Quantifying nitrous oxide emissions resulting from the production of leguminous crops in western Canada

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Introduction

Nitrous oxide (N_2O) emissions from Canadian agricultural activities are estimated using the methodology proposed by the Inter-governmental Panel on Climate Change (IPCC). This methodology suggests that legume crops account for more than 20% of the N_2O emissions assigned to agricultural activities. The N content of the legume crop is estimated from grain yields, and a percentage of this N (0.0125 %) is assumed to be lost as N_2O. Although legumes are assumed to be an important source of N_2O emissions, the IPCC emission factor has not been verified for Canadian conditions.

Pulse crops represent an increasingly significant component of the field crops grown in western Canada. In Saskatchewan for example, approximately 2.0 million hectares were seeded to pulses (field pea, chick pea and lentil) in the 2000 crop year. Despite the increasing importance of pulse crops in western Canada, little information is available regarding the N_2O emissions associated with including pulses in crop rotations. Clearly, field data are needed to fill this knowledge gap. Herein we report on results from a research project undertaken to begin to address this issue. There were three overall objectives for this work. Firstly, to quantify N_2O fluxes from soils cropped to field pea and lentil, and soils cropped to wheat on pulse stubble. Secondly, to relate N_2O emissions to estimated N flows through wheat and wheat-pulse rotations. Thirdly, to investigate possible interactions between cropping system and tillage management.

Materials and Methods

Swift Current-“Old Rotation” Study

Nitrous oxide emissions monitoring was overlain on an existing long-term study at the Semiarid Prairie Agricultural Research Centre, Swift Current, Saskatchewan (50 deg. 30 min. N; 107 deg. 70 min. W). The soil is a Brown Chernozem with a loam texture. The site is moderately well drained with uniform slopes of $\leq 2\%$. Long-term precipitation averages 334 mm, moisture deficits average 395 mm, and the annual air temperature averages 3.3 °C. Winter snow packs are often discontinuous, thus surface soil (5 cm) temperatures can reach –20 °C.

The experiment was initiated in 1967 and includes 10 cropping systems. Three systems were selected for the current study. The three systems are: 1) continuous wheat with nitrogen and phosphorus fertilizer applied as required (Cont. W $^{+}$N), 2) continuous wheat with no nitrogen applied, but phosphorus fertilizer applied as required (Cont. W $^{-}$N), and, 3) both phases of a wheat-lentil rotation (WL). The wheat phase received nitrogen and phosphorus fertilizer as required, while the lentil phase received only phosphorus fertilizer as required. The study is laid out as a Randomized Complete Block with three replications. Both phases of the lentil-wheat rotation are present every year. Plots are 10.5 m wide and 40 m long (i.e., 0.04 ha).

Stubble-mulch tillage techniques, with commercially available equipment, are used in the management of the rotations. Seedbed preparation generally consists of one operation with a heavy-duty cultivator with rodweeder attachment. The plots are seeded with a hoe-press drill at the recommended rates of 67 kg ha^{-1} for spring wheat and 75 kg ha^{-1} for lentils. Seeding takes place generally in late April to early May. Ammonium nitrate fertilizer (i.e., 34-0-0) is broadcast prior to seedbed preparation and monoammonium phosphate fertilizer (i.e., 11-48-0) is placed with the seed according to treatment specifications and in accordance with the general recommendations of the Saskatchewan Soil Testing Laboratory (Saskatchewan Agriculture, 1988). Herbicides (i.e., bromoxynil and MCPA, 2,4-D ester, triallate, and diclofop methyl) are applied as required for in-crop weed control using recommended methods and rates.

Plots are harvested at the full ripe stage. The straw and plant residue products are chopped and uniformly distributed back on the plots with straw and chaff spreader attachments on the combine. After harvest, all seeded plots receive an application of 2,4-D ester herbicide at the recommended rate to control winter annual weeds.

Soil samples are taken in early spring (i.e., pre-emergence), at harvest, and late fall (i.e., post-harvest) on all plots from the 0-15, 15-30, 30-60, 60-90, and 90-120 cm depths to measure NO_3-N, NH4-N, bicarbonate-P, and soil moisture. All cropped plots are harvested and the yield and N and P content of the grain and straw are determined. Meteorological parameters such as pan evaporation, rainfall, and temperature are recorded at the meteorological site located 1 km away.

Three Hills Tillage Study

The N_2O flux samples were taken on selected treatments at the Three Hills long-term sustainable cropping study. The study site is located beside the Three Hills airport in the M.D. of Kneehill (51 deg. 42 min. N, 113 deg. 13 min. W). This area is in the semiarid grassland vegetation zone - transitional between Mixed-Grass Prairie and Aspen Parkland. There are on average 378 mm of precipitation; 90-110 frost-free days, and 1375 growing degree-days >5 °C per year.

The sustainable cropping study was established in 1991 on a 4-ha parcel of land under a long-term government lease. The plot area occupies about 0.8 hectares. Past management has been a cereal-oilseed rotation with fallow occurring once every three or four years. The whole plot area was seeded to canola in 1991 and the rotations were initiated in 1992. The soil is classified as a Solonetzic Black Chernozem with moderately fine textured (clay loam) fluviolacustrine over fine textured (clay) glaciolacustrine parent material. The site is undulating with a 2 % slope, mid slope, and an ESE aspect.

The experiment consists of 20 main plots (9 m x 15 m) arranged in three randomized replicate blocks. The main plots represent the nine different crop rotations with every phase of each rotation present each year. The rotations utilized for this study are listed below:

1. **Continuous Wheat*** (Cont. W)
2. Canola-Barley-**Peas***-**Wheat*** (CBPW)
3. **Wheat*-Fallow*** (WF)

* The bold face treatments are those used in the N_2O study.

Only the pea and wheat phase of the CBPW rotation were used in the N_2O study. Both the wheat and fallow phase of the WF rotation were used in the study. Since the fall of 1994, the plots were split to include two tillage systems: conventional till (CT) and no till (NT) systems. N_2O chambers were setup on both tillage treatments for the selected N_2O plots. This makes for five main treatments split for two tillage systems. An example of an acronym used in this report to express the combination of rotation and crop phase is CBPW_P, referring to the pea phase of the canola-barley-pea-wheat rotation.

In the CT system, tillage is used to prepare the seedbed, control weeds at seeding, and to turn under residues in the fall. The NT system does not use tillage and the crop is seeded into the previous years standing stubble with a low disturbance John Deere 752 disc drill. In the NT system, weed control is by a pre-seed burn off with 3.7 l/ha of glyphosate. For the fallow plots, the NT plots were chemically fallowed with Rustler while the CT fallow plots were tilled 4 times over the growing season.

All seed was treated with appropriate fungicide and inoculant. In the spring of 2001 and 2002, all plots except the legume and fallow crop phases received a banded application of urea (46-0-0) at 67 kg of N per hectare. Also 12-51-0 fertilizer at 33 kg of P_2O_5 per hectare was placed with the cereal seed, and 20 kg of P_2O_5 per hectare with the pea and canola seed. All plots received an appropriate post seeding herbicide application as part of a weed management plan.

Volumetric soil-moisture (0-15 cm) was measured by using a Delta T Theta Probe ML2X with a HH2 Moisture Meter (Delta-T Devices Ltd) each time the plots were sampled for N_2O. Continuous soil temperature measurements were taken using HOBO H8 outdoor/industrial data loggers (Onset Computer Corp.) and temperature sensors. Temperature sensors were placed in the CW (continuous wheat) and fallow plots at a depth of 5 cm and 10 cm. Soil available N (NO_3, NH_4) was measured (0-15 cm) at four times over the season (frozen soil, pre seed, mid season, fall).

An Environment Canada meteorological station (Climate Num. 3026479) located on site monitors climate variables on a continuous basis. These data were processed to provide daily values of air temperature, precipitation, relative humidity, wind speed, and solar radiation.

Nitrous Oxide Sampling

Gas samples were collected using vented soil chambers as described by Hutchinson and Mosier (1981). N_2O flux was estimated from the concentration change in the chamber headspace over a 30 or 60 minute collection period. Samples were drawn from the headspace using disposable 20 ml polypropylene syringes and injected into pre-evacuated 13 ml exetainers for transport to the laboratory. The concentration of N_2O in the samples was determined using a gas chromatograph equipped with an electron capture detector. The frequency of sampling was twice a week in the spring, once a week over the summer, and less often in the fall. The sampling intensity was higher after fertilizer application and rain events when emissions are more likely. The N_2O samples were collected at midday. The average concentration of a series of ambient samples was used as the base or time zero N_2O concentration. Seasonal estimates of N_2O emissions were calculated by interpolating between data points and integrating over time assuming a constant flux (Lemke et al., 1998).

IPCC Calculations

Direct N_2O emissions from each field plot were estimated by applying the following equation as proposed in the IPCC methodology (IPCC 1996).

$$\text{Total } N_2O \text{ DIRECT} = [(FSN + FAW + FBN + FCR) * EF1] + FOS * EF2$$

The FAW and FOS terms which relate to animal wastes used as fertilizer and cultivation of organic soils respectively, do not apply to either of the studies under discussion and they can be dropped from our discussion. The equation then reduces to:

$$\text{Total } N_2O \text{ DIRECT} = [(FSN + FBN + FCR) * EF1]$$

where:

N_2O DIRECT = direct N_2O emissions from agricultural soil (kg N yr^{-1})
FSN = N added as synthetic fertilizers (kg N yr^{-1})
FCR = N in crop residues returned to soils (kg N yr^{-1})
FBN = N fixed by N-fixing crops (kg N yr^{-1})
EF1 = emissions factor for direct soil emissions (kg N_2O-N [kg N input]$^{-1}$)

Actual N-fertilizer and residue-N additions for each field plot were utilized to calculate the estimated annual N_2O emissions. At Swift Current, grain and straw yields and the N concentration of each were determined annually. At Three Hills grain and straw yields and grain N concentrations were determined annually, but straw N concentration was estimated based on an assumed mean N concentration of 0.75 %. The default value for EF1 (0.00125) was utilized.

Statistical Analysis

The data were processed to compare the effects of rotation and tillage on the seasonal loss of N_2O. The data were subjected to analysis of variance for a split plot design at Three Hills, and a randomized complete block design at Swift Current, using Proc GLM and lsmeans (SAS®). The $P<0.10$ level of significance was used for the N_2O emissions data and $P<0.05$ level of significance for other soil measurements.

Results and Discussion

Mean monthly air temperature was considerably cooler than the 30-year average during April at both Swift Current and Three Hills **(Table 1 & 2)**, and during October at Swift Current in 2002. Other mean monthly air temperatures did not differ markedly from normal during the 2001 or 2002 field seasons. Growing season precipitation was below average at both Swift Current and Three Hills during 2001 **(Table 1 & 2)**. Rainfall was particularly low during April and May of 2001 and 2002. The Three Hills site remained very dry until August of 2002, receiving somewhat higher than average rainfall during the latter part of the season. Swift Current, however, received much higher than average rainfall from mid-June through to the end of October.

Table 1. Monthly precipitation and air temperatures for 2001, 2002 and 30-year means at Three Hills.

	Precipitation			Air Temperature		
Month	2001	2002	30-yr mean	2001	2002	30-yr mean
	----------- (mm) ---------			--------- (°C) ---------		
April	0.0	20.1	31.0	4.6	0.1	4.0
May	18.3	19.2	43.8	11.8	8.2	10.0
June	85.8	52.4	68.1	13.2	16.0	14.0
July	115.3	17.2	63.0	17.0	19.0	16.6
August	24.1	80.9	45.8	18.6	14.9	16.4
September	11.3	55.0	42.8	13.4	10.3	11.0
Total	254.8	244.8	294.5	--	--	--

Table 2. Monthly precipitation and air temperatures for 2001, 2002 and 30-year means at Swift Current.

	Precipitation			Air Temperature		
Month	2001	2002	30-yr mean	2001	2002	30-yr mean
	---------- (mm) -----------			------------- (°C) ---------		
April	9.8	11.0	23.0	5.4	0.03	4.8
May	22.6	21.9	48.2	12.2	8.5	11.0
June	31.8	143.9	67.5	15.	15.7	15.6
July	63	73.1	53.1	19.7	19.6	18.2
August	3.2	102.2	41.0	20.9	15.5	17.9
September	6.2	59.6	30.5	15.0	12.2	11.9
October	20.2	18.9	17.3	4.2	0.3	5.3
Total	156.8	430.6	280.6	--	--	--

Crop yields at Swift Current were very poor in 2001, but considerably better in 2002 **(Figure 1)**. Conversely, crop yields at Three Hills were modest in 2001, but were very poor in 2002 **(Figure 2)**. At Three Hills, the best yields were attained by wheat-on-fallow in both years, followed by peas under NT management in 2001. The NT systems consistently out-yielded the CT systems.

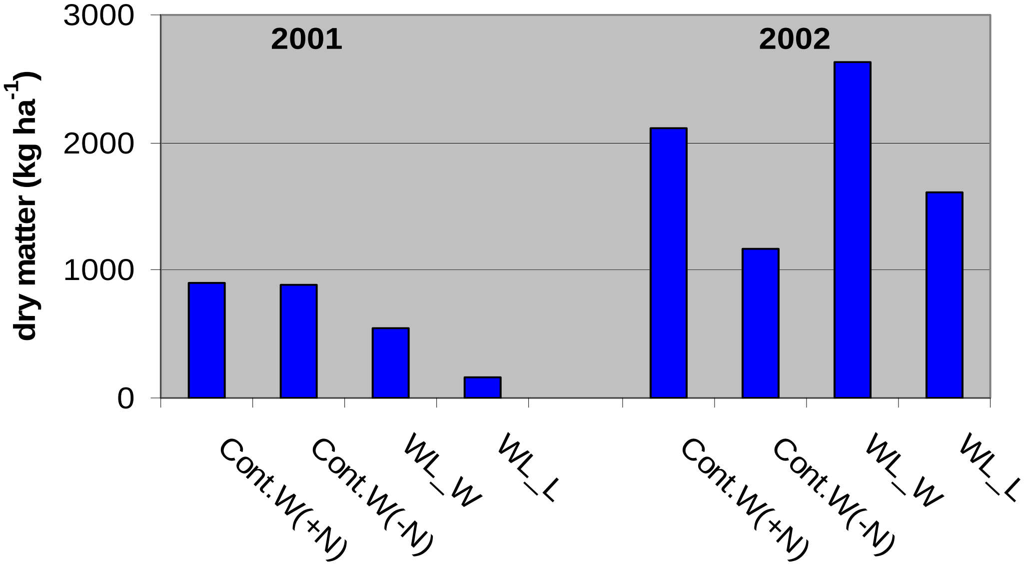

Figure 1. Mean grain yields (kg ha^{-1}) from selected treatments at Swift Current during 2001 and 2002. [Cont.W (+N) = fertilized continuous wheat; Cont.W (-N) = unfertilized continuous wheat; WL = wheat-lentil; rotation phase follows underscore].

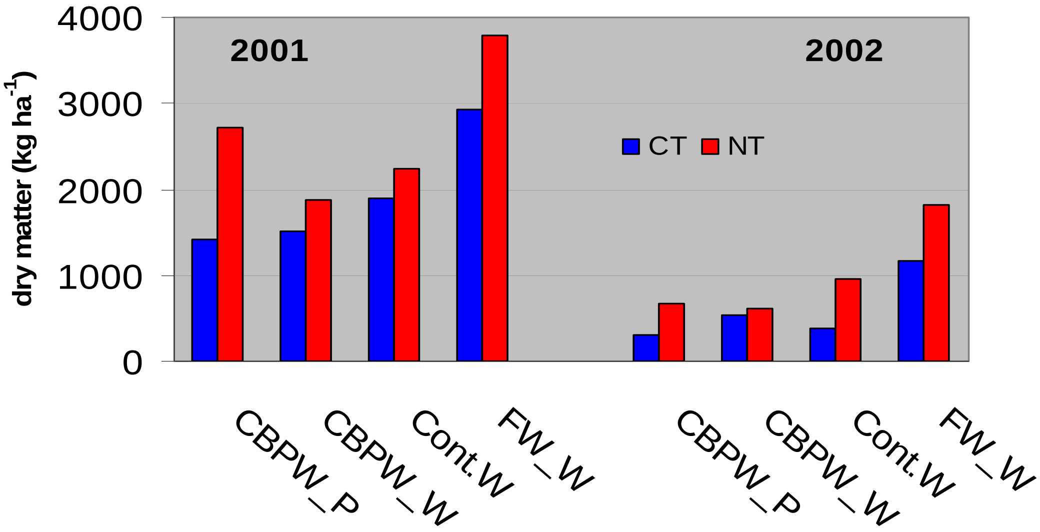

Figure 2. Mean grain yields from selected treatments at Three Hills, Alberta during 2001 and 2002. [CBPW_W = canola-barley-wheat-pea; WF = fallow-wheat; rotation phase follows the underscore].

Dry conditions during the fall of 2000, coupled with limited snow cover during the winter period resulted in relatively dry soils during the early part of the 2001 field season at Three Hills. Water-filled pore-space (WFPS) was at or below 50% in early April **(Figure 3)**, increased to around 60% in mid-season and then fell to less than 30% by October. Soil-water status is a strong controller of N_2O emission rates. Previous work has shown shown that emissions rates are generally low below 60% WFPS and begin to increase dramatically above this threshold peaking somewhere near 90%. Soil-water contents only infrequently surpassed the 60% WFPS range during 2001 at Three Hills, suggesting that the potential for large N_2O emission events was relatively low. Soil-water contents were only marginally higher during the early 2002 field season, ranging from 60% and down **(Figure 4)**, and then decreasing to 50% or less by mid-season. Limited transpiration demand (poor crop growth) and slightly higher rainfall during the latter part of the season resulted in higher fall soil-water contents in 2002 compared to 2001. Similar to the 2001 season, water contents only infrequently surpassed the 60% WFPS range during 2002, suggesting that the potential for N_2O emissions would have been modest.

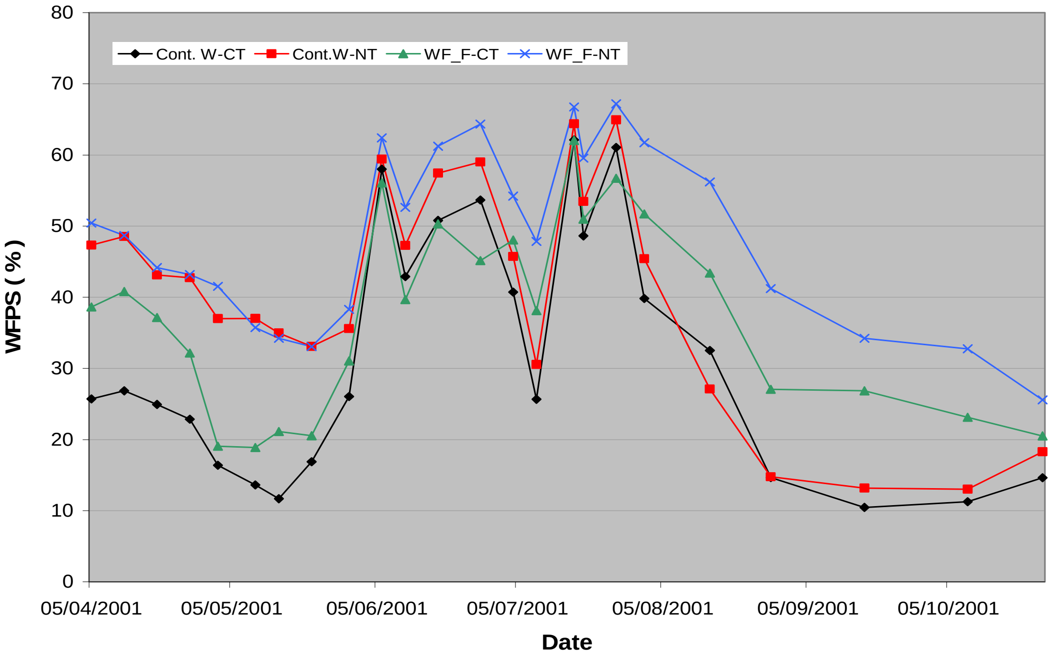

Figure 3 Soil-water content (0-15cm depth) expressed in terms of water-filled pore-space (WFPS) on selected treatments during the 2001 field season at Three Hills.

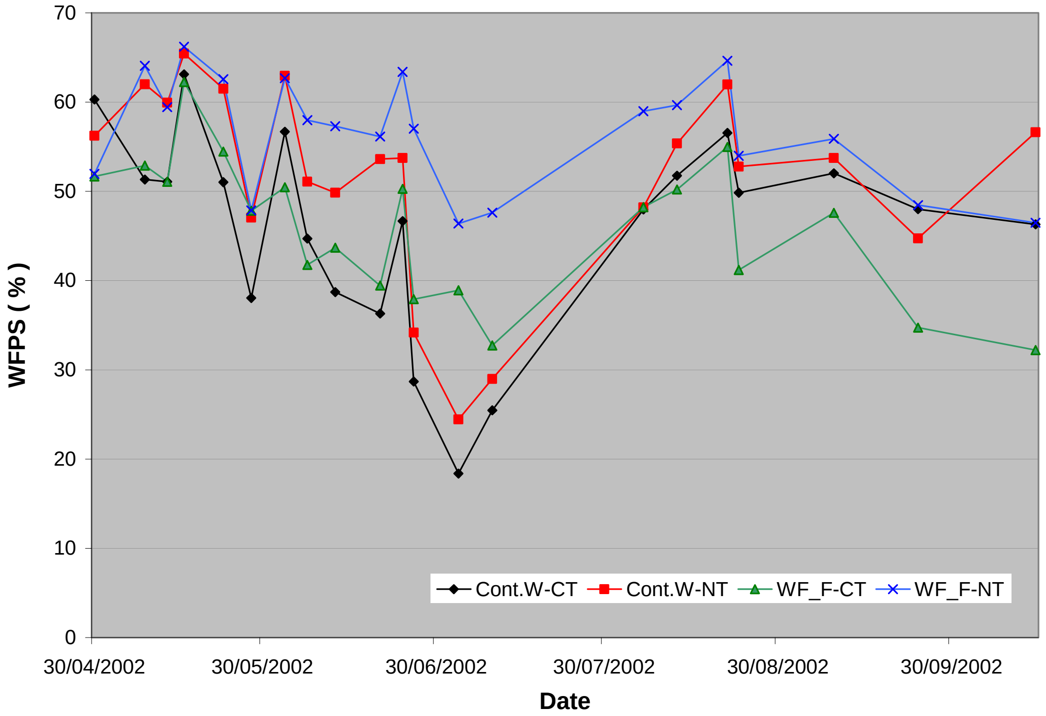

Figure 4 Soil-water content (0-15cm depth) expressed in terms of water-filled pore-space (WFPS) on selected treatments during the 2002 field season at Three Hills.

WFPS was less than 40% at the Swift Current study site prior to seeding in 2001, and dropped to less than 30% by fall **(Table 3)**. Soil-water status was even lower prior to seeding in 2002, but increased to about 40% by the fall of 2002. These WFPS values would suggest a very low potential for N_2O emissions events at Swift Current in both 2001 and 2002.

Table 3. Mean spring and fall percent soil water-filled pore space (0-120 cm depth) from selected treatments at Swift Current in 2001 and 2002.

Treatment	**2001**		**2002**	
	Pre-Seed	**Fall**	**Pre-Seed**	**Fall**
	----------------------------	(%)	----------------------------	
Cont.W ($^{+}$N)	36	26	30	43
Cont.W ($^{-}$N)	38	25	29	41
WL_W	33	24	33	37
WL_L	29	27	33	40

Table 4. Mean available soil-N for the 0-15 cm soil depth at three sample times at the Three Hills site in 2001.

Treatment	**Pre-Seed**	**Mid-Season**	**Fall**
		-------------------- (kg N ha^{-1}) ------------------	
CBPW-P	50bc	22a	42a
CBPW-W	41bc	42a	38a
Cont. W	40c	24a	52a
WF-F	54b	29a	37a
WF-W	70a	45a	23a
Tillage			
CT	51a	34a	41a
NT	51a	31a	36a

Values in columns and within main treatments followed by the same letter are not significantly different ($P<0.05$).

Table 5. Mean available soil N for the 0-15 cm soil depth at three sample times at the Three Hills site in 2002.

Treatment	**Pre-Seed**	**Mid-Season**	**Fall**
		-------------------- (kg N ha^{-1}) ------------------	
CBPW-P	39b	38c	56a
CBPW-W	48b	66b	90a
Cont. W	43b	42c	64a
WF-F	49b	48bc	66a
WF-W	95a	92a	85a
Tillage			
CT	60a	62a	80a
NT	50a	53a	64b

Values in columns and within main treatments followed by the same letter are not significantly different ($P<0.05$).

At Three Hills, available soil-N (NO_3^- + NH_4^+) values were quite low in the fall of 2001 **(Table 4)**, but considerably higher in the fall of 2002 **(Table 5)**. Lemke et al. (1999) found a significant relationship between fall available soil-N and cumulative N_2O loss during the following spring-thaw period at a site in north-central Alberta. They noted that available soil-N values tended to be lower under NT compared to CT systems, and speculated that this may have been a partial explanation for the lower N_2O losses they observed on the NT systems. In this study, there were no significant differences in fall available soil-N between cropping systems, however there was a trend for NT to have lower values than CT. In 2002 this difference was significant **(Table 5)**.

Fall soil nitrate (NO_3^-) tended to be lowest on the WL_W followed by the WL_L treatment at Swift Current **(Table 6)**. Fall soil-NO_3^- values were similar in both 2001 and 2002. Note that soil-NO_3^- was determined for the 0-60 cm depth at Swift Current, while available-N (NO_3^- + NH_4^+) was determined for the 0-15 cm depth at Three Hills.

Table 6. Mean spring and fall soil-nitrate for the 0-60 cm soil depth at Swift Current in 2001 and 2001.

Treatment	2001		2002	
	Spring	Fall	Spring	Fall
	-------------------- (kg N ha^{-1}) -------------------			
Cont.W ($^+$N)	58 a	65 a	56 ab	52 ab
Cont. W ($^-$N)	45 ab	37 b	68 a	61 a
WL_W	19 b	10 c	23 b	16 b
WL_L	22 b	34 b	50 ab	38 ab

Values in columns followed by the same letter are not significantly different ($P<0.05$).

Nitrous Oxide Measurements

Three Hills

The timing of N_2O emission events varied between 2001 and 2002 at Three Hills. In 2001, emissions activity occurred primarily in June and early July **(Figure 5)** when soil-water contents hovered at 50% to 60% WFPS **(Figure 3)**. Emission events on WF_F under CT management tended to lag a bit compared to the cropped treatments. Emissions activity began in July and continued into August. This distribution of N_2O flux is typical for dryland cropping sites in western Canada (Lemke et al., 1998; Corre et al., 1996). In 2002, soils were very dry during June **(Figure 4)** and N_2O emissions events were delayed until later in July and early August **(Figure 6)** when soil-water contents hovered in the 50% to 60% range. Although there appears to be a general concurrence with N_2O emissions events and overall soil-water content, correlation analysis of hourly flux measurements and soil-water content (data not shown) did not show a significant relationship in 2002, and a weak ($r = 0.46$) but significant ($P<0.01$) relationship in 2001. Correlation analysis revealed no significant relationship between hourly N_2O flux measurements and soil temperature or extractible soil NO_3^- or NH_4^+.

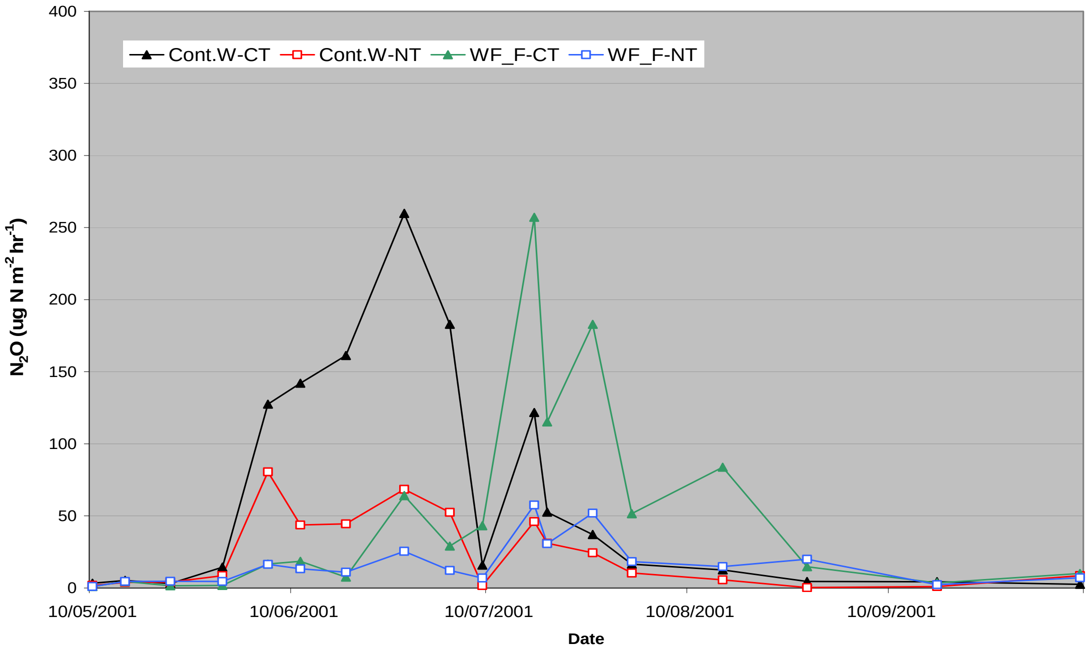

Figure 5. Mean hourly N_2O flux from selected treatments measured during the 2001 frost-free period (May-October) at Three Hills.

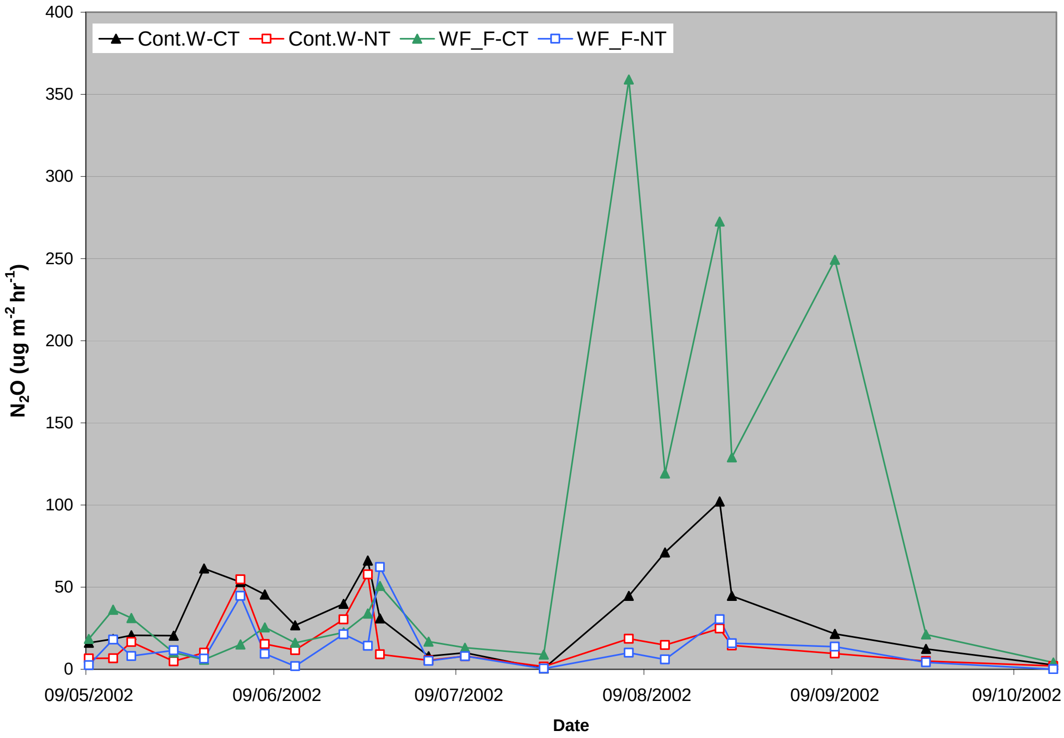

Figure 6. Mean hourly N_2O flux from selected treatments measured during the 2002 frost-free period (May-October) at Three Hills.

Despite the temporal difference in flux events during 2001 and 2002 at Three Hills, estimated N_2O losses for the frost free period were relatively similar **(Figure 7)**. In 2001, estimated loss averaged across treatments was about 1.3 kg N ha^{-1} for the CT managed systems and about 0.7 kg N ha^{-1} for the NT managed systems, the difference being highly significant ($P<0.002$). The CBPW_P treatment had the lowest estimated emissions under both tillage regimes. The CBPW_P treatment was significantly lower than the Cont.W and the CBPW_W treatments under CT management. There were no significant treatment effects within the NT managed systems.

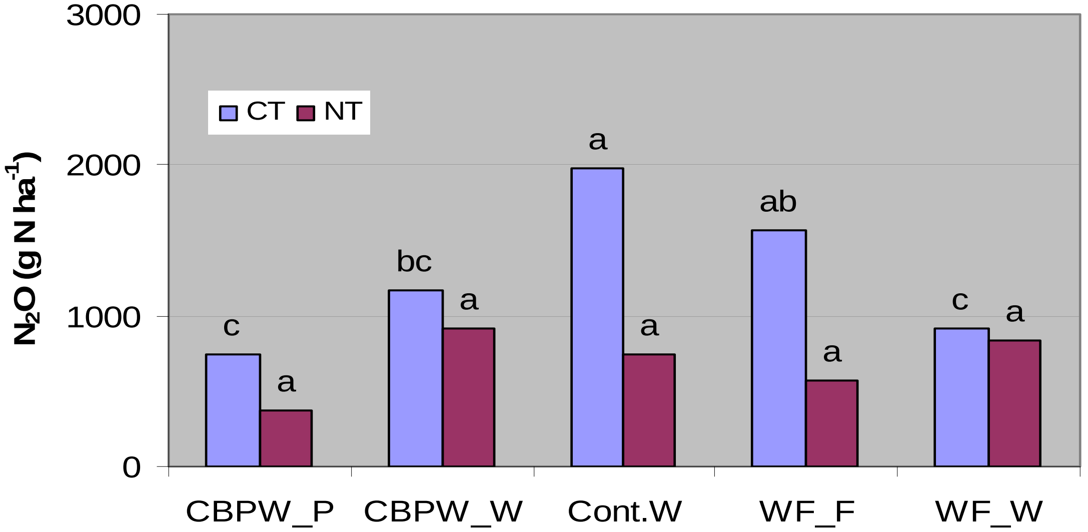

Figure 7. Estimated cumulative N_2O loss from selected treatments at Three Hills during the frost-free period of 2001. Treatments within the same tillage system with the same letter designation are not significantly different (P> 0.10).

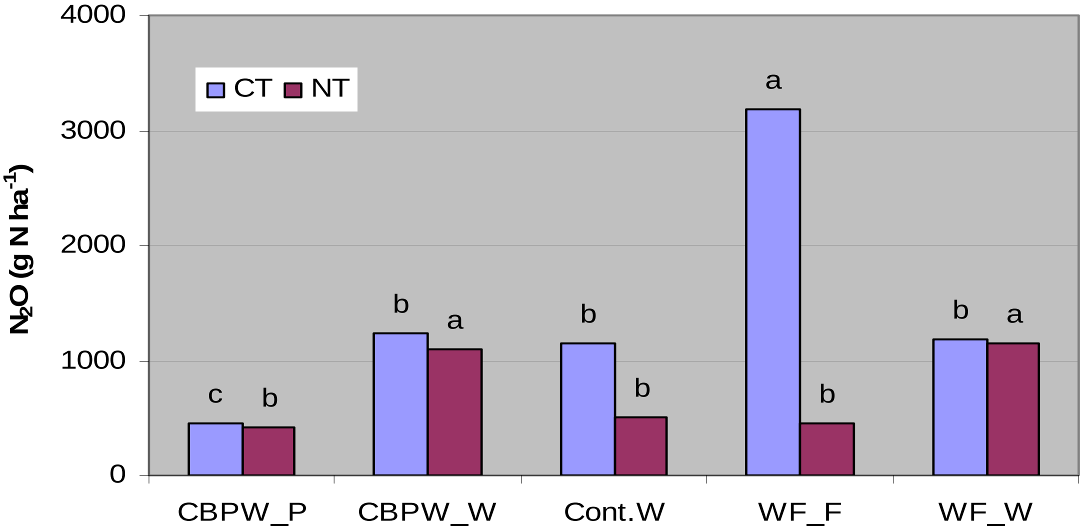

Figure 8. Estimated cumulative N_2O loss from selected treatments at Three Hills during the frost-free period of 2002. Treatments within the same tillage system with the same letter designation are not significantly different (P> 0.10).

In 2002, estimated cumulative N_2O loss averaged across treatments was about 1.4 kg N ha^{-1} for the CT managed systems and about 0.7 kg N ha^{-1} for the NT managed systems, the difference being highly significant ($P<0.001$). The CBPW_P treatment had the lowest estimated emissions under both tillage regimes **(Figure 8)**. The CBPW_P treatment was significantly lower than all other treatments under CT management, and was significantly lower than WF_W and CBPW_W under NT management. There was a highly significant tillage by treatment interaction during this time period. The WF_F treatment behaved quite differently on the two tillage regimes, having significantly higher emissions than any other treatments on the CT managed systems, but having one of the lowest emissions under NT management.

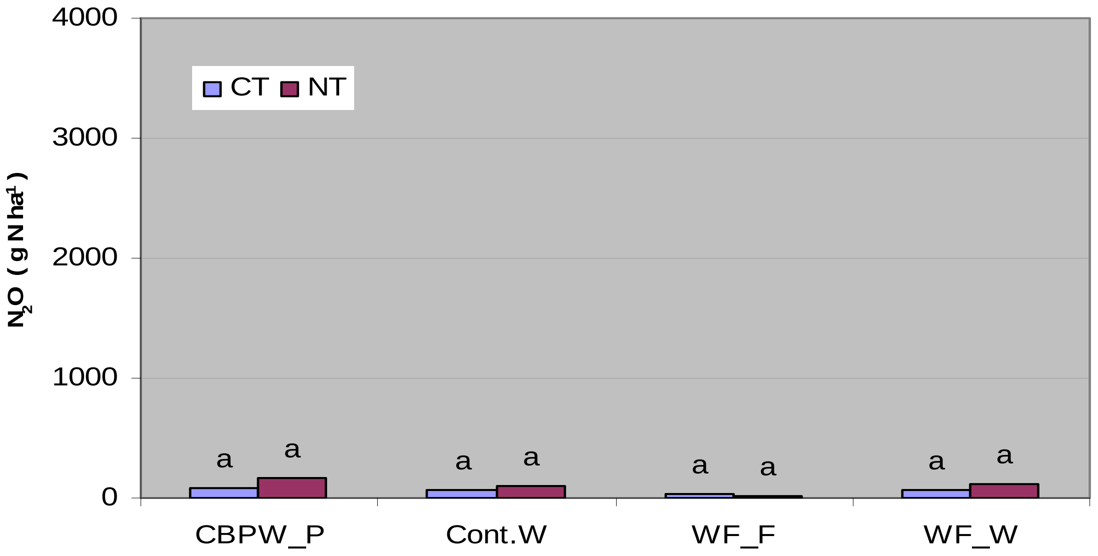

Figure 9. Estimated cumulative N_2O loss from selected treatments at Three Hills during the spring-thaw period of 2002. Treatments within the same tillage system with the same letter designation are not significantly different ($P> 0.10$).

Fall soil-water and available-N status were comparatively low in 2001. These conditions coupled with minimal snow cover during the over-winter period resulted in minimal N_2O emissions activity during the following (2002) spring-thaw period **(Figure 9)**. Estimated cumulative N_2O losses ranged from 20 to 160 grams N ha^{-1}. There were no significant differences for either treatment or tillage comparisons during this period of time. Higher soil-water content and available-N status in the fall of 2002 coupled with better over-winter snow cover resulted in considerably higher N_2O emissions during the 2003 spring-thaw event **(Figure 10)**. Although there appeared to be a strong and consistent trend for emissions to be higher from CT compared to NT, the difference was not significant. Emissions from WF_F under CT were significantly higher than from any other CT treatment. Emissions from the WF_F treatment were significantly higher than from the CBPW_P treatment under NT management. There were no other significant treatment differences. Fall soil-water and available-N status appeared to be qualitative indicators of expected N_2O emission activity at a site for a specific year. Correlation analysis found no significant relationship on a treatment by treatment basis for the 2002 spring-thaw, but soil-NO_3^- showed a weak (r = 0.43) but significant correlation with cumulative N_2O loss during the following spring. When the two years were pooled, both fall soil-NO_3^- and soil-water showed weak (r = 0.54 and 0.30, respectively) but highly significant correlations with cumulative N_2O loss during the spring-thaw.

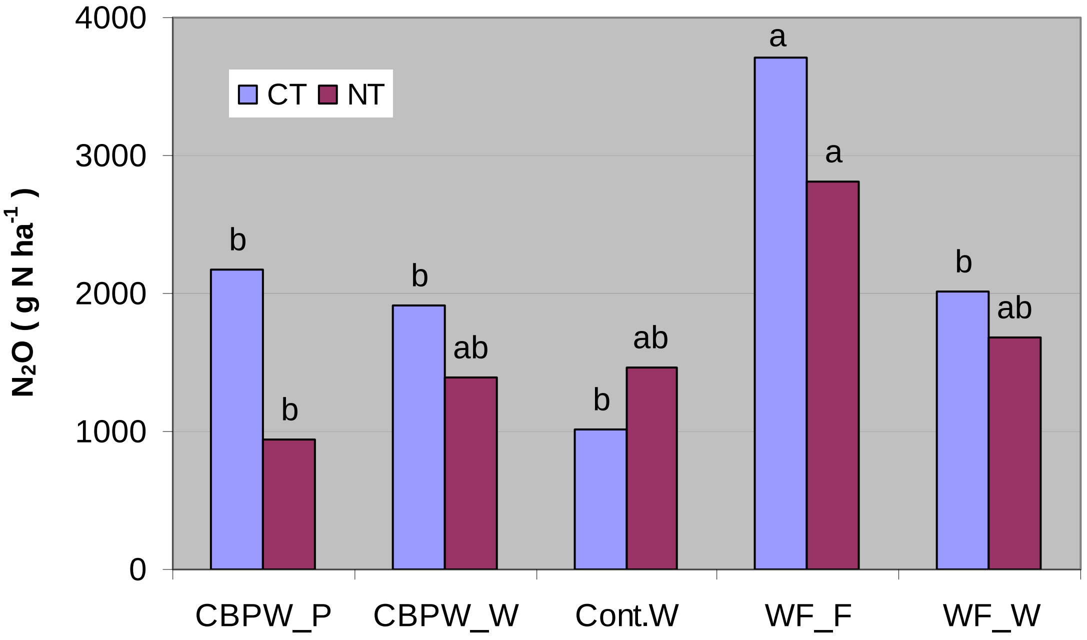

Figure 10. Estimated cumulative N_2O loss from selected treatments at Three Hills during the spring-thaw period of 2003. Treatments within the same tillage system with the same letter designation are not significantly different (P> 0.10).

Environmental conditions and farm management practices employed during the growing season can strongly influence the potential for N_2O loss during the following spring-thaw period (e.g. fall soil-NO_3^-, status) therefore annual N_2O -loss estimates were calculated by summing the frost-free period estimates and the cumulative losses during the following spring-thaw rather than on a calendar year basis. Annual N_2O -loss estimates for Three Hills are presented in **Table 7**.

Table 7. Annual N_2O loss estimates based on field measurements and calculated using the IPCC methodology for 2001 and 2002 at Three Hills.

	2001		**2002**	
Treatment	**Measured** *	**IPCC**	**Measured**	**IPCC**
	------------------------ (g N ha^{-1}) ------------------------			
Conventional Till				
CBPW_P	830 b	1438	2620 b	722
CBPW_W	na	1547	3150 b	1491
Cont. W	2050 a	1170	2150 b	1521
WF_F	1600 a	1234	6910 a	921
WF_W	980 b	844	3210 b	844
No Till				
CBPW_P	530 a	2540	1350 b	1266
CBPW_W	na	1936	2490 ab	1746
Cont. W	850 a	1709	1980 ab	1795
WF_F	600 a	1041	3270 a	1318
WF_W	960 a	844	2830 a	844
CT	1365 a	1172	3608 a	1100
NT	735 b	1534	2384 b	1394

* Estimated annual (frost-free period plus following spring-thaw) cumulative N_2O loss based on field measurements. Treatments within the same tillage system with the same letter designation are not significantly different (P> 0.10).

N_2O loss during the spring-thaw of 2002 were minimal, therefore treatment differences for the 2001/2002 cycle were largely a reflection of differences experienced during the 2001 frost-free period. There were no significant treatment differences within the NT system. Within the CT system, N_2O loss from the WF_F and the Cont.W treatments were significantly higher than WF_W and CBPW_P, but were not significantly different from each other. Overall, annual N_2O emissions were significantly higher from the CT compared to the NT system.

Nitrous oxide losses during the spring-thaw of 2003 were substantial and treatment differences observed in the annual estimates were strongly influenced by the treatment differences occurring during the spring-thaw period. Under CT management, N_2O loss was significantly higher from the WF_F treatment than from any other treatment. Under NT management, N_2O loss from the CBPW_P treatment was significantly lower than the WF_W and the WF_F treatments. Overall, annual N_2O emissions were significantly higher from the CT compared to the NT system.

Estimates calculated using the IPCC methodology did not capture inter-annual variability or the general pattern of variation within treatments **(Table 7)**. The annual estimates calculated with the IPCC approach compared very poorly with the annual estimates extrapolated from field-based measurements, however IPCC-estimated annual emissions for the CT system were very similar to the measurement-based estimates during the frost-free period (1.2 versus 1.3 kg ha^{-1} in 2001; and 1.1 versus 1.4 kg ha^{-1}in 2002), but were about 200 % of measurement-based estimates for the frost-free period on the NT system. This suggests that an estimate of N_2O emissions based on general N-flows may be a reasonable approach for the frost-free period, but also suggests that the NT systems require a different emission factor compared to the CT systems. The IPCC methodology greatly over-estimated emissions from the CBPW_P treatment in the 2001/2002 cycle for both CT and NT, and provided an estimate similar to the measurement-based approach for NT but much lower than the measurement-based estimated for the CT in the 2002/2003 cycle.

Swift Current

Nitrous oxide emissions from the Swift Current site were extremely low in 2001. Estimated losses during the frost-free period ranged between 0 and 115 g N ha^{-1} **(Figure 11)**. Losses on the Cont.W ($^{+}$N) treatment were significantly higher than on the

Cont.W ($^-$N) and the WL_L treatments . In 2002, losses ranged from 80 to 198 g N ha^{-1}. The relative ranking of N_2O loss was similar to 2001, but the differences were not significant.

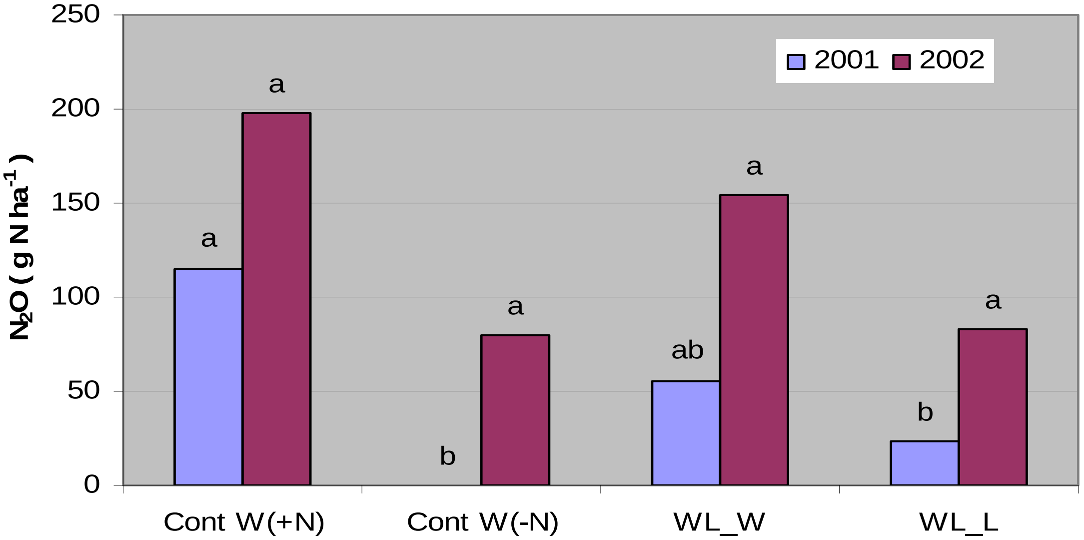

Figure 11. Estimated cumulative N_2O loss from selected treatments at Swift Current during the frost-free period of 2001 and 2002. Treatments within the same year with the same letter designation are not significantly different (p>0.10)

Very dry conditions in the fall of 2001 combined with minimal snow fall during the over-winter period resulted in extremely low emissions during the spring-thaw period of 2002, with losses ranging between 10 and 24 g N ha^{-1}. Although statistical analysis indicated a significant difference between the Cont.W ($^+$N) and the Cont.W ($^-$N) treatment, we attach no material importance to this observation. Losses during the spring-thaw of 2003 were considerably higher. Losses from the WL_W treatment were markedly higher than the other three treatments, however this difference was not shown to be statistically significant (p>0.10). Most of the cumulative loss estimated from this treatment was related to a single replication. Estimated loss from this plot was an order of magnitude higher than the other replications. Extreme spatial variability is intrinsic to N_2O emissions, and this level of variability makes treatment comparisons very difficult.

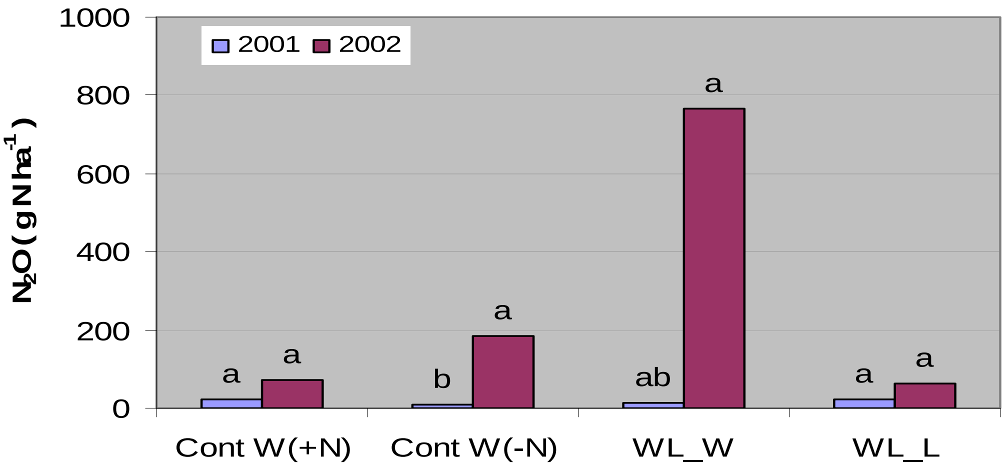

Figure 12. Estimated cumulative N_2O loss from selected treatments at Swift Current during the spring-thaw period of 2002 and 2003. Treatments within the same year with the same letter designation are not significantly different ($p>0.10$).

On an annual basis, N_2O losses were significantly higher from the Cont.W ($^{+}$N) treatment than from the other three treatments during the 2001/2002 cycle, but there were no significant treatment differences during the 2002/2002 cycle **(Table 8)**. The IPCC-based estimates were an order of magnitude higher than measurement-based estimates for 2001/2002, but the two approaches provided quite similar estimates for the Cont.W ($^{+}$N) and Cont.W ($^{-}$N) treatments for 2002/2003. The IPCC-approach greatly underestimated the N_2O loss for the WL_W treatment in 2002/2003 and greatly over-estimated the N_2O loss for the WL_L treatment during the 2002/2003 cycle. The IPCC approach did a very poor job of estimating N_2O -loss from the WL_L treatments in both years of this study.

Table 8. Annual N_2O loss estimates based on field measurements and calculated using the IPCC methodology for 2001 and 2002 at Swift Current.

	2001		2002	
Treatment	Measured *	IPCC	Measured	IPCC
	------------------- g N ha^{-1} -------------------			
Cont. W ($^{+}$N)	155 a	915	300 a	255
Cont. W ($^{-}$N)	20 b	243	287 a	231
WL_W	79 b	1855	1185 a	367
WL_L	63 b	840	191 a	1797

* Estimated annual (frost-free period plus following spring-thaw) cumulative N_2O loss based on field measurements. Values in columns followed by the same letter are not significantly different ($P<0.1$).

Nitrous oxide emissions as a fraction of N-Uptake and Apparent N-Turnover

Nitrification and denitrification are thought to be the principal processes generating N_2O in agricultural soils. Nitrification can be loosely described as the oxidation of NH_4^+ to NO_3^-, while denitrification is the reduction of NO_3^- to N_2O and/or N_2. Nitrifiers do not discriminate between NH_4^+ supplied by application of ammonium based synthetic or organic fertilizers, or that released during animal waste, crop residue and soil organic matter (SOM) decomposition. The nitrification process, in turn, supplies the NO_3^- required to drive denitrification. In general terms then, it would seem reasonable to expect cumulative N_2O-loss from any particular land area to be related to total N-turnover, which we will define as the sum of commercial N-fertilizer additions, and N mineralized from SOM, crop residues, and animal manure applications. One possible exception to this generalization may be biological N-fixation. The N fixed by rhizobium in the nodules of legume crops is taken up by the legume plant without first undergoing the nitrification process. For this reason, we argue that the potential for N_2O emissions from N inputs by N-fixation would be negligible. This obviously only applies to N-fixation process, as N released during decomposition of the legume residue would be a potential source of N for N_2O production. If there are no N_2O emissions associated with the N-fixation process, then we would predict that the percentage of N lost as N_2O relative to the amount of N taken up by the crop (i.e. N-uptake) should be lower for pulse crops than for cereal crops.

At Three Hills, the amount of N_2O lost from the CBPW_P treatment, expressed as a percentage of crop N-uptake, was consistently lower than any other treatment under NT management for both 2001 and 2002 **(Table 9)**. This was also the case for the CT management in 2002, but in 2001 losses from CBPW_P were similar but slightly higher than on WF_W. The same calculations made for the Swift Current site showed the WL_L treatment to be slightly higher than the Cont.W (-N) treatment, and lower than the other two treatments in 2001, but lower than all other treatments in 2002 **(Table 10)**. In general, these results support the contention that there are no or negligible N_2O emissions arising directly from the N-fixation process itself.

Table 9. Growing season N_2O-N loss expressed as a percentage of N-Uptake and apparent N-Turnover at Three Hills.

	2001		2002	
Treatment	N-Uptake	N-Turnover	N-Uptake	N-Turnover
	(%)			
Conventional Till				
CBPW_P	0.9	1.2	1.8	0.7
CBPW_W	1.8	0.9	7.6	0.9
Cont. W	2.2	1.5	4.9	0.8
WF_F	na	2.7	na	5.5
WF_W	0.7	0.7	2.1	0.9
No Till				
CBPW_P	0.3	0.3	1.0	0.3
CBPW_W	1.3	0.5	3.1	0.6
Cont. W	0.8	0.4	0.9	0.3
WF_F	na	0.5	na	0.4
WF_W	0.5	0.4	1.3	0.6
CT	1.4	1.4	4.1	1.8
NT	0.7	0.4	1.6	0.4

If we accept the hypothesis that there are no or negligible N_2O emissions arising from the N-fixation process, then any emissions measured from pulse treatments during the growing season must be related to N made available through decomposition of SOM and crop residue from the previous year. While N additions from crop residues and N-fertilizers can be readily documented, the amount of N mineralized from SOM is very difficult to determine. At Swift Current, wheat was grown without external additions of N. Thus, we assumed that the N taken up by the crop, less the N provided by the crop residue from the previous year, was provided by SOM decomposition and could be considered an indicator of “apparent N-mineralization”. Using this approach, apparent mineralization (2-year mean) was estimated to be 20.36 kg N ha^{-1}. We further assumed that the same amount of N would be mineralized under all treatments. Combining this estimate of apparent N-mineralization with fertilizer-N addition and crop residue N provided an estimated of “apparent N-turnover”. Lastly, we attempted to relate cumulative N_2O loss during the frost-free period to apparent N-turnover by expressing the N_2O loss as a percentage of apparent N-turnover. The resulting percentages calculated for the Swift Current site are presented in **Table 10**.

Table 10. Growing season N_2O -N loss expressed as a percentage of N-Uptake and apparent N-Turnover at Swift Current.

	2001		2002	
Treatment	N-Uptake	N-Turnover	N-Uptake	N-Turnover
	-------------------------- (%)		------------------------	
Cont. W ($^+$N)	0.3	0.2	0.2	0.3
Cont. W ($^-$N)	0.0	0.0	0.2	0.3
WL_W	0.2	0.1	0.2	0.3
WL_L	0.1	0.1	0.1	0.3

There was no “minus N” treatment available at the Three Hills site. We therefore estimated “apparent N mineralization” from the change in soil-NO_3^- during the fallow phase. The resulting estimates were similar for the two years, but the two tillage systems provided very different results. The two-year average for CT was 58 kg N ha^{-1} while the two-year average for NT was 114 kg N ha^{-1}. We assumed that this amount of N would be mineralized under all treatments. Cumulative N_2O emissions for the frost-free period expressed as a fraction of apparent N-turnover for the Three Hills site are presented in **Table 9**.

Note that N inputs via N-fixation were not included in the calculation of apparent N-turnover. If our estimates of apparent N-turnover are realistic, and our assumption that there are no N_2O emissions directly related to N-fixation, then it follows that N_2O loss during the frost-free period expressed as a percentage of apparent N-turnover should return very similar values across all treatments. Inspection of **Table 10 & 11** supports this contention - with the CBPW_F treatment under CT management being the one notable exception.

The amount of N_2O produced per unit of N nitrified or denitrified can vary substantially depending upon prevailing soil environmental conditions. Laboratory studies suggest that the amount N_2O generated during nitrification varies between 0.1 and 0.5 % of the NH_4^+-N nitrified under well aerated conditions. Evidence is mounting that nitrifiers can also denitrify when oxygen is limiting. Under these conditions yields of N_2O per unit of N nitrified may reach 1% or higher. At Swift Current, the percentage of N-turnover lost as N_2O ranged from slightly better than 0 to about 0.3 **(Table 10)**. These values suggest that most or all N_2O emissions measured at the site could have arisen from nitrification. The higher fraction of N_2O loss during 2002 compared to 2001 is consistent with the higher soil moisture conditions in that year. Emissions from the cropped treatments at Three Hills ranged between 0.7 and 1.5 on the CT treatments and 0.3 and 0.6 on the NT treatments. These values also suggest that nitrification could have been the predominant source of N_2O emissions. The higher percentage values at this site compared to Swift Current is consistent with the generally moister soil conditions at Three Hills. A greater contribution of denitrification is one possible explanation for the much higher percent losses on the CBPW_F under CT management; however, we have no evidence to support this contention.

Conclusions

Results from our study suggest that there are no or negligible N_2O emissions associated with the N-fixation process, but pulse residues tend to stimulate N losses in the following spring or growing season resulting in similar N_2O losses from the fertilized continuous wheat systems and the wheat-pulse systems. It should be noted that at Three Hills, N-fertilizer rates for the wheat-on-pulse treatments were not adjusted to accommodate for the N provided by the previous pulse crop. Thus with fine tuning of the nitrogen management, there may be opportunity to reduce N_2O emission by including pulses in the NT system. Secondly, the greenhouse gas emissions associated with N-fertilizer manufacture and transport has not been taken into consideration.

There were some subtle interactions between the wheat-pulse treatments and tillage system. During the frost-free period, N_2O emissions were consistently low from pulse crops under CT and NT management at Three Hills and at Swift Current. Emissions from the pulse plots remained low during the spring-thaw period at Swift Current and on NT at Three Hills, but in 2003 they were higher than other cereal treatments on CT management at Three Hills. Conversely, emissions during the frost-free period tended to be higher from wheat grown on pulse-residue compared to fertilized continuous wheat on the NT system at Three Hills, but were similar or lower than fertilized continuous wheat on the CT management and at Swift Current. Emissions during spring-thaw tended to be higher from wheat grown on pulse-residue compared to fertilized continuous wheat on the CT system at Three Hills and Swift Current. On an annual basis, there were no statistically significant differences between N_2O losses from the fertilized continuous wheat and either the pulse treatment or wheat on pulse-residue treatments.

Similarly, the WF system responded differently under CT compared to NT management. Under CT, the fallow treatment tended to have similar or higher emissions compared to cropped treatments, while the fallow treatment had similar or lower emissions under NT management. Overall, N_2O emissions were significantly higher on CT compared to NT treatments in both the 2001/2002 and the 2002/2003 cycles.

In this study, cumulative N_2O loss during the frost-free period expressed as a percent of apparent N-turnover returned relatively consistent values across treatments at both sites. Thus we deemed our attempt to relate N_2O emissions to assumed N-Turnover a modest success. With further refinement, this approach may provide some predictive capability – at least for the frost-free period. The results also indicate that the emission coefficients will need to be tailored to soil-water and tillage system (i.e. dryer locations or NT managed systems require lower coefficients). Our approach differed from the IPCC methodology in that it included estimates of apparent N mineralization. The IPCC approach greatly underestimated N_2O loss from the WF_F treatments in this study, particularly under CT management. Our approach may provide more realistic estimates of N_2O loss from systems that include fallow. Unfortunately, neither approach adequately describes N_2O loss during the spring-thaw period.

References

Corre, M.D., van Kessel, C. and Pennock D.J. 1996. Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. Soil Sci. Soc. Am. J**.** 60:1806-1815.

Hutchinson, G.L., and Mosier, A.R. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. 45:311-316.

Lemke, R.L., Izaurralde, R.C., Malhi, S.S., Arshad, M.A., and Nyborg, M. 1998. Nitrous Oxide emissions from agricultural soils of the Boreal and Parkland regions of Alberta. Soil Sci. Soc. Am. J. 62:1096-1102.

Lemke, R.L., Izaurralde, R.C., Nyborg, M., and Solberg, E.D. 1999. Tillage and N-source influence soil-emitted nitrous oxide in the Alberta Parkland region. Can. J. Soil Sci. 79:15-24.

OECD/IPCC. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 4 Agriculture, Section 4.6 Agricultural Soils. OECD Paris, France.

Saskatchewan Agriculture. 1988. General recommendations for fertilization in Saskatchewan. Saskatchewan Agiculture, Soils and Crops Branch, Saskatoon, SK Agdex 541.