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Gaseous Nitrogen Losses from Soils Under Zero-Till as Compared with Conventional-Till Management Systems[1]

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ABSTRACT

The gaseous losses of N from conventional-till (CT) and zero-till (ZT) crop fields were 3 to 7 and 12 to 16 kg N ha^{-1} y^{-1}, respectively. In contrast, losses from CT and ZT fallow were severalfold higher, namely, 12 to 14 and 34 kg N ha^{-1}, respectively. The more dense surface soil and consistently higher moisture content (lower air-filled porosity) were identified as major factors affecting increased denitrification under ZT. The potential denitrification rates were markedly higher under ZT, and the population of denitrifiers was up to six times higher than in CT soil samples.

The contribution of lower soil horizons towards gaseous N losses was found to be low on both CT and ZT fields, and this finding was confirmed from a survey carried out on three other widely differing soils.

Volumetric soil moisture and air temperature were the only two of several factors that accounted for a significant portion of the variations in gaseous N fluxes under field conditions.

The average mole fraction of N_2O ranged from almost 100% to as low as 28% of the total gaseous products and showed a negative relationship with soil moisture.

Additional Index Words: **acetylene inhibition technique, denitrification, nitrification, potential denitrification rates, soil moisture, mineral N.**

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There is a growing interest in the use of simplified cultivation systems such as zero-till (ZT), primarily because the possibility of wind and water erosion are very substantially reduced. In addition, ZT has been shown to be significantly more water efficient and may make it possible to reduce production costs due to lower inputs of fuel and labor (20).

The lack of soil disturbance in ZT systems leads to a reduction in large pores (17), reduced aeration (11, 19), more root growth near the surface (12), larger but less aerobic soil aggregates (14), and a significant increase in microbial biomass near the surface (8). While studying soil microbial and biochemical changes due to long-term reduced tillage at seven United States locations, Doran (10) found that the population of denitrifiers was 7.3 times higher in the surface of ZT than in the surface of plowed soils. However, quantitative field data on gaseous N losses have been limited because of the unavailability of techniques for directly measuring gaseous N losses under field conditions. The development and use of the acetylene inhibition technique (4, 29) has made it possible to quantify gaseous N losses from field soils (1, 2, 3).

Although the total amount of N lost as gases is important to the agricultural industry, N_2O may thus in-

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Table 1—Important characteristics of Elstow Orthic Dark Brown soils (Typic Haploborolls) of the fields used for experiments.

Horizon	Depth	Texture	Organic C†	Saturation paste pH	E. Ce.‡	Saturation moisture	Total N	Bulk density§	Moisture at kPa			
									33¶	100¶	300¶	1500#
	cm		g kg^{-1}		dS m^{-1}	g kg^{-1}		Mg m^{-3}	g kg^{-1}			
Conventional-tilled field:												
A	0–15	cl	30.1	7.1	0.39	620	2.5	1.03 ± 0.05	233 ± 4	228 ± 5	205 ± 11	152
B	15–28	cl	11.7	7.1	0.41	460	1.3	1.24 ± 0.17	228 ± 23	213 ± 21	204 ± 19	137
C	28+	c	5.2	7.4	0.85	605	0.7	1.18 ± 0.19	237 ± 12	218 ± 15	202 ± 12	140
Zero-tilled field:												
A	0–15	cl	28.5	7.7	0.37	630	2.6	1.25 ± 0.06	224 ± 41	220 ± 39	200 ± 31	149
B	15–29	cl	12.1	7.9	0.50	580	1.4	1.26 ± 0.15	254 ± 44	246 ± 39	220 ± 23	150
C	29+	c	5.1	7.8	0.97	750	0.6	1.19 ± 0.15	285 ± 4	263 ± 2	232 ± 2	143

† Organic C determined by improved dry combustion method (27).
‡ Electrical conductivity of the saturation extract.
§ Mean of eight replicates taken from cropped fields.
¶ Means of four undisturbed cores [5 cm (i.d.) by 5 cm long].
# Measured on disturbed soil samples.

directly contribute to health hazards including skin cancer due to the catalytic destruction of the stratospheric ozone layer (9). Therefore, it is of significance to assess the mole fraction of N_2O in gaseous N products.

In the present 2 y investigation, we have measured gaseous losses from soils under wheat-wheat (W-W), and wheat-fallow (W-F) rotations in ZT and conventional-till (CT) farming systems. Three different soils from widely scattered locations in Saskatchewan were also sampled to study the contribution of lower soil horizons towards gaseous N losses. The measurement of N_2O emissions with and without acetylene made it possible to calculate the mole fraction of N_2O in the total gaseous N products.

MATERIALS AND METHODS

The CT and ZT experimental field plots were set out in 1978 by the Saskatchewan Wheat Pool at their Watrous Research Farm. Some of the properties of the Elstow Dark Brown Chernozemic soil (Typic Haploboroll) in which the field plots were established, are given in Table 1. In May 1980, both CT and ZT fields were seeded to wheat with 75 kg N ha^{-1} (urea) applied in November 1979. The other half of the CT field [under fallow-wheat (F-W) rotation] was fallowed in 1980 and seeded to wheat in the spring of 1981 without any application of fertilizer N (as it had accumulated sufficient N during fallowing). In the spring of 1981, one-half of the ZT field, i.e., under W-W rotation was reseeded to wheat, with an application of 45 kg N ha^{-1} in the previous fall (December 1980), whereas the other half (W-F field) was fallowed. Weeds were controlled on the CT fallow fields with frequent cultivation; the ZT fallow field was sprayed with herbicides.

The procedure used for the selection and design of sampling sites for weekly removal of undisturbed soil cores from the larger experimental fields have been reported earlier (1). Gaseous N losses were measured by removing two undisturbed soil cores from each of the four or three earlier selected replicate areas using 6 cm (i.d.) by 15 cm long slotted aluminum cylinders. The soil contained in the cylinders was placed in individual jars together with a glass vial containing 2 mL of 2*M* NaOH (to absorb CO_2). Each jar was then sealed, and 0.05 m^3 m^{-3} C_2H_2 (purified by passing through deionized distilled water) was injected into one of the duplicate jars after first removing an equal amount of air and were incubated in ambient temperatures, as described earlier (1). After a 24-h period a 1 cm^3 gas sample was withdrawn from each jar, and the N_2O concentration was measured using a 5710-A HP-chromatograph equipped with a ^{63}Ni electron-capture detector and 0.20 cm (i.d.) by 245 cm long Porapak Q column. The operating temperature for the detector and column was 250 and 67°C, respectively. The data were corrected for the solubility of N_2O in the soil water (21).

Although concern has been expressed about the use of the acetylene inhibition technique for measurement of gaseous N losses under field or laboratory conditions, this technique has been validated by comparing it with the loss of ^{15}N-labeled NO_3^--N from an anaerobic soil system (22) and by ^{15}N measurements in a soil-water slurry (24). Similarly, the stoichiometric conversion of $^{15}NO_3^-$-N to $^{15}N_2O$-N has been reported and it has been shown that no change in the overall soil microbial activity (respiration) occurs due to C_2H_2 (23, 29). These observations thus indicate that the presence of very small amounts of acetone in commercially available C_2H_2 cylinders if any left after passing through distilled water, should not affect the measured denitrification activity, as proposed by Gross et al.[3] Furthermore, our recent field studies have shown that the cumulative gaseous N losses measured by the acetylene inhibition soil core technique agree very closely with the amount of unaccounted fertilizer N in ^{15}N-balance studies, when losses were relatively low (2) as well as when losses were high.[4]

For procedures used to determine soil moisture, (NO_3^- + NO_2^-)-N, and soil and air temperatures, the reader is referred to our earlier publication (1). Rainfall data were recorded at a meteorological station on the farm site.

The contribution of lower soil horizons to gaseous N losses was studied by taking soil cores from A, B, and C horizons of each field three times during April and May 1982. In addition, in mid-June 1982, gaseous N losses were measured from A, B, and C horizon samples of three widely divergent soils located along a 400 km north-south transect (Table 4). The total gaseous N losses were estimated from the higher values of N_2O evolved in the presence or absence of C_2H_2, as described earlier (1). Thus, N_2O-N values plotted in Fig. 1 and 2 include the contribution of nitrification towards N_2O evolution.

The potential denitrification rate (PDR) and denitrifier counts were determined on field moist samples (4.5-mm sieved samples) using the soil slurry method (25), and the "most probable number" technique (26, 28) as described earlier (2).

The mole fraction of N_2O in total gaseous N products, which is important in assessing the sources and quantity of N_2O, was calculated as follows (15):

$$\text{Mole fraction } N_2O = \frac{N_2O\text{-N}}{(N_2O + N_2)\text{-N}} = \frac{N_2O \text{ in absence of } C_2H_2}{N_2O \text{ in presence of } C_2H_2}.$$

In those cases where the major source of N_2O emission was nitrification and the N_2O-N values were higher in the absence of C_2H_2 than in its presence, the mole fraction of N_2O was taken as unity.

RESULTS AND DISCUSSION

Gaseous N Losses

Gaseous N losses ranged almost 10-fold (Table 2) with the lowest recorded for CT seeded to wheat and the highest for ZT fallow. Losses were substantially higher

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[3] P. J. Gross, J. M. Bremner, and A. M. Blackmer. 1982. A source of error in measurement of denitrification by the acetylene blockage method. Agron. Abstr. 1982. p. 188.

[4] M. S. Aulakh, and D. A. Rennie. 1983. The influence of nitrogen-immobilization on denitrification rates in conventional and zero till soils. Agron. Abst. 1983. p. 152.

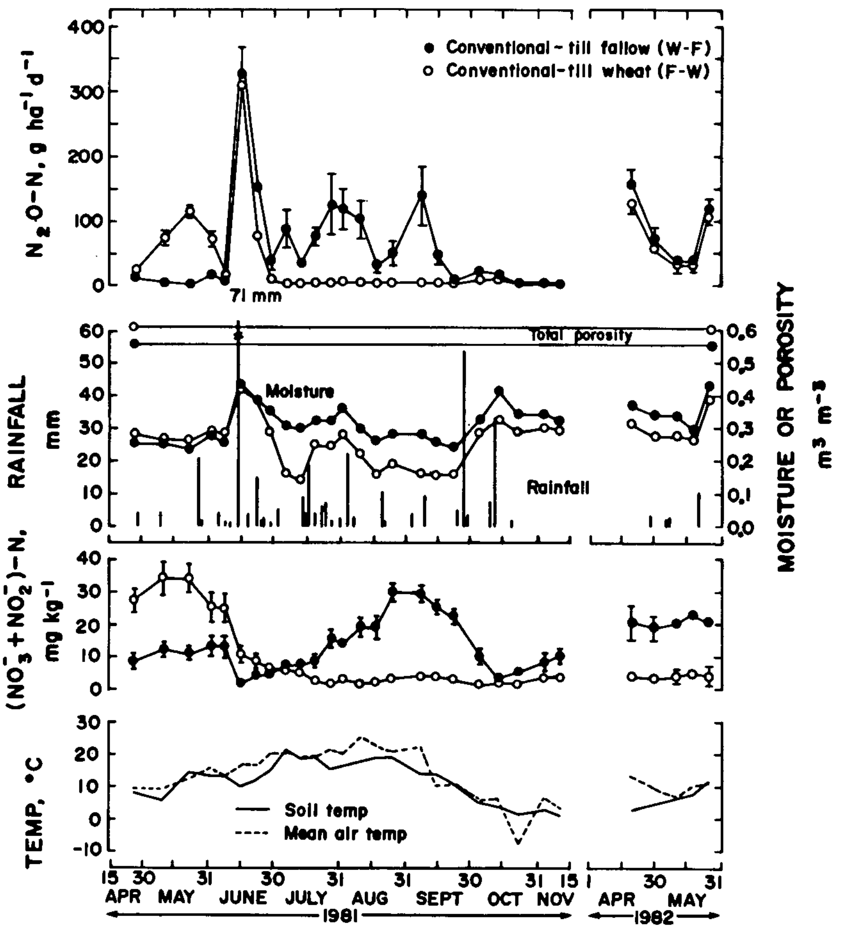

Fig. 1—Gaseous N loss (N_2O-N), soil moisture, rainfall, (NO_3^- + NO_2^-)-N, and air and soil temperature of Elstow clay loam under conventional-till wheat-fallow (W-F) and fallow-wheat (F-W) rotations for the period April 1981–May 1982. Φ indicates standard deviation.

under ZT. The data for 1981 and 1982 are illustrated in more detail in Fig. 1.

During April and May 1981 the rate of gaseous N emission from the CT F-W field continued to be several-fold higher than for the CT W-F field, perhaps due to relatively higher soil moisture and the high substrate concentration of NO_3^--N (Fig. 1). However, after the CT F-W field was cultivated and seeded to wheat, the improved soil aeration accordingly lowered gaseous N fluxes. Gaseous N losses on this CT F-W field reached approximately 125 g N ha^{-1} d^{-1} in mid-May 1981, then dropped close to that for the W-F field. The very rapid increase in rate of gaseous N emissions to > 300 g N_2O-N ha^{-1} d^{-1} in mid-June on both CT fallow and CT wheat fields was associated with a 71-mm rain. Thereafter, the fallowed field maintained a relatively high rate of N losses throughout the remainder of the summer and dropped in the fall due to cool temperatures; this was reflected for year II in a twofold higher total N loss on W-F as compared with the adjacent cropped field (Table 2). The relatively small differences in surface soil moisture content (Fig. 1) appears to be primarily responsible for very large differences in gaseous N evolution. In contrast, large variations in NO_3^--N levels were not related to the N losses. This will be discussed later.

The data obtained from the ZT plots during April and May 1981 showed that the gaseous N losses from both wheat (W-W) and fallow (W-F) fields were similar (Fig. 2). As noted earlier for the CT fields, a 71-mm rain in mid-June resulted in a very rapid increase in gaseous N emissions. Thereafter, the ZT fallow field maintained a much higher gaseous N evolution rate. The gaseous N rate varied widely, generally in response to rainfall events. The overall high rate of gaseous N loss on the ZT fallow continued until mid-October when very cool temperatures stopped the majority of the microbial activity in the soil. In the following spring of 1982, similar patterns were obtained on both ZT fields.

The amount of N lost as (N_2O + N_2) during the 2-y study have shown that the soils, when cropped to wheat, lost a small amount of N, about 3 to 7 kg N ha^{-1} y^{-1} under CT, but much more (12-16 kg N ha^{-1} y^{-1}) under ZT (Table 2). In other recent studies it was also found that gaseous N losses from CT wheat fields were generally low and ranged from 2 to 5 kg N ha^{-1} y^{-1} (1, 2, 3). While this level of N loss from CT cropped fields may be insignificant to the agricultural industry, these soils clearly serve as a source of N_2O which in turn may contribute to the catalytic destruction of stratospheric ozone (9).

The higher gaseous N losses from the ZT than CT fields, whether cropped or fallowed, are probably due to a combination of the following reasons:

1) Higher bulk density (19, also see Table 1) leads to a lower rate of air diffusion into and out of more dense ZT surface soil (less aerobic environment).

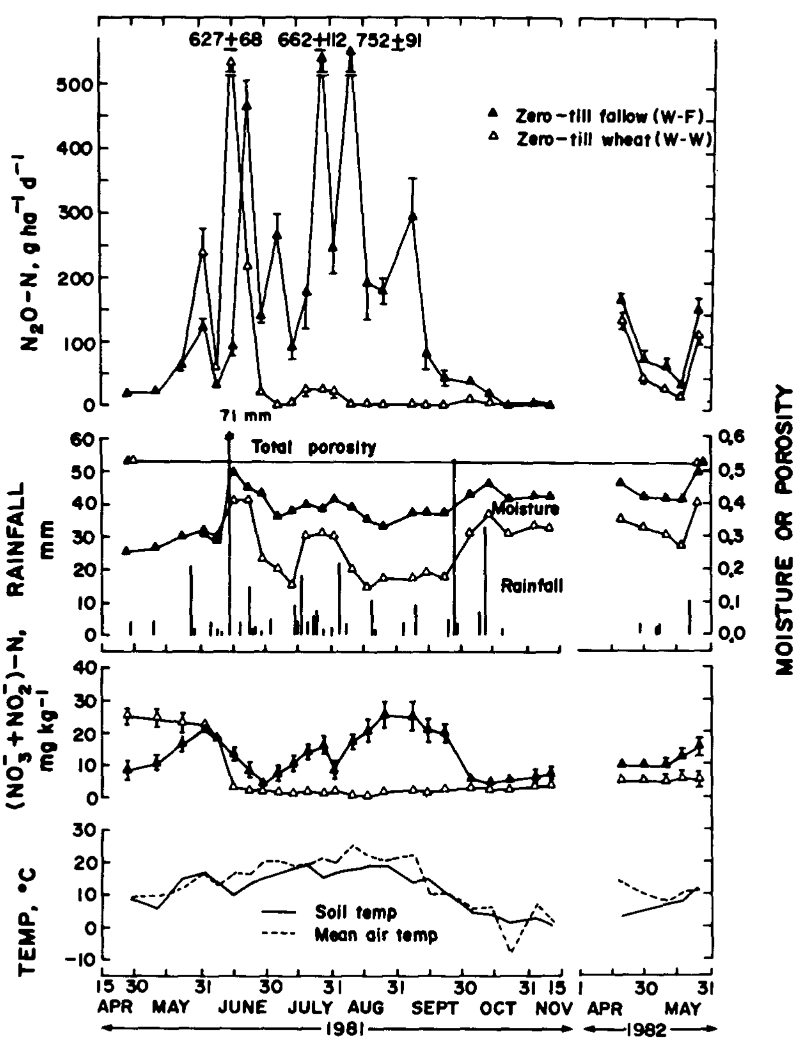

Fig. 2—Gaseous N loss (N_2O-N), soil moisture, rainfall, (NO_3^- + NO_2^-)-N, and air and soil temperature of Elstow clay loam under zero-till wheat-fallow (W-F) and wheat-wheat (W-W) rotations for the period April 1981–May 1982. Φ indicates standard deviation.

2) Zero-till have larger and more anaerobic soil aggregates than adjacent CT fields (14).
3) The greater conservation of rain and snowmelt water and reduced evaporation by straw mulch in ZT results in higher surface soil moisture content (lower air-filled porosities), i.e., less aerobic environment (7, 17, 20).[4]

All of the above encouraged a more favorable environment for denitrifiers, and this is confirmed in the severalfold higher population under ZT than CT (Table 3). Doran (10) found 7.3 times higher population of denitrifiers in the surface soils of ZT than in surface soils of CT systems. In the present study, the denitrifier counts were 1.3 to 6.6 times higher for the ZT than for CT soils (Table 3). The denitrifier population in CT- and ZT-fallow fields were three- to fivefold higher than respective cropped fields. Similarly, PDR values were higher for fallow fields, which had markedly higher accumulation of moisture and NO_3^--N than cropped fields. These findings obtained under field conditions, suggest that the longer the favorable period (higher moisture-anaerobic environment), the higher would be the population of denitrifiers (and PDR), and consequently higher gaseous N losses.

Table 2—Gaseous N losses (kg N ha^{-1}) from fields under conventional-till (CT) and zero-till (ZT) for a 2-y period.

Management system	Year I June 1980–May 1981	Year II June 1981–May 1982	Total
CT W-F†	3.3 ± 0.2a*	14.3 ± 1.3c	17.6 ± 1.2a
CT F-W	12.2 ± 0.4b	6.9 ± 0.5a	19.1 ± 0.3a
ZT W-W	15.8 ± 1.2c	11.7 ± 0.5b	27.6 ± 1.6b
ZT W-F	15.2 ± 1.1c	33.6 ± 1.8d	48.7 ± 2.7c

* In each column, values are significantly different at $P \leq 0.05$ (Duncan's Multiple Range Test) when not followed by the same letter.
† W = wheat; F = fallow.

Contribution of Lower Soil Horizons

The contribution of lower soil horizons to gaseous N losses was studied by sampling the A, B, and C horizons of all the four fields in April and May 1982 (Table 3). The data obtained from 22 April and 17 May samplings reflect gaseous N_2O rates under the moisture conditions existing at the various depths at the time of sampling. The gaseous N losses primarily originated from the A horizon material. Rates of gaseous N emission from A and B horizons were relatively higher on 22 April as compared with respective horizons of each field on 17

Table 3—Gaseous N losses and selected indices of denitrification from soil horizons of Elstow cl during 1982.†

Horizon	22 April			17 May			23 May‡			23 May (Disturbed samples)	
	N_2O-N	NO_3^--N	Moisture	N_2O-N	NO_3^--N	Moisture	N_2O-N	NO_3^--N	Moisture	PDR§	Denitrifier counts¶
	g ha^{-1} d^{-1}	mg kg^{-1}	g kg^{-1}	g ha^{-1} d^{-1}	mg kg^{-1}	g kg^{-1}	g ha^{-1} d^{-1}	mg kg^{-1}	g kg^{-1}	μg N_2O-N kg^{-1} h^{-1}	× 10^6 kg^{-1}
Conventional-till Wheat (F-W)											
A	127 ± 10	4	308	32 ± 9	4	262	110 ± 11	8	385	164 ± 37	440 ± 95
B	7 ± 2	2	267	5 ± 1	4	253	19 ± 2	4	381	16 ± 3	3 ± 1
C	0	6	262	3 ± 1	7	251	5 ± 1	7	368	5 ± 2	1 ± 0
Conventional-till Fallow (W-F)											
A	157 ± 24	21	318	44 ± 5	24	254	120 ± 17	21	370	320 ± 34	2300 ± 557
B	8 ± 1	12	285	7 ± 1	17	243	20 ± 2	9	357	18 ± 3	3 ± 1
C	0	15	251	3 ± 1	16	246	6 ± 1	8	356	6 ± 2	1 ± 0
Zero-till Wheat (W-W)											
A	140 ± 12	5	280	20 ± 2	6	214	120 ± 16	5	352	323 ± 18	1063 ± 257
B	12 ± 2	2	265	4 ± 1	1	208	16 ± 1	1	351	19 ± 3	4 ± 1
C	1 ± 0	2	251	2 ± 0	2	199	5 ± 1	2	375	7 ± 1	1 ± 0
Zero-till Fallow (W-F)											
A	171 ± 10	9	371	41 ± 8	12	334	156 ± 24	16	403	450 ± 49	2900 ± 557
B	15 ± 2	7	317	5 ± 1	6	283	18 ± 4	5	392	21 ± 3	5 ± 1
C	1 ± 0	7	303	2 ± 0	7	277	6 ± 1	7	387	7 ± 2	1 ± 0

† All values are means of three replicates.
‡ Extra water was added to soil cores of B and C horizons before sealing.
§ PDR = Potential denitrification rates obtained from soil slurry technique (25).
¶ Denitrifier counts determined by "Most Probable Number" technique (26, 28).

May due primarily to the 40 to 60 g kg^{-1} higher soil moisture; very cool soil temperatures of C horizon on 22 April was probably the reason for the very low to "zero" N_2O emissions.

Increasing the moisture content to above field capacity but still substantially below saturation percentages did not increase the rate of denitrification of the B nor C horizons relative to the A horizon; these remained relatively constant at 25:4:1 for the A, B, and C horizon materials, respectively. The PDR's and the denitrifier counts not only corroborate the conclusion that the A horizon is the primary source of gaseous N evolution from the soil, but further confirm the relatively lower significance of the B and C horizons.

The gaseous N losses from A, B, and C horizons of three widely different soils of Saskatchewan (Table 4) again show that the contribution of lower soil horizons towards gaseous N losses is very small as compared with respective surface horizons.

Factors Affecting Gaseous N Losses

Measurements of soil moisture, temperature, nitrate-N, and ammonium-N throughout the 2-y period of study made it possible to assess their effect on gaseous N losses. The correlation of gaseous N losses was highest with volumetric soil moisture (r = 0.440**) followed by air temperature (r = 0.327**) and nitrate-N (r = 0.143*) and was smallest with ammonium-N (0.057). To

Table 4—Gaseous N losses and selected indices of potential denitrification from soil horizons of Yorkton cl, Regina hvc, and Brookings cl soils.†

Horizon	Depth	Texture	O.C.‡	Saturation paste pH	E. Ce§	Saturation moisture	N_2O-N	NO_3^--N	NH_4^+-N	Moisture	PDR¶	Denitrifier counts#
	cm		g kg^{-1}		dS m^{-1}	g kg^{-1}	g ha^{-1} d^{-1}	—— mg kg^{-1} ——		g kg^{-1}	μg N_2O-N kg^{-1} h^{-1}	× 10^6 kg^{-1}
Englefield—Yorkton cl (Udic Haploboroll):												
A	0–17	cl	71.2	7.7	0.93	766	620 ± 40	40	11	351	472 ± 34	390 ± 135
B	17–35	c	15.3	8.0	4.92	565	14 ± 1	12	5	256	16 ± 4	10 ± 3
C	35 +	c	6.0	8.1	5.89	500	3 ± 1	5	4	231	6 ± 1	1 ± 0
Regina—Regina HvC (Vertic Haploboroll):												
A	0–13	hvc	20.7	7.8	0.25	770	257 ± 56	5	9	423	338 ± 40	390 ± 111
AC	13–30	hvc	13.4	7.7	0.33	816	21 ± 5	5	6	410	20 ± 4	11 ± 3
C	30 +	hvc	6.8	7.7	0.35	780	7 ± 2	4	6	413	5 ± 1	1 ± 0
Weyburn—Brookings cl (Typic Argiboroll):												
A	0–14	cl	17.2	6.8	0.56	536	91 ± 16	19	18	186	201 ± 30	253 ± 91
B	14–36	c	6.8	7.0	0.33	500	9 ± 2	10	4	201	14 ± 3	5 ± 1
C	36 +	c	4.6	7.3	0.50	500	2 ± 1	5	4	186	6 ± 1	1 ± 0

† All values are means of three replicates, taken from conventional-tilled wheat fields.
‡ Organic C determined by improved dry combustion method (27).
§ Electrical conductivity of the saturation extract.
¶ PDR = Potential denitrification rates obtained from soil slurry technique (25).
# Denitrifier counts determined by "Most probable number" technique (26, 28).

Table 5—Multiple correlation coefficients (R) of gaseous N losses (g N_2O-N ha^{-1} d^{-1}) with different parameters.

Using data at air temperature	R* value with parameters†			
	M	M+T	M+T+N	M+T+N+A
All	0.440	0.587	0.589	0.589
>5°C	0.482	0.588	0.591	0.591
>10°C	0.538	0.589	0.591	0.591
>15°C	0.581	0.593	0.595	0.596

* All multiple correlation coefficients significant at the $P \leq 0.01$ level.

† Parameters: M = moisture (m^3 m^{-3}), T = mean air temperature (°C), N = nitrate-N (mg kg^{-1}), A = ammonium-N (mg kg^{-1}).

Table 6—The average mole fraction of N_2O in the gaseous products at soil moisture content increments of 0.05 m^3 m^{-3}.

Soil	Soil moisture (m^3 m^{-3})						
	0.10–0.15	0.15–0.20	0.20–0.25	0.25–0.30	0.30–0.35	0.35–0.40	0.40–0.45
Elstow cl†	0.970 (16)¶	0.934 (68)	0.919 (56)	0.681 (148)	0.613 (116)	0.494 (64)	0.356 (56)
Hoey cl‡	0.977 (57)	0.893 (40)	0.787 (72)	0.536 (69)	0.447 (61)	–	–
Hamlin cl‡	0.971 (72)	0.852 (92)	0.820 (60)	0.597 (80)	0.488 (48)	–	–
Hoey cl§	0.965 (64)	0.847 (44)	0.740 (44)	0.587 (112)	0.458 (85)	–	–
Blaine Lake cl§	0.910 (120)	0.863 (68)	0.694 (44)	0.595 (66)	0.520 (56)	0.468 (28)	0.284 (15)

† Calculated from data of the present study.

‡ From data of a 2-y field study on continuous wheat vs. wheat-fallow rotation reported earlier (1, 2).

§ From data of a 2-y field study on wheat and clover management practices reported earlier (3).

¶ Figures in the parentheses represent the total number of samples used to calculate the average mole fraction of N_2O.

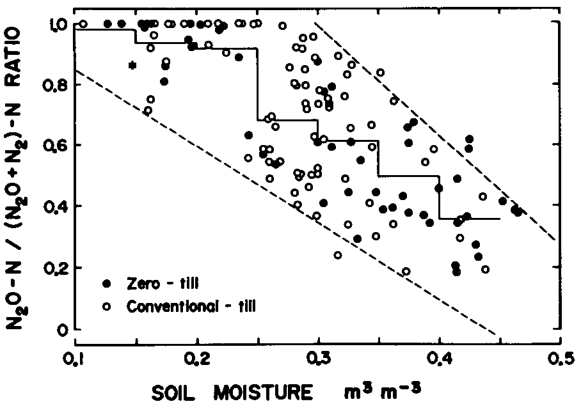

Fig. 3—Relationship between mole fraction of N_2O (N_2O-N/(N_2O + N_2)-N) and the soil moisture content. The bar graph is the mean of all mole fraction N_2O data over increments in soil moisture content of 0.05 m^3 m^{-3}, and two broken lines enclose the area within which data are scattered.

evaluate the combined effect of soil moisture and temperature, a multiple correlation analysis was performed. Combining moisture and temperature resulted in maximizing the R value at 0.587** (Table 5). Adding nitrate-N or ammonium-N did not further significantly increase the R value. Thus, this study further confirms that moisture is the primary factor (and temperature a secondary one) affecting gaseous N losses (3).

Mole Fraction of N_2O

A measure of the mole fraction of N_2O in the total gaseous products was obtained from N_2O emissions measured with and without C_2H_2 at each of the weekly sampling times during this 2-y study. The mole fraction of N_2O showed a pronounced relationshp with changes in soil moisture content (Fig. 3). The average mole fraction N_2O values calculated from data of the present study as well as other field studies clearly demonstrate that as the soil moisture content increases, mole fraction of N_2O decreases (Table 6).

The synthesis and activity of N_2O reductase, which is involved in the reduction of N_2O to N_2, is inhibited by O_2, probably by competing for electrons (16). However, the measurement of O_2 distribution in field soils in particular is extremely difficult. The existence of anaerobic microsites in the soil depends greatly on soil moisture content since this is a singular factor limiting the within and between aggregate porosities. Thus, as the moisture content of the soil increases, the air-filled porosity decreases; further, the diffusivity of the soil air is very sharply reduced. Thus, as the moisture content increases, the concentration of O_2 decreases and the ratio of N_2O-N to (N_2O + N_2)-N decreases as shown in Fig. 3. It should also be recognized that the N_2O diffuses more slowly out of a wet than a dry soil; thus, there is a greater opportunity—certainly from the physical standpoint—for its reduction under higher moisture contents. On the other hand, under aerobic conditions, nitrification may also become another substantial source of N_2O production (1, 6) and increase the mole fraction of N_2O. (The contribution of nitrification was taken care of in this study as explained in the *Materials and Methods* section.)

A further reason sometimes given for higher proportion of N_2O evolved from soils is that NO_3^- inhibits the reduction of N_2O as it is used preferentially over N_2O as an electron acceptor (13). However, our results showed that wide ranges of NO_3^--N levels had no influence on the mole fraction of N_2O. These results from field samples support the recent studies conducted with several different denitrifying cultures (5) and with soils under laboratory conditions (16, 18), where it was observed that N_2O reductase develops only after a period of time following anoxic conditions, and the mole fraction of N_2O eventually drops, even under the highest NO_3^- concentration.

CONCLUSIONS

1) Gaseous N losses from cropped fields were generally low; however, N losses were twofold higher under ZT compared with CT management systems.

2) The losses from CT fallow were more than double that from CT cropped fields; wheat followed by fallow or fallow followed by wheat lost equal amounts of N in a 2-y period.

3) In ZT systems, annual losses from a wheat-fallow rotation were 24 kg N ha^{-1} as compared with 13 kg N ha^{-1} from continuous wheat.

4) Improved water storage under ZT fallow as compared with CT fallow was an important factor leading

to two to three times higher gaseous N loss under the former.

5) The contribution of lower soil horizons towards gaseous N losses was small. The marked decrease in gaseous N flux with soil depth followed similar decreases in organic C, denitrifier counts, and potential denitrification rates.

6) The significant differences in gaseous N losses from ZT compared with CT systems are related to the increases in both soil density and soil water content for the former. In this study, water appeared to be the primary factor that influenced gaseous N losses, i.e., a short-term increase in soil moisture content resulted in dramatic increases in the gaseous N flux.

7) The very wide range of mole fraction of N_2O from almost complete (99%) to very small (28%) in the total gaseous N products varied with time and showed a negative relationship with soil moisture content; it cautions the use of any single ratio of N_2O to N_2 in the estimation of N_2O liberated from agricultural soils and instead indicates that frequent measurements over time are needed for proper assessment of N_2O evolution.

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