NITROUS OXIDE EMISSIONS FROM A NORTHERN GREAT PLAINS SOIL AS INFLUENCED BY NITROGEN FERTILIZATION AND CROPPING SYSTEMS

by

Matthew Paul Dusenbury

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APPROVAL

of a thesis submitted by

Matthew Paul Dusenbury

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency and is ready for submission to the Division of Graduate Education.

Dr. Richard E. Engel
(chair)

Approved for the Department of Land Resources and Environmental Sciences

Dr. Jon M. Wraith

Approved for the Division of Graduate Education

Dr. Joseph J. Fedock

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Matthew Paul Dusenbury

July 17, 2006

For all mankind.

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ABSTRACT

Agriculture has been identified by the Intergovernmental Panel on Climate Change (IPCC) as the major anthropogenic source of N_2O emissions. Field measurements of N_2O emissions are limited for cropping systems in the semi-arid Northern Great Plains (NGP). The study objectives were to determine temporal N_2O emission patterns for NGP cropping systems, and estimate fertilizer N induced emissions (FIE) and contrast with IPCC default methodology. No-till (NT) wheat (*Triticum Aestivum* L.)-fallow, wheat-wheat, and wheat-pea (*Pisum sativum* L.), and a conventional till (CT) wheat-fallow all with three N regimes (200 and 100 kg N ha^{-1} available N, unfertilized N control); plus a perennial grass system (CRP) were sampled over two years (15 Apr 2004 – 14 Apr 2006) using static chambers. Nitrous oxide emissions over two years were 209 to 1310 g N ha^{-1} for the cropping systems. Greatest N_2O emission activity occurred following urea-N fertilization (10-wk) and freeze-thaw cycles. The sum for these periods comprised 73-84% of total emissions. Emissions were positively correlated with urea-N fertilization rates and increased rapidly when water-filled pore was > 50%. Total N_2O-N emissions were greater ($P < 0.10$) from the fertilized (high and moderate N regimes) wheat-wheat system (1193g ha^{-1}) than fertilized wheat-fallow systems (CT and NT) (475 g ha^{-1}), and fertilized wheat-pea (711 g ha^{-1}) systems. Emissions from unfertilized cropping systems (209 to 329 g ha^{-1}) were not different from CRP (284 g ha^{-1}). Tillage (CT vs. NT) did not ($P \geq 0.10$) affect N_2O emissions in the wheat-fallow systems. Fertilizer loss coefficients ranged from 0.08 to 0.45% of the applied N rate and were well below the IPCC loss coefficient of 1.25%. A more realistic estimate of fertilizer-induced losses for this region is suggested at 0.24% ± 0.5 (± 1.0 SE) of the applied N rate, or 0.26% if 10% $NH_{3(g)}$ loss from fertilizer N is assumed. Despite modest emissions compared to more humid regions, there was some evidence emissions could be reduced by efficient N management. Broadcast applying urea-N to established stands of winter wheat in the spring resulted in lower N_2O emissions than band applications at seeding.

CHAPTER 1

REVIEW OF LITERATURE

The Soil Nitrogen Cycle: A Brief Overview

Nitrogen is a polymorphous and dynamic element that is transformed chemically or biochemically through a complex web of reactions referred to as the global N cycle (Figure 1). Within the global N cycle, > 99% of all N exists in the atmosphere as unreactive $N_{2(g)}$. The remainder is distributed among many biologically, photochemically, or radiatively reactive forms such as NO_x or NH_4^+ (Galloway et al., 2003). It is the reactive forms of N that are of greatest interest to scientists because of their essentiality to life and their impact on environmental quality. In the prehuman world, reactive N forms did not accumulate in the environment since N fixation and denitrification were in approximate equilibrium (Ayres et al., 1994). However, this is no longer the case. Reactive forms of N are accumulating in the environment due to anthropogenic activities (Galloway et al., 2003)

The soil N cycle has been described as a subset of the global N cycle (Pierzynski et al., 2005). These include transformations of organic N forms to inorganic forms, a process mediated by heterotrophic microbes and referred to as 'N mineralization'; and transformation of inorganic forms to organic forms a process referred to as 'immobilization.' The soil N cycle is an open system where N can enter the system through anthropogenic inputs such as organic and inorganic fertilizers, or via microbial

symbiotic and non-symbiotic N fixation. Conversely, N may also be lost from soils via leaching of NO_3^-, volatilization of $NH_{3(g)}$, or denitrification of NO_3^- to $N_2O_{(g)}$ or $N_{2(g)}$.

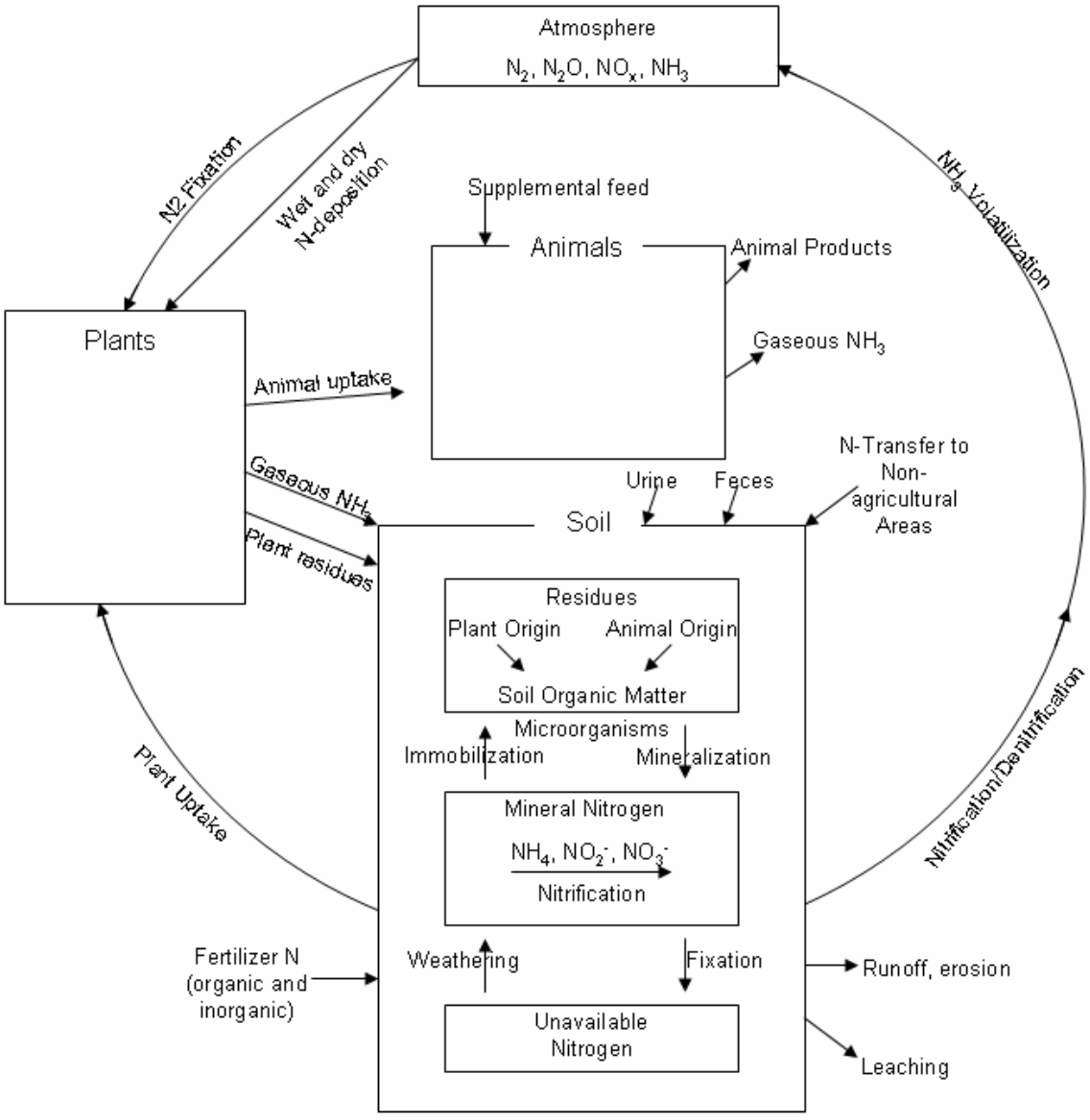

Figure 1. The global nitrogen cycle (Follett, 2001).

Anthropogenic activities have profoundly affected both the soil and global N cycle. As N is often the most limiting nutrient in crop production, it has been

increasingly applied to agricultural lands to sustain the burgeoning human population (Follett, 2001). Cultivation of leguminous and other crops that contribute to N_2 fixation and development of the Haber-Bosch process (Galloway et al., 2003), which converts N_2 to NH_3 for fertilizer production, have contributed to the immense increases in anthropogenic environmental N inputs, now considered to be greater than all natural N inputs (Galloway et al., 2003). As a result of these increases, reactive N forms are accumulating in the environment resulting in wide-ranging environmental impacts. Emissions of gaseous forms of reactive N, including nitrous oxide (N_2O), are potentially among the most environmentally damaging as they can be readily transported over long distances to sensitive habitats (Fenn et al. 2003).

Nitrous Oxide and Greenhouse Gases

Nitrous oxide is one of seven primary greenhouse gases including, carbon dioxide (CO_2), methane (CH_4), ozone (O_3), chlorofluorocarbons (CFC's), hydrochlorofluorocarbons and perfluorocarbons (HCFC's, and PFC's), and sulfur hexafluoride (SF_6) (Pierzynski et al., 2005). These gases are transparent to incoming shortwave solar radiation but absorb outgoing longwave radiation, thereby trapping heat in the atmosphere (Duxbury et al., 1993). Each gas behaves differently in regard to its effect on global warming as a result of its concentration, residence time, and ability to absorb longwave radiation in the atmosphere. Carbon dioxide is the most plentiful with a concentration of 385 ppmv (National Oceanic and Atmospheric Administration, 2006) and contributes approximately 60% of the anthropogenic greenhouse effect (Duxbury et al. 1993). Methane contributes 15% of the anthropogenic greenhouse effect (Lindau et

al. 1993). Although the methane concentration in the atmosphere (1800 ppbv) is much less than CO_2, it is 21 times more effective at trapping heat than CO_2 (Pierzynski et al., 2005). Nitrous oxide contributes approximately 5% of the anthropogenic greenhouse gas effect. Although its concentration in the atmosphere is only 317 ppbv, it has a global warming potential that is 300 times (IPCC, 2001) that of CO_2 due to its longevity in the atmosphere (approximately 150 yr) and high capacity for absorbing longwave radiation (Yung et al., 1976).

Nitrous oxide also demonstrates other adverse environmental effects beyond affecting global warming. The primary pathway of N_2O destruction in the atmosphere is via photochemical reactions (Prinn et al., 1990; Mosier et al., 1996). This leads to the production of NO (Figure 2) where O (^{1}D) denotes an electronically excited energy-rich oxygen atom (Crutzen, 1981). Atmospheric destruction of N_2O is the major source of atmospheric NO (Yung and Miller, 1997; Yan et al. 2000), which is involved in production and destruction of ozone, and generation of photochemical smog and acid rain (Fenn et al., 2003).

$$N_2O + O(^1D) \rightarrow 2\,NO$$

Figure 2. Atmospheric production of NO via N_2O (Nelson, D.W., 1982).

Pathways of Nitrous Oxide Production

Globally, 70% of N_2O emissions to the atmosphere are derived from soils (Bouwman, 1990). Soils are rarely observed as a sink for N_2O (Mosier, 1981; IPCC, 2001). Production of N_2O in the soil is a natural process within the N cycle and occurs

primarily as a result of the microbial processes of nitrification and denitrification (Knowles, 1982; Davidson and Schimel, 1995; Stevens and Laughlin, 1998).

Nitrification

Nitrification is commonly referred to as the microbial oxidation of ammonium (NH_4^+) to NO_2^- and then NO_3^- (Figure 3). The process of nitrification is dominated by autotrophic organisms that require O_2, CO_2, and NH_4^+ to survive, but can also be performed by heterotrophic nitrifiers that can utilize soil organic C (Davidson and Schimel, 1995; Wrage et al., 2001). Nitrous oxide is produced during nitrification as a result of two processes: nitrifier denitrification and chemodenitrification. During nitrifier denitrification (Figure 4), nitrifiers utilize NO_2^- as an electron acceptor and produce N_2O (Wrage et al., 2001). During chemodenitrification, production of N_2O occurs as a result of the abiotic transformations of nitrification intermediates, particularly NH_2OH and NO_2^-, (Chalk and Smith, 1983; Wrage et al., 2001). Several reactions have been proposed to explain chemodenitrification. As shown in Figure 5, nitrite (NO_2^-) reacts with H^+ to produce nitrous acid (HNO_2). Thus, this reaction is most important under acidic conditions, pH < 5 (Stevens and Laughlin, 1998; Wrage et al., 2001). Under Figs. 6 and 7, HNO_2 reacts with phenolic sites on soil organic matter and hydroxylamines, respectively, to produce N_2O (Stevens and Laughlin, 1998).

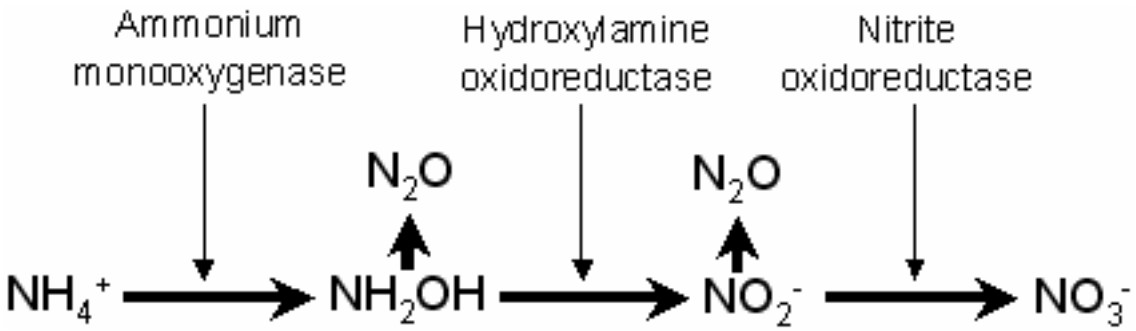

Figure 3. Pathway of nitrification with enzymes (Nelson, D.W., 1982).

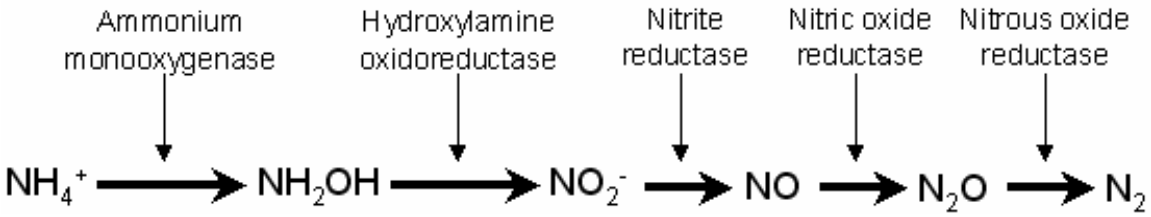

Figure 4. Pathway of nitrifier denitrification with enzymes (Nelson, D.W., 1982).

$$HNO_2 \leftrightarrow H^+ + NO_2^-$$

Figure 5. Production of HNO_2 via NO_2^- (Nelson, D.W., 1982).

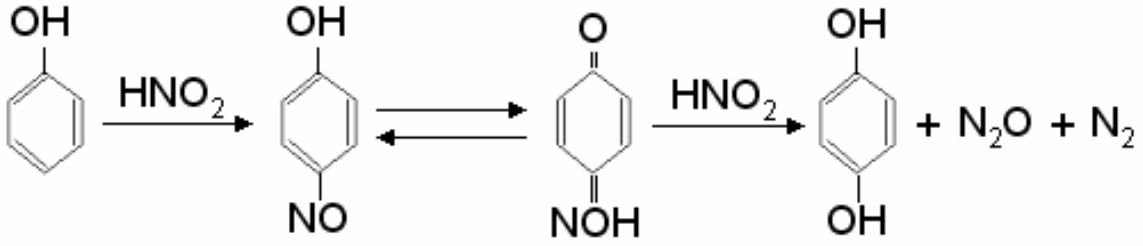

Figure 6. Reactions of HNO_2 with phenolic sites on soil organic matter to produce N_2O (Nelson, D.W., 1982).

$$NH_2OH + HNO_2 \leftrightarrow N_2O + 2H_2O$$

Figure 7. Production of N_2O via NH_2OH and HNO_2 (Nelson, D.W., 1982).

A number of environmental factors have been identified as affecting rates of nitrification and N_2O:NO_3^- product ratios, including substrate availability, soil water

content, O_2 availability, pH, and temperature (Schmidt, 1982). Ammonium substrate availability for nitrification is affected by rates of organic N mineralization and fertilizer N application (Pathak, 1999; Scott et al., 1999). Production of N_2O also increases with increasing NH_4^+ availability (Granli and Bøckman, 1994). In general, nitrification rates increase with soil moisture up to 60% water-filled pore space (WFPS) (Schmidt, 1982; Linn and Doran, 1984). As WFPS exceeds 60%, availability of O_2 and CO_2 substrate for nitrifiers declines due to severely restricted diffusion rates (Poth and Focht, 1985; Davidson and Schimel, 1995). However, production of N_2O by nitrifiers increases at low O_2 concentrations, thus N_2O emissions may still be high despite sub-optimal conditions for nitrification (Klemedtsson et al., 1987).

Soil temperature and pH further regulate nitrification and N_2O production. Soil temperatures < 5 °C are generally inhibitive to nitrifier activity (Anderson and Boswell, 1964) and rates of N2O production increase with temperature (Granli and Bøckman, 1994). Temperatures for peak activity have been shown to vary across soil types and climatic regions. Soil temperatures of 20-25 °C exhibit the highest nitrification activity in the Northern Great Plains (Mahendrappa et al., 1966). Soils of pH < 4 are inhibitive to nitrification, while soil pH ranges of 6 to 8 are optimal for nitrifier activity (Weber and Gainey, 1962).

Denitrification

Denitrification is the microbiological reduction of nitrate (NO_3^-) or nitrite (NO_2^-) to gaseous nitrogen, either as molecular nitrogen or as an oxide of nitrogen (Firestone, 1982) (Figure 8). Denitrifiers are facultative anaerobes that utilize NO_3^- as a terminal

electron acceptor when O_2 is limiting. Thus, denitrification is most likely to occur when soil water and NO_3^- contents are high and diffusion rates of O_2 into the soil are reduced. In addition, heterotrophs are the dominant organisms responsible for denitrification therefore the process is dependent on availability of oxidizable C in the soil (Stevens and Laughlin, 1998).

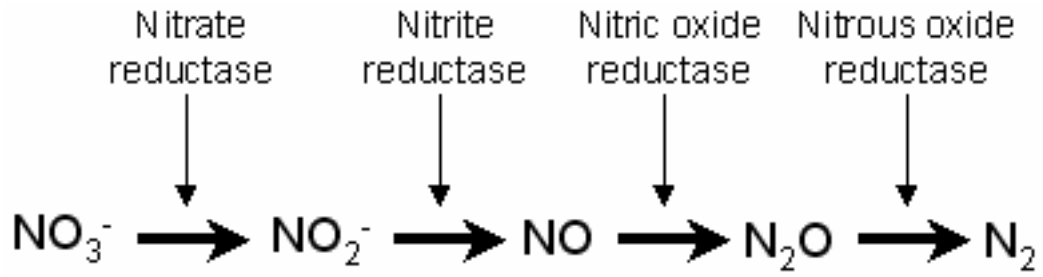

Figure 8. Pathway of denitrification with enzymes (Bryan, 1981).

In most soils, denitrification activity increases rapidly when WFPS exceeds 70% due to the lack of O_2 (Doran et al., 1990). Maximum N_2O is produced when O_2 concentrations are low enough to promote reduction of NO_3^-, but not so low as to promote reduction of N_2O to N_2 as O_2 is known to inhibit nitrous oxide reductase (Davidson and Schimel, 1995). The propensity of NO_3^- substrate to leach through most soils and the declining O_2 content with depth allows denitrification to occur at depths greater than nitrification provided there is oxidizable C substrate available (Burton et al., 1997). Denitrification has been observed at temperatures near freezing and as high as 70° C (Firestone, 1982; Fillery, 1983; Holtan-Hartwig et al., 2001). Rates of N_2O production have been shown to decrease with increasing temperature (Granli and Bøckman, 1994) and very high N_2O emissions have been observed at temperatures near freezing due to inhibition of nitrous oxide reductase (Holtan-Hartwig et al., 2001). Denitrifiers are also

adaptable to a range of soil pH, but are commonly cited to be most active between pH 7.0 and 8.2 while rates of N_2O production generally increase at pH < 5 to 6 (Firestone, 1982; Granli and Bøckman, 1994; Simek, 2002). Since nitrification also produces NO_3^-, substrate availability for denitrification can be affected by rates of nitrification in conditions favorable to both processes (Wrage et al., 2001; O'Mullan and Ward, 2005).

Despite the mutual exclusivity of both aerobic and anaerobic environments, nitrification and denitrification can occur simultaneously within the same soil profile (Renault and Stengel, 1994). The heterogeneity of most soils can support immediately juxtaposed but drastically different environments (Smith, 1980). In areas where drainage and gaseous diffusion rates are often high, such as through large inter-aggregate pores, an aerobic environment conducive to nitrification is likely to exist. Pores within soil aggregates may remain water-logged after inter-aggregate pores have drained, and may continue to support denitrification. Likewise, soils exhibiting a pH of 4 may contain microsites with pH of 6 or higher wherein nitrification or denitrification could be possible (Davidson and Schimel, 1995).

Nitrous Oxide Emissions from Agriculture

During the past 250 years there has been a 17% increase in the atmospheric N_2O concentration to the present level of 317 ppbv (IPCC, 2001). Much of the blame for this increase has been placed on agriculture, which is identified as accounting for approximately 77% of current anthropogenic emissions of N_2O (Kroeze et al., 1999; IPCC, 2001). Some estimates indicate N_2O concentrations will rise to 351 ppbv by 2020 in great measure as a result of agricultural activities (Duxbury et al., 1993; Mosier and

Kroeze, 2000). Although N_2O is produced in soils via natural pathways, anthropogenic modifications of the soil environment, including fertilizer N use (Linn and Doran, 1984; Eichner, 1990), tillage (MacKenzie et al., 1998), inclusion of legumes in cropping rotation (Eichner, 1990; Lemke and McConkey, 2000) and cropping intensification (Simojoki and Jaakola, 2000) have been shown to impact N_2O production.

Tillage

Tillage, the mechanical loosening and turning of soil, is a traditional method for soil management. Tillage is most frequently used to destroy weeds and to bury crop residues (Sprague, 1986). The effect of tillage on soil N_2O emissions is complex, possibly stimulating emissions activity in the short term, but reducing long term and total losses compared to untilled systems. Brief spikes in N_2O emissions, lasting a few hours to a few days, have been observed following tillage events, particularly when associated with wetting or precipitation (Kessavalou et al., 1998b). Tillage disturbances can also release trapped pockets of gas resulting in increases in N_2O emissions. The accelerated mineralization of organic matter in the wake of tillage can stimulate nitrifier, and subsequently denitrifier, activity and increase soil N_2O production over several days to weeks following disturbance (Jansson and Persson, 1982). The impacts of tillage on soil WFPS, however, may serve to decrease N_2O emissions over the long term, as soil disturbance reduces infiltration rates, increases aeration near the surface, and removes protective surface crop residue. Exposure, aeration, and reduced infiltration of soil can lead to drier surface soil that may impede nitrifier and denitrifier activity, particularly over the course of dry seasons (Griffith et al., 1986).

Untilled, or no-till, cropping systems are implemented to minimize soil disturbance and maintain crop residues over the course of multiple cropping seasons. Preservation of crop residues and infrequent disturbance facilitates accumulation of soil organic matter and retention of soil water (Griffith et al., 1986; Uri, 2000; Pekrun et al., 2003). No-till soils have been shown to contain less oxidative environments, higher contents of water-soluble organic C, and greater amounts of biological activity near the surface than tilled soils (Doran, 1980; Mosier and Hutchinson, 1981; Gilliam and Hoyt, 1987; Mackenzie et al., 1998; Pekrun et al., 2003). The additional organic substrate and water stored by no-till systems is conducive to denitrifier activity (Gilliam and Hoyt, 1987). Studies have thus shown no-till systems exhibiting greater N_2O emissions than tilled systems, particularly in subhumid climates (Aulakh et al., 1984; Linn and Doran, 1984; Jacinthe and Dick, 1997; Kessavalou et al., 1998a; Pekrun et al., 2003). Research in the semiarid Northern Great Plains, however, has shown little difference in N_2O emissions between tilled and no-till systems (Lemke et al., 1999).

Cropping Intensity and Diversification

The intensity and species composition of cropping systems may affect soil N_2O emissions due to the impact of plants on soil N and C cycling and soil water content (Pathak, 1999). Cropping intensification, such as when converting from wheat-fallow to wheat-wheat systems, may enhance N_2O emissions because higher fertilizer inputs are needed to maintain soil N status (MacKenzie et al., 1998; Jian-gang et al., 2004). Inclusion of leguminous crops in rotation may also enhance N_2O emissions (Eichner, 1990; Bouwman, 1996; Lemke et al., 1999; Aulakh, 2001). Though leguminous crops

typically do not require N fertilizer, legume residues decompose rapidly due to their high N content and supply additional mineral N and organic C substrates to nitrifiers and denitrifiers. In the semiarid Northern Great Plains, Lemke et al. (1999) found N_2O emissions following surface application of pea residue to be greater than control treatments and similar to emissions from urea-N fertilized plots.

Nitrogen Fertility

Numerous studies have shown increases in soil N_2O emissions following N fertilizer application (Eichner, 1990; Granli and Bøckman, 1994; Linn and Doran, 1984; Bouwman, 1996; Clayton et al., 1997; Aulakh et al., 2001b; Hao et al., 2001). Nitrous oxide emission activity following fertilization typically remains high for several weeks before returning to background levels (Duxbury et al., 1982; Conrad et al., 1983; Cates and Keeney, 1987; Granli and Bøckman, 1994). Emissions following fertilization frequently constitute the majority of cropping systems annual emissions of N_2O (Cates and Keeney, 1987; Granli and Bøckman, 1994; Lemke and McConkey, 2000; Lemke et al., 2002).

The quantity of N applied, its source, and timing of application can potentially impact the magnitude of N_2O emissions (Eichner, 1990; McSwiney and Robertson, 2005). Generally, emissions of N_2O increase with application rates (Granli and Bøckman, 1994; MacKenzie et al., 1998). Reports on the impact of the fertilizer source on N_2O emissions vary depending on climatic region (Eichner, 1990) and/or soil moisture conditions. Application of urea- or ammonium-based fertilizers has been associated with elevated N_2O emissions under conditions favoring nitrification and denitrification, such

as moist, well-aerated soils (Granli and Bøckman, 1994). Nitrate-N fertilizer sources may exacerbate emissions where denitrification is favored, such as in waterlogged soils.

Timing of N fertilization applications in accordance with crop need can minimize N_2O emissions. Hao et al. (2001) observed very high N_2O emissions following application of N fertilizer to winter wheat at seeding. Applications applied in the spring resulted in much lower emissions due to higher N demand from the growing crops. Older plants typically have more developed and prolific root architecture than younger plants, which facilitates N uptake (Hodge et al., 2000).

Effect of N fertilizer placement on emissions has not been studied extensively in the field. However, lab studies by Tenuta and Beauchamp (2000) on a calcareous soil found that N_2O emission activity from urea was greater when the fertilizer material was applied as a large granule or prill compared with a powder. The authors suggested that N_2O emission activity was elevated due to NO_2^- accumulation in the fertilizer application zone as result of high pH and increased $NH_{3(g)}$ concentrations. These results suggest that band application of urea fertilizer may result in higher emissions than broadcast or diffuse applications.

Nitrous Oxide and Full-Cost Accounting for Greenhouse Gas Mitigation

The importance of quantifying N_2O emissions from agricultural soils has arisen because of interest in managing soils to sequester C in soils for mitigating global warming. In the Northern Great Plains, no-till and crop intensification have been promoted as best management practices for soil C sequestration (Lal et al., 1998; Antle et al., 2002). Recent estimates for north central Montana suggest that soils under no-till

systems can sequester carbon at rates of 0.13 – 0.40 Mg C ha^{-1} yr^{-1} (Bricklemyer, 2003). Similarly, studies in the semiarid Canadian prairies have shown conversion to no-till and continuous cropping results in C sequestration rates of 0.32 – 0.52 Mg C ha^{-1} yr^{-1} (Campbell et al., 1996, 2000, 2001). The effect of these best management practices on N_2O emissions has not been studied extensively. Inventories by Lemke et al. (2006) suggest gains in soil C following implementation of improved cropping practices, such as no-till, may serve to reduce net cropping system global warming potential. For example, it is suggested that 30-yr mean emission rates of N_2O from no-till systems in the semiarid Canadian prairies are 192 kg CO_{2eq} ha^{-1} yr^{-1} while rates of C sequestration are 783 kg CO_{2eq} ha^{-1} yr^{-1} resulting in a net reduction in cropping system greenhouse gas emissions. Many investigators now recognize that understanding the effect of NT and crop intensification on N_2O emissions are critical to successful implementation of global warming mitigation strategies.

Intergovernmental Panel on Climate Change

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the World Meteorological Organization and the United Nations Environmental Program (IPCC, 2004) as a result of concern over rising anthropogenic greenhouse gas emissions, and the need for accurate and accessible greenhouse gas emissions inventories, and mitigation techniques. The IPCC synthesizes reports for scientists and policymakers detailing technical and socio-economic aspects of global climate change and options for mitigation. The IPCC does not perform independent research, but relies on peer-reviewed scientific literature to prepare reports. The IPCC has implicated N_2O as

a priority greenhouse gas responsible for destruction of stratospheric ozone and generation of acid rain (IPCC, 2001). Publications have outlined methods for estimating regional N_2O losses and scenarios for emission mitigation. Estimates of N_2O losses on global and regional scales most frequently use IPCC methodology and were utilized as the basis of negotiation for the Kyoto Protocol (IPCC, 1997).

The importance of agriculture in budgets of N_2O emissions has led to methodology for estimating emission rates from soils. The IPCC methodology accounts for direct and indirect losses from crop production systems and livestock operations. Current methods assume that 1.25% ('default value') of applied N from commercial fertilizers, manure, and crop residues is lost directly as N_2O. The strictly empirical method employed by the IPCC does not, however, account for the numerous physical, chemical, and biological processes that influence N_2O production and thus ignores regional agro-ecosystem characteristics (Li et al., 2001). Field studies have shown differences in N_2O emission rates across climatic and agricultural management zones with losses increasing in regions with higher precipitation and soil organic matter (Mosier and Hutchinson, 1981; Li et al., 2001). Work in the semiarid prairies has suggested rates of loss of N_2O are lower than the IPCC suggested estimate of 1.25% of applied N (Lemke et al., 1999; 2003a).

Sampling and Monitoring N_2O and Other Trace Gas Emissions

The predominant approaches for measuring N_2O and other trace gas emissions from the soil can be classified into two categories: micrometeorological and chamber techniques.

Micrometeorological Techniques

Micrometeorological techniques use analyses of the N_2O concentrations in the atmosphere and meteorological measurements such as wind speed, wet- and dry-bulb air temperatures, net radiation, and heat fluxes to estimate atmospheric gas fluxes. Micrometeorological techniques for determining field-scale fluxes, and include eddy correlation, Bowen ratio, energy balance, aerodynamic, and mass balance techniques (Smith et al., 1993; Granli and Bøckman, 1994).

Micrometeorological techniques minimize disturbance to study sites, can perform continuous monitoring, and can integrate trace gas flux rates over large footprints (1 km^2). Fluxes are inherently averaged over a surface area that increases with the height of the measurement above the surface (for tower measurements) and the length of the flight leg (for aircraft measurements) (Lenschow, 1995). Micrometeorological techniques assume, however, that horizontal concentration gradients are negligible and that exchange surfaces are homogeneous. Thus, micrometeorological techniques encounter difficulty when deployed in areas with high turbulence near the surface and in areas with heterogeneous exchange surfaces (Denmead and Raupach, 1993; Granli and Bøckman, 1994; Mosier et al., 1996). Additionally, micrometeorological methods are often expensive to employ and can give erroneous results when attempting to monitor small trace gas fluxes (Granli and Bøckman, 1994). Newer, more sensitive instrumentation based on tunable lasers may enhance performance of micrometeorological techniques into the future.

Chamber Techniques

Chamber techniques utilize enclosures placed atop the soil to restrict soil air exchange with the atmosphere. Effective capture of emissions with chambers ensures a change in trace gas concentration can be detected readily without disturbing the natural processes controlling gas transport (Denmead and Raupach, 1993; Anthony et al., 1995). Due to their inexpensive and simple fabrication, portability, sensitivity to low emissions rates (+/- 1 ppbv), and ability to provide information about spatial variability, chamber techniques have gained wide acceptance in N_2O and trace gas emissions monitoring (Matthias et al., 1980; Granli and Bøckman, 1994; Scott et al., 1999). Installation and utilization of chambers, however, has also shown possible drawbacks and sources of bias. Carefully designed protocol has been shown to minimize these issues (Hutchinson and Mosier, 1981; Matthias et al., 1980; Granli and Bøckman, 1994; Scott et al., 1999).

Rates of gas transport from the soil to the atmosphere are primarily controlled via advective processes and molecular diffusion (Anthony et al., 1995). Advective transport occurs in response to changes in pressure between soil air and the overlying atmosphere. Sudden decreases in pressure near the soil surface can accelerate rates of gas transport from the soil, while pressure increases impede transport (Scott et al., 1999). Molecular diffusion is the net flow of molecules by random molecular motion from areas of high concentration to areas of low concentration. Both processes are highly variable due to the numerous sources and sinks involved in soil gas generation. Reviews by Hutchinson and Mosier (1981), Hutchinson and Livingston (1993) Anthony et al. (1995), and Scott et al. (1999), have examined the impacts of chamber techniques on local temperatures,

pressures, gas concentrations, and soil porosity and tortuosity, and their implications for soil gas emissions.

Chamber deployment has been shown to impact air temperatures within the enclosure. Since many trace gas flux rates are dependent on soil biological factors, increases in temperature can bias biological production rates relative to the surrounding environment. Soil temperature typically lags behind changes in air temperature, therefore relatively short chamber deployment times have been shown to minimize temperature perturbations within the enclosure. Chambers constructed of opaque, insulative, or reflective materials have also been shown to reduce temperature perturbations (Anthony et al., 1995).

Pressure changes within enclosures are possible following chamber deployment which may adversely impact advective transport of trace gases. Proper venting of chambers can ensure chamber pressure effectively mimics atmospheric pressure. Chamber vents constructed of an open tube with an internal volume sufficiently large enough to capture displaced air during atmospheric pressure changes have been shown to reduce pressure-induced bias within chambers to negligible levels. Optimum vent volume can be determined as a function of chamber volume and estimated wind speed (Hutchinson and Mosier, 1981).

Molecular diffusion can also be impacted by chamber presence. During sampling events the accumulation of gases within the enclosure causes a reduction in the concentration gradient between the soil and atmosphere. The decreasing concentration gradient may lead to a reduction in diffusion of gases from the soil. Since trace gas flux rates are often assumed to be linear, restriction of molecular diffusion due to excessive

gas buildup may lead to underestimation of trace gas fluxes. By utilizing flow-through chambers that constantly replace air within the chamber or by ensuring deployment times are as short as logistically possible, concentration effects on molecular diffusion can be minimized (Anthony et al., 1995).

Chamber installation and service can impact the soil physical and biological microenvironments near the enclosure. Rates of soil gas transport increase with coarseness of soil texture and connectivity of soil pores. Soil porosity can be disturbed, however, during the installation of gas enclosures. A reduction in pore connectivity as a result of soil compaction can increase horizontal gas transport and invalidate estimations of net trace gas production within the enclosed area. Regular foot traffic during chamber service can be additionally damaging to the area near to the chamber and is likely to cause soil compaction. Chamber installation and foot traffic can also result in plant damage and alterations in plant nutrient uptake and nutrient availability to microbial communities. Disturbance issues can be minimized by emplacement of elevated walkways for chamber access and installation of a permanent collar in the soil sufficiently prior to sampling to allow attenuation of disturbance effects (Anthony et al., 1995).

Addressing temporal variability of soil trace gas emissions can prove challenging with chamber techniques. Due to logistic limitations, typically the most convenient sampling interval is daily or longer. Given the episodic nature of trace gas emissions and their rapid response to environmental factors such as rainfall, temperature, and substrate application, low sampling frequencies may fail to detect peak periods of activity. Adherence to regular and frequent (at least once every 3 – 7 days) sampling intervals,

particularly during periods of peak emissions, can effectively address issues of temporal variability, however (Hutchinson and Mosier, 1981; Smith and Dobbie, 2001).

Gas samples taken from chambers can be analyzed in a laboratory with gas chromatography (GC). The gas chromatograph utilizes principles of solubility to partition gas mixtures and facilitate detection of their individual components (Karasek and Clement, 1988). Configuring a gas chromatograph with an electron capture detector (ECD), flame ionization detector (FID), and thermal conductivity detector (TCD) allows the detection and quantification of N_2O, CH_4, and CO_2, respectively, with sensitivities of 10^{-12} g s^{-1}. The absorbance of some gases, notably N_2O, of infrared light and the resulting photoacoustic effect allows quantification of trace gas emissions on site (Granli and Bøckman, 1994). Long path IR spectrometers in ultra-large chambers have been shown to detect emissions in-situ with similar accuracy to GC analyses (Smith et al., 1993).

Each technique for trace gas sampling has advantages and disadvantages and no single methodology is applicable to all study sites. Development and implementation of a specific and well-designed protocol for trace gas sampling can assist in minimizing sources of human error. It is believed, however, that the greatest proportion of uncertainty in N_2O emissions estimates is caused by the complex physical and biological factors that control soil gas flux over spatial and temporal scales rather than the specific measurement techniques utilized (Mosier et al., 1996).

CHAPTER 2

NITROUS OXIDE EMISSIONS FROM A NORTHERN GREAT PLAINS SOIL AS INFLUENCED BY NITROGEN FERTILIZATION AND CROPPING SYSTEMS

Introduction

Recent concern about the build-up of CO_2 in the atmosphere has stimulated interest in management practices that sequester carbon in agricultural soils. In the Northern Great Plains (NGP), no-till and continuous cropping practices have been identified as best management practices (BMP) for C sequestration (Lal et al., 1998; Antle et al., 2002). Studies in north central Montana have suggested gains in soil carbon of up to 0.4 Mg ha^{-1} yr^{-1} after 10 yr of no-till (Bricklemyer, 2003) while no-till management in southwestern Saskatchewan sequestered up to 0.52 Mg C ha^{-1} yr^{-1} after 11 yr (Campbell et al., 1996, 2001). Adoption of intensified cropping systems in southwestern Saskatchewan, such as continuous wheat and wheat-lentil, has resulted in increases in soil C of 0.32 Mg ha^{-1} yr^{-1} and 0.28 Mg ha^{-1} yr^{-1} respectively.

Although adoption of BMP may provide partial offsets to the build-up of CO_2 in the atmosphere, a number of investigators (Kessavalou et al., 1998b; Mosier et al., 1998; Lemke et al., 2006) believe a more complete budget of other soil-emitted greenhouse gases needs to be considered when examining the potential benefits of BMP to greenhouse gas emissions mitigation. Nitrous oxide is frequently the gas of greatest interest as it has about 300 times the global warming potential of CO_2 (IPCC, 2001) and because agriculture is the primary anthropogenic source of N_2O into the atmosphere, accounting for 77% of emissions (Kroeze et al., 1999). Inputs of N to agricultural soils

from commercial N fertilizer applications, organic manures, biological N_2 fixation, and green manures or crop residues have been identified as major contributors to N_2O emissions from agriculture (Eichner, 1990).

Current information on N_2O emissions from agricultural soils and as affected by N fertilization and cropping systems remains very limited for the NGP. Efforts to estimate N_2O emissions from agriculture in the NGP, and other regions have utilized the methodology of the International Panel on Climate Change. IPCC methodology states that 1.25% (default value) of all N inputs (fertilizer and residue) will be lost directly as N_2O (IPCC, 1997). Given that soil N_2O emissions are influenced by a myriad of soil factors and conditions including soil available N and C, water content, pH, and temperature, it is likely there will be strong regional differences in fractions of N lost as N_2O. For example, fractions of N fertilizer lost as N_2O have been found to range from > 0.01 to 6.84% for differing climatic regions of the United States and Europe (Eichner, 1990). In semiarid northern Colorado, Mosier and Hutchinson (1981) found N fertilizer loss equivalent to 1.3%, similar to IPCC methodology.

Investigations by Lemke et al. (1998, 2003a) in Saskatchewan indicate that IPCC methodology may overestimate N_2O emissions from fertilizer for the semiarid NGP. Lemke et al. (1998, 2002) found N_2O emissions from fertilized cropping systems ranged from 0.19 to 2.1 kg N ha^{-1} yr^{-1} in that environment. Further, N_2O emissions from no-till systems were equivalent to, or lower than conventional till systems, and contributions of pulse crops to emissions were minimal.

Further research is needed to determine the impact of best management practices on N_2O emissions in the semiarid NGP, and to establish the veracity of the IPCC default

value to this region. It was the overall goal of this project to develop N_2O emission data at a field site where the effect of best management practices (no-till and cropping intensification) on soil carbon sequestration were being monitored. The specific objectives of this study were:

i) To measure seasonal/temporal patterns and cumulative N_2O emissions for four cropping systems and an alfalfa-perennial grass system applicable to the Northern Great Plains

ii) To determine if, and how, best management practices for carbon sequestration in the Northern Great Plains affect N_2O emissions.

iii) To quantify fertilizer-induced N_2O emissions.

iv) To contrast field-measured losses of N_2O against predicted N_2O losses using IPCC methodology.

Materials and Methods

Site Description and Experimental Design

Field studies were conducted during 2004 – 2006 at the Montana State University – Arthur H. Post Farm in Bozeman, MT (45˚40′20″ N, 111˚09′3″ W). The study site was established in the fall of 2002 by the project directors (Drs. Perry Miller and Richard Engel) as part of a long-term study to examine the impact of cropping systems on soil carbon levels. The soil at the field site is classified as an Amsterdam silt loam (fine-silty, mixed, superactive, frigid Typic Haplustolls) with 8.8% sand, 82.5% silt, 8.6% clay, pH 6.9, 9.0 g kg^{-1} organic C in the upper 0.1 m, and with excellent soil infiltration and drainage characteristics (> 1 cm hr^{-1}). Seven cropping system main-plots (24.4 x 7.4 m) were replicated four times in a random complete block design (Table 1). The site was managed as a single-phase cropping system study with only one phase of the rotation occurring in any one season. Systems 1-5 were divided into sub-plots representing low (unfertilized control), moderate (available N =100 kg N ha^{-1}), and high N fertility (available N = 200 kg ha^{-1}) regimes.

Table 1. Description of cropping system treatments at MSU-Post farm.

System #	Cropping Sequence (2004-2005)
1	winter wheat – fallow (conventional tillage)
2	winter wheat – fallow (no-till)
3	winter wheat – spring wheat (no-till)
4	winter wheat – spring pea (grain) (no-till)
5	winter wheat – winter pea (forage) (no-till)
6	spring wheat – winter pea (manure) (conventional tillage-organic)
7	Grass-legume mixture of western wheatgrass (*Pascopyrum smithii*), slender wheatgrass (*Elymus trachycaulus*), green needlegrass (*Nassella viridula*), alfalfa *(Medicago sativa* L.)

Fertilization Practices, Soil Sampling and Analysis, and Harvest procedures

Urea-N fertilizer (46-0-0) was applied during phases of the rotation where spring or winter wheat was grown to produce the target available N rate. The available N pool was estimated from the sum of soil NO_3-N + fertilizer N for systems 1-3, and soil NO_3-N + fertilizer N + pulse credit for systems 4 and 5, respectively (Table 2). The pulse credit was given at 20 kg ha^{-1} following pulse grain crops (system 4) and 40 kg ha^{-1} following pulse forage crops (system 5) based on recent work by Miller et al. (2006). Soil NO_3-N levels were determined from samples collected prior to seeding, except in the case of the 2004 winter wheat crop (systems 1-5). During 2004, soil NO_3-N levels were based on samples collected on 20 March, or prior to spring regrowth. Soil samples were dried and ground, and then analyzed for NO_3-N according to established procedures (Mulvaney, 1996). Urea applications in the spring 2004 (13 Apr) were broadcast applied to the surface with a granule applicator (Gandy Company, 528 Gandrud Road, Owatonna, MN 55060-0528). Following the broadcast application, sufficient precipitation (14 mm) occurred between 17 and 21 Apr to dissolve the urea granules. In the spring 2005 (spring wheat) and fall 2005, urea was applied in a band at seeding 2.5 cm below and 5 cm to the side of the seed-row.

In all cases, direct-seeding equipment with disc-openers for minimal disturbance was used to seed the plot areas. Seed row width for pea and wheat crops was 26 cm except in the organic systems where row width was 13 cm. Cultivars, seeding rates, and dates for systems 1-5, and 6 and CRP are presented in Tables 3 and 4, respectively. Conventional tillage was performed in systems 1 and 6 with tandem discs and cultivators

equipped with sweeps. Harvest operations were performed with small-plot combines and forage harvesters both using sickle-bar cutters. Harvested grain yields were corrected for a moisture content of 9.1%. Harvest and tillage dates are presented in Appendix H. Subsamples of grain were analyzed via Leco (Leco Corporation, St. Joseph, MI) dry combustion for N content.

Table 2. Urea N fertilizer (46-0-0) application rates to study site and date of application.

	Fertilizer N applied (kg ha^{-1})		
Cropping system (N level)†	Spring 2004 14 April	Spring 2005 15 April	Fall 2005 30 September
1(M)	-	-	50
1(H)	68	-	150
2(M)	-	-	50
2(H)	90	-	150
3(M)	55	30	90
3(H)	90	65	90
4(M)	35	-	50
4(H)	135	-	150
5(H)	101	-	125

† M= moderate or 100 kg ha^{-1} available N; H = high or 200 kg ha^{-1} available N

Table 3. Cultivars, seeding rates, and dates for each of the crop types utilized.

Crop	Cultivar	Seed rate (seeds m^{-2})	Seeding date by year 2003	2004	2005
Winter Wheat	Promontory	200	11-Sep	-	30-Sep
Spring Wheat	Hank	200	21-Apr	-	13-Apr
Winter Pea	Melrose	100	-	18-Sep	-
Spring Pea	CDC Mozarts	100	21-Apr	-	13-Apr
Spring Wheat (organic)	Hank	300	-	27-Apr	-
Winter Pea (organic)	Melrose	120	-	15-Sep	-

Table 4. Cultivars and seeding rates and dates for each of the species utilized in the CRP.

CRP	Cultivar	Seeding rate (kg ha^{-1})	Seeding date 2003
Western Wheatgrass (*Pascopyrum smithii*)	Rosana		
Green Needlegrass (*Nassella viridula*)	Ladorne	5.62*	15-May
Slender Wheatgrass (*Elymus trachycaulus*)	Pryor		
Alfalfa (*Medicago sativa* L.)	Ladak	0.44	

* CRP grasses: western wheatgrass, green needlegrass, and slender wheatgrass account for 35%, 45% and 20%, respectively, of total seeding rate.

Gas Sample Collection and Analysis

Gas sampling was conducted in all systems using a modified vented chamber technique (Hutchinson and Mosier, 1981). The chambers were made of plexi-glass and had an insulated top (Figure 9). The design was similar to one used by Dr. Reynald Lemke (Soil Biochemist, at the Semiarid Prairie Agricultural Research Centre. Saskatoon, SK - personal communication). Chamber dimensions were sufficient to cover a 1000 cm^2 area and were inserted 5-cm deep into the soil to produce a 10 l headspace. Chambers were placed in all subplots (one chamber per plot). Chambers were left uncovered, except during the periods when gas samples were being collected.

Figure 9. Vented chamber placed between crop rows of a continuous wheat rotation. Chambers were sealed during gas sampling with an insulated cover.

Sample collection and analysis followed the protocols of Lemke et al. (1998) and is briefly described here. Gas samples were collected from the headspace during the early to mid-afternoon (1300-1500 h) after 1 h. Samples were drawn from the headspace using a 25 ml syringe and then transferred to pre-evacuated 13 ml Exetainers (Labco International Inc. Dept 845, PO Box 4346, Houston, TX 77210-4346). The concentration of N_2O in the sample exetainer was measured using a gas chromatograph equipped with a ^{63}Ni electron capture detector. A Varian 3400 manual injection gas chromatograph (Varian, Inc. Walnut Creek, CA) was used for the first (15 Apr 2004 – 22 Mar 2005) of

this study. A Varian 3800 gas chromatograph equipped with a CombiPal auto-injector was used the second year (22 Mar 2005 – 14 Apr 2006).

Nitrous oxide flux was estimated from the concentration change in the chamber headspace over a 1-h collection period as described by Nyborg et al. (1997). Changes in concentration over time were assumed to be linear and were calculated by subtracting the time-zero (i.e. background) concentration from the final concentration. Time-zero concentrations were calculated using the approach of Anthony et al (1995). Four ambient air samples were collected at each sampling event. The mean of these samples was used as the T_0 concentration.

Sampling was initiated in the early spring of 2004 immediately following the spring thaw (early April). Samples were collected approximately twice weekly during the early-season when the potential for large N_2O emissions was great due to high soil-water contents and N substrate (fertilizer, mineralized N). Sampling frequency was reduced (e.g. once per week) during the summer, fall, and winter months when soil water contents were low and the potential for N_2O losses was reduced. Nitrous oxide emissions are episodic in nature and abrupt changes in weather (e.g. periods of high rainfall), tillage events, and N applications can be followed by periods of high emissions. Therefore, the sampling frequency was increased during periods of high expected N_2O emissions. A total of 120 sampling events were captured over the course of this 2-yr investigation.

Ancillary Variables

Air-temperatures were recorded continuously with temperature sensors and data-loggers outside and inside the chambers, and 2 cm below the soil surface. Soil cores (0-8

cm) were collected at all sampling events to determine volumetric soil water content and soil water-filled pore space except on few dates during the winter when the ground was frozen and we were unable penetrate the surface. Water-filled pore space was calculated as described by Izaurralde et al. (2004). Additional samples of soil NO_3-N (0-15 cm depth) were collected on 24 May, 17 June, 24 June, 14 Nov 2005 and 14 Apr 2006.

Data Analysis and Interpretation

The arithmetic mean of N_2O concentration in the gas samples across the four replicates was used to estimate emission fluxes for individual sampling dates. Nitrous oxide emissions vs. time profiles were then developed for each cropping system x N regime. Fertilizer was not applied to the moderate N regime within the wheat-fallow systems (CT and NT) in the spring of 2004 because soil NO_3-N levels were > 100 kg N ha^{-1}. Hence, the wheat-fallow main plots contained only two subplots (high and low) for the initial 18 months of this study. Moderate N regimes were initiated 30 Sept 2005, following N fertilization. Gas emissions for the low and moderate N regimes over the initial 18 months of this investigation (15 Apr 2004 – 19 Sep 2005) were equivalent and based on measurements from the low regime set of four chambers.

Analysis of variance and repeated measures tests of N_2O emission data from the cropping system study was performed using the PROC Mixed procedure (SAS Institute, 1988). Block and block x cropping system factors were treated as random variables. Contrasts were performed using the pdiff option in SAS. Differences at $P < 0.10$ were considered significant due to the high variability often observed in N_2O emissions data (Bouwman, 1996; Yanai et al., 2003). Emission data were developed for individual

sampling events, selected periods of the cropping system cycle (i.e. 10 wks post-fertilization and freeze-thaw cycles), the cropping system rotation, and 2-yr totals. Fertilizer-induced emissions (FIE) were calculated by subtracting the emissions of a control plot from those of a fertilized plot, similar to Eichner (1990). The net value was expressed as a percentage, or fraction, of N applied. Fertilizer-induced emissions were not corrected for losses of NO_x or NH_3. These losses were assumed to be small as a subsurface band application was used in 2005, and rainfall after the surface broadcast application in 2004 was believed sufficient to have allowed for fertilizer urea-N incorporation.

An exploratory analysis of the data was performed to determine the distribution of N_2O emission rates at all sampling events. The Proc Univariate Normal procedure of SAS (SAS Institute, 1988) was used in this analysis to examine normality of the residuals. The results indicated whether the data needed to be transformed in order to satisfy the normal distribution assumption of analysis of variance (ANOVA). Some data sets of cumulative N_2O emissions (2-yr totals, FIE, and rotation totals) failed a normality test utilizing Shapiro-Wilk ($W \leq 0.10$). A $\log_{10}$ normal transformation was then performed. In most cases, the results of the $\log_{10}$ transformation did not change our interpretation of the results. Transformed data are presented in Appendix K. This analysis has been described by Jacinthe and Dick (1997).

Results and Discussion

Cumulative precipitation over the two years of this investigation (15-April 2004 to 14-April 2006) was 823 mm which is similar to the long term average (Figure 10). April, May, and June are typically the wettest three-month period at this location. Precipitation amounts from 1-April to 30-June equaled 161 mm in 2004 and 165 mm in 2005, or approximately 40% of the year total which is consistent with historical averages at this site. Monthly precipitation amounts in 2004 were near normal with the exception of the dry months of November and December. In 2005, October and November were characterized by above normal precipitation, while precipitation in May was much below normal. Air-temperatures at gas sampling (1300-1500 h) were similar to long-term daily mean temperatures, except during the fall of 2004 and winter of 2005 (Figure 11). Fall temperatures in 2004 were warmer than the 30-yr average. Though surface soils froze early in 2004 before snows fell, temperatures were much higher than normal during mid-winter (January) triggering early snowmelt. In 2005, temperatures were comparable to normal, though slightly warmer in the late summer and fall.

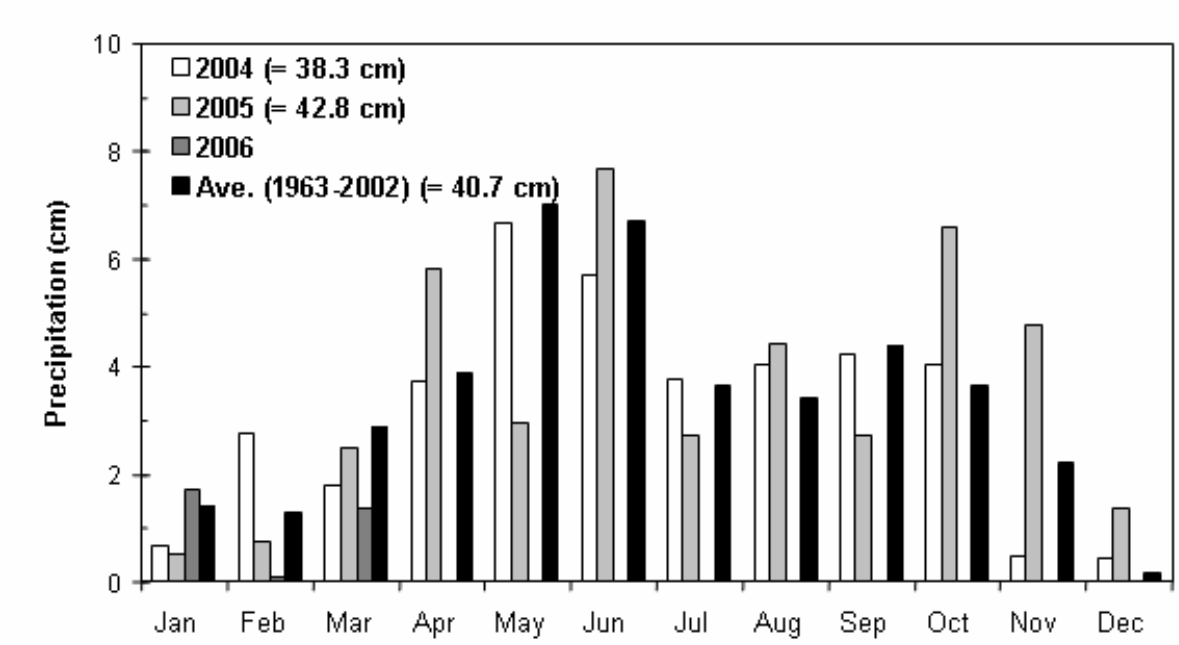

Figure 10. Cumulative monthly precipitation for the 2 yr study and 40 yr average. Year totals presented in parentheses.

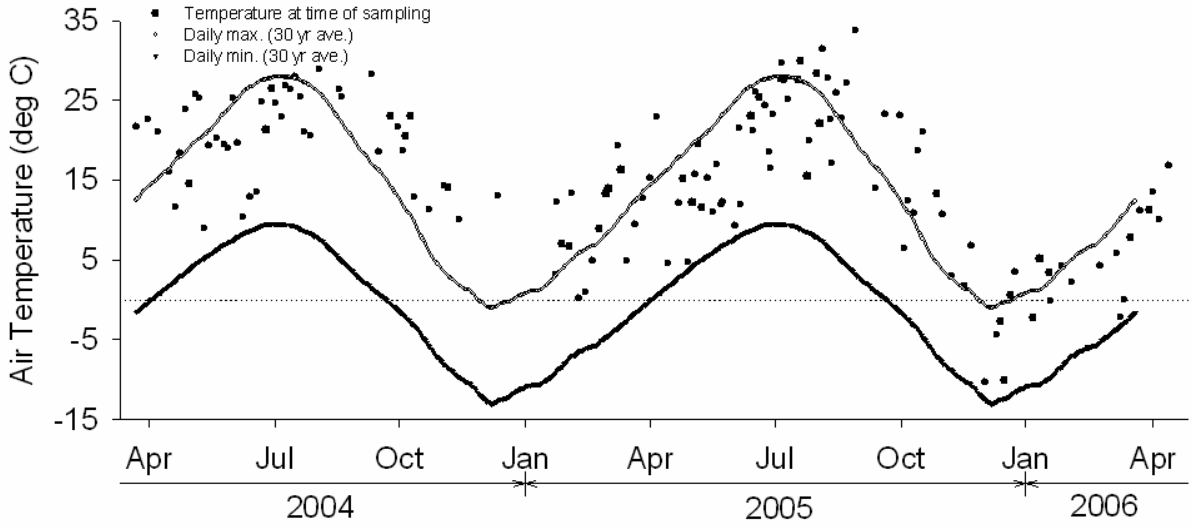

Figure 11. Air temperature taken at the time of sampling and 30 yr average daily temperature for the 2 yr study.

Background and CRP Emission Profiles

Nitrous oxide emission rates from the unfertilized CRP system were established as background, or control levels, for the course of the 2 yr study as emissions from this system were representative of undisturbed and native grassland conditions. Emissions rates vs. time profiles for CRP (Figure 12) indicate losses were generally < 5 μg N_2O-N m^{-2} hr^{-1} over the course of the 2 yr study with the exception of thaw events during the winter and early spring. Emissions during these thaw events were elevated for approximately 6 wk, and peaked at 27 and 19 μg N_2O-N m^{-2} hr^{-1} on 8 Feb 2005 and 10 Mar, 2006, respectively. Emission rates from CRP did not vary greatly with season, and averaged 2.1 ± 0.7 (±2σ), 1.0 ± 0.6, 0.7 ± 0.6, and 1.7 ± 1.3 μg m^{-2} hr^{-1} for spring (22 Mar – 20 June), summer (21 June – 21 Sep), fall (22 Sep – 21 Dec), and winter (22 Dec – 21 Mar excluding spring thaw events), respectively. Overall, the emission rate from CRP averaged 1.4 ± 0.6 (±2σ) μg m^{-2} hr^{-1} for the two years excluding the thaw events. Emissions above this interval, i.e. 2.0 μg m^{-2} hr^{-1} were considered elevated emission rates above background. The low emission activity from CRP was not surprising as soil NO_3^- levels remained near or < 5 mg NO_3^--N kg^{-1} soil throughout the study. Dobbie et al. (1999) suggested 5 mg NO_3^--N kg^{-1} soil as a critical value below which N_2O emissions are greatly reduced even though WFPS may be high (> 60%).

Nitrous oxide emission losses from CRP were equivalent to 0.28 kg N ha^{-1} for the two years, or 0.14 kg N ha^{-1} yr^{-1} at this field site. Emissions from unfertilized grasslands in semiarid regions have been reported at 0.17 kg N ha^{-1} yr^{-1} in Colorado (Mosier et al., 1997) and 0.06 – 0.21 kg N ha^{-1} yr^{-1} in the Inner Mongolia region of China (Wang et al.,

2005). Hence, our estimated losses of N_2O-N were similar to these investigators. Unfertilized grasslands in wetter regions have been shown to exhibit higher emissions than those in the NGP, but typically remain substantially lower than fertilized cropland (Ruser et al., 2001).

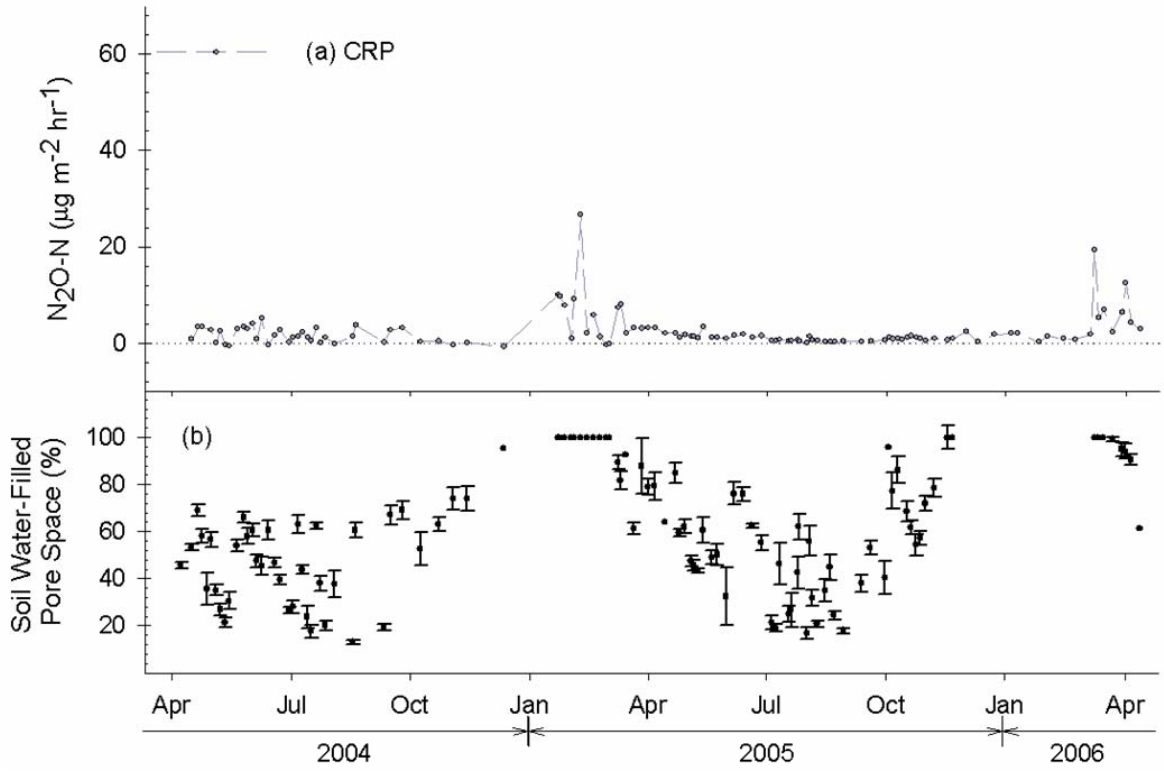

Figure 12. Nitrous oxide emission vs. time profile for CRP (a). Soil water-filled pore space vs. time (b). Bars represent standard error.

Cropping Systems Emissions Profiles

Nitrous oxide emissions for the four cropping systems (Figs. 13 – 16) were episodic and responsive to periods of high soil moisture (WFPS) and availability of N substrate (soil or fertilizer) over the two years of the investigation. Although the emission profiles differed for

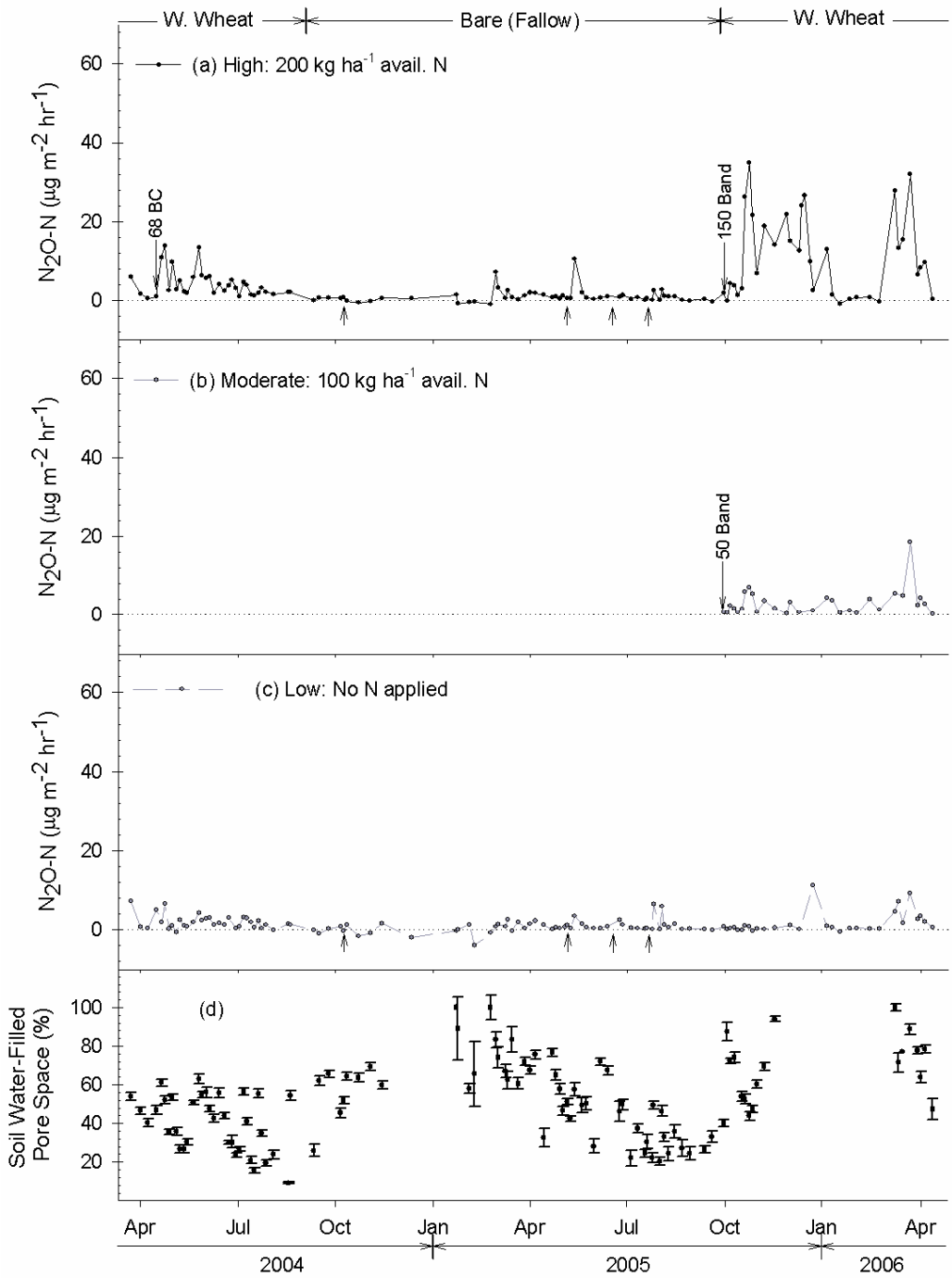

Figure 13. N_2O emission-time profiles over wheat-fallow (CT) for the high (a), moderate (b), and low (c) available N regimes. Soil water-filled pore space vs. time (mean of N regimes) (d). Bars represent standard error. Arrows with numbers indicate dates, rates (kg ha^{-1}), and method of N fertilization (BC = broadcast, Band = subsurface band). Up arrows indicate tillage events.

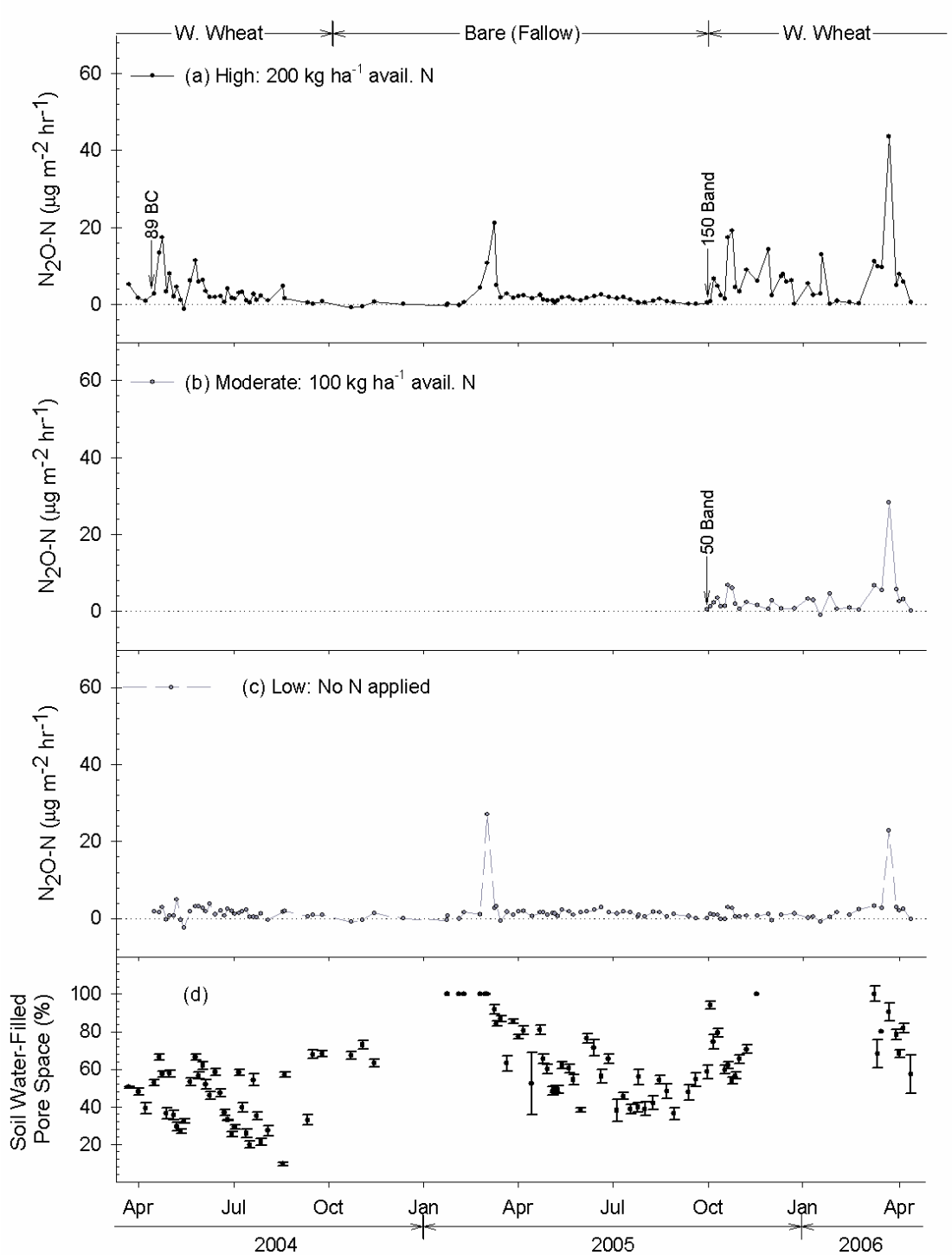

Figure 14. N_2O emission-time profiles over wheat-fallow (NT) for the high (a), moderate (b), and low (c) available N regimes Soil water-filled pore space vs. time (mean of N regimes) (d). Bars represent standard error. Arrows with numbers indicate dates, rates (kg ha^{-1}), and method of N fertilization (BC = broadcast, Band = subsurface band).

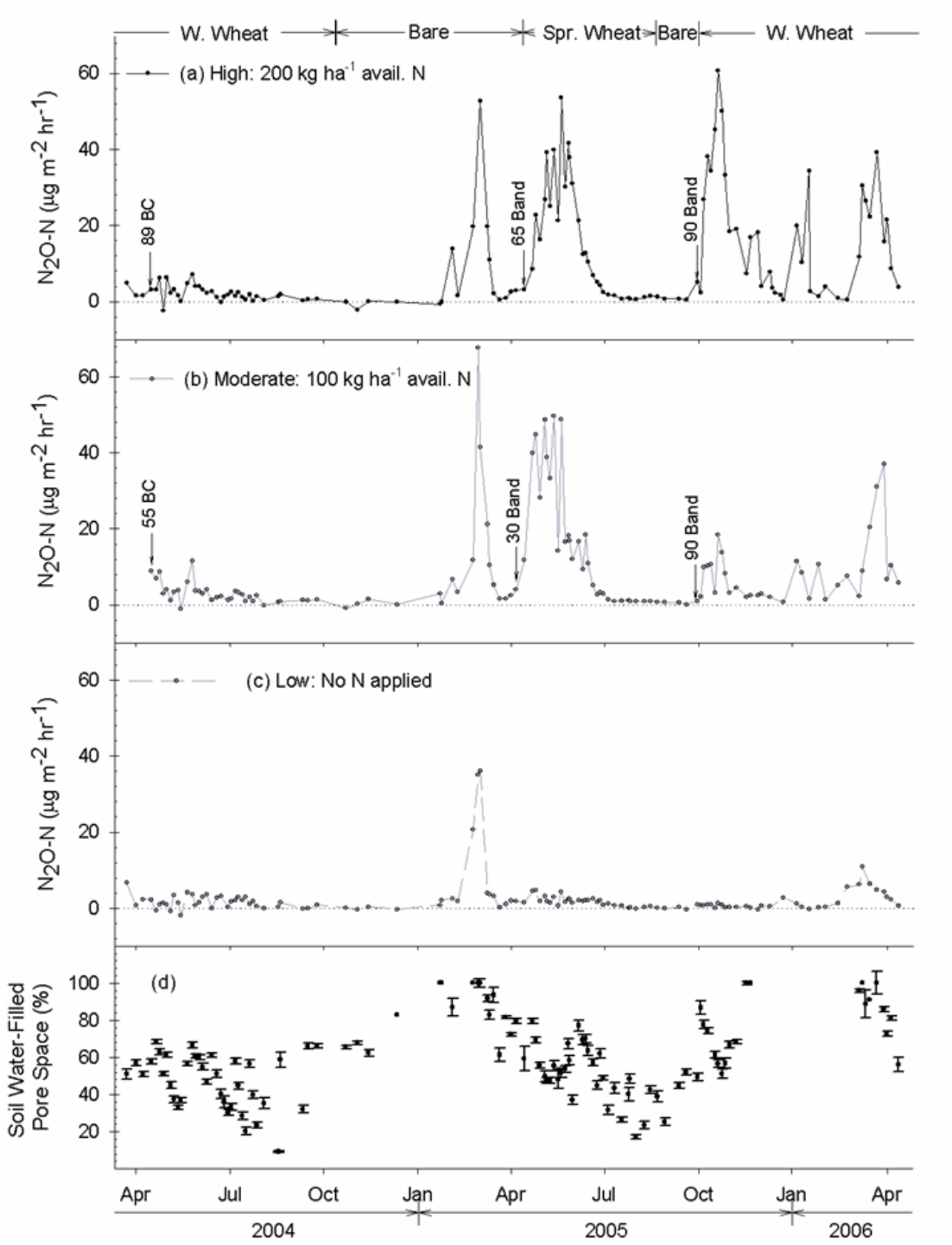

Figure 15. N_2O emission-time profiles over wheat-wheat (NT) for the high (a), moderate (b), and low (c) available N regimes Soil water-filled pore space vs. time (mean of N regimes) (d). Bars represent standard error. Arrows with numbers indicate dates, rates (kg ha^{-1}), and method of N fertilization (BC = broadcast, Band = subsurface band).

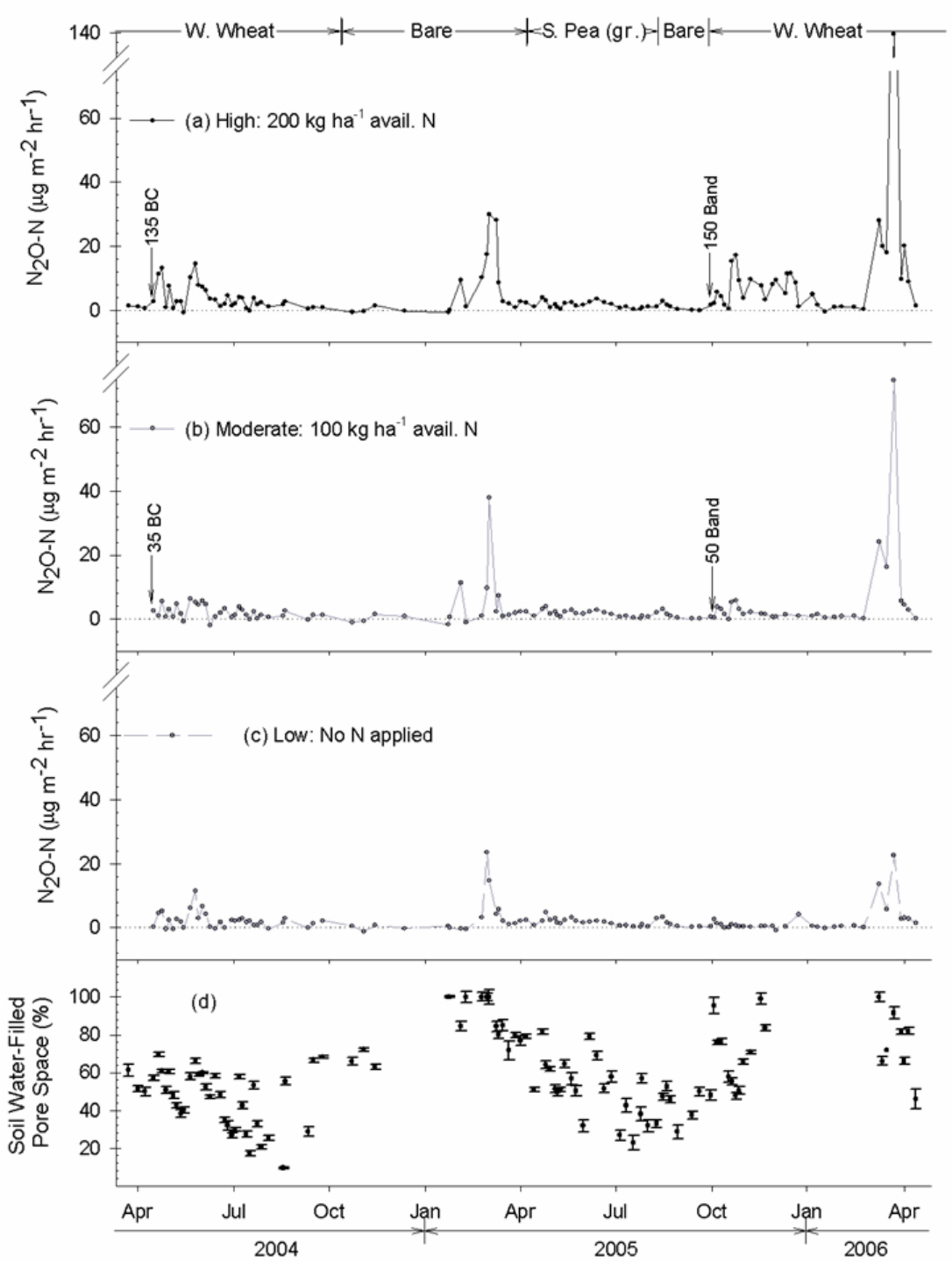

Figure 16. N_2O emission-time profiles over spring wheat-pea (NT) for the high (a), moderate (b), and low (c) available N regimes. Soil water-filled pore space vs. time (mean of N regimes) (d). Bars represent standard error. Arrows with numbers indicate dates, rates (kg ha^{-1}), and method of N fertilization (BC = broadcast, Band = subsurface band).

the cropping systems and N regimes, there were several commonalities evident. First, N_2O emission activity was elevated over a 10-wk period following N fertilization and during freeze-thaw cycles in the winter and early spring. Second, the combined winter-spring thaw cycles and 10-wk post-fertilization periods accounted for the majority of emissions over the two years. These periods comprised 73, 78, 86, and 84% of total emissions for wheat-fallow (CT), wheat-fallow (NT), wheat-wheat (NT), and wheat-pea (NT) rotations (high N fertility regime only), respectively. Third, all cropping systems exhibited significant periods of low activity equivalent to rates observed from CRP. Fourth, N_2O emissions across the four replicates exhibited high variability.

Post-Fertilization Activity. Nitrogen fertilization typically resulted in an increase in N_2O emission activity for the four cropping systems. The enhancement in N_2O emission activity following N fertilization was not surprising given similar responses have been observed by other investigators (Bremner and Blackmer, 1978; Mosier and Hutchinson, 1981; Bouwman, 1996; Henault et al., 1998; Lemke et al., 1999; Hao et al., 2001). The duration of elevated emissions above background (>2.0 μg N_2O-N m^2 hr^{-1}) for spring applications on 15 Apr 2004 and 14 Apr 2005 was approximately 10 wk, but extended somewhat longer than this for the fall application on 30 Sep 2005. The fall of 2005 was characterized by above normal precipitation and a snowfall event (15.5 mm water equivalent) on 26-27 Nov. Soil moisture conditions were wet and temperatures remained above freezing at the 2 cm depth until 18 Dec, perhaps extending the period of elevated emissions. Emissions summed over the 10-wk post-fertilization periods accounted for 22-64% of 2-yr total emissions. The highest percentages were observed

from the wheat-wheat system, perhaps due to the additional N fertilization event in spring 2005.

For the wheat-wheat system, N_2O emissions during the 10-wk post-fertilization were lower in 2004 than 2005 (Table 5). Lower soil moisture content in 2004 (vs. 2005) during the 10-wk post-fertilization period likely contributed to the reduced N_2O emissions (Figure 19). The lower emissions in 2004 may also have resulted from better synchrony of the fertilizer N applications with wheat nutrient demand. Nitrogen fertilizer was broadcast applied (90 kg ha^{-1}) to an established stand of winter wheat in 2004, while in 2005 fertilizer was band applied to spring (65 kg ha^{-1}) and winter wheat (90 kg ha^{-1}) at seeding. Previous research has shown spring applied N fertilizer was more available to winter wheat than fall applications (Vaughn et al., 1990), and that N_2O emissions from N fertilizer were greater for fall applications (vs. spring) in Alberta, Canada (Hao et al., 2001). In addition, the broadcast placement method used in 2004 may have contributed to lower emissions. Pot studies conducted by Bembenek (Appendix A), and Tenuta and Beauchamp (2000) suggested that diffuse applications of urea-N to soils, i.e. broadcast, result in lower fertilizer N_2O emissions than more localized applications, i.e. band.

Nitrous oxide emission rates during the 10 wk following N fertilization were correlated ($P < 0.01$) with WFPS and precipitation (summed over 5 d prior to sampling event) in 2004, respectively (Figs. 17 and 18). Similar relationships were not found in 2005. Nitrogen fertilizer was broadcast on the soil surface in 2004, while sub-surface band applications (5-7 cm below surface) were used in the spring and fall 2005. The

Table 5. Total N_2O emissions (absolute and fraction of 2 yr total) during the 10-wks post fertilization for the high N regime.

Period	Wheat-fallow (CT)	Wheat-fallow (NT)	Wheat-wheat (NT)	Wheat-pea (NT)
	---------- g N_2O-N ha^{-1}----------			
Spring 2004	96a*	88a	51a	96a
Spring 2005	-	-	387b	-
Fall 2005	193a	101a	343b	100a
	-----10 wk post-fertilization expressed as % of 2 yr total-----			
Spring 2004	14a	16a	5a	12a
Spring 2005	-	-	37b	-
Fall 2005	27b	17a	22b	11a
Totals	41z	31zy	64x	23y

* Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).

proximity of fertilizer to the soil surface may have made emissions more responsive to precipitation events. It is possible the gravimetric methodology (0-8 cm depth) used to estimate WFPS more accurately estimated the moisture environment of the fertilizer N enrichment zone in 2004 than in 2005.

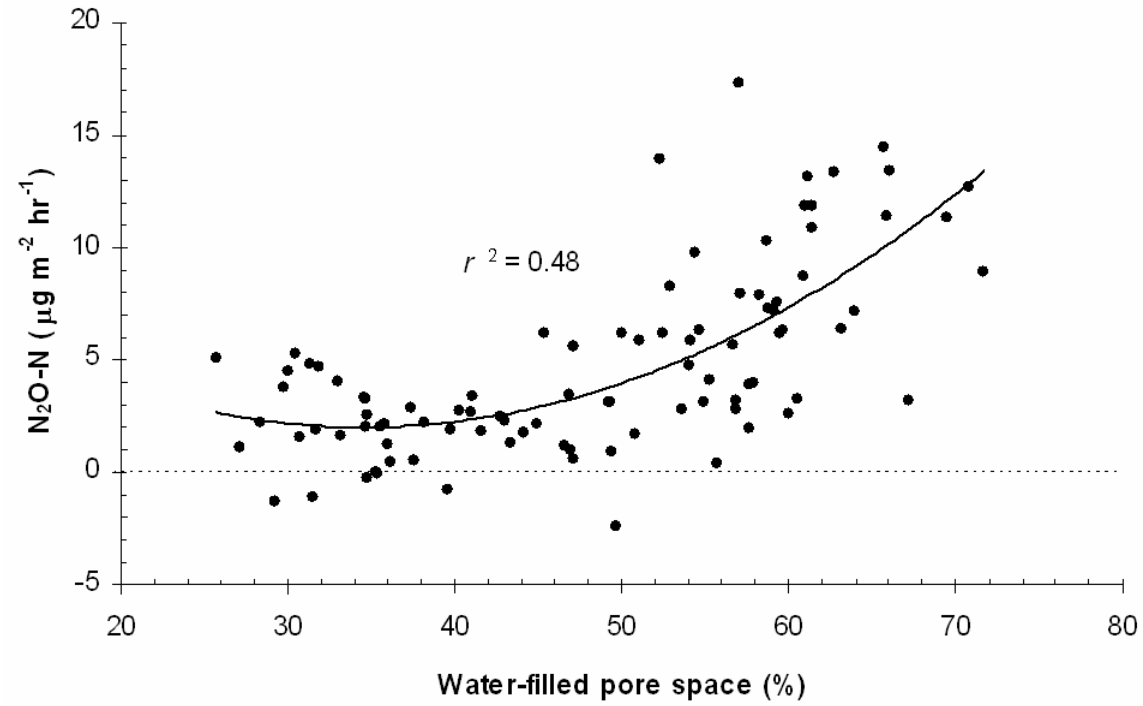

Figure 17. Relationship between N_2O-N flux ($\mu g\ m^{-2}\ hr^{-1}$) and water-filled pore space during the 10-wk period of spring 2004.

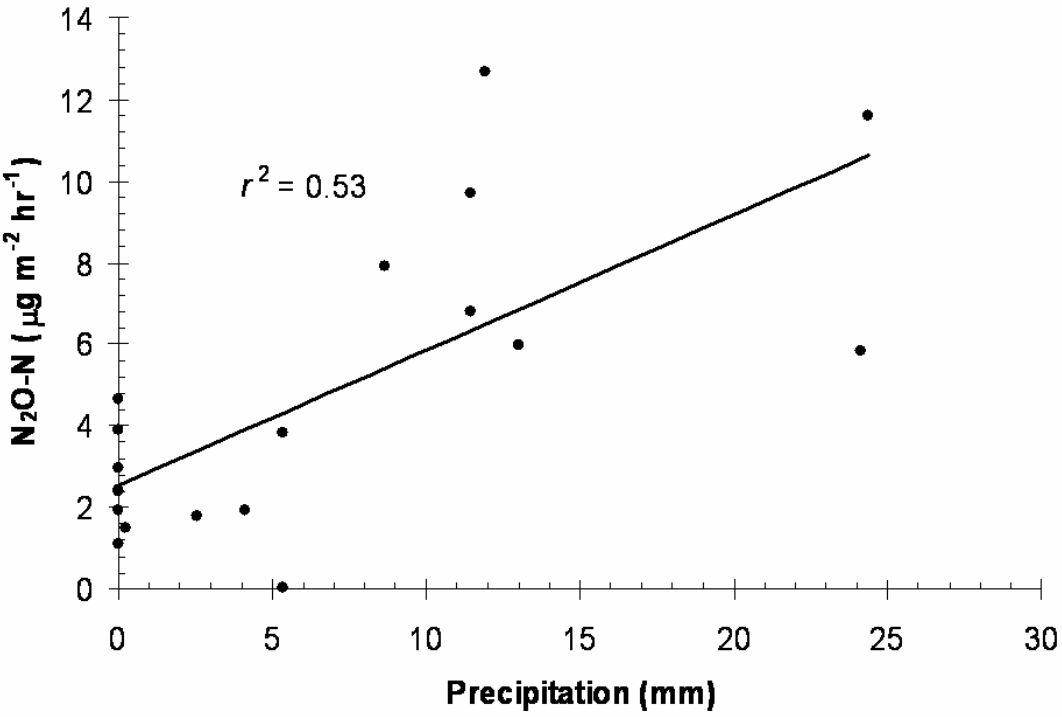

Figure 18. Relationship between cumulative precipitation (summed over 5 days) and mean emission rates from systems 1-4 during the 10-wk period of spring 2004.

The majority of N_2O losses for 10 wk following spring N fertilization events in 2004 and 2005 were probably a result of nitrification. Soil WFPS rarely exceeded 70% during this period (Figure 19). Previous research has indicated that aerobic microbial activity, such as nitrification peaks at WFPS < 60% (Linn and Doran, 1984; Davidson and Schimel, 1995). The anaerobic processes of denitrification becomes dominant at WFPS > 80% due to low soil oxygen content (Linn and Doran, 1984; Davidson and Schimel, 1995; Nyborg et al., 1997). Nitrifier denitrification also increases when soil O2 content is low (Wrage et al., 2001). Thus, denitrification and nitrifier denitrification may have played a more important role in N_2O emissions during the fall of 2005. Cool temperatures and higher-than-average precipitation resulted in high WFPS, frequently > 70%, during the 10-wk post-fertilization period. Water filled pore space was generally greater than observed for the spring post-fertilization periods.

Further evidence that nitrification was the primary process responsible for N_2O emissions was provided from an N fertilizer source experiment conducted at this field site (Appendix B), and N placement study conducted in the greenhouse (Appendix A). In these studies, the Amsterdam silt loam soil was heavily fertilized with N (rate = 200 kg ha^{-1}). Nitrous oxide emissions were substantial for urea-N fertilized treatments, but insignificant for KNO_3 fertilized treatments.

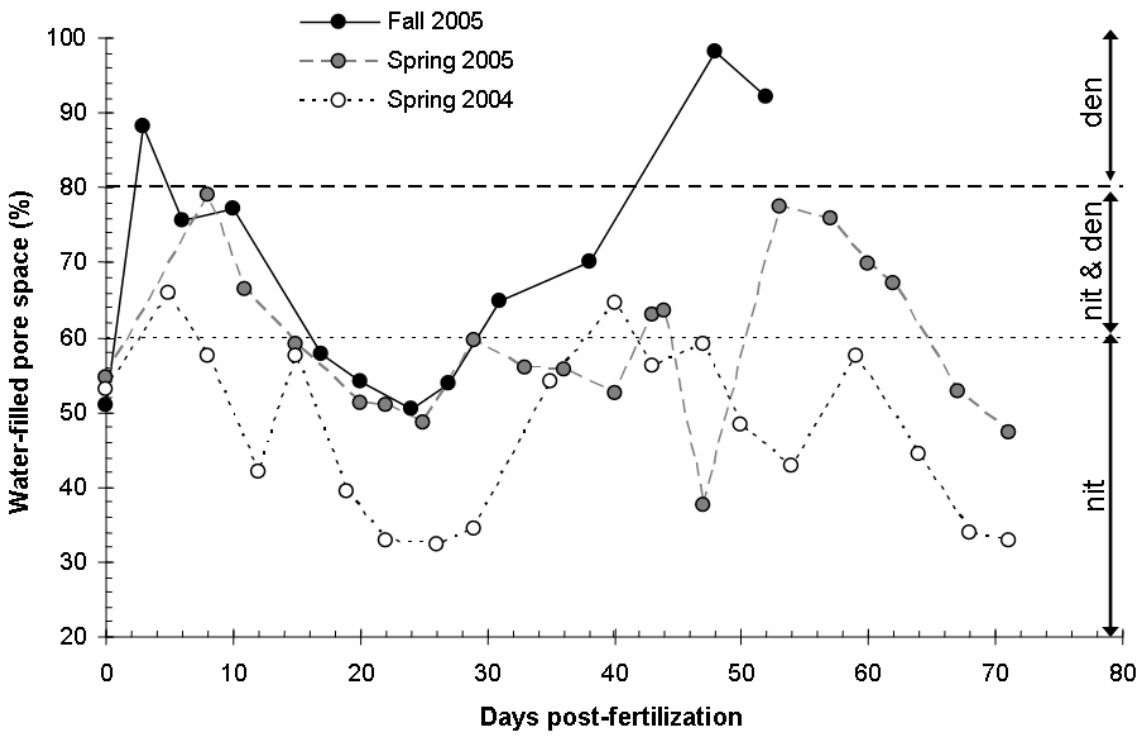

Figure 19. Soil water-filled pore space 10 wk following fertilization (spring 2004 and 2005, and fall 2005). Reference lines at 60 and 80% signify moisture regimes where nitrification (nit) and denitrification (den) processes predominate according to Linn and Doran (1984).

Though soil NO_3-N data for this investigation were limited, relationships between soil NO_3-N content in the upper 15 cm and N_2O emissions were observed. During the spring of 2005, N_2O emissions declined and returned to background levels in conjunction with soil NO_3-N levels. In addition, soil NO_3-N content in the late fall (14 Nov 2005) was found to correlate ($r^2 = 0.53$; $P < 0.01$) with total emissions for the corresponding 10-wk post fertilization period (30 Sep to 1 Dec 2005). These relationships are congruent with previous research that has shown soil NO_3-N content as being closely correlated with N_2O activity (Dobbie et al., 1999; Ruser et al., 2001).

Freeze-Thaw Cycles. Some of the highest N_2O emissions occurred during freeze-thaw cycles in Mar 2005 (Cycle 1), Jan 2005 (Cycle 2), and Mar 2006 (Cycle 3) (Figure 20). Emissions followed a rise in air temperature above 0 °C, which triggered snowmelt and resulted in saturated conditions near the soil surface. During these periods (3 to 8 wk), substantial N_2O emissions were observed even though soil temperatures just below the surface (i.e. 2 cm depth) were < 0 °C. Emissions remained elevated during spring thaw events (Cycles 1 and 3) until soil temperature increased to > 0 °C, subsoil thawed, and soil moisture drained or evaporated. Overall, the high N_2O emissions observed during freeze-thaw cycles were congruent with other studies in cold climates (Christensen and Tiedje, 1990; Lemke et al., 1998; Ruser et al., 2001). Also, Phillips (2006) found significant N_2O emissions from frozen (-2 °C) intact soil cores.

Losses during the freeze-thaw cycles were likely attributed to denitrification as soil moisture (0-8 cm depth) during the winter and early spring was frequently >85% WFPS (Linn and Doran, 1984). The product ratio of N2O:N2 from denitrification was likely greatly increased during this period as the enzyme nitrous oxide reductase is inhibited at soil temperatures near 0 °C (Holtan-Hartwig, 2001). The freeze-thaw action may have facilitated denitrification due to the sudden release of carbon from frost-killed soil organisms and disintegrating soil aggregates (Christensen and Tiedje, 1990a; Dobbie et al., 1999; Ruser et al., 2001). Also, Burton and Beauchamp (1994) showed that N_2O emissions may be released from trapped pockets beneath the frozen soil layer following soil thawing.

Nitrous oxide emissions for the three freeze-thaw cycles comprised 15 – 48% of the 2-yr total emissions (Table 6). Freeze-thaw emissions were observed to increase with N regime. In addition, late fall soil NO_3-N content (0-15 cm depth) was correlated with total spring-thaw (10 Mar – 14 Apr 2006) emissions ($r^2 = 0.22$; $P < 0.01$). Continuous cropping systems (wheat-wheat, wheat-spring pea) exhibited higher N_2O emissions during the freeze-thaw cycles than wheat-fallow systems (CT and NT). The highest freeze-thaw emissions were observed in Cycle 3 of the wheat-pea rotation possibly due to the high N content of the decomposing legume residues. Kaiser et al. (1998) observed winter and spring thaw emissions were greatest in soils amended with crop residues with narrow C:N ratios. Nitrous oxide emissions during the spring thaws of early 2005 and 2006 (Cycles 1 and 3) were not different except within wheat-fallow (CT). A tillage event in the fall 2004 likely improved water infiltration, allowing for a more rapid thaw and drainage of snowmelt during Cycle 1.

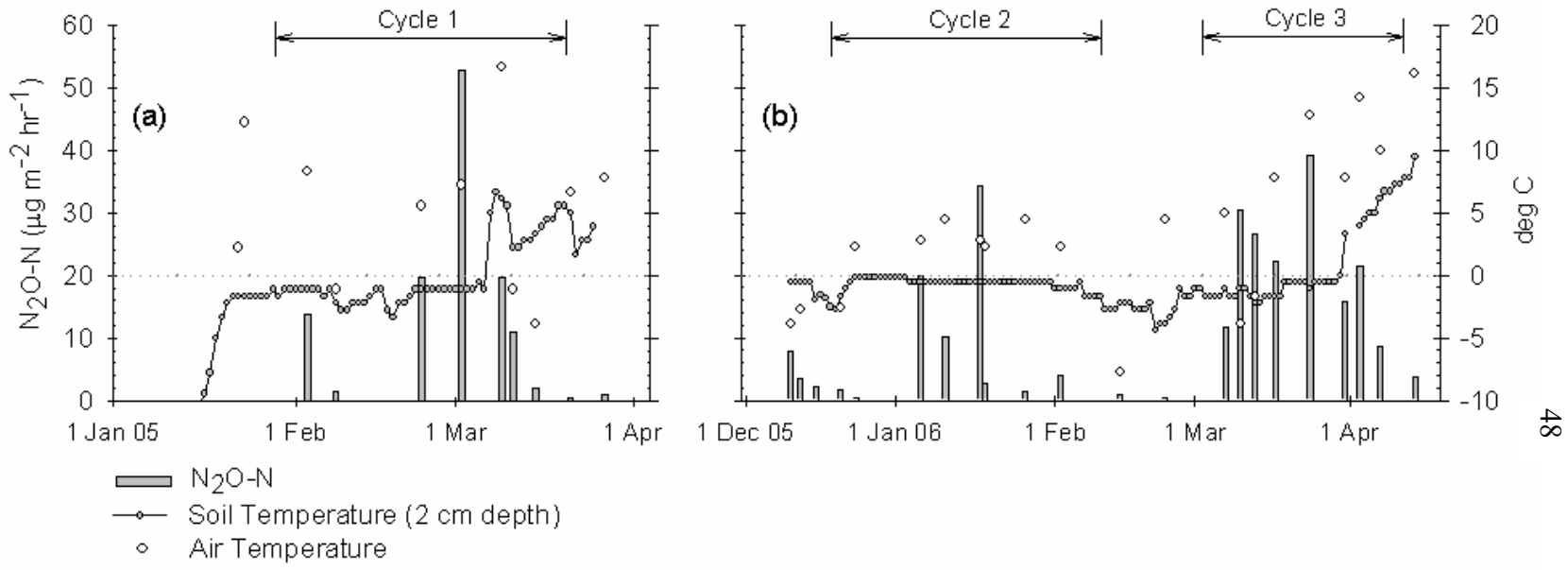

Figure 20. Nitrous oxide emissions during freeze-thaw cycle in February-March 2005 (a), and during the winter of 2005-2006 (b) from wheat-wheat (high N regime only) 2006. Air temperature at time of sampling (open circles), and average daily soil temperature (line and scatter plot) (2 cm).

Table 6. Cumulative late winter/early spring thaw emissions and fraction of total two yr emissions for the 2-yr sampling period (15 Apr 2004 – 14 Apr 2006) as affected by cropping system and N fertility regime.

Cropping System (CS)	N regime	N rate	N_2O-N
		kg ha^{-1}	g ha^{-1}
1. wheat - fallow (CT)	Low	0	44a
	Moderate	50	69ab
	High	218	193b
CS Mean			102a (24%)†
2. wheat - fallow (NT)	Low	0	111a
	Moderate	50	156a
	High	240	228a
CS Mean			165ab (28%)
3. wheat - wheat (NT)	Low	0	128a
	Moderate	175	282b
	High	245	346b
CS Mean			252bc (15%)
4. wheat - s. pea (NT)	Low	0	141a
	Moderate	85	323b
	High	285	513c
CS Mean			325c (42%)
Mean of N regimes	Low		106a
	Moderate		207b
	High		320c

Summary Statistics

Effect	df	F Value	P > F
Cropping System (CS)	3	4.45	0.04
Nitrogen regime (NR)	2	17.87	< 0.01
CS*NR	6	1.45	0.24

Contrasts (1 df)	t Value	P > t
wheat-fallow (CT) vs. wheat-fallow (NT)	-0.96	0.36
wheat-fallow (NT) vs. wheat-wheat (NT)	-1.12	0.29
wheat-wheat (NT) vs. wheat-pea (NT)	1.32	0.22
fallowed (1,2) vs. annual (3,4)	3.34	> 0.01

† Numbers in parentheses reflect the fraction of total two year emission loss during freeze-thaw cycles.

Periods of Low Activity. Low, or background, emissions were defined as those within two standard deviations of the CRP mean (1.4 ± 0.6 μg m^{-2} hr^{-1}) or 2.0 μg m^{-2} hr^{-1}. Low emission activity was observed in the summer (all cropping systems), during pulse phases of the wheat-spring pea system, and during of the fallow phases of the wheat-fallow (CT and NT) systems with the exception of a few brief pulses noted near dates of tillage events (CT only). In addition, emissions were low in the unfertilized cropping systems year-round except for the freeze-thaw cycles. The reasons for periods of low activity can be traced to the extensive time the soil surface remained < 50% WFPS and/or an absence of available N substrate for nitrification. For example, the soil surface WFPS averaged 37% and 39% for the summer of 2004 and 2005, respectively. Even after significant rainfall (> 8 mm) events WFPS returned to < 60% after only 48 hr. Soil emissions of N_2O have been found to negligible when WFPS < 50% (Izaurralde et al., 2004).

Emissions during the fallow phases (wheat-fallow systems) and pulse phases (wheat-spring pea system) were minimal, probably due to low rates of soil N mineralization, and minimal rates of N leakage from growing legumes (Lindemann and Glover, 2003) and minimum production of N_2O during N fixation, respectively. No residual effect from prior fertilizer applications in either pea or fallowed rotations was observed during the spring 2005 season as emissions from previously fertilized and unfertilized subplots were not different (P = 0.89). Emissions also did not increase notably following harvest of legumes (9 Aug 2005) suggesting low N content and slow rates of decomposition of straw and root residues. Our results were consistent with Lemke et al. (2002) where pulse crops contributed minimally to cumulative N_2O

emissions. Substrate was also limiting in unfertilized cropping systems. As an example, soil NO_3-N levels (0-15 cm depth) in the unfertilized wheat-wheat system were ≤ 3.0 mg kg^{-1} on all dates sampled (1 Apr, 24 May, 17 June, 24 June, 8 Sep, and 14 Nov 2005, and 14 Apr 2006). Dobbie et al. (1999) noted that emissions of N_2O are very much reduced when soil NO_3-N is < 5 mg kg^{-1}.

Variability and Normality of N_2O Emissions. Coefficients of variability across the four replications, varied from 19 to 500%, and were in excess of 100% for more than half of sampling events. The results were not surprising as many works have cited high spatial variability in soil N_2O emissions (Mosier, 1994; Ball et al., 1999; Pathak, 1999; Choudhary et al., 2002; Grant and Pattey, 2003; Yanai et al., 2003) with soil N_2O emissions varying by orders of magnitude even within small areas (Bouwman, 1996). No relationships were observed between N_2O emission rates and coefficients of variability ($r^2 < 0.01$). An example of variability, expressed as ± 1σ around the N_2O emission vs. time profile means, within the wheat-wheat system is presented in Figure 21.

Greatest variability in emissions occurred within the continuous cropping systems (wheat-wheat and wheat-spring pea). Variability was often induced by high emissions from a single subplot. High variability has been attributed to localized areas of high rates of denitrification termed ‘hot spots’ (Christensen et al., 1990b). Christensen et al. (1990b) described ‘hot spots’ as persistent over the course of a season primarily as a result of available soil carbon. It is possible, though not quantified in this study, that the continuous cropping systems contained higher levels of available soil carbon due to the additional residue inputs. Soil heterogeneity, particularly in terms of spatial distribution

of organic matter (Yanai et al., 2003), topography and soil water regime (Izaurralde et al., 2004), and clay content (Lemke et al., 1998) have also been cited as key contributors to N_2O emissions and variability.

Data sets were rarely normally distributed (Shapiro-Wilk $W \leq 0.10$) (Table 7). Emissions totals for 10 wk post-fertilization periods and the 2-yr totals were statistically abnormal due to one or two outliers within the data set (df = 47, or 48 chambers). Outliers were defined as data points > three standard deviations from the cropping system x N regime mean. Emissions data from 10-wk post-fertilization 2-yr totals could be made normal following the omission of outliers. The two largest outliers occurred in the wheat-wheat system from moderate and high N regimes during the 10-wk periods of spring and fall 2005, respectively. Removal of these data points did not change our interpretation of the results except for the comparisons of 10-wk periods between 2004 and 2005 (Table 5). Following removal of one outlier, mean emissions for the fall 2005 were reduced to from 343 to 174 g N_2O-N ha^{-1}. This value was higher than emissions for the 10-wk period of spring 2004 and lower than the 10-wk period of spring 2005. No outliers were removed from the data presented, however.

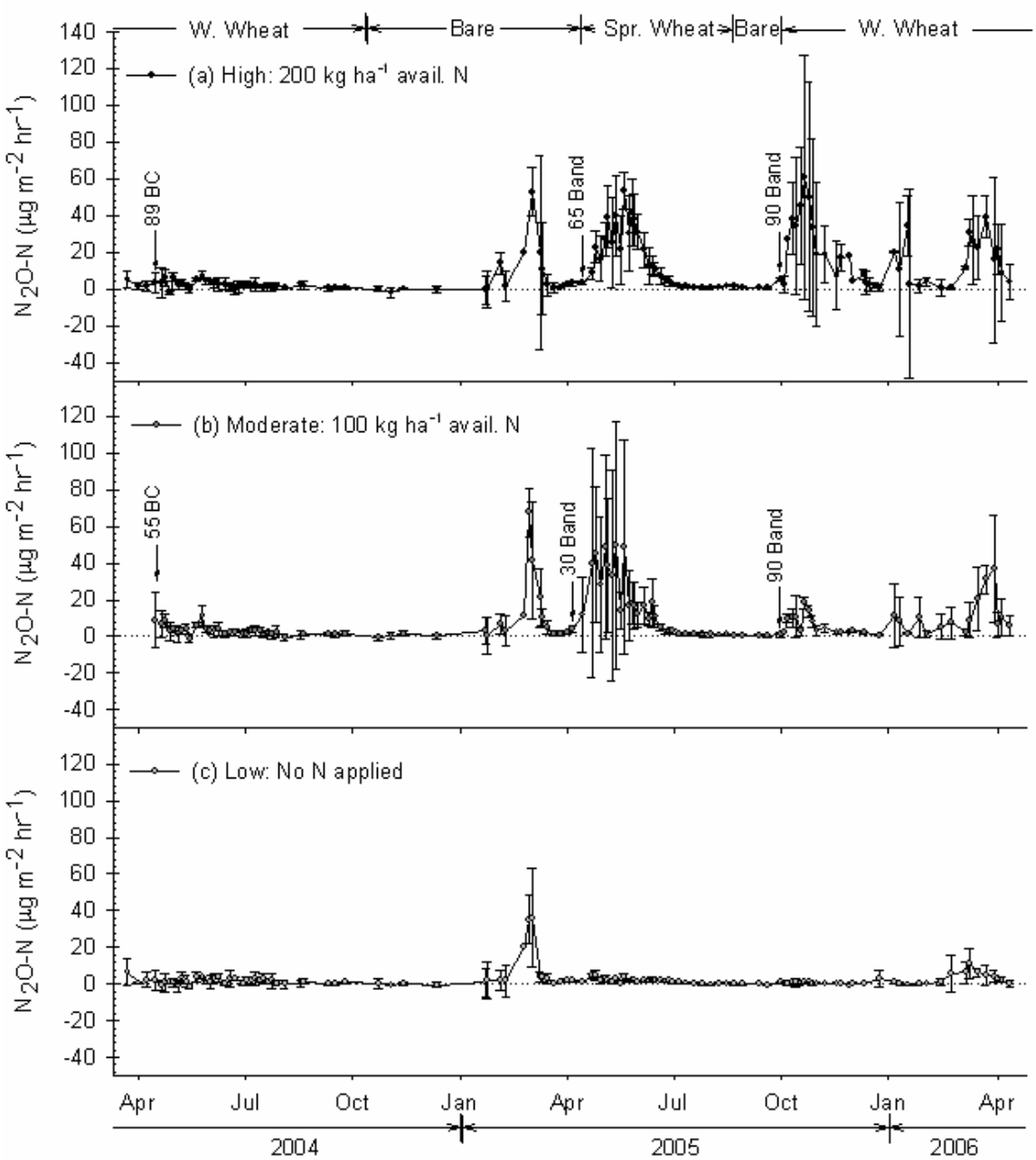

Figure 21. N_2O emission-time profiles over wheat-wheat (NT) for the high (a), moderate (b), and low (c) available N regimes Arrows with numbers indicate dates, rates (kg ha^{-1}), and method (BC = broadcast, Band = subsurface band) of N fertilization. Bars represent single standard deviations across 4 replicates.

Table 7. Tests of normality for selected periods of high N_2O emissions.

Time Period	Shapiro-Wilk test (full data set) P > *W*	# of outliers *P* = 0.01	Shapiro-Wilk test (outliers removed) P > *W*
10 wks 2004	< 0.01	2	0.89
10 wks 2005 spring	< 0.01	2	0.10
10 wks 2005 fall	< 0.01	2	0.02
spring thaw 2005	0.27	0	-
spring thaw 2006	0.15	0	-
2 yr FIE	< 0.01	1	0.37
2 yr total	< 0.01	1	0.32

Cumulative N_2O Emissions for Wheat-Fallow, Wheat-Wheat, Wheat-S. pea

Total N_2O emissions over two years were significantly ($P < 0.10$) affected by N regime, cropping systems, and cropping systems x N regime (Table 8). Within the unfertilized (low) N regime, total N_2O emission losses averaged 0.29 kg N_2O-N ha^{-1} and were not affected by cropping system. This level of emissions losses was not significantly different from the CRP (0.28 kg N_2O-N ha^{-1}). Total emissions in fertilized systems (moderate and high) was greater in the wheat-wheat system than the wheat-fallow systems ($P < 0.01$) and the wheat-pea system ($P = 0.05$). Urea fertilizer was not applied in the spring of 2005 to fallow and peas. Hence, higher emissions under wheat-wheat can be attributed to the additional fertilizer event in the spring of 2005. Although fertilizer N enhanced N_2O emissions overall, a significant stepwise increase in emissions with N fertility was not always observed in each cropping system for the low, moderate, and high regimes. The significance of the interaction (i.e. cropping system x N regime)

was due to the greater impact of N fertilization on N_2O emissions from the wheat-wheat systems compared to other rotations.

Total N_2O emissions were not different ($P = 0.89$) between CT and NT fallow-wheat cropping systems. Tillage only affected emission activity for brief periods (1 – 2 sampling events) following disturbance. The comparatively dry climate of this site and good infiltration rates diminished the impact of tillage on surface moisture content. Hence, an enhancement in N_2O emissions in response to reduced tillage, or NT, that has been reported in more humid regions (Aulakh et al., 1984; Goodroad et al., 1984; Lal et al., 1995; Paustian et al., 1995; Gregorich et al., 2005) was not observed here. Our responses were similar to reports from semiarid regions climates in Saskatchewan (Lemke et al., 1999) and Nebraska (Kessavalou, 1998a). In addition, the pea-wheat systems were not different ($P = 0.14$) from wheat-fallow systems (CT and NT) due to the minimal contribution of the pulse phase to total N_2O emissions.

Results from this study support the thesis that utilization of NT systems to sequester carbon in the semiarid NGP will probably have a minimum impact on N_2O emissions. Overall, the level of N_2O emissions observed at this site were modest in contrast to those reported for more humid regions, i.e. 2.9 – 5.0 g ha^{-1} d^{-1}, as reported by MacKenzie et al. (1998) and Grant and Pattey (2003) for Quebec and Ontario, respectively. Our results were within the range of those reported for other semiarid regions, i.e. 0.5 – 2.1 g N ha^{-1} d^{-1}, as reported by Mosier et al. (2003), Lemke et al. (1999), and Kessavalou et al. (1998) for Colorado, Alberta, and Nebraska respectively.

Table 8. Total emissions of N_2O-N for the two year sampling period (15-April 2004 to 14-April 2006) as affected by cropping system and N fertility regime.

Cropping System (CS)	N regime	N fert. events	N rate†	N_2O-N
		#	kg ha^{-1}	g ha^{-1}
1. fallow - wheat (CT)	Low	0	0	209a‡
	Moderate	1	50	250a
	High	2	218	702b
CS Mean				387z*
2. fallow - wheat (NT)	Low	0	0	265a
	Moderate	1	50	372ab
	High	2	240	576b
CS Mean				404z
3. wheat - wheat (NT)	Low	0	0	289a
	Moderate	3	175	1074b
	High	3	245	1311b
CS Mean				891y
4. wheat - s. pea (g) (NT)	Low	0	0	329a
	Moderate	2	85	527a
	High	2	285	895b
CS Mean				584z
Mean of N Regimes	Low			281a
	Moderate			549b
	High			871c

Summary Statistics			N_2O-N
Effect	df	F Value	P > F
Cropping System (CS)	3	6.15	0.01
Nitrogen Regime (NR)	2	23.25	< 0.01
CS*NR	6	2.59	0.04

Contrasts	df		
wheat-fallow (CT) vs. wheat-fallow (NT)	1	-0.14	0.99
wheat-fallow (NT) vs. wheat-wheat (NT)	1	3.64	< 0.01
wheat-wheat (NT) vs. wheat-pea (NT)	1	2.31	0.05
fallowed (1,2) vs. annual (3,4)	1	3.62	< 0.01

† Total amount of N applied over two years.
‡ Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).
* CS Means followed by the same letter are not different ($P \geq 0.10$).

Fertilizer-Induced Emissions for Wheat-Fallow, Wheat-Wheat, Wheat-S. pea

Fertilizer-induced emissions (FIE) were calculated for each cropping system by subtracting total N_2O emissions for unfertilized N regimes from total N_2O emissions for fertilized regimes. Fertilizer-induced emissions were affected by N regime (Table 9) and were correlated with N rate ($r^2 = 0.55$; $P < 0.01$) (Figure 22). Fertilizer-induced emissions were also affected by cropping system with the highest emissions occurring from the wheat-wheat system. The higher FIE losses under wheat-wheat compared to the wheat-pea and wheat-fallow was a function of the additional N fertilizer event applied to this rotation in spring 2005. This suggests diversified systems are preferable strategies for mitigating greenhouse gas emissions because N fertilizer is only applied in alternate years.

Emissions were low in the spring of 2004 (compared with spring 2005 and fall 2005) when a broadcast urea-N application was top-dress applied to growing winter wheat in all cropping systems. Hence, the 2-yr FIE estimates in Table 9 are somewhat biased by the larger emissions observed in 2005. These factors highlight the difficultly in comparing emission results across diverse rotations with varying numbers of N fertilizer applications over a short term, and in an environment where a large portion of emission losses are focused on short periods following N fertilization events.

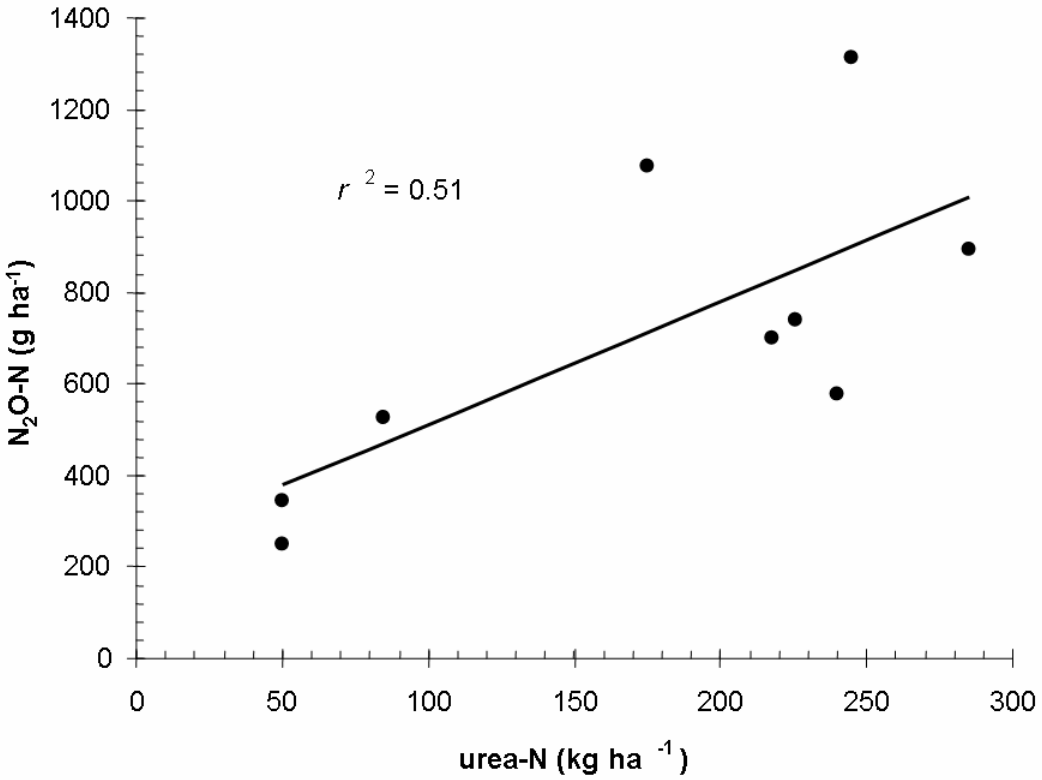

Figure 22. Relationship between total urea-N fertilizer applied and total 2-yr fertilizer induced N_2O-N emissions.

Fertilizer loss coefficients were affected by cropping systems between moderate and high N regimes with the highest losses occurring in the wheat-wheat system. Fertilizer loss coefficients were similar among wheat-fallow (CT and NT) and wheat-pea. Fraction of N-fertilizer lost as N_2O-N ranged from 0.08 to 0.45% (Table 9) and was similar to results reported by Lemke (2003a) and Li et al. (2001) in the semiarid regions of Saskatchewan and China, respectively. Due to the comparatively dry climate of the NGP, emission losses are confined to a very few specific periods, i.e. post N fertilization and freeze-thaw cycles in the winter-early spring. The remainder of the year, emissions are near background levels that are similar to what might be found from grasslands. The author suggests the lower, more conservative coefficient of 0.24 % ± 0.05 (or ± 1

standard error) provides a more realistic estimate of N fertilizer induced losses for the semiarid NGP. This coefficient is based on a mean of the four cropping systems. Although, coefficients of fertilizer N loss were significantly higher for the wheat-wheat system, there was considerable spatial and temporal variability in our measurements that preclude us from having sufficient confidence to justify a separate coefficient for the wheat-wheat system at this time.

Calculated percentages, or fractions, of fertilizer N lost as N_2O are considerably below the IPCC default value. Fertilizer induced emission losses in Table 9 are not adjusted for potential $NH_{3(g)}$ losses, which are assumed to be 10% of N fertilizer inputs using IPC default methodology. Hence the fertilizer N_2O-N losses percentages in Table 9 need to be adjusted upward 10% to contrast with the 1.25% IPCC default value. According our results indicate that IPCC default methodology will overestimate fertilizer-induced losses of N_2O by a factor of 4.7 times when the 0.24% value, or 0.264% adjusted value (0.24% $\div$ 0.90) is applied. This factor ranges from 7.6, 6.7, 2.6, and 5.3 for wheat-fallow CT, wheat-fallow NT, wheat-wheat NT, and wheat-pea NT, respectively.

Although, the fraction of N fertilizer lost as N_2O was low, N management issues such as fertilizer N placement and timing (seeding vs. established stand) may impact losses. We noted considerable differences in the fraction of N lost as N_2O-N during the 10-wk following fertilization within the wheat-wheat NT between spring 2004 and 2005. In spring 2004, fertilizer N was surface broadcast applied to an establish stand of winter wheat. Nitrous oxide emissions (10-wks) were equivalent to 31, 84, and 51 g N_2O-N ha^{-1} for low, moderate (65 kg N ha^{-1}) and high N (90 kg N ha^{-1}) regimes, respectively. This

equates to fertilizer induced losses of 0% and 0.05%, respectively. In spring 2005, fertilizer N was applied in a subsurface band to spring wheat at seeding. Nitrous oxide emissions (10-wks) were equivalent to 45, 441, and 388 g N_2O-N ha^{-1} for low, moderate (30 kg fertilizer N ha^{-1}) and high N (65 kg fertilizer N ha^{-1}) regimes, respectively. This equates to fertilizer N losses of 1.14% and 0.61%, respectively. Although, results from a greenhouse pot study found diffuse applications of fertilizer resulted in lower emissions than localized, more concentrated placements (Appendix A) the effect of N placement on emission was not great enough to account for these differences. This suggests that timing fertilizer N applications to be in synchrony with crop N demand may have a great effect on the fraction of N lost as N_2O. If true, best management practices to sequester carbon might delay fertilizer N applications to the spring during cropping phases with winter wheat, provided losses of $NH_{3(g)}$ can be minimized.

Table 9. Fertilizer induced emissions (FIE) of N_2O and fraction of applied N lost as N_2O for the two year sampling period (15-April 2004 to 14-April 2006) as affected by cropping system and N fertility regime.

Cropping System (CS)	N regime	N fertilizer†	FIE	Fraction applied N lost as N_2O
		kg ha^{-1}	g ha^{-1}	%
1. wheat - fallow (CT)	moderate	50	40	0.08
	high	218	492	0.23
CS Mean			266a‡	0.15a
2. wheat - fallow (NT)	moderate	50	107	0.21
	high	240	311	0.13
CS Mean			209a	0.17a
3. wheat - wheat (NT)	moderate	175	785	0.45
	high	245	1022	0.42
CS Mean			904b	0.43b
4. wheat - s. pea (NT)	moderate	85	198	0.23
	high	285	565	0.20
CS Mean			382a	0.22a

Summary statistics		FIE	Fraction lost
Effect	df	P > F	P > F
Cropping System (CS)	3	< 0.01	0.03
Nitrogen Regime (NR)	1	< 0.01	0.66
CS*NR	3	0.85	0.65

Contrasts	df	P > t	P > t
wheat-fallow (CT) vs. wheat-fallow (NT)	1	0.99	0.67
wheat-fallow (NT) vs. wheat-wheat (NT)	1	< 0.01	0.01
wheat-wheat (NT) vs. wheat-pea (NT)	1	< 0.01	0.07
1, 2 vs. 3, 4	1	< 0.01	< 0.01

FIE – Fertilizer induced emissions.

† Total amount of N applied over two years.

‡ Values for cropping systems followed by the same letter are not significantly ($P \geq 0.10$) different.

Cropping Systems Production and Nitrogen Efficiencies

Production efficiency, calculated as the ratio of seed yield (kg ha^{-1}) to N_2O-N emissions (g ha^{-1}) for the period of the first full rotation (15 Apr 2004 to 19 Sept 2005), was affected by N regimes (only low and high N regimes presented) and cropping systems. In most cases, wheat yields increased with N fertility. However, N_2O emissions increased at a proportionally greater rate with N fertility than seed yield. Thus, production efficiency declined with N fertility ($r^2 = 0.43$; $P < 0.01$). Production efficiency was lower in continuous cropping systems (wheat-wheat and wheat pea) than wheat-fallow (CT and NT) rotations. Efficiency was highest in wheat-fallow system and lowest in wheat-wheat systems due to the higher N rates required in the wheat-wheat system (Table 10). A cropping systems N efficiency value was calculated as a ratio of grain N yield (kg ha^{-1}) to N_2O-N emissions (g ha^{-1}) with results similar to production efficiency (Table 11). Our approach for calculating production was similar to Lemke et al. (2003b). Production efficiency values reported by Lemke et al. (2003b) at four sites in Saskatchewan were generally lower than our values, reflecting the high seed yield potential at Bozeman. Also, our results indicated higher production and cropping systems N efficiency in CT systems than in NT.

Table 10. Seed yield, rotation cumulative N_2O-N emissions, and production efficiency (yield/N_2O-N) as affected by cropping systems and N regime.

Cropping system (CS)	N regime	Seed yields			∑ Rotation N_2O-N emissions	Production efficiency Seed yld. (kg ha^{-1}): N_2O-N (g ha^{-1})
		2004	2005	2-yr		
		---------- kg ha^{-1} ----------			g ha^{-1}	
1. wheat-fallow (CT)	low	4.87† (0)**	-	4.87a	105a	47.6
	high	5.39 (68)	-	5.39b	198b	27.6
CS Mean		5.13z*		5.13z	151z	37.6z
2. wheat-fallow (NT)	low	5.42 (0)	-	5.42a	176a	33.9
	high	5.72 (90)	-	5.72a	244a	24.7
CS Mean		5.57z		5.57zy	210zy	29.3yx
3. wheat-wheat (NT)	low	2.88 (0)	2.01 (0)	4.89a	196a	26.5
	high	4.54 (90)	2.54 (65)	7.08b	654b	11.8
CS Mean		3.71y	2.49a	5.99zy	425x	19.2x
4. wheat- s. pea (NT)	low	4.16 (0)	1.08 (0)	5.24a	193a	29.1
	high	4.49 (135)	- (0)	5.57a	315a	18.3
CS Mean		4.32x	1.08b	5.41zy	254y	23.7yx

† Values within a cropping system followed by the same letter are not different ($P \geq 0.10$).

* CS Means followed by the same letter are not different ($P \geq 0.10$).

** N fertilization rate given in parentheses.

Table 10 cont'd.

Summary Statistics		Seed yields 2004	Seed yields 2005[§]	2-yr	∑ Rotation N_2O-N emissions	Production efficiency
Effect	df	P > F				
Cropping System (CS)	3	< 0.01	< 0.01	0.25	< 0.01	< 0.01
Nitrogen Regime (NR)	1	< 0.01	-	< 0.01	< 0.01	< 0.01
CS*NR	3	0.15	-	0.04	< 0.01	0.14
Contrasts		P > t				
1 vs. 2	1	0.19	-	0.20	0.21	0.07
2 vs. 3	1	< 0.01	-	0.22	< 0.01	0.03
3 vs. 4	1	0.08	< 0.01	0.10	< 0.01	0.30
1 & 2 vs. 3 & 4	1	< 0.01	-	0.16	< 0.01	< 0.01

[z] All contrasts were performed between Low and High N regimes only unless otherwise noted.
[§] Contrasts in 2005 were performed only between Low N regimes.

Table 11. Total N harvested in grain, N_2O-N emissions, and percent of grain N emitted as N_2O-N as affected by cropping systems and N regime.

		Total Production for 15 Apr 2004 – 19 Sept 2005		
Cropping System (CS)	N rate	∑ Rotation Grain N**	∑ Rotation N_2O-N emissions	N efficiency
	---------kg ha^{-1}--------		g ha^{-1}	Grain N: N_2O-N
1. wheat - fallow (CT)	0	95a†	105a	0.93
	68	118b	198b	0.61
CS Mean		107z*	158z	0.77z
2. wheat - fallow (NT)	0	104a	176a	0.68
	90	131b	244a	0.57
CS Mean		118z	210zy	0.63zy
3. wheat - wheat (NT)^z	0	98a	196a	0.57
	155	199c	654b	0.33
CS Mean		149y	425x	0.45y
4. wheat - s. pea (NT)	0	131a	193a	0.78
	135	163b	315a	0.53
CS Mean		147y	254y	0.65zy
Summary Statistics*		Grain N	N_2O-N	Grain N: N_2O-N
Effect	df	----------P > F----------		
Cropping System (CS)	3	< 0.01	< 0.01	0.12
Nitrogen Regime (NR)	1	< 0.01	< 0.01	< 0.01
CS*NR	3	< 0.01	< 0.01	0.67
Multiple comparisons	df	----------P > t----------		
1 vs. 2	1	0.17	2.15	0.26
2 vs. 3	1	< 0.01	< 0.01	0.16
3 vs. 4	1	0.85	< 0.01	0.12
1 & 2 vs. 3 & 4	1	< 0.01	< 0.01	0.11

† Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).
* CS Means followed by the same letter are not different ($P \geq 0.10$).
** Sum of grain N over two years

Legume Residue Management

Cropping systems 1 – 4 were the main focus of this study, however, gas measurements were also collected from winter wheat-winter pea (forage) rotation over 2-yr (15 Apr 2004 – 14 Apr 2006) and an organic system cropped to spring wheat-winter pea (CT) over 17 months (15 Apr 2004 – 19 Sep 2005). The organic system was contrasted with other unfertilized regimes including the CRP, while winter wheat-winter pea system was contrasted with the winter wheat-spring pea system.

Organic system (spring wheat-winter pea). Cumulative N_2O emissions for the organic system were generally very low for the 17 months that gas samples were collected, including the freeze-thaw cycle in the winter-early spring 2005 (Cycle 1) (Table 12). Total N_2O emissions over 17 months were similar to CRP and the other unfertilized cropping systems, except for wheat-fallow (CT). During the 10 wk period corresponding to post-fertilization in other cropping systems, the organic system exhibited slightly higher emissions than the other unfertilized regimes except for the winter wheat-spring pea system (Figure 23). Emissions from organic systems during this period were also correlated with WFPS ($P < 0.01$), though the relationship was not strong ($r^2 = 0.39$). The legumes incorporated the previous season (24 June 2003) likely released mineral N and organic C that contributed to the increased emissions (Aulakh et al., 1991). However, till-down of pea residue on 8 July 2005 did not result in elevated emissions for the remainder of the season.

Table 12. Ten wk post-fertilization, spring thaw, and cumulative (17 month) N_2O-N emissions, seed yield totals, and production efficiency (yield:N_2O-N) for unfertilized, organic, and CRP systems.

Cropping system	----------N_2O-N----------			Seed	Production
Low N regimes only	10 wk	Thaw	Total	Yields	Efficiency
	----------g ha^{-1}----------			Mg ha^{-1}	Yield: N_2O-N*
w. wheat-fallow (CT)	41a†	2a	105a	4.87ab	46.4a
w. wheat-fallow (NT)	31a	61b	176b	5.42b	30.8b
w. wheat-s. wheat (NT)	30a	85b	196b	4.89ab	24.9b
w. wheat-s. pea (NT)	47ab	37ab	193b	5.24b	27.2b
w. wheat-w. pea (NT)	31a	60b	173b	4.34a	25.1b
s. wheat-w. pea (CT - organic)	77b	28a	168b	4.31a	25.6b
CRP	41a	48ab	184b	-	-

† Values within a column followed by a different letter are different at P<0.10.
* Production efficiency calculated as a function of seed yield only (yield (kg ha^{-1})/N_2O-N (g ha^{-1}).

Direct comparison of wheat grain yields from the organic system with the conventional systems is biased by differences between spring wheat and winter wheat, and the effects of tillage, and cropping intensity on yield potential. The best comparison of the organic system is with the diversified winter wheat-winter pea rotation. Organic spring wheat yields were 16% lower than winter wheat yields from this rotation. Production efficiency for organic systems was similar to the other unfertilized cropping systems, except wheat-fallow CT. Organic systems production efficiency was greater than high N regimes in the continuous cropping systems (wheat-pea and wheat-wheat) ($P < 0.01$), but not different from high N regimes in wheat-fallow ($P = 0.42$) or pea (forage)-wheat systems ($P = 0.37$). The high production efficiency of organic systems warrants further evaluation of their effectiveness in mitigation of greenhouse gases.

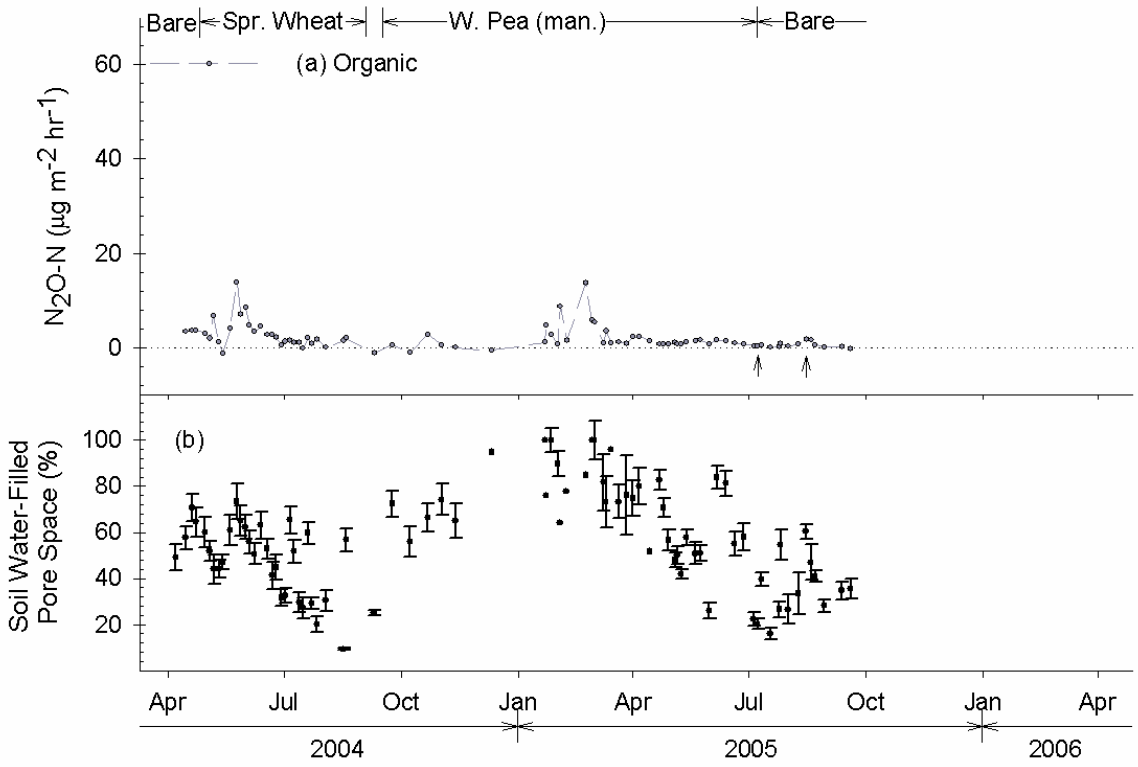

Figure 23. Mean N_2O-N emission rates (4 replicates) from organic systems (s. wheat – w. pea manure (CT – organic) (a). Soil water-filled pore space vs. time (mean of N regimes) (b). Up arrows indicate tillage events.

Grain vs. Forage Harvests: Wheat-W. Pea vs. Wheat-S. Pea. Magnitude and patterns of emissions from the wheat-winter pea (forage) closely followed those of wheat-spring pea (grain) (Figs 16 and 24). There were no differences between these two systems in N_2O emissions for any of the time periods examined, or for fertilizer-induced emissions or N loss coefficients (Table 13). This suggested early termination of pulse crops will have little effect on cumulative N_2O emissions. However, several years may be necessary before pulse crops can contribute substantially to soil N levels (Miller et al., 2006).

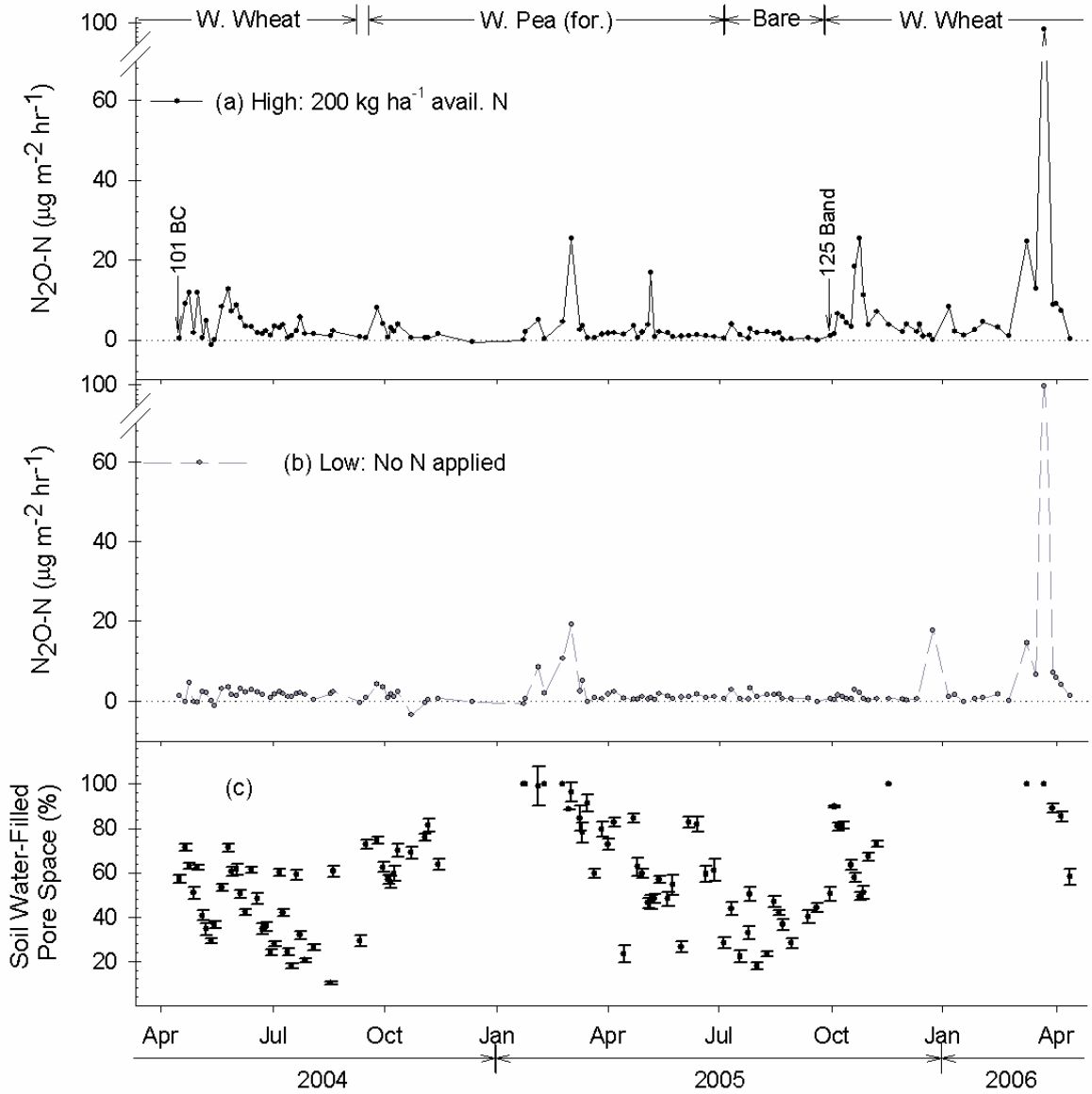

Figure 24. Mean N_2O-N emission rates (4 replicates) from wheat-pea (w. wheat-w. pea forage (NT)), for the high (a) and low (b) available N regimes Soil water-filled pore space vs. time (mean of N regimes) (c). Arrows with numbers indicate dates of fertilization, application method (BC = broadcast, Band = subsurface band), and rates of N fertilizer applied (kg ha^{-1}).

Table 13. 10-wk post-fertilization, spring thaw, total, FIE, and fertilizer loss coefficients of N_2O-N emissions, yield totals and production efficiency (yield/N_2O-N) for s. pea (g)-w. wheat (NT) and w. pea (f)-w. wheat (NT).

			----------N_2O-N----------					Yields	
Cropping system (CS)	N regime	N rate‡	10 wks	Thaws	2 yr	FIE	Frac. N lost	2004	2005*
		----------g ha^{-1}----------					(%)	--------Mg ha^{-1}---------	
wheat - s. pea (g) (NT)	Low	0	55	141	330	-	-	4.16	1.08
	High	285	196	513	895	564	0.20	4.49	-
CS Mean			126	327	612	564	0.20	4.32	1.08
wheat - w. pea (f) (NT)	Low	0	44	326	585	-	-	4.34	1.86
	High	226	189	351	739	155	0.06	4.89	-
CS Mean			116	356	662	155	0.06	4.62	1.86
Summary Statistics									
Effect		df	----------P > F----------						
Cropping System (CS)		1	0.82	0.81	0.69	0.19	0.30	0.44	
Nitrogen regime (NR)		1	0.01	0.16	0.02	-	-	0.23	
CS*NR		1	0.96	0.14	0.12	-	-	0.76	

‡ Total N applied over 2 yr

* Forage yields from 2005 not included in comparisons

CHAPTER 3

SUMMARY AND CONCLUSIONS

Nitrous oxide emissions vs. time profiles were developed for four cropping systems and the CRP over two years. Two-year cumulative losses of N_2O-N ranged from 209 to 1310 g ha^{-1} among the cropping systems. The emission profiles revealed consistencies in temporal patterns of N_2O emissions with the greatest emission activity following fertilizer application (10-wk duration) and during winter and early-spring freeze-thaw cycles. Emissions during the remainder of the year were equivalent to background levels observed in the alfalfa-perennial grass system.

The results of this study indicate that best management practices for carbon sequestration (no-till and crop intensification) will impact N_2O emissions to the extent that N fertilization practices are changed. For example, emissions from wheat-wheat systems may be higher than wheat-fallow and wheat-pea systems due to the additional N fertilization required. Tillage did not impact N_2O emissions from wheat-fallow systems.

Although, fertilizer induced emissions increased with application of urea-N the estimated fraction of fertilizer N lost as N_2O was modest for all cropping system x N regimes. Fertilizer loss coefficients averaged 0.24% (or 0.26% when adjusted for 10% ammonia losses) of the applied N rate for the four cropping systems. This level of emissions losses is considerably lower (average 4.7 times) than the IPCC default value of 1.25%. A revised, lower coefficient for estimating fertilizer losses is likely appropriate for this semiarid region.

Overall, N_2O emissions were modest compared to more humid regions. Our results closely paralleled observation from other semiarid regions, including Saskatchewan, Colorado, and the Inner Mongolia region of China. Even though emissions are relatively low for semiarid climates, our results suggest that N fertilizer timing and/or placement strategies can further mitigate N_2O emissions assuming losses of NH_3 or NO_x are minimal. For example, spring top-dressing N applications might be preferable to band applications at seeding in winter wheat systems because of better synchrony with crop N demand. Also, this strategy would minimize residual soil NO_3-N during the winter and early spring and thus reduce emissions from freeze-thaw cycles. Adoption of pulse crops in rotations also represents a potential for mitigating soil N_2O emissions as fertilizer N inputs are not required during the pulse phase, and may reduce fertilizer N inputs for subsequent cereal crops.

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APPENDICES

APPENDIX A

NITROGEN PLACEMENT EXPERIMENT

N Placement Experiment

The aim of this study was to determine the effect of urea-N fertilizer placement techniques on total N_2O emissions from soil. A greenhouse pot study was conducted using chambers filled with an Amsterdam silt loam soil. Chambers were fertilized at a rate of 200 kg N ha^{-1} equivalence. Four urea-N placement techniques were tested: broadcast surface, broadcast incorporated, subsurface band, nest, and two controls: KNO_3 (broadcast incorporated) and unfertilized treatments. Gas samples from the static vented chambers were collected and analyzed for N_2O using gas chromatography on a daily basis for eight weeks. Soil moisture content was maintained at 60% water-filled pore space. Soil emissions of N_2O were enhanced with all urea-N applications. Results indicated that placement of urea in localized areas, i.e. nest treatments, exhibited higher fertilizer induced emissions than broadcast surface and broadcast incorporated treatments ($P < 0.10$). Greatest emission activity occurred 18 days after fertilization for band and nest treatments, peak emissions were 99 μg N_2O-N m^{-2} hr^{-1} and 150 μg N_2O-N m^{-2} hr^{-1}, respectively. Highest emission activity for the broadcast treatments was approximately 60 μg N_2O-N m^{-2} hr^{-1} and did not exhibit a distinctive peak. Nitrous oxide emissions from KNO_3 were low and only slightly higher than the unfertilized control, indicating nitrification was the primary process responsible for N_2O production in this experiment.

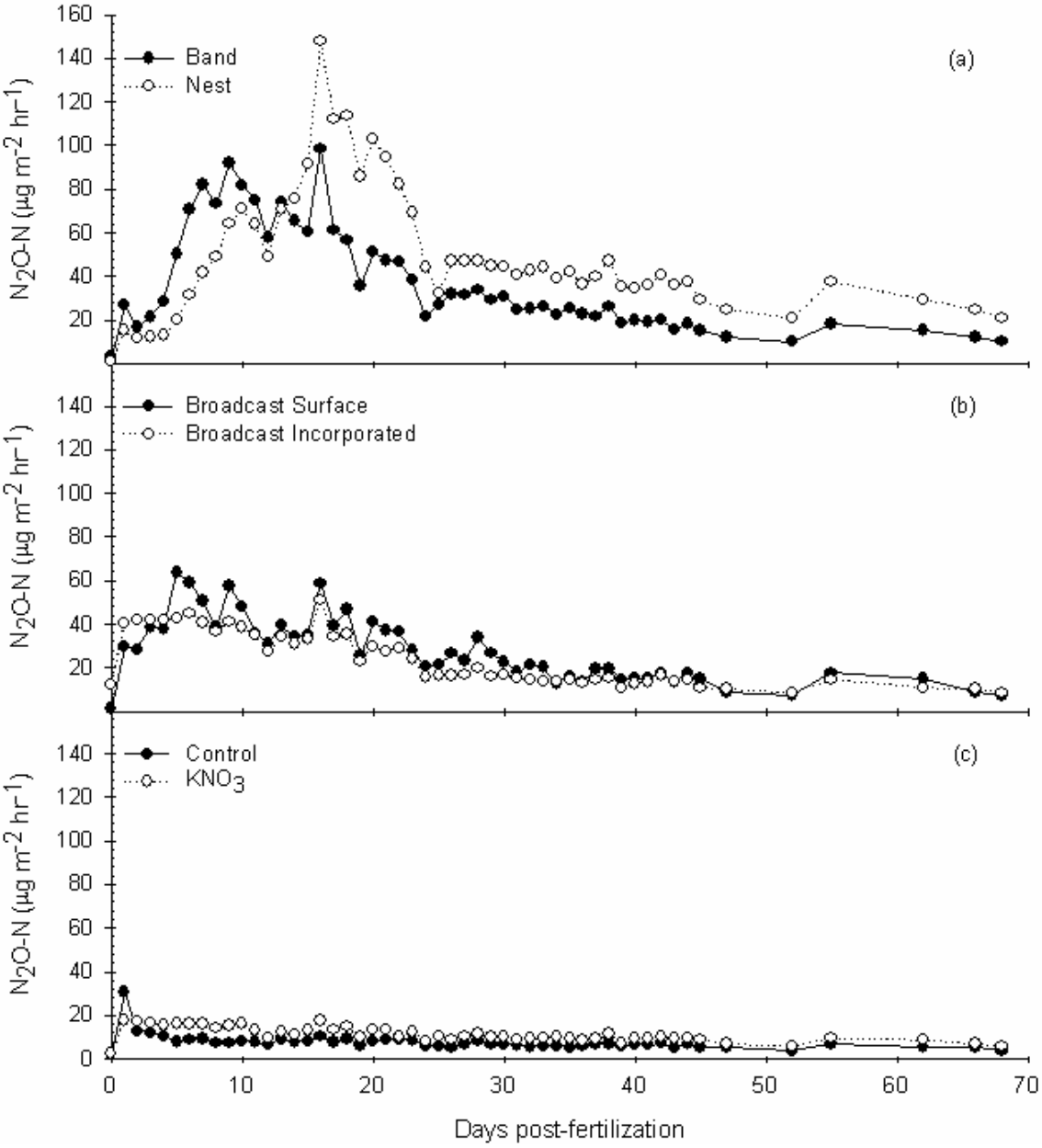

Figure A1. N_2O emission-time profiles over band and nest (a), broadcast surface and incorporated (b), and KNO_3 and unfertilized (c) available N regimes.

Table A1. Total N_2O-N fertilizer induced (FIE), and peak emissions, and fertilizer loss coefficient as affected by N placement.

N application strategy	Total N_2O-N	FIE	Peak emissions	Fert. Loss coefficient
	----------g ha^{-1}----------		μg m^{-2} hr^{-1}	%
Ctrl	120a†	-	31a	-
KNO_3	179ab	59a	18a	0.03a
Broadcast	430c	294b	64b	0.15b
Surface Broadcast Incorporated	364bc	238ab	51ab	0.12ab
Band	560cd	421bc	99c	0.21bc
Nest	765d	620c	148d	0.31c

† Values followed by the same letter are not different ($P \geq 0.10$).

APPENDIX B

NITROGEN SOURCE EXPERIMENT

Importance of nitrification vs. denitrification

This study was conducted to more effectively explain the processes responsible for N_2O emissions in the NGP. A microplot study examining the impacts of two different substrates (NH_4^+ and NO_3^-) on soil N_2O emissions was established during the spring of 2005 and continued for 10 weeks. Static vented chambers were centered in 1 m^2 bare soil subplots in the field. Both chamber and subplot were fertilized with 200 kg N ha^{-1} equivalence. Field samples of N_2O were taken twice a week while samples of soil N (NH_4^+ and NO_3^-) in the upper 15 cm were taken approximately once a week. Gas samples were analyzed utilizing gas chromatography while soil samples were processed with spectrophotometry. Results from the study indicated nitrification was the primary process responsible for N_2O emissions. Primarily, cumulative emissions from the urea-fertilized plots were significantly higher than KNO_3-fertilized and control plots while emissions from KNO_3-fertilized plots were not different from the control. Secondarily, nitrate contents were shown to increase over time in plots fertilized with urea. In addition, soil WFPS did not exceed 70% during the course of the study. It is thus likely that nitrification is primarily responsible for spring-summer N_2O emissions in the NGP.

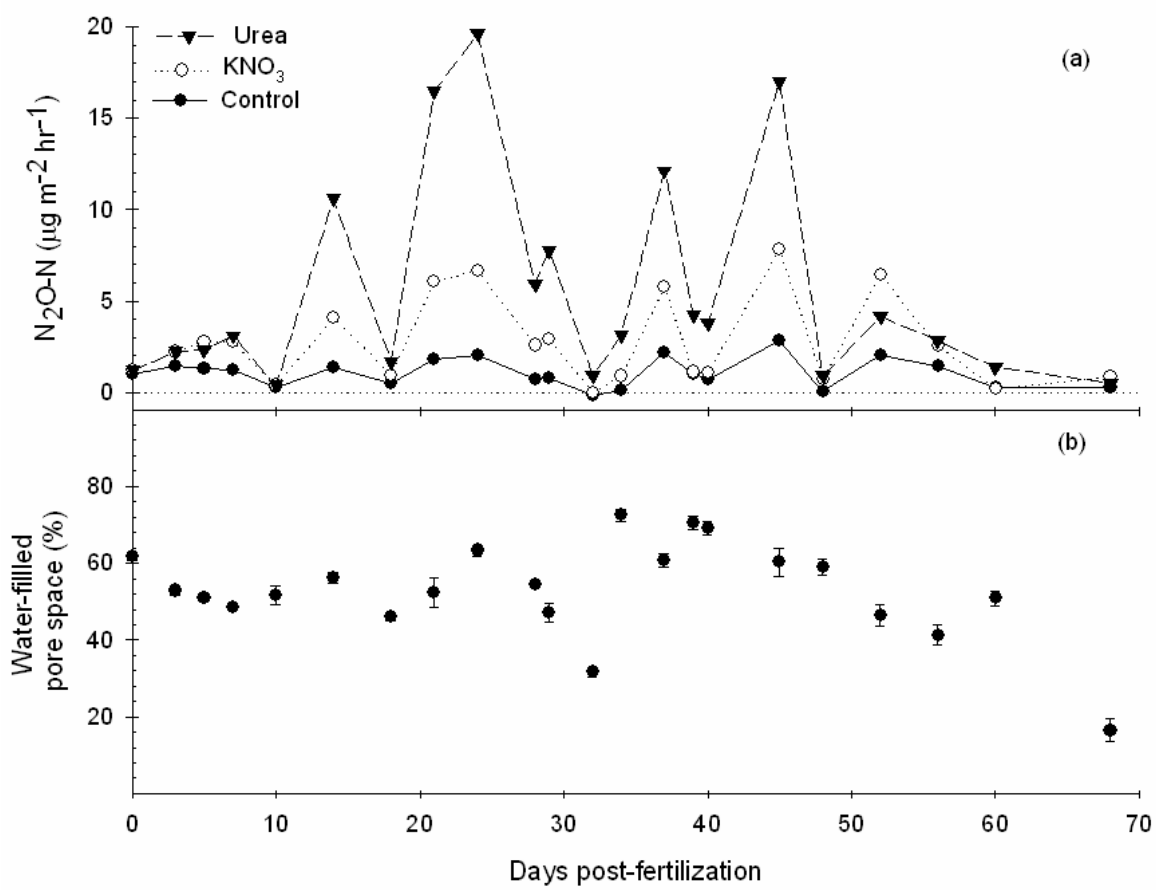

Figure B1. Mean N_2O-N emission rates (4 replicates) from two N fertilizer sources (Urea, KNO_3) and an unfertilized control (a). Soil water-filled pore space vs. time (mean of N regimes) (b).

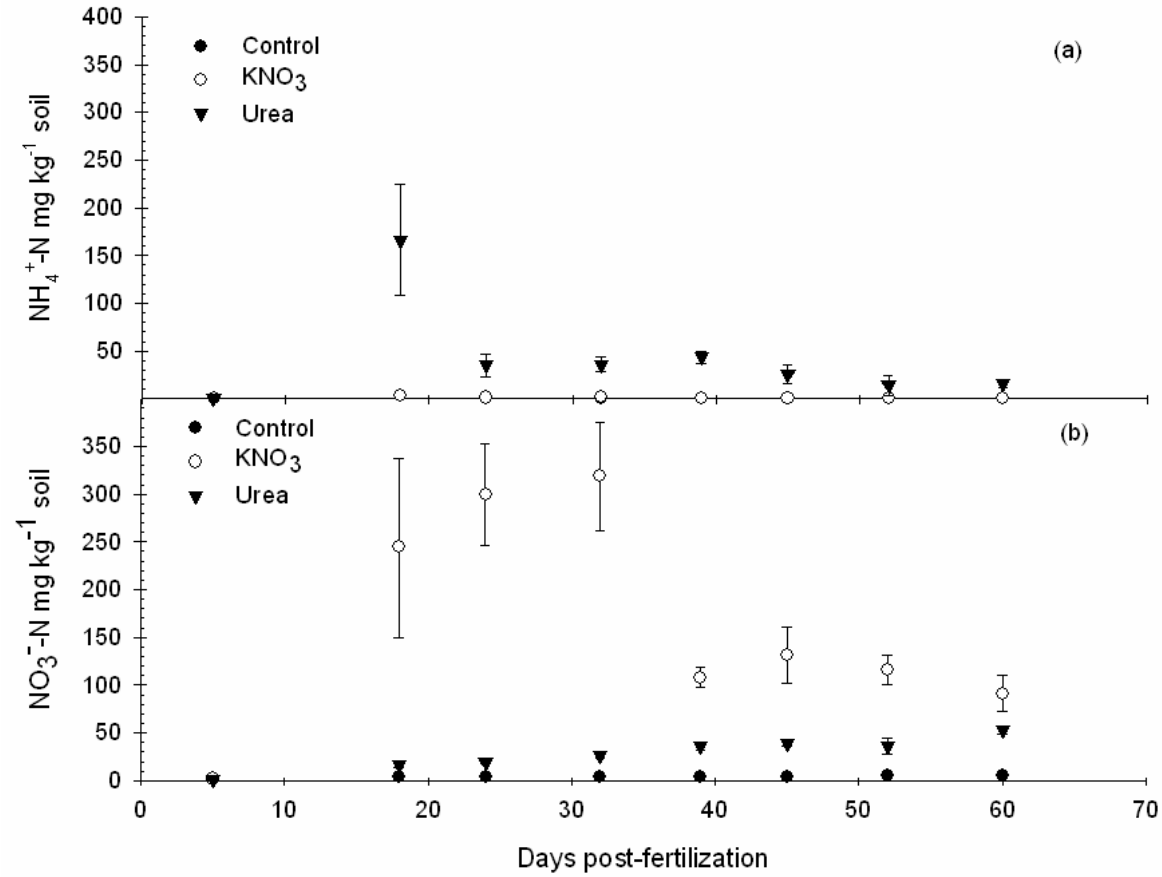

Figure B2. Soil NH_4^+ content (a) and soil NO_3^--N content (b) in each of the N source treatments. Bars represent standard error.

Table B1. Cumulative, fertilizer induced (FIE) and peak N_2O emissions over the 10 wk study as influenced by N source.

N source	Total N_2O-N	FIE	Peak emissions	Frac. N Fertilizer lost
	----------g ha^{-1}----------		μg m^{-2} hr^{-1}	%
Ctrl	17a†	-	2.83a	-
KNO_3	45a	28a	7.80a	0.01a
Urea	91b	74a	19.65b	0.03a

† Values followed by the same letter are not different ($P \geq 0.10$).

APPENDIX C

DIURNAL VARIATIONS IN N_2O EMISSIONS

Diurnal variations in N_2O emissions

To examine diurnal variability for N2O emissions, gas samples were taken from all N regimes within the wheat-wheat rotation every three hours from 0700 hrs 27 May to 1100 hrs 28 May 2005. Significant differences were noted between hours over the course of the study. Highest emissions occurred in the late afternoon/early evening (1700 and 2000 hrs) with the highest temperatures though there was no correlation between N_2O emissions and air or soil temperatures (r^2 = 0.34 and 0.43 respectively). A significant nitrogen level*time interaction was noted likely due to the low emissions exhibited by the control treatment.

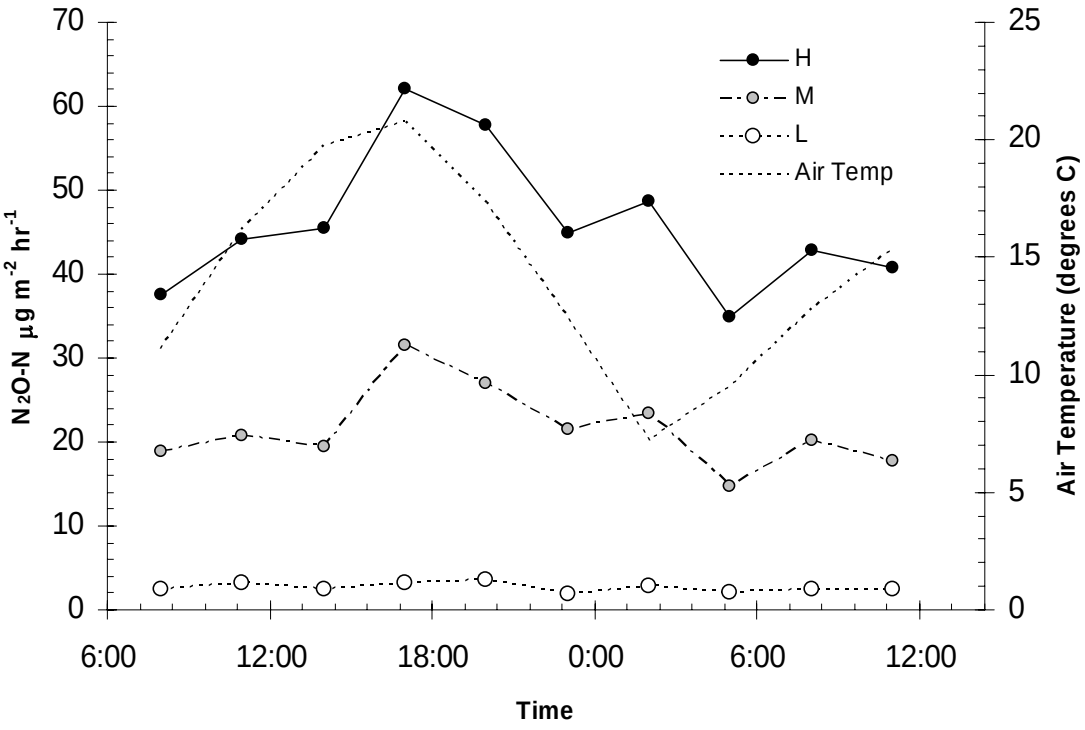

Figure C1. Nitrous oxide emissions over time from 0700 hrs 27 May to 1100 hrs 28 May 2005 for each of the three N regimes, High (H), Moderate (M) and Low (L). Site air temperature at the time of sampling.

Table C1. Nitrous oxide emissions for low, moderate, and high N regimes within the wheat-wheat cropping system as affected by time of day (27-28 May 2005).

	N regime			
Time	Low	Moderate	High	Time Mean
	N_2O μg m^{-2} hr^{-1}			
08:00	2.5	18.8	37.7	19.7ad*
11:00	3.2	20.7	44.9	22.9bc
14:00	2.5	19.5	45.8	22.6abc
17:00	3.2	31.6	62.6	32.5e
20:00	3.5	27.1	57.8	29.5e
23:00	1.9	21.6	43.6	22.4abc
02:00	2.7	23.3	47.6	24.6c
05:00	2.0	14.6	34.3	17.0d
08:00	2.5	20.2	42.4	22.0abc
11:00	2.5	17.8	41.2	20.5ab
24 hr N regime mean	2.7	21.9	46.3	

Effect	P < F			
Nitrogen Regime (NR)	-	-	-	< 0.01
Time	0.06	< 0.01	< 0.01	< 0.01
NR*Time	-	-	-	< 0.01

* Values followed by the same letter are not different ($P \geq 0.10$).

Estimation of emissions across time using a single daily sample may not effectively capture the diurnal variability of N_2O emissions. Emissions from low, moderate and high N regimes at 1400 hrs were slightly lower (7, 9, and 2%, respectively) than the 24-hr mean indicating a possible underestimation of cumulative emissions. However, this underestimation was well within the range of variability across the four replications of each N regime. Thus, sampling during 1300-1500 hrs was likely representative of the mean daily flux rate of N_2O.

APPENDIX D

N_2O BUILDUP WITHIN CHAMBERS

Rates of N_2O Buildup within Chambers.

To observe rates of buildup within chambers, multiple samples were collected within a single one-hour incubation period. Samples were taken every 15 minutes from all three N regimes of wheat-wheat during the spring and summer of 2005. Rates of N_2O accumulation within chambers were found to be highly linear ($r^2 > 0.9$) (Figure D1). Rates of accumulation were also found to be highly linear ($r^2 > 0.9$) for emissions of CO_2, even at high concentrations (> 100 μg m^{-2} hr^{-1}) (data not shown). Curvilinearity was noted in three of the twelve tests shown (a, b, c). In these instances, a quadratic relationship was more explanatory of the N_2O buildup than a linear relationship. Utilizing the instantaneous slope for quadratic regression, flux rates at 60 minutes were estimated at 160, 170, and 187% higher than those observed for the low, moderate, and high N regimes, respectively (Table D1). Leakage around the chamber seals may have caused this aberration (Lemke, 2005 personal communication). Overall, however, it was shown that when seals were well maintained, confidence in chamber representation of emission rates is high.

Table D1. N_2O-N flux rates for 1 hr based on observed values and linear or quadratic estimates.

N Regime (24 June 2005)	Observed	Linear Estimate	Quadratic Estimate
	----------μg m^{-2} hr^{-1}----------		
Low (a)	1.69	1.95	2.95
Moderate (b)	2.91	3.42	5.46
High (c)	6.88	7.26	11.03

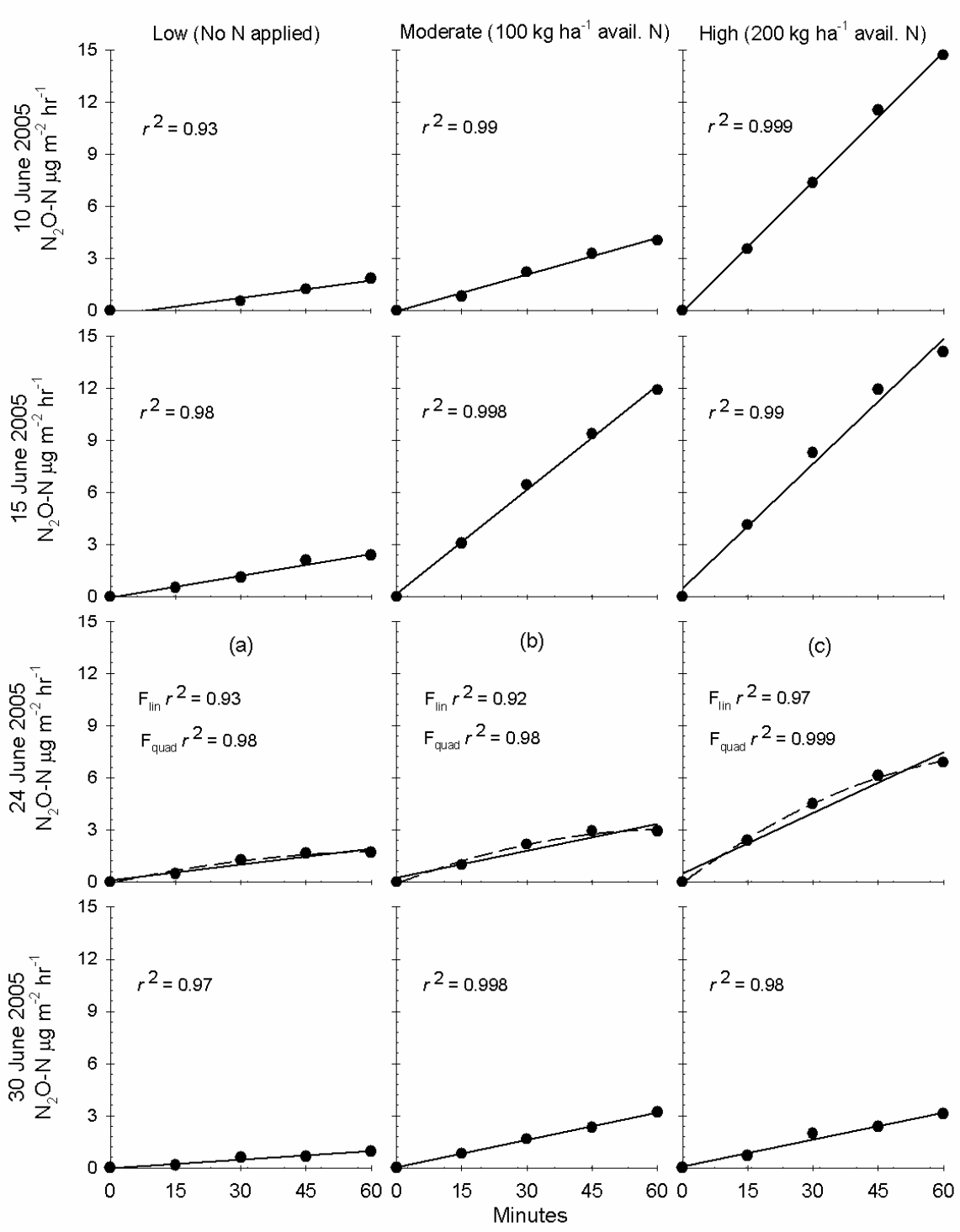

Figure D1. Relationship between N_2O-N flux (µg m^{-2} hr^{-1}) and time during four 1-hr sampling events from wheat-wheat in the spring and summer of 2005.

APPENDIX E

SITE TEMPERATURE DATA

Table E1. Daily maximum temperatures in 2004 (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	0.6	-0.6	5.6	18.9	18.9	20.0	28.3	33.3	32.8
2	2.2	-0.6	0.6	10.6	24.4	23.3	24.4	30.6	29.4
3	-12.2	-1.1	2.8	13.3	25.0	27.2	27.2	27.2	16.7
4	-20.6	0.0	3.9	16.1	26.7	26.1	22.2	29.4	18.9
5	-18.9	-1.1	3.3	20.6	26.7	30.0	22.8	30.6	21.1
6	-14.4	0.0	3.3	18.3	25.6	29.4	23.9	30.6	20.0
7	-2.8	-1.1	10.0	17.2	26.7	20.6	25.6	25.0	25.0
8	1.7	0.0	12.8	17.2	25.0	19.4	23.9	24.4	25.6
9	6.1	1.1	-1.7	12.8	20.0	15.0	27.8	25.6	29.4
10	6.1	-0.6	12.8	10.6	25.0	15.6	28.9	25.6	24.4
11	2.8	0.0	9.4	14.4	13.9	15.6	27.2	26.7	32.2
12	1.7	-1.1	14.4	22.8	3.9	18.3	27.8	28.9	27.8
13	5.0	1.7	13.3	23.9	10.0	19.4	31.1	30.6	13.9
14	6.7	2.2	6.1	20.6	16.1	22.2	33.3	31.7	13.9
15	3.3	4.4	8.3	16.1	17.2	21.1	32.2	31.7	17.8
16	7.2	5.0	12.2	14.4	18.9	18.3	32.8	31.1	18.3
17	7.2	6.1	15.0	13.9	15.6	17.8	35.0	26.1	25.6
18	7.2	10.0	18.9	11.7	14.4	12.8	32.8	22.8	25.0
19	3.9	8.9	17.8	13.3	15.6	18.3	32.2	23.9	17.8
20	3.9	3.3	12.2	13.3	16.1	20.6	35.0	25.6	9.4
21	1.7	5.0	14.4	11.1	17.2	21.7	32.2	29.4	10.6
22	1.7	3.3	18.3	13.9	11.7	26.1	31.7	18.9	11.1
23	4.4	5.6	22.8	20.6	6.1	27.8	22.8	20.0	18.9
24	4.4	7.2	20.6	21.1	8.9	23.9	27.8	22.2	19.4
25	0.0	7.2	16.7	21.7	16.1	22.8	32.2	17.8	23.3
26	-1.7	6.7	15.6	22.8	16.7	23.9	30.6	16.7	22.8
27	2.8	7.2	10.0	25.6	21.1	22.2	27.8	18.9	19.4
28	6.7	4.4	11.1	23.3	20.0	26.1	25.6	20.0	20.6
29	7.2	5.6	18.3	13.3	11.1	27.8	28.9	23.3	20.6
30	4.4		24.4	15.0	15.0	27.8	30.0	27.8	20.6
31	-0.6		23.3		16.7		31.1		

Table E1 cont'd (deg C).

Day	Oct	Nov	Dec
1	17.2	4.4	-0.6
2	20.6	13.3	2.8
3	20.6	6.7	5.6
4	21.1	5.6	3.3
5	21.7	16.7	2.2
6	22.2	17.2	5.0
7	21.7	17.2	6.7
8	23.9	15.6	9.4
9	27.2	15.6	7.2
10	15.6	11.7	12.2
11	15.0	8.3	16.7
12	14.4	7.8	12.2
13	16.7	10.0	2.2
14	21.1	8.9	10.0
15	19.4	10.0	5.6
16	19.4	7.2	6.1
17	12.8	10.0	8.3
18	25.6	9.4	5.6
19	12.2	7.8	12.8
20	10.6	2.2	14.4
21	11.7	2.8	1.1
22	12.8	3.3	-1.7
23	10.0	2.8	-3.9
24	6.1	4.4	1.1
25	7.2	8.9	1.7
26	12.8	6.1	2.2
27	13.3	-0.6	1.7
28	9.4	-2.2	2.8
29	6.7	-2.2	4.4
30	7.8	0.6	4.4
31	6.1		-6.1

Table E2. Daily minimum temperatures in 2004 (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	-8.3	-7.2	-10.0	4.4	-1.1	3.3	8.3	10.6	11.7
2	-18.9	-13.9	-11.7	-1.1	1.7	6.1	7.2	12.2	9.4
3	-22.8	-11.1	-15.0	-0.6	4.4	5.0	8.9	9.4	3.9
4	-27.8	-11.7	-4.4	0.0	4.4	6.7	10.6	8.3	2.8
5	-31.7	-7.2	-7.8	0.0	8.3	7.8	7.8	10.6	6.7
6	-32.8	-12.2	-6.1	1.7	3.3	10.6	7.8	10.0	1.7
7	-18.3	-9.4	-7.8	-0.6	7.8	4.4	8.3	10.0	5.0
8	-10.0	-3.9	-2.2	5.6	4.4	6.7	4.4	5.6	4.4
9	-5.6	-5.6	-0.6	0.0	5.0	5.6	5.0	10.0	5.6
10	-11.7	-10.0	-3.3	-3.9	2.8	7.8	11.1	7.8	8.9
11	-6.7	-13.9	-4.4	-1.1	1.7	6.7	8.9	5.6	4.4
12	-10.6	-16.7	-3.3	-1.1	-3.9	3.3	9.4	6.7	8.9
13	-10.6	-11.7	-1.7	0.0	-1.7	8.9	15.6	6.1	6.1
14	-6.7	-14.4	-4.4	5.6	-3.3	4.4	11.7	7.8	5.6
15	-10.0	-11.1	-6.7	-1.7	-0.6	3.9	16.7	9.4	1.1
16	-6.7	-11.7	-6.7	-2.2	2.2	0.0	11.7	16.1	7.2
17	-11.1	-6.1	3.9	1.1	8.3	2.8	13.3	14.4	3.3
18	-12.2	1.1	4.4	1.7	4.4	3.9	13.9	11.7	7.2
19	-6.1	0.0	3.3	0.0	6.7	5.6	15.6	6.1	5.6
20	-6.7	-5.6	-5.0	-1.7	2.2	4.4	13.9	12.2	0.6
21	-11.7	-11.1	-1.7	-2.2	5.6	5.6	12.8	11.1	1.7
22	-11.7	-9.4	0.0	-2.2	5.6	6.7	13.3	9.4	2.2
23	-8.3	-11.1	2.2	-1.7	0.0	5.6	11.7	2.8	7.2
24	-11.1	-7.2	-1.1	-2.2	0.0	7.8	9.4	6.1	6.7
25	-13.9	-1.7	-1.1	-1.7	-1.7	10.0	10.0	5.6	2.8
26	-17.2	0.0	2.2	4.4	5.0	8.3	13.3	5.6	5.0
27	-12.2	-2.2	-11.7	5.0	8.3	9.4	10.6	7.2	5.0
28	-17.2	-3.3	-0.6	-0.6	7.2	7.8	8.9	6.1	3.3
29	0.0	-3.3	-1.7	-2.8	2.2	7.2	7.2	5.6	2.2
30	-7.2		-1.7	-2.2	3.3	12.8	11.7	7.2	2.2
31	-7.2		7.2		3.9		10.0		

Table E2 cont'd (deg C).

Day	Oct	Nov	Dec
1	1.1	-5.6	-7.8
2	0.6	-3.3	-5.0
3	2.2	-3.9	-3.3
4	0.0	-3.3	-6.7
5	3.9	-3.3	-9.4
6	4.4	-1.1	-5.0
7	8.3	-0.6	-3.3
8	1.7	-1.7	-5.6
9	10.0	3.9	-6.7
10	1.7	0.6	-1.7
11	-1.7	-6.7	3.3
12	3.3	-6.1	-1.7
13	-0.6	-7.2	-9.4
14	5.6	-6.7	-12.2
15	3.3	-4.4	0.0
16	4.4	-2.8	-5.6
17	1.7	-3.9	-4.4
18	-1.7	-7.2	-3.9
19	-3.9	-6.7	-2.8
20	-1.1	-5.6	-2.2
21	0.6	-14.4	-6.7
22	-2.2	-7.8	-3.3
23	0.0	-5.0	-26.7
24	-5.0	-4.4	-17.2
25	-6.7	2.2	-12.8
26	-3.9	-1.1	-10.0
27	-0.6	-9.4	-11.1
28	-1.1	-13.3	-12.8
29	1.1	-13.9	-5.6
30	-1.7	-13.9	-7.8
31	-3.3		-13.3

Table E3. Daily maximum temperatures in 2005 (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	-12.8	7.8	11.1	15.0	10.0	8.3	27.2	29.4	25.0
2	-11.1	10.0	11.1	16.7	12.8	8.9	27.2	28.9	29.4
3	-7.8	12.8	11.1	17.2	13.9	13.9	26.7	23.3	32.8
4	-11.1	17.2	12.2	10.0	12.8	12.2	25.0	29.4	29.4
5	-17.8	11.1	13.9	18.3	17.2	22.8	28.3	32.8	26.7
6	-6.7	1.7	15.6	21.7	16.7	9.4	28.9	35.0	25.6
7	-6.1	-1.7	14.4	20.6	13.3	12.8	30.0	35.0	27.8
8	-3.9	0.6	15.0	9.4	16.7	11.7	33.9	33.3	31.1
9	-12.2	5.0	18.3	10.6	14.4	12.2	33.9	30.0	31.1
10	-2.2	8.3	11.1	16.1	10.6	17.2	23.9	30.0	11.7
11	-2.2	10.0	18.3	20.6	5.0	14.4	27.2	26.7	16.7
12	0.6	6.7	13.3	24.4	7.2	7.2	33.3	25.6	16.7
13	0.0	10.0	2.2	21.1	13.9	17.8	32.8	18.3	17.2
14	-12.8	2.2	1.7	12.2	21.1	23.3	27.8	23.3	20.0
15	-13.3	1.1	5.6	21.1	18.9	30.0	33.9	27.8	23.9
16	-2.2	0.0	8.9	23.9	18.3	18.9	32.8	28.9	23.9
17	3.3	4.4	8.9	10.6	12.2	25.0	22.2	29.4	21.1
18	9.4	4.4	8.3	3.9	18.3	17.2	30.0	26.7	16.7
19	16.1	6.7	8.9	5.6	16.7	22.8	32.2	23.9	25.0
20	15.0	4.4	7.2	5.6	18.9	28.9	34.4	29.4	27.8
21	11.7	6.7	11.1	13.9	17.2	27.8	33.3	32.8	25.0
22	10.6	5.6	8.9	18.9	26.7	31.7	32.8	32.2	23.3
23	12.8	7.8	7.8	18.3	16.1	21.1	33.3	29.4	19.4
24	13.9	10.6	-1.1	17.8	9.4	25.6	30.0	25.6	7.2
25	11.1	12.2	6.1	17.8	15.6	18.9	13.9	23.3	14.4
26	8.3	11.7	10.0	18.3	17.8	17.8	22.8	28.3	23.3
27	9.4	8.9	14.4	13.3	21.1	18.9	27.8	29.4	21.7
28	8.9	11.1	12.2	1.7	26.1	19.4	25.6	30.6	17.8
29	7.2		7.8	5.0	18.3	16.7	30.6	31.7	26.7
30	6.7		5.6	6.1	18.3	22.8	30.6	31.1	25.0
31	10.0		9.4		17.8		30.6		

Table E3 cont'd. (deg C)

Day	Oct	Nov	Dec
1	27.8	17.2	-3.9
2	7.8	10.0	-5.0
3	10.0	5.6	-2.8
4	6.1	7.2	-3.9
5	8.9	5.6	-1.7
6	15.0	8.9	-3.3
7	19.4	5.0	-15.6
8	19.4	7.2	-10.0
9	10.6	3.9	-1.1
10	12.2	9.4	1.1
11	13.3	13.3	4.4
12	14.4	8.3	2.8
13	20.0	2.8	-1.7
14	22.2	6.1	0.0
15	23.9	-1.1	-6.1
16	23.9	2.8	-5.6
17	22.2	6.1	-8.3
18	17.2	5.6	-15.0
19	17.2	9.4	-7.8
20	20.0	10.0	4.4
21	13.9	10.0	5.6
22	16.7	11.1	12.8
23	18.3	10.6	9.4
24	20.6	8.3	6.1
25	18.9	7.8	8.3
26	22.2	5.0	9.4
27	17.2	-0.6	5.6
28	12.2	-1.7	5.6
29	10.0	-3.9	6.7
30	8.3	-5.0	1.1
31	11.7		6.1

Table E4. Daily minimum temperature in 2005 (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	-18.9	-3.9	-3.3	-2.2	-4.4	5.0	8.9	11.1	5.6
2	-19.4	-2.2	-6.1	2.8	-5.6	5.0	7.2	12.2	5.6
3	-17.8	-3.9	-5.6	-1.7	-2.2	5.6	5.0	10.0	6.1
4	-18.9	0.0	-6.7	0.0	2.8	7.2	6.7	8.3	10.0
5	-22.2	-2.8	-2.2	-2.2	1.7	2.8	7.2	10.6	7.8
6	-22.2	-5.0	-3.3	-2.8	3.9	2.8	12.2	11.7	10.0
7	-13.3	-11.7	-1.7	0.6	5.6	2.2	13.9	11.7	4.4
8	-17.2	-9.4	1.7	5.6	6.7	3.9	12.8	14.4	6.7
9	-17.8	-11.7	-1.1	0.0	5.6	-1.7	13.9	11.1	10.6
10	-19.4	-11.1	-0.6	1.1	4.4	0.0	11.1	10.6	6.7
11	-16.1	-11.1	-1.7	-5.0	3.3	0.0	10.6	10.6	4.4
12	-16.7	-9.4	-2.8	-1.7	-2.8	0.6	9.4	10.0	1.7
13	-20.6	-4.4	-5.6	1.7	-0.6	3.9	16.1	5.6	1.7
14	-20.6	-9.4	-6.7	-1.1	2.2	3.9	10.0	0.6	2.2
15	-9.4	-8.9	-7.2	-6.1	7.2	10.0	9.4	5.0	3.3
16	-21.1	-13.9	-1.1	-5.0	9.4	5.6	13.3	7.8	5.6
17	-7.8	-11.7	-8.3	-5.6	5.6	10.0	6.7	10.0	7.8
18	-1.1	-12.2	-8.9	-6.7	5.6	7.8	6.1	8.9	6.7
19	3.9	-11.7	-6.7	-0.6	8.3	4.4	13.3	6.7	3.3
20	2.2	-6.1	-3.9	0.0	6.1	8.9	8.9	6.7	3.9
21	1.1	-3.3	-1.7	-1.7	4.4	11.1	10.6	8.3	8.9
22	-4.4	-8.3	-1.7	-1.7	2.2	10.6	18.9	12.2	2.2
23	-1.1	-7.8	-6.7	0.0	5.0	12.2	15.6	9.4	6.1
24	-2.2	-7.8	-9.4	0.6	3.3	6.7	10.6	20.0	2.2
25	-2.8	-6.1	-13.9	2.8	0.0	7.2	9.4	21.1	3.9
26	-5.0	-6.7	-11.1	2.8	0.0	7.2	5.0	7.2	-0.6
27	-4.4	-7.2	3.3	-2.2	0.6	5.0	7.2	8.9	8.9
28	0.0	-7.8	3.3	-5.6	2.2	6.7	8.9	7.8	-0.6
29	6.1		-3.3	-8.9	2.2	8.3	9.4	11.1	1.7
30	3.3		-4.4	-4.4	3.3	8.3	13.3	5.0	13.9
31	-3.9		-3.9		2.2		11.7		

Table E4 (cont'd). (deg C)

Day	Oct	Nov	Dec
1	10.0	9.4	-13.3
2	0.0	0.0	-14.4
3	1.7	-0.6	-15.0
4	1.7	0.0	-13.3
5	-1.1	-2.2	-9.4
6	-3.3	-2.2	-23.3
7	0.0	0.0	-28.9
8	3.3	-2.8	-26.1
9	1.1	-11.7	-16.7
10	-2.2	-8.3	-12.2
11	-1.1	1.1	-7.8
12	1.7	-1.1	-10.6
13	0.6	-8.3	-12.2
14	0.6	-3.9	-8.3
15	5.6	-12.2	-15.6
16	3.3	-3.9	-13.3
17	4.4	-1.1	-18.3
18	4.4	-6.1	-26.7
19	1.7	-2.2	-26.1
20	1.7	-3.9	-14.4
21	2.2	-2.2	-3.9
22	-1.1	-2.8	2.2
23	-0.6	-2.8	1.1
24	1.7	-4.4	-3.3
25	2.2	-5.6	-2.8
26	2.8	-3.9	0.0
27	7.8	-5.6	0.0
28	5.6	-11.1	1.1
29	0.6	-9.4	-1.1
30	-1.7	-12.8	-11.7
31	-4.4		-1.1

Table E5. Daily maximum temperatures in 2006 (deg C).

Day	Jan	Feb	Mar	Apr
1	6.1	5.6	8.3	12.8
2	7.2	3.9	5.0	7.8
3	6.1	4.4	5.6	16.1
4	3.3	6.7	5.0	17.8
5	2.8	5.0	6.7	13.9
6	7.2	2.2	10.6	5.6
7	7.2	5.6	7.2	10.6
8	7.2	7.2	5.6	17.2
9	4.4	7.2	3.3	13.9
10	7.8	-0.6	0.6	13.9
11	8.3	-1.7	1.7	12.8
12	3.3	3.3	1.7	17.2
13	5.0	5.0	2.8	17.8
14	10.6	6.7	6.1	18.9
15	8.3	-6.1	5.0	18.9
16	0.6	-6.7	6.7	16.1
17	7.2	-14.4	10.0	7.8
18	5.0	-15.6	8.3	5.6
19	3.9	-9.4	1.1	12.2
20	2.2	-1.1	1.1	17.2
21	1.7	0.0	3.9	21.7
22	0.0	3.3	7.2	21.7
23	6.7	6.1	10.6	3.3
24	7.2	5.6	13.3	3.3
25	6.1	1.1	17.8	12.2
26	6.1	11.7	15.6	20.6
27	5.0	12.8	10.6	20.6
28	1.1	11.1	15.0	20.6
29	2.8		13.3	21.1
30	8.3		10.0	20.6
31	5.6		10.0	

Table E6. Daily minimum temperature in 2006 (deg C).

Day	Jan	Feb	Mar	Apr
1	0.0	-8.3	1.7	0.6
2	-5.0	-2.8	-6.1	-1.7
3	-2.2	-6.1	-6.7	1.1
4	-6.1	-5.6	-5.0	5.0
5	-12.2	-3.9	-6.1	3.9
6	-6.7	-10.6	-1.1	0.6
7	-4.4	-7.2	-1.1	2.2
8	-12.2	-3.9	-5.0	0.0
9	-12.8	-3.9	-5.6	2.2
10	-3.3	-11.7	-8.3	0.0
11	-0.6	-14.4	-11.7	-1.7
12	-5.6	-10.0	-11.1	-1.7
13	-11.7	-6.7	-12.2	-1.7
14	-1.7	-9.4	-8.3	-0.6
15	-2.8	-15.0	-2.8	-0.6
16	-8.9	-15.6	-10.0	1.7
17	-7.8	-27.2	-5.0	-0.6
18	-1.1	-30.6	-3.9	-1.7
19	-6.7	-25.6	-5.6	-3.3
20	-4.4	-19.4	-6.1	-3.9
21	-5.0	-6.7	-9.4	-3.3
22	-11.1	-2.8	-3.3	-3.9
23	-3.3	-1.7	-3.9	-3.9
24	-5.6	0.6	-2.8	-3.9
25	-7.8	-8.3	1.1	-2.2
26	-5.6	-10.6	-0.6	-2.2
27	-5.6	3.3	-6.7	-2.2
28	-8.3	4.4	-2.8	-2.2
29	-3.9		0.0	-2.2
30	-4.4		0.0	6.7
31	-2.8		1.1	

Table E7. Daily mean soil temperature in 2004 (5 cm depth) (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	-1.1	-2.2	-1.1	5.0	17.8	18.3	15.6	26.1	28.9
2	-15.6	-5.0	0.6	3.9	22.2	22.8	22.8	21.7	12.2
3	-20.6	-4.4	-2.2	12.2	10.0	26.1	20.0	16.7	10.6
4	-22.2	-1.7	0.6	15.0	26.1	18.3	21.1	25.6	17.2
5	-26.7	-6.7	2.8	18.3	23.9	27.8	18.9	26.7	17.8
6	-17.2	-6.7	0.0	15.0	21.1	18.9	22.2	23.9	18.9
7	-2.8	-1.1	8.9	16.1	21.1	18.3	18.9	19.4	23.9
8	-1.1	-2.2	7.2	12.2	17.8	11.1	23.3	23.9	25.0
9	2.2	-2.8	12.2	5.6	17.8	13.9	25.6	22.2	22.2
10	-2.2	-2.2	3.3	7.2	6.1	9.4	18.9	24.4	22.8
11	1.1	-10.0	6.1	12.2	20.0	15.0	7.8	23.9	26.7
12	-2.2	-7.2	12.2	19.4	1.7	16.1	9.4	27.8	12.2
13	1.7	-1.1	3.3	11.7	6.7	17.2	29.4	29.4	13.3
14	1.7	-1.7	5.0	13.3	13.3	20.0	31.1	29.4	8.9
15	-3.3	-1.1	6.1	11.1	15.6	11.1	28.9	30.6	16.7
16	3.3	-3.3	7.2	12.8	6.7	17.2	31.1	25.6	17.8
17	-3.3	2.8	11.7	4.4	3.9	11.1	32.8	21.7	24.4
18	-3.3	7.8	16.1	7.8	11.7	11.1	23.9	13.9	16.7
19	1.1	1.7	11.7	7.8	12.2	17.2	27.8	23.3	8.9
20	-2.8	3.3	10.6	3.3	13.9	20.0	23.9	24.4	7.8
21	-3.9	2.2	13.9	7.2	10.0	21.1	25.6	20.6	8.9
22	-1.7	0.6	14.4	11.1	7.2	25.0	21.7	17.8	10.6
23	0.6	2.8	20.0	20.0	4.4	19.4	20.6	17.2	14.4
24	-0.6	5.6	4.4	19.4	7.8	20.0	26.7	12.8	18.3
25	-14.4	4.4	15.0	16.1	15.6	18.3	27.8	16.1	21.1
26	-5.6	2.2	1.1	21.7	16.1	21.1	26.1	11.7	17.8
27	-12.2	3.9	1.7	22.8	17.8	18.3	25.0	17.8	15.0
28	5.0	2.2	10.6	2.2	8.3	21.7	24.4	20.0	19.4
29	5.0	-0.6	11.7	8.9	5.6	26.1	26.7	22.8	18.3
30	-1.7		19.4	12.2	13.9	24.4	27.8	26.7	16.7
31	-0.6		18.9		15.0		28.9		

Table E7 cont'd. (deg C).

Day	Oct	Nov	Dec
1	12.2	-0.6	-2.8
2	19.4	10.0	0.6
3	19.4	3.3	0.6
4	20.0	4.4	-1.1
5	20.0	10.0	-0.6
6	21.1	2.8	3.9
7	16.7	7.2	1.7
8	20.0	8.9	5.6
9	15.6	10.0	-2.2
10	7.8	1.7	10.0
11	10.0	7.2	12.2
12	11.7	3.9	1.7
13	15.6	1.1	-1.1
14	18.3	6.7	3.3
15	6.1	4.4	2.8
16	11.7	5.0	-1.1
17	4.4	7.2	4.4
18	6.7	5.6	3.3
19	9.4	-1.7	12.2
20	6.1	-2.2	0.0
21	10.0	1.1	-5.6
22	6.1	0.0	-6.7
23	5.6	-0.6	-12.8
24	5.0	3.3	-6.7
25	0.0	5.6	-0.6
26	11.1	-1.7	1.1
27	8.9	-7.2	-1.1
28	6.7	-6.7	1.1
29	2.2	-8.9	3.9
30	5.0	-3.3	-7.2
31	0.6		-13.3

Table E8. Daily mean soil temperature in 2005 (5 cm depth) (deg C).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	-13.3	0.6	6.7	13.3	9.4	7.8	26.7	27.8	24.4
2	-11.7	7.8	7.2	15.6	12.2	8.3	24.4	20.0	27.2
3	-11.7	8.3	6.1	14.4	13.3	12.8	18.3	23.9	30.0
4	-15.0	10.6	4.4	1.7	12.2	12.2	24.4	27.8	26.1
5	-18.3	-1.1	3.3	9.4	16.7	21.7	27.8	32.2	22.8
6	-6.7	-5.0	13.9	17.8	15.6	8.9	28.9	32.2	23.9
7	-17.2	-3.9	12.8	20.0	12.8	12.2	30.0	33.3	26.7
8	-12.8	-1.1	12.8	8.3	15.6	11.1	33.9	23.9	28.3
9	-15.0	0.6	16.7	3.9	10.0	3.3	26.1	28.3	27.2
10	-14.4	7.2	11.1	8.9	7.2	5.0	18.9	22.8	8.9
11	-4.4	7.8	-1.1	15.0	4.4	17.2	27.2	25.0	14.4
12	-0.6	8.3	0.0	18.3	5.6	5.6	33.3	13.3	15.6
13	-17.2	0.0	-1.1	19.4	10.6	18.9	26.7	13.9	16.7
14	-18.9	-2.8	0.0	6.1	20.6	22.8	27.2	19.4	18.3
15	-17.8	-2.2	-3.9	11.7	18.3	25.0	33.9	27.8	21.7
16	-3.3	-1.1	3.3	14.4	17.8	18.3	13.3	27.8	20.0
17	1.7	3.3	7.2	10.6	11.7	25.0	22.8	25.6	7.8
18	7.2	2.8	3.3	3.3	17.8	16.7	30.0	21.7	15.6
19	14.4	2.8	1.7	2.2	16.1	22.2	31.7	23.3	22.8
20	8.3	2.8	0.6	3.3	15.6	28.9	34.4	27.2	24.4
21	9.4	3.9	6.7	2.2	4.4	27.2	32.8	31.1	17.8
22	2.2	-1.7	4.4	12.2	23.9	31.1	30.0	22.8	18.3
23	12.2	5.6	6.7	15.6	15.6	20.6	28.9	25.0	6.7
24	10.6	8.9	-5.6	15.6	9.4	25.0	27.8	8.3	5.0
25	3.3	10.6	-2.8	16.1	12.8	18.3	13.3	2.2	12.8
26	7.2	8.3	-3.3	11.7	17.2	17.2	22.2	27.2	21.1
27	6.7	5.0	7.8	0.6	20.0	18.3	27.8	28.3	17.8
28	5.6	10.0	11.7	1.1	13.9	19.4	24.4	28.9	15.6
29	-3.9		3.3	4.4	8.9	16.7	30.0	31.1	21.7
30	0.0		3.9	5.6	13.9	22.8	30.0	8.9	22.8
31	3.9		6.1		17.2		22.8	20.0	

Table E8 cont'd. (deg C)

Day	Oct	Nov	Dec
1	24.4	13.3	-11.7
2	9.4	3.9	-10.0
3	5.6	4.4	-5.6
4	2.8	2.2	-9.4
5	7.2	1.7	-5.0
6	14.4	4.4	-21.1
7	18.9	1.7	-23.9
8	3.3	-1.7	-10.0
9	7.2	-5.0	-3.9
10	10.0	6.7	-3.9
11	10.0	7.8	0.0
12	10.6	2.2	-2.8
13	17.8	1.7	-4.4
14	21.1	-2.2	-7.8
15	16.1	-3.3	-9.4
16	13.3	1.7	-8.9
17	18.3	-0.6	-16.7
18	14.4	0.6	-20.0
19	15.6	4.4	-12.8
20	6.7	9.4	-1.7
21	12.2	2.8	3.3
22	15.6	8.9	8.9
23	17.2	2.2	3.3
24	11.1	7.8	5.6
25	13.9	2.8	7.2
26	13.9	-2.2	3.3
27	10.0	-3.9	4.4
28	10.0	-10.0	2.8
29	3.3	-7.2	0.6
30	3.3	-11.7	-1.1
31	10.0		4.4

Table E9. Daily mean soil temperature in 2006 (5 cm depth) (deg C).

Day	Jan	Feb	Mar	Apr
1	2.2	2.2	3.9	-
2	1.1	2.2	1.7	-
3	0.0	1.1	2.2	3.9
4	1.7	4.4	3.3	4.4
5	2.8	0.0	5.6	5
6	2.8	-2.2	6.1	5
7	4.4	2.2	5.0	6.1
8	-1.1	4.4	3.3	6.7
9	-2.2	-3.9	-2.8	6.7
10	4.4	-7.8	-3.9	7.2
11	0.6	-2.8	1.1	7.2
12	0.6	-0.6	-3.9	7.8
13	1.7	3.3	-1.7	7.8
14	4.4	-7.8	3.3	9.4
15	0.0	-6.7	0.0	
16	-5.0	-15.0	5.6	
17	2.8	-18.9	7.8	
18	2.2	-17.2	0.0	
19	0.6	-10.0	-3.9	
20	-1.1	-2.8	-3.3	
21	-1.7	-1.1	-0.6	
22	-2.2	0.6	6.7	
23	3.3	4.4	9.4	
24	2.8	0.6	12.8	
25	0.6	-1.7	16.1	
26	4.4	7.2	5.0	
27	0.6	7.8	8.9	
28	-1.1	7.8	2.2	
29	-3.3		6.7	
30	3.9		9.4	
31	0.6		7.8	

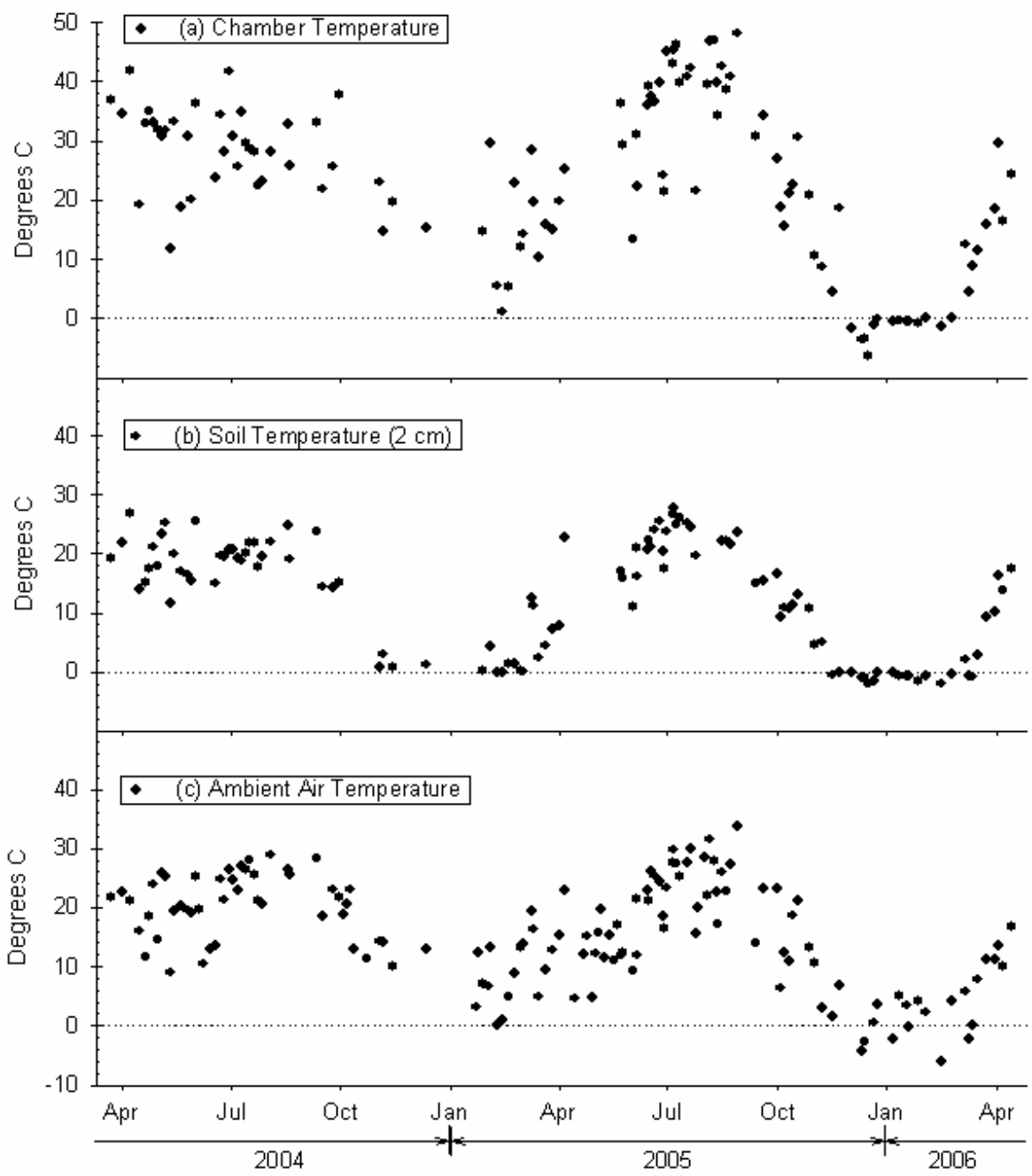

Figure E1. Chamber (a), soil (b), and air (c) temperatures recorded at the field site during sampling.

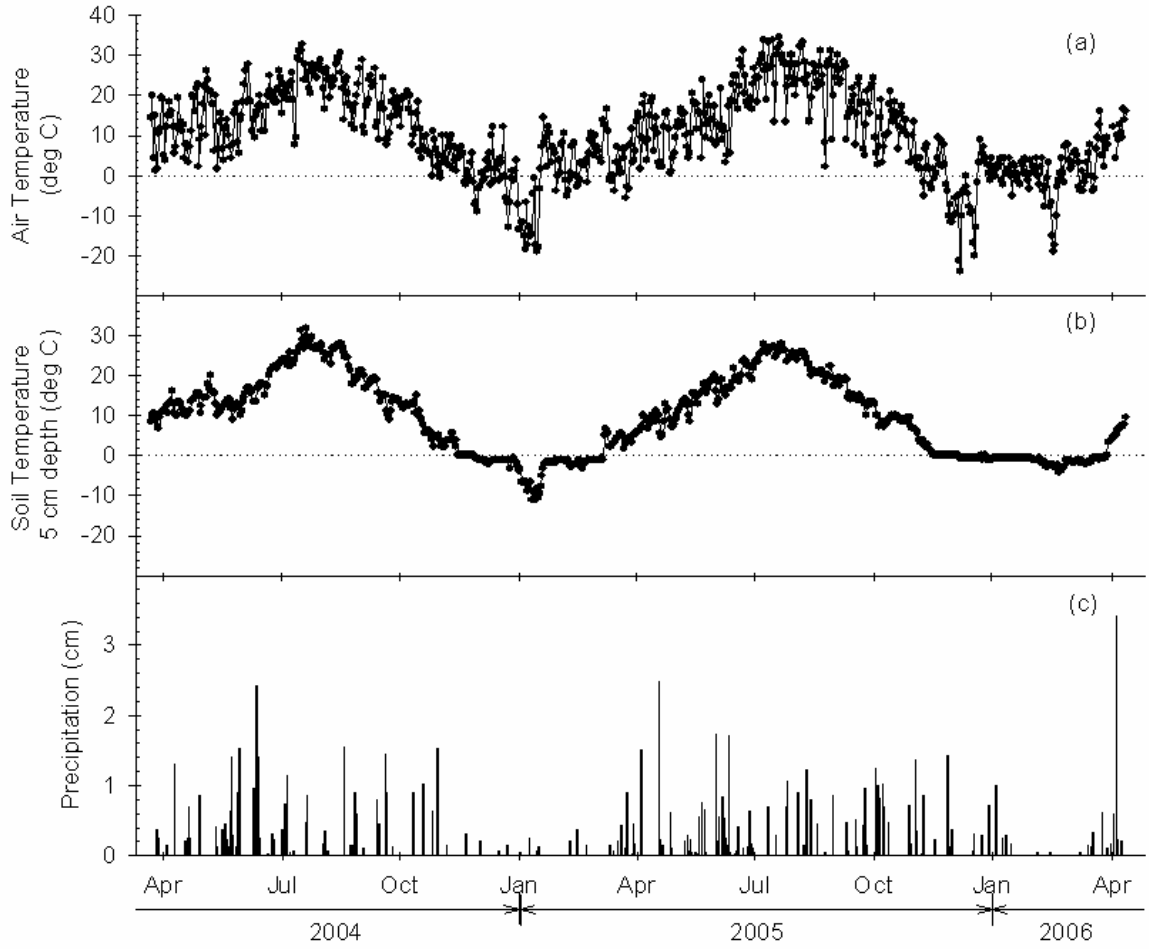

Figure E2. Daily air temperature (a), soil temperature at the 5 cm depth (b), and cumulative daily precipitation (c) as observed by the Arthur C. Post Farm MET Station.

APPENDIX F

SITE PRECIPITATION DATA

Table F1. Daily cumulative precipitation for 2004 (cm).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	0	0	0	0	0	0	0.38	0	0
2	0	0	0	0	0	0	0.05	0.18	0.10
3	0	0	0	0.15	0	0	0.74	0.36	0
4	0	0	1.02	0	0	0	0	0	0
5	0	0.28	0	0	0	0	1.14	0.08	0
6	0	0	0.13	0	0	0	0	<0.01	0
7	0	<0.01	<0.01	0	0	0	0.05	0	0
8	0	<0.01	0	0	<0.01	0	0	0	0
9	0	0.30	0	1.30	0	0.97	0	0	0
10	0	0	0	0	0	0.13	0.08	0	0
11	0	<0.01	0	0	0.41	2.41	0	0	0
12	0	0	0	0	0.13	1.40	0	0	0.79
13	0	0	0	0	0	0	0	0	0.43
14	0	0	0	0	0	0.25	0	0	0.46
15	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0.38	0	0	0	0
17	0	0	0	0.20	0.08	0	0	0	0
18	0	0	0	0	0.46	0	0	1.55	0
19	<0.01	0.89	0	0.25	0.23	0	0.48	0	1.45
20	<0.01	0	0	0.69	0	0.03	0.86	<0.01	0.89
21	0	0	0	0.25	0.13	0	0	0	0
22	0	0	0	0	0.64	0	0	0	0
23	0	0	0	0	1.40	0.30	0	0.15	0
24	0.15	0	0	0	0.28	0	0	0.13	0.13
25	0.51	0	0	0	0	0.23	0	0.15	0
26	0	0	0.38	0	0.13	0	0	0.89	0
27	0	0.51	0.25	0	<0.01	0	0	0.58	0
28	0	0.51	0	0.86	0.89	0	0	0	0
29	0	0.28	0	0	1.52	0	0	0	0
30	<0.01		0	0	0	0	0	0	0
31	0		0		0		0	0	

Table F1 cont'd. (cm).

Day	Oct	Nov	Dec
1	0	0	0.20
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0.15	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	<0.01
10	0.89	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0.08
16	<0.01	0	0
17	0	0	0
18	1.02	0	0
19	0	0	0
20	0	0.30	0
21	0	0	0
22	0	0	0.15
23	0	0	0
24	0	0	0
25	0.64	<0.01	0
26	0	0	0
27	0	0	0
28	0	0	0
29	1.52	0	0
30	0	0	<0.01
31	0		<0.01

Table F2. Daily cumulative precipitation for 2005 (cm).

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	0.05	0	<0.01	0	0	1.73	0	0	0
2	0	0	0	0	0	0.20	0	<0.01	0
3	0	0	0	0	0	0.56	0	0.89	0
4	0	0	0	1.50	<0.01	0	0	0	0
5	0	0	0	0.76	<0.01	0	0	0	0
6	0	0	<0.01	0	0	0.84	0	<0.01	0
7	0	0	0	0	0	0.53	0	0	0
8	0.25	0.20	0	0	0.20	0.25	0	0.15	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	<0.01	0.28	0.15	0	1.22	0.48
11	0	0	0.15	0	0.08	1.70	0.69	0	0.08
12	0	0	0	0	0.23	0.05	0	0	0
13	0	0	0	0	0.05	0	0	0.79	0
14	0.08	0.38	0.08	0	0	0	0	0	0
15	0.13	0	0	0	0	0	0	0	0
16	0	0	0	0	0.05	0.03	0	0	0
17	0	0	0.20	0	0.03	0.08	0.28	0	0.51
18	0	0	0	2.49	0	0.41	0	0.46	0.13
19	0	0	0	0.23	0.56	0	0	0	0
20	0	0	0.43	0	0	0	0	0	0
21	0	0.15	0	0.15	0.76	0	0	0	0
22	0	0	<0.01	0	0	0.10	0	0	0
23	0	0	0.10	0	0.66	0	0	0	0.43
24	0	0	0.89	0	0.05	0	0	0.05	0.97
25	0	0	0	0	0	0	0.69	0	0.15
26	0	0	0	0	0	0.13	1.07	0	0
27	<0.01	0	0	0.61	0	0.64	0	0	0
28	0	0	0.03	0.10	0	0.18	0	0	0
29	0		0.46	0	0	0.10	0	0	0
30	0		0.18	0	0	0	0	0.86	0
31	0		0		0		0	0	

Table F2 cont'd. (cm)

Day	Oct	Nov	Dec
1	0	0	0
2	1.24	1.37	0
3	0.46	0.36	0
4	0.99	0	0
5	0.81	0	0
6	0	0	0
7	0	0.03	0
8	1.02	0.86	0
9	0.69	0	0
10	0	0	0
11	0	0	0
12	0.48	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0.08
17	0	0.23	0.30
18	0	0	0
19	0	0	0
20	0	0	0
21	0	0	0
22	0	0	0
23	0	0	0.28
24	0	0	0
25	0	0	0
26	0	0	0
27	0	1.42	0
28	0.71	0.13	<0.01
29	0.18	0	0.71
30	0	0.38	0
31	0		0

Table F3. Daily cumulative precipitation for 2006 (cm).

Day	Jan	Feb	Mar	Apr
1	0	0	0	0
2	0	0	0	0.18
3	0.99	0	0	0
4	0	0.05	0	0.58
5	0	0	0	0
6	0	0	0	3.40
7	0	0	0	0.23
8	0.25	0	0	0
9	0	0	0.05	0
10	0	0	0	0.20
11	0.28	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0.05	0	0
15	0.18	<0.01	0.15	0
16	0	0	0	0
17	0	0	0	1.27
18	0	0	0.13	0.05
19	0	0	0.33	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0
23	0	0	0	1.19
24	0	0	0	0.15
25	0	0	0	0
26	0	0	0.61	0
27	0	0	0	0
28	0	0	0	0
29	0		0	0
30	0		0.10	0.38
31	0		0	

APPENDIX G

SAS CODING

SAS Coding for ANOVA and Contrast Statements

```
options ls=95 ps=65 nocenter;
Title1 "Nitrous oxide emissions from cropping sytem study";
data crop;
input plot block cropsys NL N2ORT;
cards;

;
proc mixed data=crop;
classes block cropsys NL;
model N2ORT = cropsys NL cropsys*NL/outp=new residual alphap=0.01;
random block block*cropsys;
lsmeans cropsys*NL/pdiff;
lsmeans cropsys/pdiff;
ods output diffs=diffs;

estimate 'wht-fallow vs continuous crop'  cropsys -1 -1 1 1;
estimate 'CT vs NT within wht-fallow'   cropsys 1 -1 0 0;
estimate 'monoculture vs diversified' cropsys 0 0 1 -1;
estimate 'wht fallow vs cont wht NT' cropsys 0 -1 1 0;
proc print data=new;
proc univariate data=new normal plot;
var resid;
proc plot data=new;
plot resid*plot;
run;
quit;
```

SAS Coding for Repeated Measures:

```
data n2o;
input blk cs n2o time;
cards;

;
run;

proc mixed data=n2o;
class blk nl time;
model n2o = nl time nl*time ;
random blk blk*nl;
lsmeans nl time;
lsmeans nl*time/slice=time;


proc mixed data=n2o;
class blk nl time;
model n2o = nl time nl*time ;
random blk blk*nl;
lsmeans nl time;
lsmeans nl*time/slice=time;

REPEATED /sub = blk*cs type=toep(4) r;

proc mixed data=n2o;
class blk nl time;
model n2o = nl time nl*time ;
random blk blk*nl;
lsmeans nl time;
lsmeans nl*time/slice=time;

REPEATED /sub = blk*nl type=ar(1) r;

proc print data=new;
proc univariate data=new normal plot;
var resid;
proc plot data=new;
plot resid*plot;

run;
quit;
```

APPENDIX H

AGRONOMIC NOTES

Table H1. Dates of harvest for each year and cropping system.

Cropping system	2003 (I)	2004 (II)	2005 (I)
fallow – w. wheat (CT)	-	8 Sept	-
fallow – w. wheat (NT)	-	8 Sept	-
s. wheat - w. wheat (NT)	12 Aug	8 Sept	16 Aug
s. pea (g) - w. wheat (NT)	23 Jul	8 Sept	4 Aug
w. pea (f) - w. wheat (NT)	27 Jun	8 Sept	8 Jul
w. pea (m) - s. wheat (CT - organic)	24 Jun	8 Sept	8 Jul
CRP*	-	-	8 Jul

Table H2. Dates of tillage operations in wheat-fallow and w. pea-wheat (organic) treatments. Phase given in parentheses.

Cropping system	2003 (I)	2005 (I)
wheat-fallow (CT)	21 May	6 May
	16 Jun	16 Jun
	16 Jul	20 Jul
	5 Sept	
s. wheat-w. pea (m) (CT - organic)	24 Jun	8 Jul
	3 Jul	15 Aug
	5 Sept	

APPENDIX I

SOIL N CONTENT DATA

Table I1. Soil NO_3-N data (0-15 depth cm) mg kg^{-1} soil. All values means of 4 replications.

Cropping system	N regime	20 Mar 04	1 Apr 05	24 May 05	17 Jun 05	24 Jun 05	8 Sept 05	14 Nov 05	14 Apr 06
fallow - w. wheat (CT)	Low	-	-	-	-	-	8.09	1.42	1.25
	Moderate	-	-	-	-	-	-	-	1.45
	High	24.80	2.21	-	-	-	11.17	46.06	11.50
fallow - w. wheat (NT)	Low	-	-	-	-	-	12.51	11.32	1.16
	Moderate	-	-	-	-	-	-	1.26*	2.72
	High	13.62	1.89	-	-	-	12.90	27.50	12.08
s. wheat - w. wheat (NT)	Low	5.81	1.87	2.47	0.92	1.48	3.00	1.96	1.60
	Moderate	-	-	-	-	-	2.91	-	2.86
	High	15.33	3.75	39.61	19.46	11.06	11.60	31.39	4.16
s. pea (g) - w. wheat (NT)	Low	-	-	-	-	-	7.25	1.29	1.05
	Moderate	-	-	-	-	-	6.80	-	1.42
	High	9.34	2.09	-	-	-	8.59	16.70	11.02
w. pea (f) - w. wheat (NT)	Low	-	-	-	-	-	10.38	-	1.69
	High	9.08	2.48	-	-	-	9.84	-	3.31
Organic	-	8.64	2.71	-	-	-	-	-	-
CRP	-	5.54	1.45	-	-	-	-	3.25	4.59

* Only one value collected

APPENDIX J

CARBON DIOXIDE AND METHANE DATA

Table J1. Methane data for 25 July 2005 – 14 Apr 2006 as affected by N regime and cropping system.

Cropping System (CS)	N regime	N rate* kg ha^{-1}	CH_4 uptake g ha^{-1}
fallow-wheat (CT)	Low	0	29a**
	Moderate	50	50a
	High	218	22a
CS Mean			32z***
fallow-wheat (NT)	Low	0	46a
	Moderate	50	45a
	High	240	38a
CS Mean			43z
s. wheat – w. wheat (NT)	Low	0	50a
	Moderate	175	61a
	High	245	70a
CS Mean			60y
s. pea – w. wheat (NT)	Low	0	84a
	Moderate	85	55b
	High	285	56b
CS Mean			65y

Summary Statistics

Effect	df	P < F
Cropping System (CS)	3	0.02
Nitrogen Regime (NR)	2	0.67
CS*NR	6	0.21

Contrasts	df	P < t
wheat-fallow (CT) vs. wheat-fallow (NT)	1	0.33
wheat-fallow (NT) vs. wheat-wheat (NT)	1	0.09
wheat-wheat (NT) vs. wheat-pea (NT)	1	0.63
1, 2 vs. 3, 4	1	< 0.01

* Total N applied over 2 yr.

** Values followed by the same letter are not different ($P \geq 0.10$).

*** CS Means followed by the same letter are not different ($P \geq 0.10$).

Table J2. Carbon dioxide emissions for 21 Mar 2005 – 14 Apr 2006 as affected by N rate and cropping system.

Cropping System CS	N regime	N rate*	CO_2 emissions
		kg ha^{-1}	g ha^{-1}
1. fallow-wheat (CT)	Low	0	2192a**
	Moderate	50	2300a
	High	218	2512a
CS Mean			2335z***
2. fallow-wheat (NT)	Low	0	2408a
	Moderate	50	2520a
	High	240	2611a
CS Mean			2513z
3. s. wheat – w. wheat (NT)	Low	0	3748a
	Moderate	175	5247b
	High	245	5756c
CS Mean			4917x
4. s. pea – w. wheat (NT)	Low	0	3622a
	Moderate	85	3945ab
	High	285	4239b
CS Mean			3935y

Summary Statistics

Effect	df	P < F
Cropping System (CS)	3	< 0.01
Nitrogen Regime (NR)	2	< 0.01
CS*NR	6	< 0.01

Multiple Comparisons	df	P < t
wheat-fallow (CT) vs. wheat-fallow (NT)	1	0.60
wheat-fallow (NT) vs. wheat-wheat (NT)	1	< 0.01
wheat-wheat (NT) vs. wheat-pea (NT)	1	0.06
1, 2 vs. 3, 4	1	< 0.01

* Total N applied over 2 yr.

** Values followed by the same letter are not different ($P \geq 0.10$).

*** CS Means followed by the same letter are not different ($P \geq 0.10$).

APPENDIX K

LOG TRANSFORMATIONS OF SELECT N_2O DATA SETS

LOG Transformations of select N_2O data sets

Table K1. Log_{10} transformed total N_2O emissions during the 10-wks post fertilization for the high N regime.

Period	Fallow-wheat (CT)	Fallow-wheat (NT)	Wheat-wheat (NT)	Pea-wheat (NT)
	----------gm N_2O-N ha^{-1}----------			
Spring 2004	50a*	54a	27a	67a
Spring 2005	-	-	378b	-
Fall 2005	169a	86a	221b	72a

* Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).

There were no changes in significance following the log transformation.

Table K2. Log_{10} transformed total emissions of N_2O-N for the two year sampling period (15-April 2004 to 14-April 2006) as affected by cropping system and N fertility regime.

Cropping System (CS)	N regime	N fert. events	N rate†	N_2O-N
		#	kg ha^{-1}	g ha^{-1}
1. fallow - wheat (CT)	Low	0	0	202a‡
	Moderate	1	50	243a
	High	2	218	692b
CS Mean				324y*
2. fallow - wheat (NT)	Low	0	0	256a
	Moderate	1	50	362b**
	High	2	240	567c
CS Mean				375y
3. wheat - wheat (NT)	Low	0	0	285a
	Moderate	3	175	1020b
	High	3	245	1151c
CS Mean				694z
4. w. wheat - s. pea (NT)	Low	0	0	321a
	Moderate	2	85	512b**
	High	2	285	863c
CS Mean				521z**
Mean of N Regimes	Low			253a
	Moderate			450b
	High			790c

Summary Statistics

Effect	df	F Value	P > F
Cropping System (CS)	3	6.00	0.01
Nitrogen Regime (NR)	2	55.67	< 0.01
CS*NR	6	3.41	< 0.01

Multiple comparisons	df	t value	P > t
1 vs. 2	1	-0.47	0.77
2 vs. 3	1	3.28	< 0.01
3 vs. 4	1	1.41	0.18**
1, 2 vs. 3, 4	1	3.98	< 0.01

† Total amount of N applied over two years.

‡ Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).

* Cropping systems means compared separately. Values followed by the same letter are not different ($P \geq 0.10$)

** Significance has changed due to log_{10} transformation.

Table K3. Log_{10} transformed fertilizer induced emissions (FIE) of N_2O and fraction of applied N lost as N_2O for the two year sampling period (15-April 2004 to 14-April 2006) as affected by cropping system and N fertility regime.

Cropping System (CS)	N regime	N fertilizer†	FIE	Fraction applied N lost as N_2O
		kg ha^{-1}	g ha^{-1}	%
1. fallow - wheat (CT)	moderate	50	34a	0.07a
	high	218	479b	0.22b
CS Mean			127z‡	0.12z
2. fallow - wheat (NT)	moderate	50	77a	0.15a
	high	240	292b	0.12a
CS Mean			150zy**	0.13z
3. wheat - wheat (NT)	moderate	175	723a	0.41a
	high	245	838a	0.34a
CS Mean			779x	0.38y
4. s. pea - wheat (NT)	moderate	85	188a	0.22a
	high	285	528b	0.19a
CS Mean			315y**	0.20yz**

Summary statistics

Effect	df	P > F	
Cropping System (CS)	3	< 0.01	0.04
Nitrogen Regime (NR)	1	< 0.01	0.38
CS*NR	3	< 0.01**	0.04**

Multiple comparisons	df	P > t	
wheat-fallow (CT) vs. wheat-fallow (NT)	1	0.12	0.82
wheat-fallow (NT) vs. wheat-wheat (NT)	1	< 0.01	0.02
wheat-wheat (NT) vs. wheat-pea (NT)	1	0.01	0.11**
1, 2 vs. 3, 4	1	< 0.01	0.01

FIE – Fertilizer induced emissions.

† Total amount of N applied over two years.

‡ Values for cropping systems followed by the same letter are not different ($P \geq 0.10$).

** Significance has changed due to log_{10} transformation.

Table K4. Log_{10} transformed rotation (15 Apr 2004 – 19 Sep 2005) cumulative N_2O-N emissions as affected by cropping systems and N regime.

Cropping system (CS)	N regime	N rate	∑ Rotation N_2O-N emissions
			g ha^{-1}
1. wheat-fallow (CT)	low	0	102a
	high	68	195b
CS Mean			141z
2. wheat-fallow (NT)	low	0	166a
	high	90	234b
CS Mean			200y**
3. wheat-wheat (NT)	low	0	191a
	high	155	631b
CS Mean			347x
4. wheat- s. pea (NT)	low	0	182a
	high	135	309c
CS Mean			240y

Summary Statistics

Effect	df	F	P > F
Cropping System (CS)	3	12.06	< 0.01
Nitrogen Regime (NR)	1	214.66	< 0.01
CS*NR	3	15.26	< 0.01

Multiple comparisons	df	t	P > t
1 vs. 2	1	-2.22	0.05**
2 vs. 3	1	3.67	< 0.01
3 vs. 4	1	2.45	0.04
1 & 2 vs. 3 & 4	1	5.02	< 0.01

† Values within cropping systems followed by the same letter are not different ($P \geq 0.10$).
* CS Means values followed by the same letter are not different ($P \geq 0.10$).
** Significance has changed due to log_{10} transformation.