Regional-scale Quantification of Nitrous oxide Emission

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ABSTRACT

The increasing atmospheric N_2O concentration and the imbalance in the budget of its global sources and sinks create the need for detailed investigations on N_2O emissions at scales relevant to atmospheric chemistry. This study was conducted to determine the spatial patterns and seasonal fluctuations of N_2O emission, and to quantify N20 emission activity at the landscape and regional scales. An area of the Black soil zone of central Saskatchewan was stratified into three main textural areas: clay loam, fine sandy loam, and sandy areas. Within each area, representative sites were selected in different land uses: unfertilized- and fertilized-cropped sites, fallow, pasture, and forest sites. A consistent landscape-scale pattern of N20 emission was observed: footslope positions had higher N20 fluxes than shoulder positions. Pulses of activity were observed in spring and in summer after rainfall events following N-fertilizer application. The spatial and temporal patterns of N_2O emission were controlled largely by hydrologic processes which, in turn, were influenced by precipitation and topography. At the regional scale, the sandy area had lower N_2O emissions than the fine-textured areas. The general order of N20 evolved among the land uses was: forest < pasture < fallow = unfertilized-cropped < fertilized-cropped sites. The average regional N20 flux, weighted by the areal extent of the different soil landscape systems in the region, was 170 g N_2O-N ha-1 yr^{-1}.

INTRODUCTION

Interest in quantifying N_2O flux rates from various ecosystems has been stimulated by the finding that the atmospheric N20 concentration has increased since monitoring began in the 1970s (Khalil and Rasmussen, 1992). Analysis of the global N20 budget (Vitousek, 1994) also presented the need for detailed investigations, as the estimates of global sources are 30 % lower than the estimates of global sinks. Reliable estimates are critical for the development of approaches to regulate sources of N_2O. Data on N_2O emission are particularly scanty from ecosystems whose emissions are not significant to N budgets (i.e., semi-arid boreal region). However, such data may be important in defining global balances.

The major sink for N_2O is photolysis in the stratosphere, leading to N oxide products which influence levels of stratospheric ozone. It also absorbs the infrared energy reradiating from the Earth's surface, and contributes approximately 5 % of the global warming potential in the greenhouse effect assessments. Its lifetime of 150 years suggests that the effects of the present N20 loading rate (0.25% yr-I) will be long-lasting (Duxbury et al., 1993).

Nitrous oxide is produced mainly by nitrification and denitrification under conditions of low 02 availability. The complexity of the interacting factors important to these processes results in high degree of spatial and temporal variability of N20 emission activity (Mosier et al., 1983). High variability is found at small scales, within experimental units and between sites which vary in vegetation, soil properties, or water balance. Groffman (1991) argued that increasing the scale of investigation in both time (seasonal rather than daily) and space (landscape scale rather than field scale) appears to be useful in overcoming the variability problem. At the landscape scale, it is essential to select meaningful sampling units ("field" units) that would characterize the range of conditions within a landscape. The landscapes are, in turn, the sampling units at the regional scale.

Recent studies in Saskatchewan, Canada have analyzed the spatial patterns of denitrification and how these patterns interact with soil water, N, and C dynamics in the landscape (Elliott and de Jong, 1992; Pennock et al., 1992; Van Kessel et al., 1993). Data from these studies suggest the presence of distinct controls on denitrification in this region, and that evaluation of the spatial pattern of these controls could be used to extrapolate N20 emission activity from landscape to regional scale.

For our study, we hypothesized that geomorphology and land use should be strong controllers of N20 emission at the landscape and regional scale. The physical nature of the geomorphic deposits likely influences N20 emission activity through its control on differences in soil texture in the region. Land use is often strongly related to nitrogen availability (Groffman, 1991); differences in land use should also exhibit differences in N20 emission. Hence, the region was stratified based on geomorphology and land use, and N20 emission was investigated in soil landscape systems chosen as representative units in the region. Our objectives were (i) to determine the spatial patterns and seasonal fluctuations of N_2O emission in different soil landscape systems, (ii) to infer the linking relationship between large-scale/distal controllers and microbial/proximal factors of N20 emission, and (iii) to quantify N_2O emission activity at the landscape and regional scales.

MATERIALS AND METHODS

Research Design

The initial stage of the research was to stratify the region into representative units based on geomorphological characteristics (mainly by soil texture) and land use. The delineated region (64 km x 74 km) was located in the Black soil zone with its center near St. Louis, Saskatchewan, Canada (105° 45' W, 53" 1' N). The region was stratified into three main textural areas: moderately fine to fine (represented by a clay loam area), medium (represented by an area of fine sandy loam overlying clay loam), and sandy. Hereafter, the first two areas will be referred to as clay loam and fine sandy loam areas, respectively. At each area, representative sites depicting different land use conditions were selected. To assess the seasonal pattern of N20 emission, sufficient frequency of sampling had to be undertaken to characterize the rate of the process under different environmental conditions throughout the years of study (Table 1).

Landscape-scale Sampling Scheme and Site Description

All sites were characterized as having a hummocky surface form with complex sequence of slopes extended from rounded depressions to conical knolls. A systematic grid design was employed to quantitatively derive the spatial sampling units within each study site, similar to the method employed by Van Kessel et al. (1993). Two landform complexes were chosen as the spatial sampling units of interest at each site: shoulder and footslope complexes. On each landform complex, at least ten grid points were randomly chosen to serve as the sampling points.

In the clay loam area, three sites were selected in 1993: fallow and cropped sites on a long-term cropped field, and a pasture site which has been converted to pasture twenty years previously. The fallow site was summer fallowed from July 1993 until April 1994. The cropped site was seeded to unfertilized canola ***(Brassica campestris)*** and fertilized wheat ***(Triticum vulgare) in*** 1993 and 1994, respectively. The inclusion of an unfertilized field in the beginning of the study was intended to provide base line information of its N_2O emission activity for comparison to fertilized fields. In 1994, fertilizers were applied at 28 kg N ha^{-1} as anhydrous ammonia at seeding (May 11) and 57 kg N ha-l as urea at seedling stage (June 10). In the pasture site, the shoulder complex was dominated mainly by smooth bromegrass ***(Bromus inermis)*** while the footslope complex included an uncleared area occupied by aspen (Populus ***tremuloides).***

In the fine sandy loam area, N20 emissions were measured in a site seeded to fertilized canola beginning on 18 May 1994. Anhydrous ammonia was applied (62 kg N ha^{-1}) at seeding (15 June 1994). In the sandy area, N20 emissions were measured beginning on 30 June 1994 at three sites: cropped, pasture, and forest sites. The cropped site was seeded to fertilized oat ***(Avena sativa).*** A rate of 45 kg N ha-l as arnmonium sulfate was applied at seeding (10 June 1994). The pasture site had a seeded alfalfa ***(Medicago sativa)*** cover and the forest site had a continuous aspen cover.

N_2O Flux Measurement

Direct in-field measurement of N20 emission was carried out using a sealed chamber method. At each selected grid point, a sealed chamber was inserted into the surface of the soil.

Table 1. Dates of N20 emission measurements at each site.

Sampling dates	sampling code number†	Clay loam			Fine sandy loam	Sandy		
		Cropped	Fallow	Pasture	Cropped	Cropped	Pasture	Forest
1993								
17 May	1	x						
28 May	2			x				
12 June	3	x						
13 June	4	x						
14 June	5	x						
15 June	6	x						
26 June	7	x		x				
27 June	8	x		x				
6 July	9	x		x				
7 July	10	x	x					
19 August	11	x	x					
21 October	12	x	x	x				
25 November	13	x	x	x				
1994								
17 March	14	x	x	x				
24 March	15	x	x	x				
29 March	16	x	x	x				
5 April	17	x	x	x				
9 April	18	x	x	x				
18 April	19	x	x	x				
25 April	20	x	x	x				
18 May	21	x		x	x			
23 May	22	x		x	x			
14 June	23	x		x	x			
16 June	24	x		x	x			
30 June	25	x		x-fs ‡	x	x	x	x-fs
8 July	26	x		x-fs	x	x	x-fs	x
19 July	27	x		x	x	x	x-fs	x-fs
30 July	28	x		x-fs	x	x	x	x-fs
8 August	29	x		x-fs	x	x	x-fs	x
18 August	30	x		x	x	x	x-fs	x-fs
29 August	31	x		x-fs	x	x	x	x-fs
20 September	32	x		x	x	x	x-fs	x-fs
4 October	33	x		x-fs	x	x	x	x-fs
8 November	34	x		x-fs	x	x	x	x-fs
1995								
14 March	35	x		x	x	x	x	x
21 March	36	x		x	x	x	x	x
13 April	37	x		x	x	x	x	x
18 April	38	x		x	x	x	x	x
21 April	39	x		x	x	x	x	x
26 April	40	x		x	x	x	x	x
3 May	41	x		x	x	x	x	x
12 May	42	x		x	x	x	x	x
19 May	43	x		x	x	x	x	x

† These numbers are indicated on the figures showing the N_2O emission activity at each site.

‡ N20 emission was measured only on the footslope complex.

Gas samples were withdrawn through the injection port using a 15-mL syringe, stored in 20-mL vacutainers (pre-evacuated to 40 Pa), and transported to the laboratory for analysis.

The vertical N20 flux density above the soil was determined by measuring the increase in N_2O concentration beneath the sealed chambers at 0, 2, and 4 h of trapping and by using the estimation model established by Hutchinson and Mosier (198 1):

$$\text{N20 flux} = \frac{V\,(C_1 - C_0)^2}{A\,t_1(2C_1 - C_2 - C_0)}\ \text{In}\ \frac{(C_1 - C_o)}{(C_2 - C_l)}$$

$$\text{fort2} = 2t_1 \text{ and } \frac{(C_1 - C_0)}{(C_2 - C_l)} > 1$$

where V is the volume of enclosed air, A is the area of soil covered, C_0 is the initial N_2O concentration, and Cl and C2 are the N20 concentrations after t_1 and t2 (t2 = 2 tl).

RESULTS AND DISCUSSION

Spatial Patterns and Seasonal Fluctuations of N_2O Emission

Our results showed that distinct N20 emission activities were associated with each landform complex, except in the clay loam-pasture and sandy-forest sites. In the sites where significant spatial pattern was observed, higher N20 emissions had occurred on the footslope than on the shoulder complex (Figs. 1A, 1B, 1C, 2A, 2B, and 3). This spatial pattern remained consistent across the seasons regardless of the magnitude of N20 emission activity. The role of topography is attributed to its strong influence on the hydrologic and pedologic processes in the landscape which, in turn, regulate the soil factors directly controlling the process at the microbial level. The lower N_2O emission activity associated with the shoulder compared to the footslope complex reflects the influence of topographically-induced water redistribution and better internal drainage condition of the soils on the upper than on the lower landscape positions. This was shown clearly by the parallel spatial patterns of N20 emissions and soil moisture contents (i.e., clay loam cropped site; Figs. 1A-B, and 4). Our results showed that in an area of similar geomorphological characteristics and vegetation type, topography is the basic factor controlling the spatial variability of N_2O emission at the landscape level.

In the sandy-forest site, the spatial pattern of N_2O emission was not statistically distinct because this site had low activity regardless of topographical position in the landscape (Fig. 2C). On the other hand, the absence of a statistically-distinct topographic response in the clay loam-pasture site could be attributed to the difference in vegetation between the landform complexes. The shoulder and footslope complexes were dominated by bromegrass and aspen, respectively. Spatial variation in N and C dynamics has been related to differences of vegetation in the landscape (Smith et al., 1994). It is likely that in our study the N_2O-producing process(es), regulated by the availability of N and C, was also affected by the difference in vegetation. The response to vegetation difference might have confounded the topography-related effects resulting to an indistinct spatial pattern.

Generally, N20 emissions increased towards the early summer (Figs. 1 to 3), which corresponded with the occurrence of frequent and high rainfall events. For the fertilized-cropped sites, application of N fertilizer itself did not enhance N20 emission (i.e., first N application; Fig. 1B), but N fertilization followed by rainfall triggered N20 emission (i.e., application in June 1994; Figs. 1B, 2A, and 3). Similar results were obtained in other studies (Van Kessel et al., 1993). Nitrogen fertilization followed by rainfall increased N_2O emissions due to the increase in N availability (particularly NO_3^-) and anaerobiosis in the soil. For the uncultivated/unfertilized sites, considerable N20 fluxes were also observed following periods of heavy rainfall during the summer (Figs. 1D, 2B, and 2C). The N20 emission activity then decreased towards the end of summer and virtually ceased by the onset of frost in the fall (Figs. 1 to 3). This undoubtedly reflects the decrease in soil moisture which might have reduced the microbial production of N20.

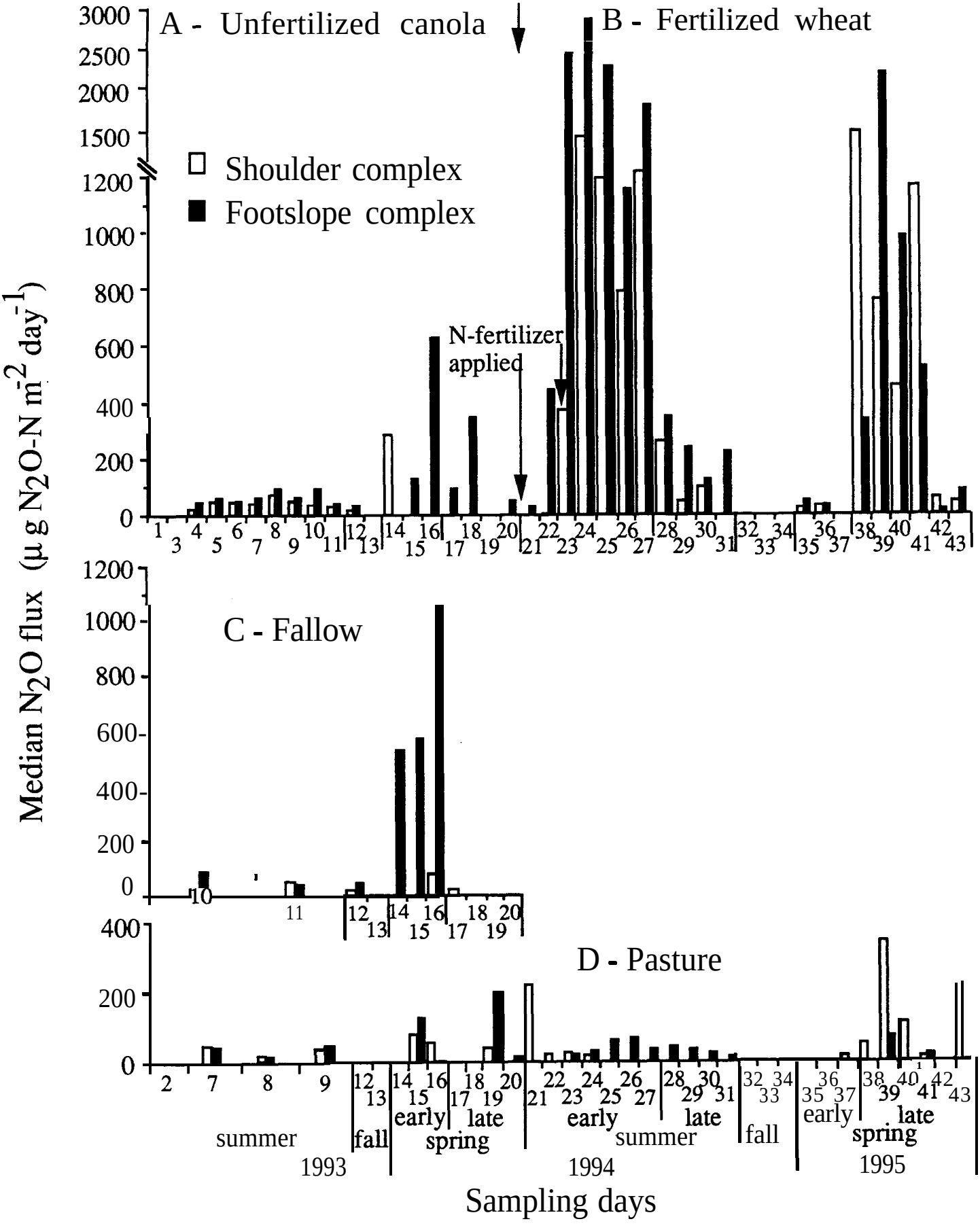

Fig. 1. Spatial and temporal patterns of N_2O emissions in the clay loam area. Numbers on the X-axes indicate the codes of the sampling dates.

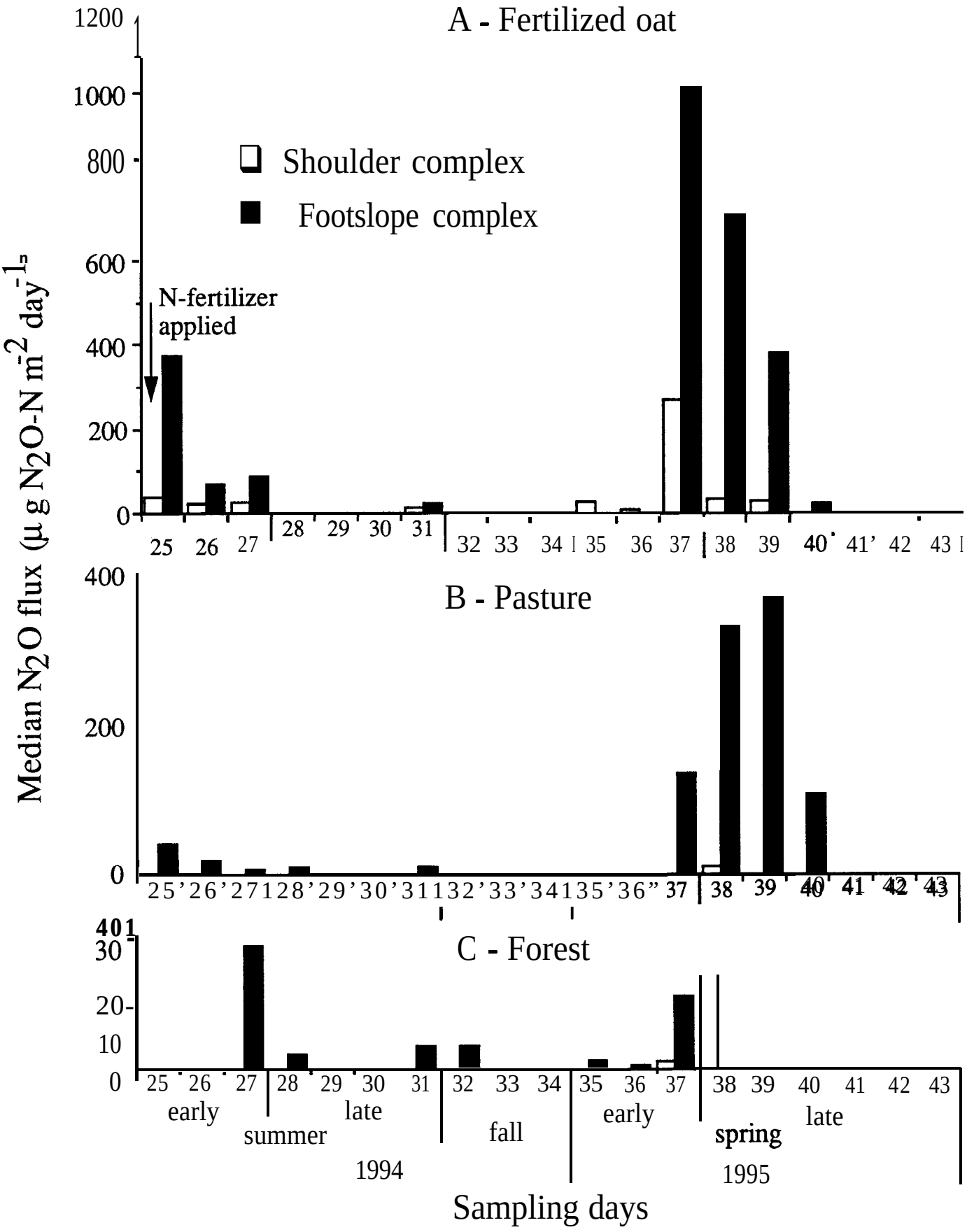

Fig. 2. Spatial and temporal patterns of N20 emissions in the sandy area. Numbers on the X-axes indicate the codes of the sampling dates.

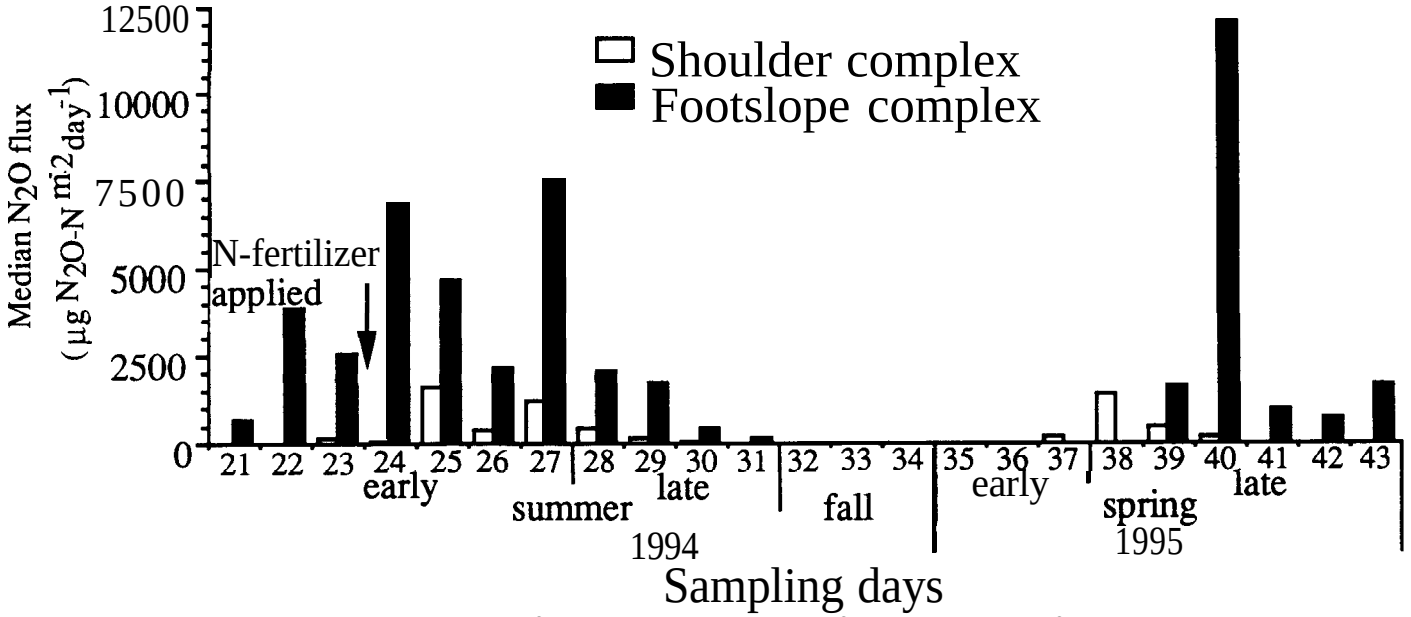

Fig. 3. Spatial and temporal patterns of N_2O emissions in the fine sandy loam-fertilized canola site. Numbers on the X-axis indicate the codes of the sampling dates.

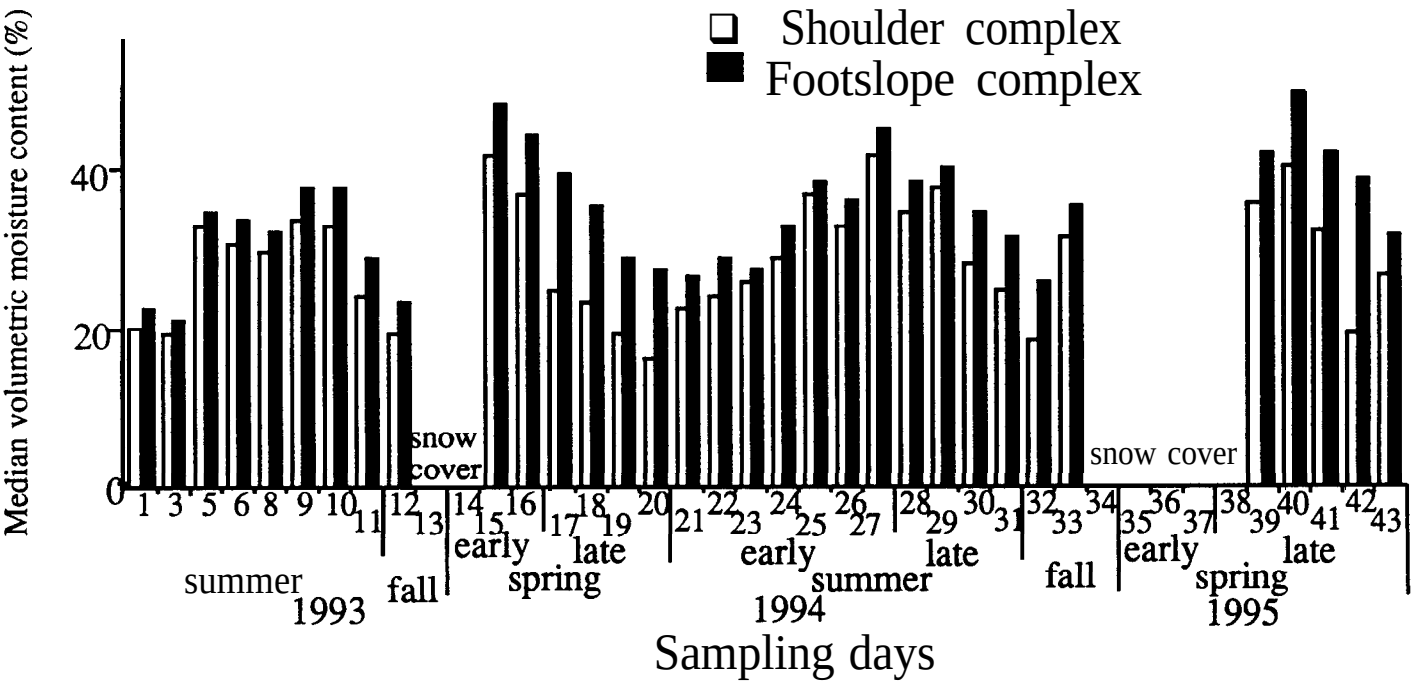

Fig. 4. Spatial and seasonal patterns of soil moisture content in the clay loam -cropped site. Numbers on the X-axis indicate the codes of the sampling dates for N_2O emission.

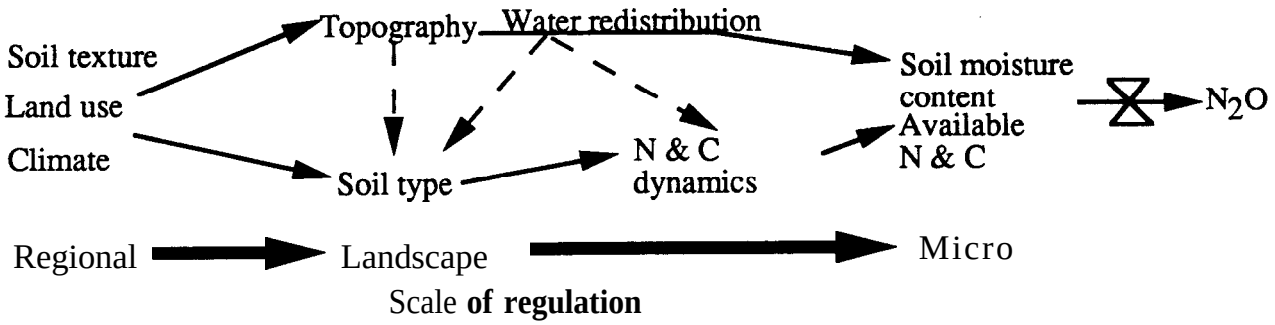

Fig. 5. Conceptual links between large-scale controllers and proximal factors of N_2O emission.

Like the spatial pattern, the temporal pattern of N_2O emissions closely paralleled the patterns of soil moisture contents (i.e., clay loam cropped site; Figs. 1A-B, and 4).

Although the soil temperatures were still near freezing, large pulse of N_2O emission activity was observed during the spring thaw (Figs. 1 to 3). The spring pulse of activity has been attributed primarily to high soil moisture (Groffman et al., 1993a). High N and C availability also occurred in spring due to low plant activity, and lysis of microbial cells as a result of freezing and thawing (Groffman and Tiedje, 1989). High N_2O emissions during spring thaw can also result from changes in solubility of N_2O, production of N_2O near the soil surface, and diffusion from depth of accumulated N_2O during winter (Burton and Beauchamp, 1994). In our study, soil moisture, and available N and C were higher in spring than in summer and fall. The relatively low temperatures during the early spring may also have hindered the further reduction of N_2O to N_2 in the denitrification series, and resulted in a higher N_2O/N_2 ratio in spring than in summer. Conditions during the early spring clearly had an important effect on annual budget of N_2O emissions from this region.

Controls on N_2O Emission

To address the significance of N_2O emission to regional atmospheric chemistry, a conceptual basis for linking the relationships between large-scale controllers and proximal factors of N_2O emission is necessary (Fig. 5). Understanding the factors that influence the variation of N_2O emission within the landscape and across the region provide a means of extrapolating the information to a regional scale. This study showed that the most important proximal control of N_2O emission is the soil moisture content, which likely regulated the soil aeration status. Certainly, the parallel spatial and temporal patterns of N_2O emissions and soil moisture contents would support this argument. Similar results were obtained in other studies conducted in semi-arid ecosystems, which showed that dynamics of soil water potential is the primary factor controlling N cycling processes (Smith et al., 1994). When soil moisture was favorable, N and C availability became important. Depending on the dominant N_2O-producing process(es) that occurred (denitrification and/or nitrification), the interaction of these factors at the microscale level would determine the magnitude of N_2O evolved. The hierarchy of importance of these factors was similar in other studies conducted at the landscape scale (Van Kessel et al., 1993). These factors are, in turn, influenced by topography. Earlier studies showed that soil-slope associations occur because of the influence of hillslope morphology on the surface and subsurface water movement (Pennock et al., 1987). These topography-related differences in soil and moisture distribution in the landscape have also been shown to influence the spatial variation in soil N and C cycling processes (Groffman et al., 1993b). The distinct spatial pattern of N_2O emissions observed in this study assessed that our spatial sampling scheme accounted for the variation of soil characteristics and moisture redistribution in the landscape.

In this study, we used soil texture as the geomorphological attribute in stratifying the region because aside from being an indicator of the distribution of the parent sediments in the region, this relates to the differences of soil moisture regimes in the area as well. Comparison of N_2O emissions among the textural areas showed that the sandy area had lower activity than the fine-textured areas. Furthermore, the different land. uses also differed in N_2O emissions. The general order of N_2O evolved among the land uses was: forest $<$ pasture $<$ fallow $\approx$ unfertilized-cropped $<$ fertilized-cropped sites. The low N_2O emissions in the forest and pasture sites reflected the tight and conservative N cycling in uncultivated ecosystems (Smith et al., 1994). The high N_2O emissions in the cropped sites were due the application of N fertilizers. However, it should be pointed out that among the cropped sites the effect of fertilization on N_2O emission was only favored in areas with high moisture retention capacity. This was showed by the lower N_2O emissions of the sandy cropped site. Groffman et al. (1993a) stated that the ecological or large-scale controls of N_2O emission may vary from region to region depending on the geomorphic process(es) that contributed to the differences of soils in an area. In this glaciated region, soil

texture and land use proved to be useful integrative variables for extrapolating N20 fluxes to a regional scale.

Annual and Regional Estimates of N_2O Flux

Annual estimates of N_2O flux for each landscape type are summarized in Table 2. The landscape-scale estimates was calculated by using the median N20 fluxes reported at each sampling day, and following a trapezoidal quadrature method for temporal interpolation of fluxes. Only the days with rainfall event $\geq$ 5 mm were consider for the interpolation. Ancillary data collected during the study revealed that the minimum rainfall level of which detectable N_2O emission activity occurred was 5 mm. The landscape-scale estimates were further weighted by the areal coverage of the two landscape positions in a particular site.

Estimates of the annual N_2O emission in the fallow and unfertilized-cropped sites were 10 % of the emissions in the fertilized-cropped sites. In the fertilized-cropped sites, the emitted N20 represents a loss of < 1 % of the applied N. From agronomic point of view, the N_2O loss from this area is not important. However, considering the total emission from this relatively small region in the Black soil zone, the data suggest considerable importance to regional atmospheric chemistry. The cropped area contributed 94 % of the total regional emission. If we assumed that the proportions of the area covered by the different soil landscapes in our study region are representative of the Black soil zone in Saskatchewan, the average annual flux for this soil zone is 170 $g\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$.

Table 2. Estimates of N_2O emission at the landscape and regional scales.

	landscape-scale ($g\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$)	area† (10^2 ha)	regional-scale ($Mg\ N_2O\text{-}N\ yr^{-1}$)	weighted average ($g\ N_2O\text{-}N\ ha^{-1}\ yr^{-1}$)
Cropland	310	2187	68	160
mod. fine - fine	510	830	42	100
medium	230	991	23	50
sandy	90	366	3	10
Pasture	25	782	**2**	**4**
Forest	20	1352	**3**	**6**
Regional estimate		4321	73	170

† Determined from a geographic image of combined soil texture and land use data. Information on soil texture was taken from GIS data, while the land uses were characterized from a LANDSAT thematic mapper data.

CONCLUSIONS

The mechanisms responsible for N_2O evolution are a combination of environmental and soil factors. It was clear that soil moisture was the most important factor controlling N20 emission. At the landscape scale, soil moisture content was, in turn, influenced by topography, and on the seasonal scale, it was affected by climatic factor(s) (i.e., precipitation). As a consequence consistent spatial pattern of N20 emission was observed. Nitrogen fertilization during high-rainfall summer months and spring pulse of activity also showed significant contributions to annual N_2O emissions. Management strategies that favor N retention processes during these periods will likely reduce N_2O emission from this region.

The differences in N20 emissions among the textural areas and land uses signified the appropriateness of stratifying a region based on ecological factors that are proven to influence dynamics of N cycling at a large scale. The approach presented here of extrapolating N_2O fluxes from landscape to regional scale is not new but, rather, is rooted in systems analysis and hierarchy theory (O'Neill, 1988). The choice of variables for integrating N_2O emission at different scales of

investigation was guided by mechanistic understanding of the factors governing the process. The regional estimate of 170 g N_2O-N ha^{-1} yr^{-1} suggests considerable importance to regional atmospheric chemistry and to defining the global balance of N20, because of the relatively large area that the Black soil zone occupies. In addition, as the highest N_2O emission in this region was observed in the cropped area, further refinement of the regional estimate could be achieved by considering different agricultural production systems to encompass their differences in the extent of N fertilization. The approach used in this study might also aid in improving research tools for those attempting to quantify regional-level nutrient fluxes or storage.

ACKNOWLEDGMENTS

The financial support of this study was provided by Agriculture and Agri - Food Canada (AAFC) Greenhouse Gas and Climate Change Initiatives. The technical assistance of K. Elliott, Dr. F. Walley, R. Anderson, C. Wong, Q. Chen, and G. Parry is greatly appreciated. The cooperation of the farmers and P. Flaten together with the Conservation Learning Center, AAFC, is also recognized.

REFERENCES

Burton, D.L., and E.G. Beauchamp. 1994. Profile nitrous oxide and carbon dioxide concentrations in a soil subject to freezing. Soil Sci. Soc. Am. J. 58: 115-122.

Duxbury, J.M., L.A. Harper, and A.R. Mosier. 1993. Contributions of agroecosystems to global climate change. p. 1-18. In L.A. Harper et al. (ed.) Agricultural ecosystem effects on trace gases and global climate change. ASA Spec. Publ. 55. ASA, CSSA, and SSSA, Madison, WI.

Elliott, J.A., and E. de Jong. 1992. Quantifying denitrification on a field scale in hummocky terrain. Can. J. Soil Sci. 72:21-29.

Groffman, P.M. 1991. Ecology of nitrification and denitrification in soil evaluated at scales relevant to atmospheric chemistry. p. 201-217. In J.E. Rogers and W.B. Whitman (ed.) Microbial production and consumption of greenhouse gases: Methane, nitrogen oxides, and halomethanes. Am. Soc. Microbiol., Washington, DC.

Groffman, P.M., and J.M. Tiedje. 1989. Denitrification in north temperate forest soils: Spatial and temporal patterns at the landscape and seasonal scales. Soil Biol. Biochem. 21:613-620.

Groffman, P.M., C.W. Rice, and J.M. Tiedje. 1993a. Denitrification in a tallgrass prairie landscape. Ecology 74:855-862.

Groffman, P.M., D.R. Zak, S. Christensen, A.R. Mosier, and J.M. Tiedje. 1993b. Early spring nitrogen dynamics in a temperate forest landscape. Ecology 74: 1579- 1585.

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.

Khalil, M.A.K., and R.A. Rasmussen. 1992. The global sources of nitrous oxide. J. Geophys. Res. 97:14651-14660.

Mosier, A.R., W.J. Parton, and G.L. Hutchinson (1983). Modeling nitrous oxide evolution from cropped and native soils. In R. Hallberg (ed.) Ecol. Bull. Stockholm 35:229-241.

O'Neill, R.V. 1988. Hierarchy theory and global change. In T. Rosswall et al. (eds.) Scales and global change. SCOPE. John Willey and Sons Ltd., New York.

Pennock, D.J., B.J. Zebarth, and E. de Jong. 1987. Landform classification and soil distribution in humrnocky terrain, Saskatchewan, Canada. Geoderma 40:297-315.

Pennock, D.J., C. van Kessel, R.E. Farrell, and R.A. Sutherland. 1992. Landscape-scale variations in denitrification. Soil Sci. Soc. Am. J. 56:770-776.

Smith, J.L., J.J. Halvorson, and H. Bolton Jr. 1994. Spatial relationships of soil microbial biomass and C and N mineralization in a semi-arid shrub-steppe ecosystem. Soil Biol. Biochem. 26:1151-l 159.

Van Kessel, C., D.J. Pennock, and R.E. Farrell. 1993. Seasonal variations in denitrification and nitrous oxide evolution at the landscape scale. Soil Sci. Soc. Am. J. 57:988-995.

Vitousek, P.M. 1994. Beyond global warming: Ecology and global change. Ecology 75:1861-1876.