Contribution of ephemeral wetlands to annual nitrous oxide flux from an agricultural landscape

T.T. Yates[1], B.C. Si[1], R.E. Farrell[1], R. McDougal[2], A. Bedard-Haughn[1], J. Braidek[3], and D.J. Pennock[1]

[1]Department of Soil Science, University of Saskatchewan
[2]Ducks Unlimited Canada
[3]Saskatchewan Agriculture and Food

Key Words: nitrous oxide, ephemeral wetland, landscape, cumulative emission, flux

Abstract

Measurement of soil nitrous oxide emissions from soil in the Canadian Prairie Region rarely includes uncultivated ephemeral wetlands (UW) within agricultural landscapes. Accurate inventories and a better understanding spatial and temporal variability for soil N_2O in agricultural terrains requires flux measurements from non-agricultural areas of the field. The purpose of this study was to measure soil nitrous oxide flux from an agricultural landscape that includes UW. Measurements were taken weekly and bi weekly from July to October of 2003 and from March to October of 2004 and 2005. Cumulative emissions were highest from concave elements (cultivated ephemeral wetlands) (CV) elements in 2003 and 2004 and highest from the basin centers (BC) of UW in 2005. High flux events were associated with rainfall in 2003, and the recession of standing water at CV and BC elements in 2004 and 2005. However, there are differences between ephemeral wetlands in their emission response to water recession. Accounting for aerial extent of landscape units reveals that CV elements make greatest contribution to total yearly flux. Beneficial management practices intended to reduce annual emissions from this site should be designed to reduce emission from CV elements and UW should not be cleared for crop production. Sampling designs for measurement of emissions from UW need not distinguish between riparian grass and riparian tree elements within the UW.

Introduction

The content of atmospheric nitrous oxide (N_2O) is increasing (FAO and IFA, 2001). Nitrous oxide is a greenhouse gas and is converted to nitric oxide (NO) in the troposphere where it reacts with and destroys ozone (Agriculture and Agri-Food Canada, 1998). Human sources include the consumption of fossil fuels, industrial processes and agriculture. Agriculture, particularly the use of mineral fertilizers is considered the most important of these sources (FAO and IFA, 2001). It is estimated that 70% of N_2O

emissions due to human activity comes from agriculture (Agriculture and Agri-Food Canada, 1998) and approximately 50% of these emissions come from the soil.

Oxygen (O_2), carbon (C) and nitrogen (N) are important factors that control the production of soil N_2O at a process level (Robertson, 1989). Anaerobic conditions and the production of N_2O via the microbial process of denitrification occur when the diffusion of O_2 is slowed by the presence of water in soil pores and as films on soil aggregates (Renault and Stengel, 1994).

To date there has been little research published on emission measurements from hummocky agricultural landscapes, common to the Prairie region that can contain considerable within-field variation in landform and land use. Most agricultural landscapes in the Prairie region, especially those with variable topography such as a hummocky terrain, contain numerous ephemeral wetlands. The magnitude of N_2O emissions from the wetlands in the Canadian Prairie region is virtually unknown.

Ephemeral wetlands include both cultivated and uncultivated depressions. Water is gained through snow melt and summer precipitation and lost through evapotranspiration and vertical drainage (van der Kamp et al., 1999). Typically, the uncultivated ephemeral wetlands (UW) have a center that is surrounded by a complete ring of trees or shrubs or a combination of a partial tree ring and grass fringe. The outer boundary of both the tree ring and grass fringe is controlled by cultivation of the surrounding agricultural area of the field.

The UW represent a hydrology and suite of soil types, soil physical properties and nutrient cycling distinct from the surrounding cultivated area of the landscape. Within these wetlands the center, tree ring and grass fringe also differ in vegetation type, hydrology, and nutrient cycling. Such differences may result in distinct differences between cultivated elements and subunits of the UW in terms of net N_2O flux. It is necessary to know what these differences are so that accurate inventory estimates for these landscapes can be made.

The objective of this study was a) to quantify annual N_2O flux from ephemeral wetlands in a hummocky terrain in the Dark Brown soil zone of Saskatchewan, and b) show the relationship between N_2O flux and pond water level.

Methods and Materials

The research site was approximately 40 km east of Saskatoon, located in the St. Denis National Wildlife Area (52° 12’ N latitude, 106° 5’W longitude) in Saskatchewan, Canada. The site was on a hummocky, glacial till terrain (Figure 1).

Locations in the cultivated area of the site were classified as either convex (CX), concave (CV) landscape elements. Convex elements are topographically high positions with an overall positive profile curvature such as top and mid-slope of a knoll. Concave elements represent cultivated ephemeral wetlands and are positions with an overall negative profile curvature such as foot-slopes and depressions.

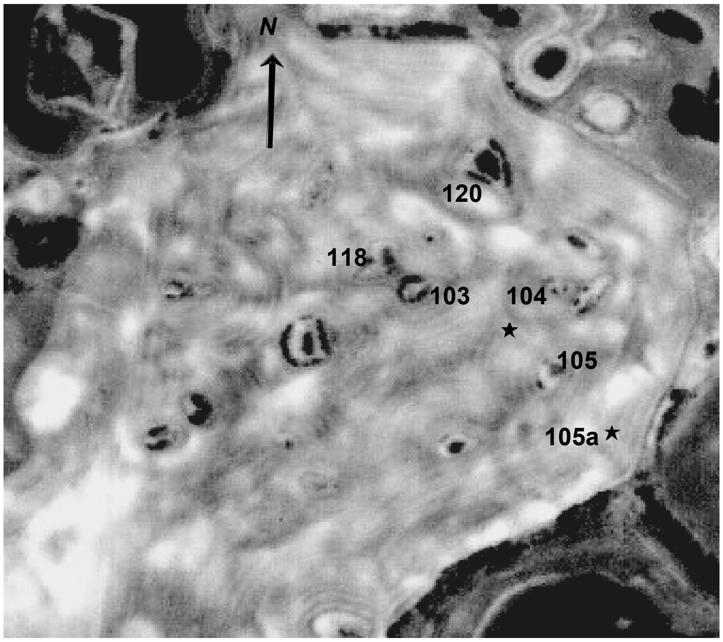

Figure 1: Air photograph of the main research site at the St. Denis Wildlife Area before seeding of grass. Uncultivated ephemeral wetlands show as dark circular features. Sampled wetlands are marked with pond number as per Hogan and Conly (2002). Grey shaded areas are low relative elevation. White shaded areas are high relative elevation.

The UW represents uncultivated ephemeral wetlands, although all had been cultivated prior to 1968 when they were taken out of production by the Canadian Wildlife Service (Bedard-Haughn et al., 2006). For the purposes of this study, these wetlands were further sub-divided into three landscape elements after preliminary surveys of soils and vegetation (Figure 2). The basin center (BC) is a level area covered by a variety of non grasses. The riparian grass (RG) is a non-level fringe area covered with grasses. The riparian trees (RT) are a partial fringe of mixed trees and shrubs.

The hydrological pattern on the site is controlled primarily by the CV and UW, which act as focal points for inputs and redistribution of precipitation and snowmelt water. The bulk of the water entering these topographically low elements infiltrates laterally through the depression margins where it is recycled through evaporative and transpiration processes (Hayashi et al., 1998). The primary source of water for the ephemeral wetlands is spring snowmelt runoff. Summer precipitation extends the life of the ephemeral wetlands; however, water loss from these closed basins is almost entirely by evapotranspiration (Hayashi et al., 1998).

In July of 2003 a 50-point stratified sampling design was established at the site in the ephemeral wetlands and on the adjacent cultivated land, which had been fallow since 2002. The previous crop had been *Hordeum vulgare* L. This provided 10 locations per landscape element. The 50 locations were distributed in short transects over four uncultivated wetlands and two landform cycles (knoll-depression) within the cultivated uplands.

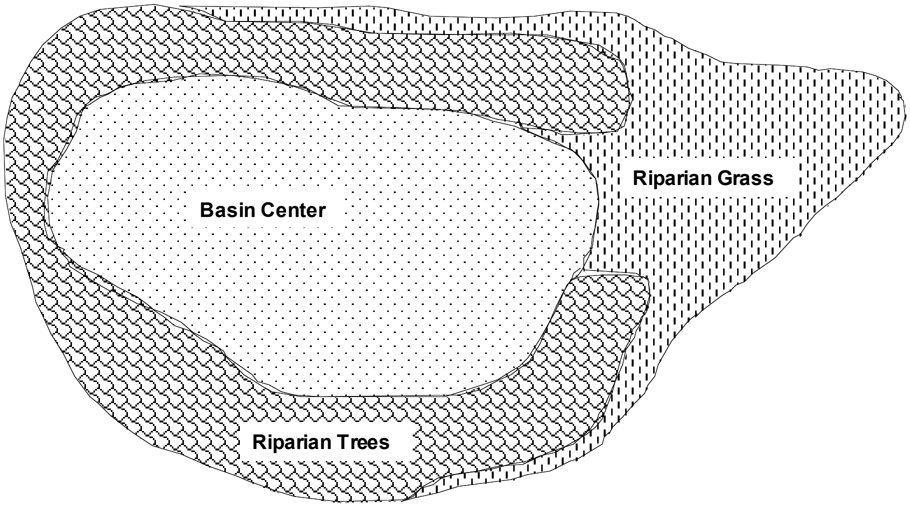

Figure 2: Drawing of typical uncultivated ephemeral wetland at St. Denis Wildlife Area showing riparian grass, riparian trees and basin center elements.

At each location, soil N_2O flux was measured using a two-piece, closed, vented chamber (International Atomic Energy Agency, 1992) consisting of a polyvinyl chloride (PVC) ring base and vented cap with sampling port similar to Hutchinson and Mosier (1981). At each sampling event, the chamber was placed onto the base and sealed by a rubber ring within the cap. During sample collection, the chamber is place on the base and samples of the head space gas are drawn at timed intervals to obtain a change in N_2O concentration over time and calculate the amount of N_2O leaving the unit area of soil over time (flux). Flux measurements from locations under snow, when sampling early in the spring snowmelt season, were taken directly from the snow surface. Later in the season, when run off from the cultivated uplands into the CV and UW elements submerged the sample locations, measurements were taken from the surface of the water using an acrylic, non-vented chamber accessed from a wooden walkway and held in place by a metal rod imbedded into the ground below.

Nitrous oxide concentrations were determined using a Varian CP3800 GC (Varian Canada Inc., Mississauga, ON) equipped with dual electron capture detectors (ECD). Ambient air samples were included as reference samples in each analytical run to check the ‘within run’ precision, calculate the minimum detectable concentration difference (MDCD), and correct for detector drift (Yates et al., 2006).

It has been demonstrated that the concentration (ng L^{-1}) *vs*. time (min) relationship is not linear due to decreasing concentration gradient (Hutchinson and Mosier, 1981). Measuring N_2O concentration at t_0 and after three 8-min time intervals produces 4 points for a concentration *vs*. time curve. The vertical flux of N_2O at the soil–atmosphere interface (ng N_2O-N m^{-2} s^{-1}) was then calculated as the slope of the line tangent to the concentration *vs*. time curve at t_0 (Yates et al., 2006). In cases where ‘rogue’ data points prevented the use of the 2nd-order polynomial model (i.e., only 3 points available instead of 4) the flux was calculated as the slope of the linear model that best described the concentration *vs.* time relationship (Hutchinson and Mosier, 1981).

In addition to soil N_2O flux measurements, hourly precipitation was recorded and water levels in the ephemeral wetlands were measured over the sampling season. Flux measurements were made weekly and bi-weekly starting in July 2003 through to October 2005. Measurements were not made after October or before March in each year of the study.

Results and Discussion

For the measurement period of March 30 to October 31 the cumulative precipitation for 2003, 2004 and 2005 was respectively, 238, 282, and 400 mm (Figure 3). Normal precipitation for the Saskatoon area over this period of time is 259 mm (Environment Canada, 2005). Rainfall events in 2003 were less frequent than in 2004. In 2005 rainfall was both frequent and intense (for the region) reaching as higher than 100 mm over 48 hours (June 17 and 18).

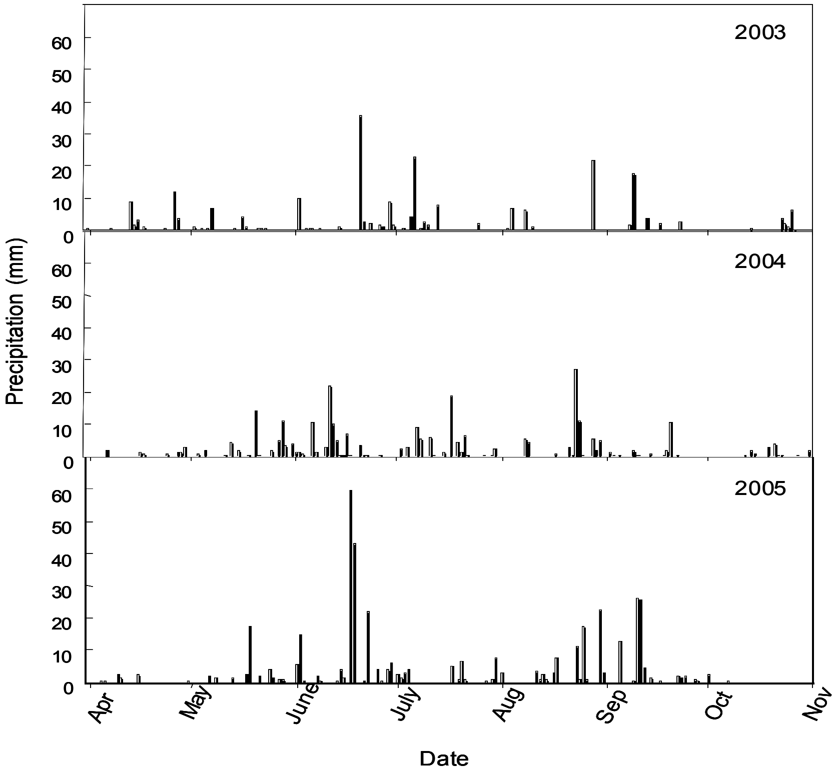

Figure 3: Daily rainfall (mm) for 2003, 2004 and 2005 at St. Denis Wildlife Area.

In 2003 CV elements had the highest mean cumulative flux (1707.0 g N_2O-N ha^{-1} 108.5 d^{-1}) followed by CX elements (Figure 4). The lowest cumulative mean flux was measured at BC elements (180.1 g N_2O-N ha^{-1} 108.5 d^{-1}). Cumulative mean flux was also highest for CV elements in 2004 (1953.5 g N_2O-N ha^{-1} 232.5 d^{-1}) (Figure 5); however, the second highest cumulative flux was for BC elements (973.9 g N_2O-N ha^{-1} 232.5 d^{-1}).

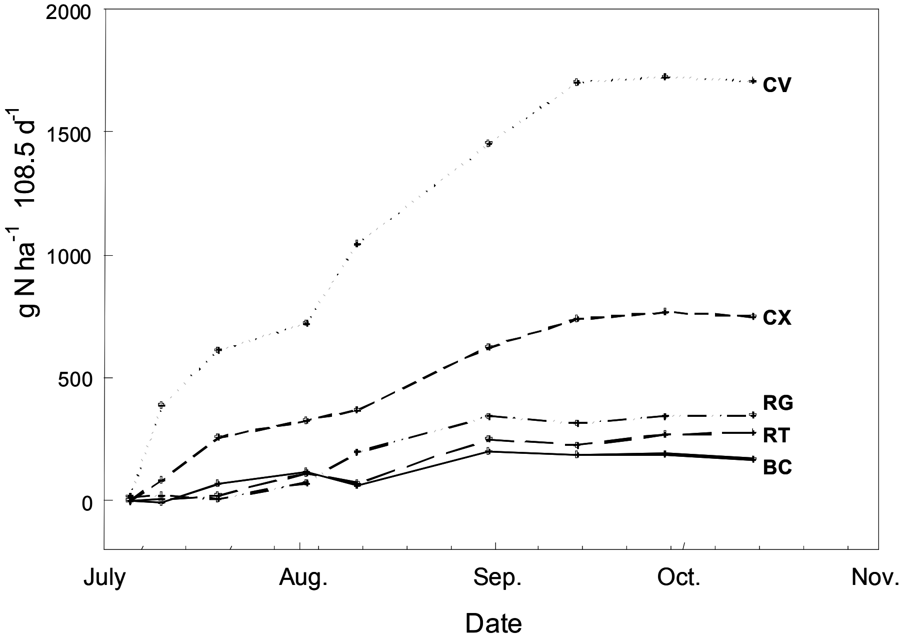

Figure 4: Mean cumulative N_2O flux (g N_2O-N ha^{-1} 108.5 d^{-1}) for 2003 from the landscape elements at St. Denis Wildlife Area. Concave (CV), convex (CX), riparian grass (RG), riparian trees (RT) and basin center (BC).

In contrast to 2003, in 2004 CX elements had a negative cumulative flux (-20.2 g N_2O-N ha^{-1} 232.5 d^{-1}) (Figure 5) having a positive cumulative flux at only one point in the year (March 12).

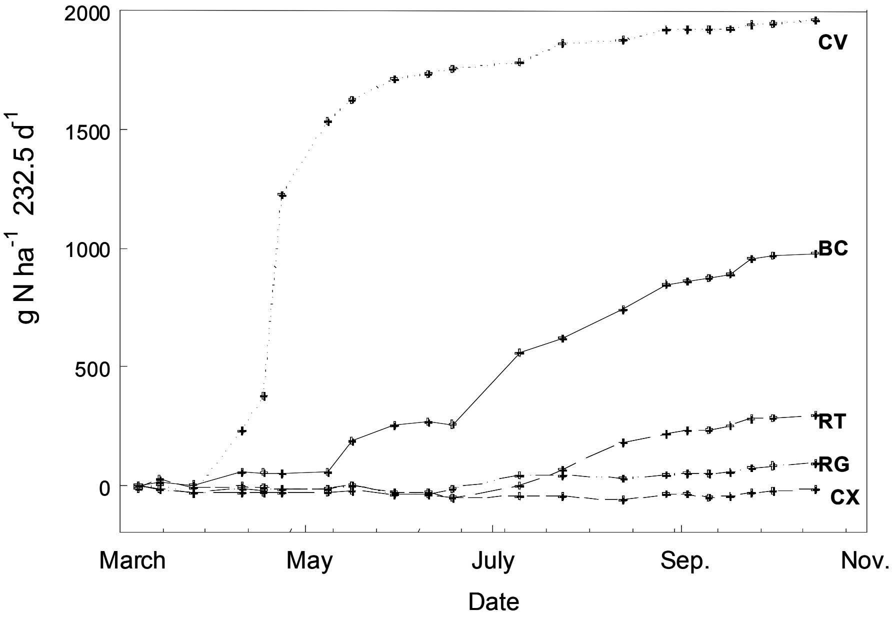

Figure 5: Mean cumulative N_2O flux (g N_2O-N ha^{-1} 232.5 d^{-1}) for 2004 from the landscape elements at St. Denis Wildlife Area. Concave (CV), convex (CX), riparian grass (RG), riparian trees (RT) and basin center (BC).

The RG and RT elements showed a negative cumulative flux until early and late July, respectively. For CV elements, a large increase in cumulative flux occurred in April, whereas large increases in cumulative flux occurred in BC elements in May and June (Figure 5).

By comparison, cumulative flux in 2005 increased over the previous year with higher cumulative fluxes for all landscape elements except CV units (Figure 6). Cumulative flux in the BC elements exceeded that for the CV elements (2098.7 and 1616.7 g N_2O-N ha^{-1} 231.5 d^{-1}, respectively). The CX, RG and RT elements increased in cumulative flux steadily over the period of emission sampling, whereas CV elements had large increases in cumulative flux in May and again in July. Cumulative flux for BC elements increased gradually, like that of the other wetland elements, until August when cumulative flux increased rapidly and eventually exceeded that for CV elements (Figure 6).

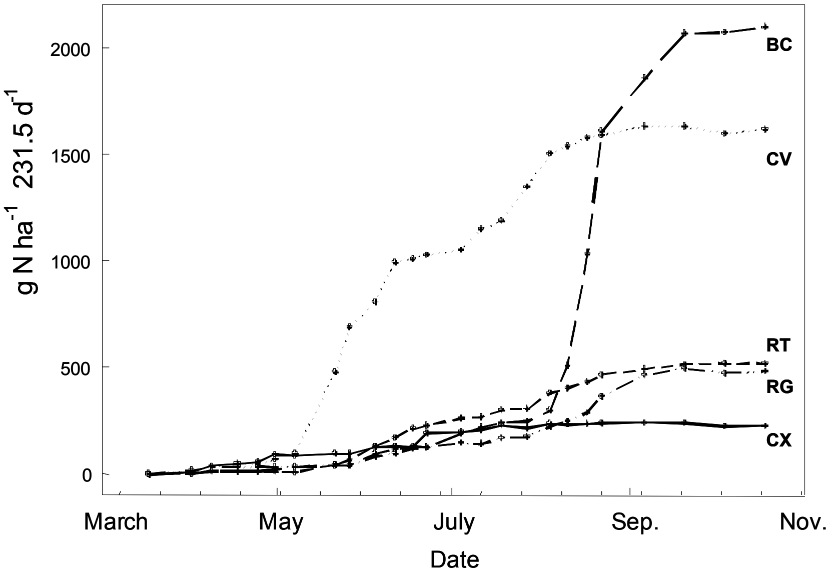

Figure 6: Mean cumulative N_2O flux (g N_2O-N ha^{-1} 231.5 d^{-1}) for 2005 from the landscape elements at St. Denis Wildlife Area. Concave (CV), convex (CX), riparian grass (RG), riparian trees (RT) and basin center (BC).

Water levels in the wetlands were recorded in 2004 and 2005 (Table 1). In 2003 standing water in the wetlands had dropped to zero well before the start of gas sampling on 3 July. In 2004, water levels in most wetlands had dropped to zero by mid-May. Standing water was maintained in pond 120 until Aug. In 2005, standing water persisted in most of the ponds until Aug. and ponds 105 and 120 maintained standing water until the end of gas sampling in mid Oct.

The rapid increase in cumulative flux in the spring of 2004 at CV elements (Figure 5) coincided with the decline in pond water levels at ponds 104 and 105a though Apr. and May. Mean flux > 10 ng N_2O-N m^{-2} s^{-1} occurred at this time at ponds 104 and 105a and lasted after standing water had disappeared. Mean flux > 10 ng N_2O-N m^{-2} s^{-1} at ponds 103 and 120 coincided with the loss of standing water in those ponds. For both CV and UW, major emissions occur when all or part of the pond bottom was exposed.

Table 1: Pond water level (cm) and mean N_2O flux (ng N_2O-N m^{-2} s^{-1}) at St. Denis Wildlife Area for most sampling dates in 2004 and 2005. Concave (CV), uncultivated ephemeral wetland (UW).

	Pond (landscape element)											
	103 (UW)		104 (CV)		105 (UW)		105a (CV)		118 (UW)		120 (UW)	
2004	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm
4/4		44		41		39		25		51		56
4/5		49		39		45		20		62		59
4/8	5.08	52	1.46	31	2.33	42	51.90	14	0.62	57	2.20	58
4/16	-2.25	44	-0.69	14	9.78	27	52.68	0	-1.93	47	-2.28	47
4/21	-0.96	30	76.51	6	0.00	20	110.48		-0.47	34	1.17	44
5/6	0.42	8	61.36	0	0.00	9	1.08		0.76	13	0.00	35
5/19	15.20	0	17.20		0.86	0	1.66		1.70	0	1.47	27
5/27	1.65		17.67		2.83		-1.29		4.07		-5.96	23
6/9	2.10		4.99		0.00		0.08		0.21		0.18	22
6/16	-2.69		2.38		0.00		1.13		2.41		-0.29	31
7/8	4.39		2.63		32.88		0.57		4.36		-0.34	10
7/22	2.07		7.95		4.24		2.84		4.21		1.47	8
8/11	4.28		2.15		3.09		0.00		-1.18		13.20	0
8/25	7.42		4.57		0.64		5.12		0.96		13.00	

	Pond (landscape element)											
	103 (UW)		104 (CV)		105 (UW)		105a (CV)		118 (UW)		120 (UW)	
2005	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm	N_2O	cm
4/8	2.58	80	2.28	63	4.81	81	3.96	no	0.96	85	1.68	103
4/22	-1.13		-1.10		0.07		3.09	data	-0.30		1.06	
5/5	-0.44		3.28		0.00		3.05		1.09		0.00	
5/19	1.30		88.62		4.96		3.99		0.38		2.38	
5/24	0.00		67.79		0.12		1.30		0.00		3.85	
6/2	7.77		21.17		19.87		13.15		6.24		1.31	
6/9	6.76		61.26		3.90		-4.04		2.81		2.86	
6/22	1.15	54	4.07	35	0.89	66	0.86		2.46	56	-1.18	111
7/4	10.23	47	-2.22	27	2.88	60	7.77		0.93	45	6.55	110
7/13	-0.95	36	24.61	16	0.00	55	7.11		3.70	39	2.30	101
7/25	1.68	17	51.92	0	0.76	40	-1.89		0.73	15	0.37	85
8/2	11.43		42.29		21.46		9.11		7.83		2.53	
8/8	34.29		11.50		5.81		0.16		19.38		4.37	
8/16	83.04	0	4.06		5.15	16	9.51		40.96	0	9.02	75
8/22	72.52		1.52		6.10	12	0.90		15.92		11.78	72
9/6	26.30		4.06		1.27		1.86		5.97		9.11	
9/20	23.38		1.29		0.50		-1.34		4.93		3.21	
10/19	1.80		1.20		1.96	2	1.70		0.22		0.26	70

In 2005 the recession of water was also linked to mean flux > 10 ng N_2O-N m^{-2} s^{-1}. Emission events that coincided with the disappearance of water occurred in ponds 103, 104, and 118 (Table 1). The emission event from pond 103 was much stronger than the previous year. Pond 118 had an emission event in 2005 where it did not in 2004. There was no indication of a flux event related to pond water level from pond 105 in either year. This suggests that there are differences between uncultivated wetlands in their response to conditions that lead to the production of soil N_2O. Therefore additional research is required to understand the reason for the difference between ponds such as 103 and 105. An event did not occur at pond 120 as it maintained a substantial level of standing water past the end of the field season in 2005.

The true contribution of N_2O flux from each landscape element is made clear by taking into account its aerial extent (Table 2). As per Bedard-Haughn et al. (2006) the CX elements account for the largest portion of the area of the site (14.4 ha), and thus can have a large impact on the total emissions from the research site. For example, in 2003, 10920 g N_2O-N were produced by the CX elements, which is close to 35% of the total emissions produced from the site that year (Table 2). In 2004, CX elements were a net sink for N_2O (Figure 5) reducing the total emissions (23868 g N_2O-N) by comparison to 2003 (31923 g N_2O-N) (Table 2). By contrast, the aerial extent of the BC elements (0.6 ha) contributed much less to the total emissions from the site (Table 2) even in 2005 when BC elements produced the highest cumulative emissions on a hectare basis (Figure 6). Concave elements, with an aerial extent similar to the CX elements (11.8 ha), produced the largest portion of the total emissions in each year and in terms of annual emissions are the most important landscape elements, especially in 2004 and 2005 (Table 2). The RG and RT elements, on the other hand, have small aerial extents and were not major contributors to the total emissions in any year.

Table 2: Mean cumulative N_2O flux (g N_2O-N y^{-1}) and area (ha) per landscape element across the main research site at the St. Denis National Wildlife Area for 2003, 2004 and 2005.

Landscape Elements	Area (ha)	Year 2003	2004	2005
Cultivated				
Convex	14.4	10920	-291	3289
Concave	11.8	20143	23051	19077
Uncultivated				
Riparian Grass	1.0	339	88	520
Riparian Trees	1.5	413	436	726
Basin Center	0.6	108	584	1259
Total	29.3	31923	23868	24871

Per hectare, wetland units (CV and BC) were the primary source areas for the emission events because precipitation and snow melt runoff concentrate in these positions allowing

WFPS to reach levels that are known to trigger denitrification (Lemke et al. 1998; Davidson and Verchot, 2000). The background emission pattern was distributed over the CX, RG and RT elements. At this site, the background emissions can be a significant contributor to total yearly emissions as in 2003 (Table 2), by virtue of the land area represented by the CX elements.

The distribution of cumulative flux across the site fits a general model called the event-based / background emission pattern (Brumme et al.,1999) as described in relation to the site by Yates et al. (2006). Brumme et al. (1999) describes the event-based / background emission pattern as consisting of extreme flux events that interrupt the continuous, low-level background pattern. So is the case at the St. Denis site. However, the timing of the events follow the recession of water from the ponds, and thus during 2004 and 2005, the spatial pattern of the flux events was dependent upon how much the ponds fill and in what order they dried out. In 2003 the flux events were dependent upon the CV positions and their response to precipitation. One can argue that the event-based pattern, even though it relied on the same units overall, was spatially different each year. Therefore, N_2O fluxes from this site have a long-term cycle and one or even two years of data is insufficient to describe this activity. In 2003 the ponds were dry through out the period of flux measurement. Pond water lasted until mid Aug. in 2004 and in 2005 there will be a carry over of water to the spring of 2006 in at least one pond (Table 1). Excess water from 2005 creates the potential for even higher water levels in 2006.

The importance of the CV elements to cumulative annual emission from this site suggest that best management practices designed to minimize N_2O emissions from these parts of the terrain. Such best management practices should either encourage the removal of these elements from annual crop production or discourage the introduction of existing uncultivated ephemeral wetlands into annual crop production. The reduction in cumulative emissions that measured in 2004 to that in 2005 at the CV elements may be due to the establishment of the grass cover. It is possible that cumulative emissions from these elements may continue to decrease as emissions reach a new equilibrium in response to the change in management from conventional cultivation. It does, however, seem likely that conversion of an existing UW to a CV element would increase the likelihood of emission events over the long term and increase annual cumulative emissions from this site.

Conclusions

The highest cumulative emissions over the three years of the study came from the CV and BC elements. The CV elements were an important source of soil N_2O in all three years where as the BC units were important in 2004 and dominant in 2005. Precipitation events drove flux activity in 2003, primarily from the CV elements, suggesting that such events are generally of insufficient magnitude to trigger emission events in UW units possibly because of the high porosity or lack of available N. Major emission events from UW units occurred after flooding of BC elements and recession of standing water. The longer the duration of standing water at BC elements, the higher the emissions after recession.

The spatial and temporal pattern of emissions follow an event-based / background emission pattern with CV and BC elements the sources areas for the N_2O flux events and the CX, RG and RT elements contributing the background emissions. The difference in pond water levels from year to year changed the spatial pattern of the event-based / background emissions. In 2003 the CV elements were important to the event-based pattern and in 2004 / 2005 both CV and BC elements were important; however the CV elements were important early in the season, and the BC elements later.

Taking aerial extent of landscape units into account, the CV elements were the important source areas of N_2O in all three years where as the RG, RT and BC elements were not, even with a high cumulative flux per hectare from BC elements in 2005.
The magnitude of flux activity and direction of flux from the CX elements can have a impact on the total cumulative flux across the site by virtue of the large aerial extent of this element. Management practices intended to reduce soil N_2O emissions at this site would be most effective if they are designed to decrease N_2O production from CV elements. Practices designed to reduce flux from CV elements may be effective, but not practical if it involves restoration to UW, especially if some UW units are prone to emission events. Cultivation of existing UW would likely increase the total cumulative N_2O emissions from the site.

For future measurement of fluxes from UW in these terrains it is necessary to distinguish the BC as a unit separate from the tree or grass margins of the wetland. More research may be necessary to establish if RG and RT elements need be kept separate; however, the relatively low fluxes from these units may not warrant this. Certainly, N_2O emission research in these terrains require at least three years data to account for the range in climatic conditions that lead to water level differences in the UW. Additional research in this area should be directed at discovering the reasons for differences between UW in soil N_2O flux and monitor the effect of the grass cover on cumulative emissions from CV and CX elements.

References

Agriculture and Agri-Food Canada. 1998a. The health of our air: Towards sustainable agriculture in Canada. Publication 1981/E, Research Branch, Ottawa, ON.

Bedard-Haughn, A., F. Jongbloed, J. Akkerman, A. Uijl, E. de Jong, T. Yates, D.Pennock. 2005. The effects of erosional and management history on soil organic carbon stores in ephemeral wetlands of hummocky agricultural landscapes. Geoderma. (in press).

Brumme, R., W. Borken, and S. Finke. 1999. Hierarchical control on nitrous oxide emission in forest ecosystems. Global Biogeochemical Cycles 13:1137-1148.

Davidson, E.A., and L.V. Verchot. 2000. Testing the hole in the pipe model of nitric oxide emissions from soils using the TRAGNET database. Global Biogeochemical Cycles 14:1035-1043.

Environment Canada, 2005**.** Canadian climate normals, 1971-2000. [Online] Available at http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html (verified 27 June 2005).

FAO and IFA. 2001. Global estimates of gaseous emissions of NH_3, NO and N_2O from agricultural land. International Fertilizer Industry Association and Food and Agriculture Organization of the United Nations, Rome.

Hayashi, M., G. van der Kamp, and D.L. Rudolph. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. water balance. J. Hydrol. 207:42-55.

Hogan, J.M., and F.M. Conly. 2002. St. Denis National Wildlife Area land Cover Classification: 1997. Technical Report Series No. 384, Canadian Wildlife Service, Prairie and Northern Region.

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

International Atomic Energy Agency. 1992. Manual on measurement of methane and nitrous oxide emissions from agriculture. IAEA-TECDOC-674. INIS Clearinghouse, Vienna.

Lemke, R.L., R.C. Izaurralde, and M. Nyborg. 1998. Seasonal distribution of nitrous oxide emissions from soils in the parkland region. Soil Sci. Soc. Am. J. 62:1320-1326.

Renault, P., and P. Stengel. 1994. Modeling oxygen diffusion in aggregated soils: I. anaerobiosis inside the aggregate. Soil Sci. Soc. Am. J. 58:1017-1023.

Robertson, G.P. 1989. Nitrification and denitrification in humid tropical ecosystems: potential controls on nitrogen retention. p. 55-69 *In* J. Procter (ed). Mineral nutrients in tropical forest and savanna ecosystems. Br. Ecol. Soc. Spec. Publ. no. 9. Blackwell Scientific, Oxford, UK.

van der Kamp, G., W.J. Stolte, and R.B. Clark. 1999. Drying out of small prairie wetlands after conversion of their catchments from cultivation to permanent brome grass. Hydrological Sciences Journal 44:387-397.

Yates, T., B. Si, R. Farrell, and D. Pennock. 2005a. Probability distribution and spatial dependence of N_2O emission: temporal change in a hummocky terrain. Soil Sci. Soc. Am. J. 70:753-762