effect of crop species on soil total C and NO_3-N contents at the 0-120 cm depth averaged across years in spring wheat-pea/ barley hay-fallow rotation in late fall.

	Soil depth										
Crop species	0-5 cm	5-15 cm	15-30 cm	30-60 cm	60-90 cm	90-120 cm	0-15 cm	0-30 cm	0-60 cm	0-90 cm	0-120 cm
					Soil total C (Mg C ha^{-1})						
Fallow	17.7ab†	34.1a	39.9a	41.3a	64.4b	72.4a	51.7ab	91.6a	132.9a	197.3b	269.7b
Pea/barley	18.1a	35.0a	38.5a	42.5a	69.6ab	73.1a	53.1a	91.5a	133.3a	203.6a	276.6a
Spring wheat	16.7b	33.3a	39.3a	38.6a	73.9a	73.4a	50.0b	89.2b	130.8a	201.7ab	277.0a
					Soil NO_3-N content (kg N ha^{-1})						
Fallow	17.1a	30.7a	37.9a	33.6a	33.7a	32.4a	47.8a	85.7a	119.3a	153.0a	185.3a
Pea/barley	14.9a	21.5b	28.0b	12.9b	15.9b	27.7a	36.4b	64.4b	77.3b	93.2b	120.9b
Spring wheat	6.1b	13.1c	12.9c	9.1b	10.1c	19.5b	19.2c	32.1c	41.2c	51.2c	70.7c

† Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

Nitrous oxide flux peaked from 1 g N ha^{-1} d^{-1} in May 2011 to 90 g N ha^{-1} d^{-1} in June 2010 (Figs. 5 to 7). Most of the fluxes (>70%) occurred from May to July, regardless of treatments and years. The N_2O flux range observed in this experiment was within or greater than the range of -8 to 21 g N ha^{-1} d^{-1} under spring wheat-pea rotation and fallow in western Montana and central North Dakota (Dusenbury et al., 2008; Liebig et al., 2010). The greater N_2O flux from May to July was likely due to both N fertilization and increased soil water content from substantial precipitation (>12 mm) (Figs. 3 and 4). Several studies (Mosier et al., 2006; Dusenbury et al., 2008; Liebig et al., 2010) found increased N_2O flux immediately after N fertilization and/or substantial precipitation.

Nitrous oxide flux was greater in GRAZ than in CHEM in June and July 2010 and 2011 (Fig. 5). Similarly, N_2O flux was greater in CSW than in CA and W-P/B-F in June 2010 and greater in CSW and W-P/B-F than in CA in June and July 2011 (Fig. 6). Total N_2O flux from May to October was greater with CSW than with CA and W-P/B-F in CHEM and GRAZ in 2010 and 2011 (Table 10). Averaged across fallow management and sampling dates, total N_2O flux was greater in CSW than in CA and W-P/B-F in 2010 and greater in CSW and W-P/B-F than in CA in 2011. Averaged across treatments, N_2O flux was greater in 2010 than in 2011.

The greater N_2O flux in CSW and W-P/B-F than in CA in June and July was clearly a result of N fertilization to spring wheat and pea/barley hay during periods of higher temperature and precipitation. Nitrogen fertilizer was applied to spring wheat at 202 kg N ha^{-1} in CSW and at 252 kg N ha^{-1} in W-P/B-F and to pea/barley hay at 134 kg N ha^{-1} in W-P/B-F but none was applied to alfalfa. Increased N substrate availability due to

N fertilization was shown to increase N_2O flux due to enhanced nitrification (Drury et al., 2006; Mosier et al., 2006; Dusenbury et al., 2008). Although legumes can produce significant N_2O emissions due to their lower C:N ratio compared to nonlegumes (Mosier et al., 2006; Dusenbury et al., 2008), N_2O flux from alfalfa in CA had been minimal. Greater N_2O flux in 2010 than in 2011 may be a result of increased precipitation and soil temperature and water content (Tables 1 and 9), that stimulated microbial activity and N mineralization (Parkin and Kaspar, 2003; Dusenbury et al., 2008; Liebig et al., 2010).

Among cropping phases within W-P/B-F, N_2O flux was greater under spring wheat and pea/barley hay than under fallow in June and July, 2010 and 2011 (Fig. 7). Total N_2O flux from May to October was greater under spring wheat and pea/barley hay than under fallow in both years (Table 11). Although soil temperature and water content during the sampling period and NO_3-N content after crop harvest in the fall were greater under fallow than under spring wheat and pea/barley hay (Tables 11 and 12), N fertilization in May probably increased N_2O flux under spring wheat and pea/barley hay. Most nitrification process likely occurred in June and July, resulting in greater N_2O flux under spring wheat and pea/barley hay. This shows that N fertilization was probably the dominant factor for N_2O emissions compared to soil temperature and water content.

<u>Methane</u>

Methane flux varied with cropping sequence and date of sampling in 2010 and 2011, with a significant fallow management × date of sampling interaction in both years (Table 10). The CH_4 flux ranged from -5 g C $ha^{-1}d^{-1}$ in May to 15 g C $ha^{-1}d^{-1}$ in June

2010 (Figs. 5 to 7). This range was within or greater than the range of -12 to 5 g C ha^{-1} d^{-1} under dryland spring wheat-fallow and fallow systems in western Nebraska and central North Dakota (Kessavalou et al., 1998; Liebig et al., 2010). About half of the flux was negative, suggesting CH_4 uptake by soil. It is not unusual for dryland soil to act as sink for CH_4 due to its consumption by methanotrophs (Sylvia et al., 1998) and CH_4 uptake can be higher as soils become drier (Liebig et al., 2010).

Methane flux was greater in GRAZ than in CHEM in May and June 2010 and July 2011 but was greater in CHEM than in GRAZ in early June 2010 and 2011 and September 2011 (Fig. 5). Averaged across fallow management practices, total CH_4 flux from May to October was greater in CA than in W-P/B-F in 2010 and greater in CA than in CSW and W-P/B-F in 2011. Averaged across treatments, total CH_4 flux was greater in 2010 than in 2011.

Although manure management has been reported to be a significant source of CH_4 flux (USEPA, 2011), sheep grazing does not appear to produce substantial CH_4 emissions compared to herbicide application for weed control, since CH_4 flux varied with fallow management during the sampling period, with nonsignificant effect on overall flux. Greater CH_4 flux in CA than in CSW and W-P/B-F was probably a result of N fertilization, since N fertilizer was not applied to CA but was applied to CSW and W-P/B-F. Nitrogen fertilization has variable effect on CH_4 emissions (Bronson and Mosier, 1994; Powlson et al., 1997; Amos et al., 2005; Mosier et al. 2006). Greater CH_4 flux in 2010 than in 2011 was probably a result of higher precipitation, soil temperature and water content (Tables 1 and 9) that stimulated microbial activity and C mineralization.

Crop species effect on CH_4 flux within W-P/B-F during the sampling period was minimal (Fig. 7). Total CH_4 flux from May to October was, however, greater under spring wheat than under fallow and pea/hay barley in 2010 (Table 11). Since N fertilizer was applied at 252 kg N ha^{-1} to spring wheat and 134 kg N ha^{-1} to pea/barley hay but not to alfalfa, it appeared that N fertilization promoted CH_4 flux under spring wheat. Several researchers (Bronson and Mosier, 1994; Powlson et al., 1997) have reported N fertilization increased soil CH_4 flux compared to no N fertilization due to competitive inhibition at the enzyme level, while others (Amos et al., 2005; Mosier et al. 2006) found no effect of N fertilization on the flux.

Global Warming Potential

Factors affecting CO_2 emissions responsible for GWP in each treatment are described in Table 13. Equipment used for farm operations, such as planting, fertilization, harvest, and herbicide and pesticide applications consume fuel and therefore emit CO_2. Since sheep grazing controls weeds by consuming plants during fallow periods (Entz et al., 2002), CO_2 emissions associated with equipment use were lower in the grazing than in the chemical treatment. In CA, equipment was used only for initial planting and annual hay harvest in the chemical treatment and planting in the grazing treatment; therefore CO_2 emissions were lower in CA than in other cropping sequences.

Carbon dioxide equivalents of N fertilizer production and application varied by treatments and years because of differences in N fertilization rates as a result of variations in the ability of crops for N uptake and residual NO_3-N levels in soil after crop harvest in

Table 13. Effects of fallow management and cropping sequence on net global warming potential (GWP) and greenhouse gas intensity (GHGI).

FM†	CS‡	Farm operation (A)§	N fertilizer (B)¶	N_2O flux (C)#	CH_4 flux (D)#	CH_4 flux enteric fermentation (E)††	C sequestration rate (0-15 cm) (F)‡‡	Net GWP (G) §§	Annualized grain and/or biomass yield (H)¶¶	GHGI (I)##
		---------------------kg CO_2 equiv. ha^{-1} yr^{-1}----------------------------						Mg CO_2 equiv. ha^{-1} yr^{-1}	kg ha^{-1}	kg CO_2 equiv. ha^{-1} yr^{-1} kg^{-1} grain and/or biomass
						2010				
Chem	CA	8	0	992	8	0	-8950	9.96	6407	1.55
	CSW	85	480	4854	5	0	-8950	14.37	2774	5.28
	W-P/B-F	85	303	1913	6	0	-8950	11.26	3332	4.31
Graz	CA	4	0	3709	10	527	-8950	13.20	7387	1.79
	CSW	65	512	4630	9	1123	-8950	15.29	2818	5.43
	W-P/B-F	65	323	2268	6	2088	-8950	13.70	2887	2.65
						2011				
Chem	CA	8	0	496	4	0	-8950	9.46	6407	1.48
	CSW	85	383	933	2	0	-8950	10.35	1768	5.91
	W-P/B-F	85	155	602	2	0	-8950	9.79	3172	3.09
Graz	CA	4	0	461	4	527	-8950	9.95	7387	1.35
	CSW	65	348	1594	-2	263	-8950	11.22	1173	9.56
	W-P/B-F	65	269	874	-1	1295	-8950	11.45	2734	4.19

† Fallow managements are chemical where herbicide is applied and grazing where sheep are grazed to control weeds.

‡ Cropping sequence are CA, continuous alfalfa; CSW, continuous spring wheat, and W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Fuel combustion for equipments used for planting, fertilization, herbicide and pesticides applications, and harvest (estimated from Mosier at al., 2005).

¶ N fertilizer production = 45.5 kg CO_2 ha^{-1} for application + 3.0 kg CO_2 kg^{-1} N applied (Follett, 2001).

Total gas flux from linear interpolation of flux measurements from May to October + 27% of the total fluxes from November to April (Liebig et al., 2010). 1 kg N_2O ha^{-1} = 298 kg CO_2 ha^{-1} and 1 kg CH_4 ha^{-1} = 25 kg CO_2 ha^{-1} (IPCC, 2007).

†† Enteric fermentation of sheep for CH_4 flux = 488 g CO_2 $sheep^{-1}$ d^{-1} (Judd et al., 1999).

‡‡ Carbon sequestration rate calculated from linear regression of change in soil organic C at the 0-5 cm depth from 2009 to 2011.

§§ Column (G) = Column (A) + Column (B) + Column (C) + Column (D) + Column (E) – Column (F).

¶¶ Annualized spring wheat grain yield or (spring wheat grain + pea/barley biomass) yield or alfalfa biomass yield removed from the soil.

Column (I) = Column (G)/Column (H).

the fall. Nitrogen fertilization rates also varied by grain yield goals for spring wheat which were 3.87 and 4.84 Mg ha^{-1} in CSW (202 kg N ha^{-1}) and W-P/B-F (252 kg N ha^{-1}), respectively. Since alfalfa fixes N from the atmosphere, no N fertilizer was applied. Because of non-N fertilization and absence of crops during fallow, CO_2 equivalent was lower in W-P/B-F than in CSW.

Nitrous oxide emission is the largest source of GWP from the agroecosystem due to its potent nature (Robertson et al., 2000; Mosier et al., 2005, 2006). For estimating GWP and GHGI, total annual N_2O and CH_4 emissions were calculated by adding total emissions from May to October with emissions from December to April, which were assumed to be 27% of the total annual emissions under dryland cropping systems (Liebig et al., 2010). Nitrous oxide emissions accounted for 19 to 136% of GWP (Table 13). Carbon dioxide equivalent of N_2O emissions was greater in CSW than in other cropping sequences in both chemical and grazing treatments in 2010 and 2011 due to greater N fertilization rate. Although no N fertilizer was applied to CA, it still produced N_2O flux, probably due to leaf fall and incorporation of root residue into the soil. In alfalfa, the amount of leaves returned to the soil due to litter fall and harvest loss constitutes about 35% of the total aboveground biomass (Tomm et al., 1995) and leaf fall can contribute substantial emissions of N_2O (Pal et al., 2012). The fact that greater CO_2 equivalent of N_2O emissions occurred in CA in the grazing than in the chemical treatment in 2010 was likely a result of greater leaf fall due to hailstorm damage and/or increased urine and feces returned to the soil during sheep grazing. Emissions of greenhouse gases from agricultural ecosystems are highly variable (Parkin, 1985) and uneven distribution of animal feces and urine during grazing (Abaye et al., 1997) can further increase the variability of estimates.

In contrast to N_2O emissions, CO_2 equivalent of CH_4 emissions was usually low (≤10 kg CO_2 equivalent ha^{-1} yr^{-1}). Although some treatments acted as a CH_4 sink, most were minor emitters of CH_4, probably the results of anaerobic conditions in soil aggregates (Gregorich et al., 2006) and/or additions of sheep urine and feces to the soil. Estimated methane emissions due to enteric fermentation from sheep contributed a large amount of CO_2 equivalent in the grazing treatment (Judd et al., 1999). The emissions varied among cropping sequences due to differences in number and duration of sheep grazed in each treatment and year, which ranged from 539 sheep ha^{-1} yr^{-1} in CSW in 2011 to 4280 sheep ha^{-1} yr^{-1} in W-P/B-F in 2010 in the grazing treatment.

Carbon sequestration calculated from the linear regression of changes in soil organic C levels at the 0-15 cm depth declined from 2009 to 2011, regardless of treatments (Table 13). All treatments were CO_2 emitters. Since the experiment was initiated in 2009, it could be possible that soil C levels were not stabilized and high variability existed among treatments. Changes in soil organic C levels are slow during a short period due to inherent spatial variability (Franzluebbers et al., 1995). Long-term experiments are needed to estimate C sequestration rates. Most researchers (Robertson et al., 2000; Mosier et al., 2005, 2006) have used a time span of 10 years to estimate C sequestration rates for calculating net GWP.

The calculated net GWP of 9.46 to 14.37 Mg CO_2 equivalents ha^{-1} yr^{-1} obtained in this experiment were much higher than the reported ranges of -803 to 311 kg CO_2

equivalents ha^{-1} yr^{-1} under dryland cropping systems in Colorado and Michigan (Robertson et al., 2000; Robertson and Grace, 2004; Mosier et al., 2005). Differences in soil and climatic conditions, management practices, and duration of the experiment likely influenced estimated GWP among locations. Although GWP varied among treatments and years, all treatments were sources of GWP. An explanation for this might be higher N_2O emissions and enteric fermentation of CH_4 in the grazing treatment and higher CO_2 sources in all treatments (Robertson et al., 2000; Robertson and Grace, 2004; Mosier et al., 2005), since all treatments lost soil total C from 2009 to 2011 (Table 4). Increased N fertilization rates to spring wheat increased N_2O emissions and therefore net GWP in CSW compared to other cropping sequences. Greater GWP in the grazing than in chemical treatment was due to higher enteric fermentation of CH_4.

Alfalfa biomass was not measured in 2010. For calculating GHGI, however, alfalfa biomass yield in 2010 was assumed to be similar to that in 2011. Annualized spring wheat grain yield in CSW was similar between fallow management practices in 2010 but was greater in the chemical than in the grazing treatment in 2011. Similarly, annualized spring wheat grain and pea/barley biomass yields in W-P/B-F were greater in the chemical than in the grazing treatment in both years. It is not surprising that alfalfa and pea/barley biomass was greater than spring wheat grain yield but alfalfa biomass yielded higher than pea/barley biomass in 2011.

The GHGI ranged from 1.35 to 9.56 kg CO_2 equivalents ha^{-1} yr^{-1} kg^{-1} grain and/or biomass which were r greater than the values of 0.01 to 0.36 kg CO_2 equivalents ha^{-1} yr^{-1} kg^{-1} grain yield reported for irrigated cropping systems (Mosier et al., 2006). The GHGI values in both fallow management practices followed the order: CSW>W-P/B-F>CA, probably due to lower grain yield in CSW compared to grain and/or biomass yields in other cropping sequences. Average GHGI across cropping sequences and years was greater in the grazing than in chemical treatment (4.16 vs. 3.60 kg CO_2 equivalents ha^{-1} yr^{-1} kg^{-1} grain and/or biomass) and was greater in 2011 than in 2010 (4.26 vs. 3.50 kg CO_2 equivalents ha^{-1} yr^{-1} kg^{-1} grain and/or biomass) due to greater GWP.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Fallow management and cropping sequence influenced soil C and N levels, greenhouse gas emissions, and global warming potential by returning various amounts of C and N through crop residue, feces, and urine to the soil and consumption of weeds and crop residue by sheep grazing in dryland cropping systems. Spring wheat grain and biomass yields and C and N contents were greater in W-P/B-F than in CSW but pea/barley and alfalfa biomass and C content were similar for W-P/B-F and CA. Annualized spring wheat biomass and C and N returned to the soil were, however, greater in CSW than in W-P/B-F. Soil C and N levels were greater in CSW and W-P/B-F than in CA due to N fertilization and greater amount of crop residue returned to the soil. In contrast, continuous root respiration and the absence of N fertilizer increased CO_2 and CH_4 emissions in CA but N fertilization increased N_2O emissions in CSW and W-P/B-F. While increased C substrate availability increased CO_2 emissions under pea/barley hay, increased N fertilization rate increased N_2O emissions under spring wheat within W-P/B-F. Greenhouse gas emissions usually peaked immediately following precipitation events and/or N fertilization during periods of elevated soil temperature and water content, regardless of treatment. Fallow management had little influence on soil C and N levels and greenhouse gas emissions. Although all treatments were sources of global warming potential, both global warming potential and greenhouse gas intensity were greater in CSW than in other cropping sequences due to increased N_2O emissions and lower C sequestration rate, regardless of fallow management practices. Enteric fermentation emissions increased global warming potential more in the sheep grazing over those from the herbicide application treatment. Because of minimal impacts on crop yields, soil C and N levels, and greenhouse gas emissions, sheep grazing may be used to sustain crop yields and soil and environmental quality compared to herbicide application for weed control during fallow periods. High variability in greenhouse gas emissions and C sequestration rates, however, suggest that long-term experiments are needed to accurately estimate global warming potential and greenhouse gas intensity under dryland cropping systems.

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