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9 Nitrous Oxide Emissions and Methane Consumption in Wheat and Corn-Cropped Systems in Northeastern Colorado

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Agricultural soils serve as a significant source of atmospheric nitrous oxide (N_2O), and can be sinks for atmospheric methane (CH_4) in aerated soils (Bouwman, 1990). Nitrous oxide emissions during both oxidation of NH_4 and denitrification (Bouwman, 1990) are increased by N fertilizer applications to soil (Eichner, 1990). Nitrous oxide, an important "greenhouse gas," is 300 (mass basis) times more radiatively active than CO_2 (Rodhe, 1990), and participates in ozone (O_3) destruction in the stratosphere (Crutzen, 1976). Globally, N_2O flux from fertilized soils is estimated to be 1 to 2 Tg N_2O-N yr^{-1} (Seiler and Conrad, 1987).

Methane also is a greenhouse gas that is about 15 times more effective than CO_2 (mass basis) at absorbing infrared radiation (Rodhe, 1990). Recent decreases in the CH_4 consumption or sink activity in soils, in addition to sources such as rice (*Oryza sativa* L.) paddies, cattle, landfills, and biomass burning, might account for the 1% yr^{-1} increase in CH_4 in the atmosphere (Ojima et al., 1992). Consumption of atmospheric CH_4 in soil has been reported in a variety of ecosystems (Steudler et al., 1989; Keller et al., 1990; Whalen & Reeburgh, 1990; Mosier et al., 1991). Methane oxidation or consumption in soils is done by a diverse group of methanotrophic bacteria (Whittenbury et al., 1970) and by nitrifying bacteria (Jones & Morita, 1983). Nitrogen fertilizer, especially NH_4-based fertilizers, have recently been reported to strongly repress CH_4 consumption in forest (Steudler et al., 1989) and prairie (Mosier et al., 1991) soils.

In this paper, recent research on N_2O emissions and CH_4 consumption in wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.)-cropped soils of the Northern Plains is summarized. Soil properties, such as texture, organic matter content, and inorganic N concentrations are discussed in terms of how they control the flux rates of these trace gases.

MATERIALS AND METHODS

Dryland Wheat–Fallow Rotation

Six plots were established in a wheat field and in an adjacent fallow field in June 1990 in the Central Plains Experimental Range in northeastern Colorado (Mosier et al., 1991). The soil is a sandy clay loam (fine-loamy, mixed, mesic Ustollic Haplargid) that has not been fertilized. Nitrous oxide and CH_4 fluxes were measured weekly by taking samples from vented chambers (0, 15, and 30 min) after placing them over the soil (Hutchinson & Mosier, 1981). The samples were analyzed by gas chromatography (Mosier and Mack, 1980; Mosier et al., 1991). Cumulative flux for the growing season was calculated for each plot by linearly interpolating data points and integrating the area by Simpson's rule. Soil samples were taken at each gas sampling date from the 0- to 15-cm layer were analyzed for 2 *M* KCl-extractable NH_4 and NO_3 by a flow-injection autoanalyzer. Soil moisture was determined gravimetrically, and soil temperature was measured at the 2.5-cm depth by digital thermometer on each gas sampling date.

Irrigated Wheat

Nitrous oxide and CH_4 fluxes were measured (1–3 times wk^{-1}) from a flood-irrigated wheat field from planting in September 1990 to harvest in July 1991 from vented chambers with 1-h incubation periods. Cumulative flux was calculated as described above. The clay soil (fine, montmorillonitic, mesic Aridic Arginstoll) at the site had 60 mg NO_3-N kg^{-1} in the surface 30 cm. Four blocks in the experiment received the following fertilizer treatments 1 d after planting: urea alone, urea plus the nitrification inhibitors (NIs) encapsulated Ca carbide (ECC) (Banerjee & Mosier, 1989) at 20 kg CaC_2 ha^{-1} or dicyandiamide (DCD) (10% of N rate), and unfertilized control. The urea-fertilized treatments were applied at the rates of 50, 100, or 150 kg N ha^{-1}. Soil moisture and exchangeable N were determined periodically, as described above, in the 0- to 15- and 15- to 30-cm layers of soil. Soil temperature was measured at the 7.5-cm depth of soil. Additionally, a total denitrification study was conducted adjacent to the experiment after the irrigation on 230 days after fertilization (DAF) using the CaC_2–C_2H_2 inhibition technique (Aulakh et al., 1991) to determine N_2O–(N_2 + N_2O) ratios during denitrification in this soil. Six 180-cm^2 plots received 50 mg NO_3-N, and three of these had CaC_2 added prior to 1-h incubations in vented covers.

Irrigated Corn

Periodic (weekly or less) measurements of N_2O and CH_4 were made on four replicates of a furrow-irrigated corn field from planting in April 1990 to harvest in September 1990, and cumulative flux calculated as described above (Bronson et al., 1992). The clay loam soil (fine, montmorillonitic, mesic Aridic Argiustoll) at this site had 6 mg NO_3-N kg^{-1} in the surface 25 cm. Fertilizer treatments (at time of planting) included 0 and 218 kg urea-N ha^{-1} and applications of the NIs nitrapyrin [2-chloro-6-(trichloromethyl)-pyridine] (0.5 L a.i. ha^{-1}) and ECC (20 kg CaC_2 ha^{-1}). Soil water, temperature, and exchangeable N were determined as described in the irrigated wheat.

RESULTS AND DISCUSSION

Dryland Wheat-Fallow Rotation

Nitrous Oxide Emissions

Nitrous oxide emissions in dryland wheat-fallow system were low throughout fall and winter (0–240 d after planting) (Fig. 9-1a), with no differences between wheat-cropped and fallow soil ($P > 0.05$). After two spring rains, large N_2O fluxes were measured in both wheat-cropped and fallow soils. Nitrate-nitrogen in the surface 15 cm of soil was apparently not related to N_2O fluxes ($P > 0.05$). Relatively high levels of NO_3-N were present in the wheat-cropped soil (27 mg NO_3-N kg^{-1}), which probably accumulated during mineralization of organic N during the previous fallow. Soil moisture (Fig. 9-1c) was higher in the fallow field ($P < 0.05$) throughout the growing season, but it was not related to N_2O emissions ($P > 0.05$).

Methane Consumption

Methane consumption rates were about 1 g CH_4-C ha^{-1} for the fall and winter in both wheat-cropped and fallow soils (Fig. 9-1b). The adjacent grassland, of a similar soil type, however, (last cropped 50 yr ago and allowed to go back to native grass species) consumed CH_4 at about twice this rate (Ojima et al., 1992). By early summer when soil moisture was declining in the wheat-cropped soil, CH_4 consumption increased to a maximum of 4.9 g CH_4-C ha^{-1} d^{-1} 302 d after planting. Methane consumption was negatively correlated with soil moisture (Fig. 9-1c) in the 0- to 15-cm layer of soil ($r = -0.55$, $n = 21$, $P < 0.01$) after 259 d after planting, but was not related with NH_4 or NO_3 in soil ($P > 0.05$) at any time.

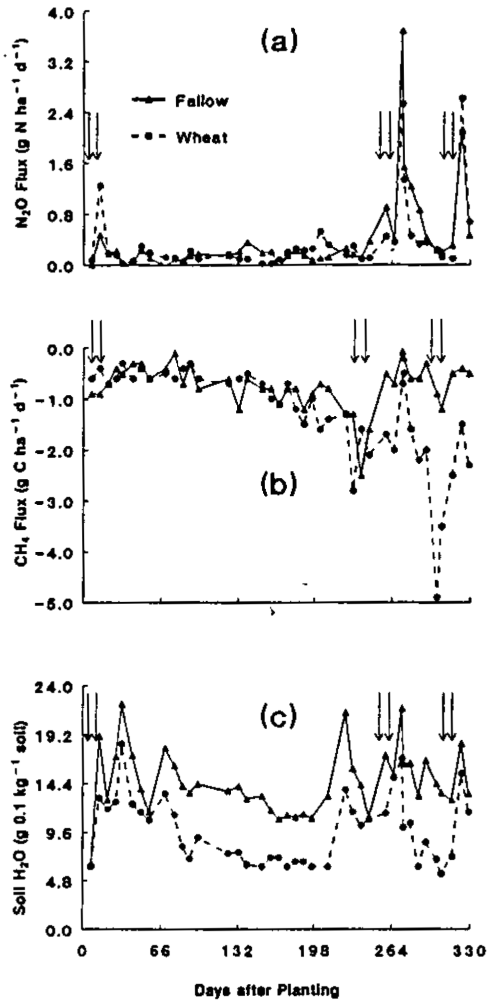

Fig. 9-1. Trace gas fluxes in wheat and fallow cropping systems: (a) N_2O, (b) CH_4, and (c) soil H_2O in surface 2.5 cm. Double arrows indicate a rainfall >25 mm.

Irrigated Wheat

Nitrous Oxide Emissions

Emissions of N_2O were highest early in the growing season and after irrigations (Fig. 9-2a). In the first 60 DAF, fluxes were highest with urea alone, compared to urea plus NIs ($P < 0.05$). Aulakh et al. (1984) and Magalhaes et al. (1984) reported that NIs can indirectly reduce N_2O emissions by retarding NH_4 oxidation in soil. The N_2O emitted in the fall, in the first 60 DAF was probably largely from nitrification of NH_4 (Bremner & Blackmer, 1978). This can be inferred because ample NO_3-N (60 mg kg^{-1}) (Fig. 9-2c)

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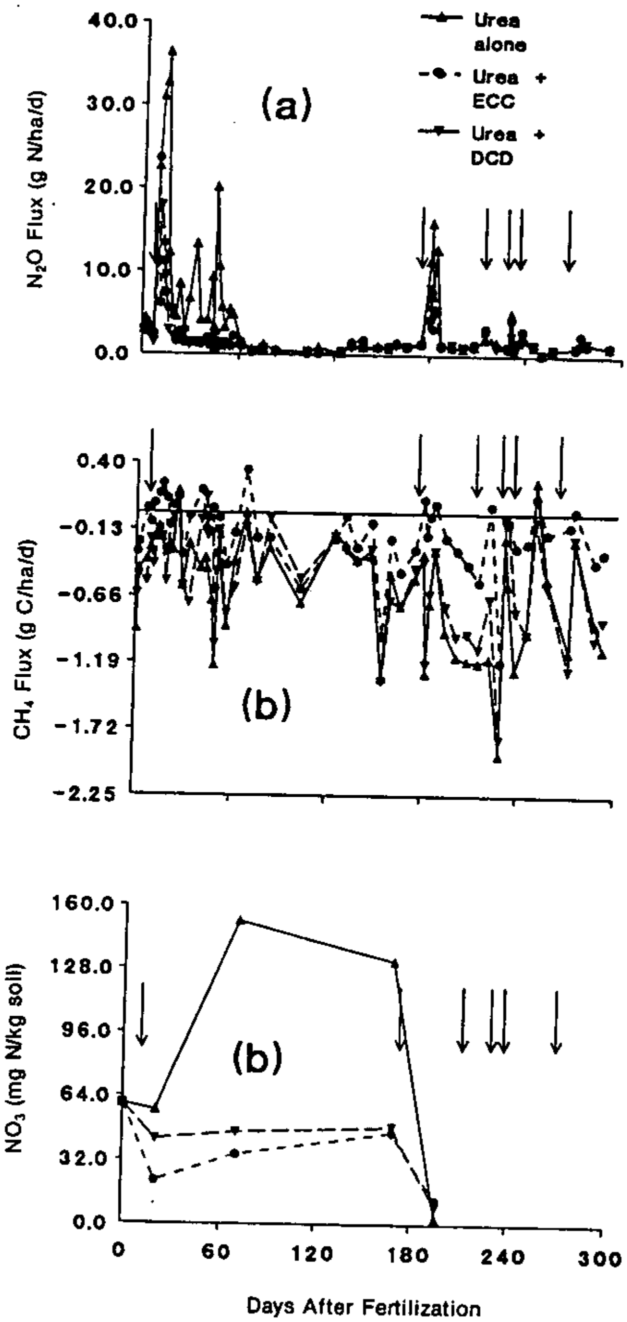

Fig. 9-2. Trace gas fluxes from irrigated wheat as affected by urea with and without encapsulated calcium carbide (ECC) or dicyandiamide (DCD): (a) N_2O, (b) CH_4, and (c) soil NO_3 in surface 15 cm. Single arrows indicate an irrigation and double arrows indicate a rainfall >25 mm.

was available in all plots at the time of the first irrigation, but during the first 60 DAF, 528 g N_2O-N were emitted from urea-treated plots, and only 116 g N_2O-N from the unfertilized plots (that also had 60 mg NO_3-N kg^{-1}). Nitrous oxide emissions in the spring after the 177-DAF irrigation were small (<18 kg N ha^{-1} d^{-1}), and no treatment differences were apparent ($P > 0.05$). The results of a total denitrification study conduced after the irrigation at 230 DAF (Bronson & Mosier, 1991) indicated that at soil moistures near field capacity, high rates of denitrification occurred, but that the product was almost entirely N_2. Nitrous oxide was only about 2% of the total NO_3 denitrified. The spring N_2O fluxes, therefore, were probably due to denitrification of the NO_3 that was still present in all plots, and represent a much smaller amount of NO_3 reduced than other sites with lighter-textured soils.

Methane Consumption

Consumption rates of CH_4 in irrigated-wheat soil were about one-half those in dryland-wheat soil, but likewise increased as the growing season progressed (Fig. 9-2b). The highest CH_4 consumption rates were observed from the unfertilized control, urea alone, and urea plus DCD. Methane consumption was significantly inhibited by C_2H_2 ($P > 0.05$) in this study, as has been reported in pure cultures of methanotrophic bacteria (Dalton, 1977), but not by DCD ($P > 0.05$). Other studies have indicated that NH_4 fertilizers inhibit CH_4 oxidation in pure culture (Ferenci et al., 1975) and in soil (Steudler et al., 1989; Mosier et al., 1991), but this was not observed in this study.

Irrigated Corn

Nitrous Oxide Emissions

For the first 7 DAF in the ECC-treated plots, blockage of the N_2O to N_2 reduction step of denitrification by C_2H_2 (Yoshinari et al., 1977) was observed (Fig. 9-3a). Laboratory studies (Bronson et al., 1992) indicated that in this soil maximum blockage of N_2O reduction to N_2 occurs with C_2H_2 concentrations of 1000 $\mu L\ L^{-1}$. Nitrous oxide flux with ECC alone (Bronson et al., 1992) was not different from the high level of ECC with urea during the first 6 DAF ($P > 0.05$). This indicates that N_2O emissions from the ECC-treated plots during the 7 DAF (when C_2H_2 production was high) came from denitrification of residual soil NO_3 (6 mg N kg^{-1}) and not from fertilizer N. Urea alone resulted in the highest N_2O emissions for most of the growing season ($P < 0.05$). Nitrous oxide fluxes peaked at 32 DAF, two d after the second irrigation. Flux from urea-treated soil without NIs was 246 g N ha^{-1} d^{-1}, urea plus nitrapyrin emitted 116 g N ha^{-1} d^{-1}, and N_2O fluxes from the other plots were less than 3 g N ha^{-1} d^{-1} (three groups are significantly different at $P < 0.01$). Nitrous oxide emissions declined after the hailstorm at 32 DAF, and since no further irrigations were applied, N_2O fluxes became negligible by 62 DAF.

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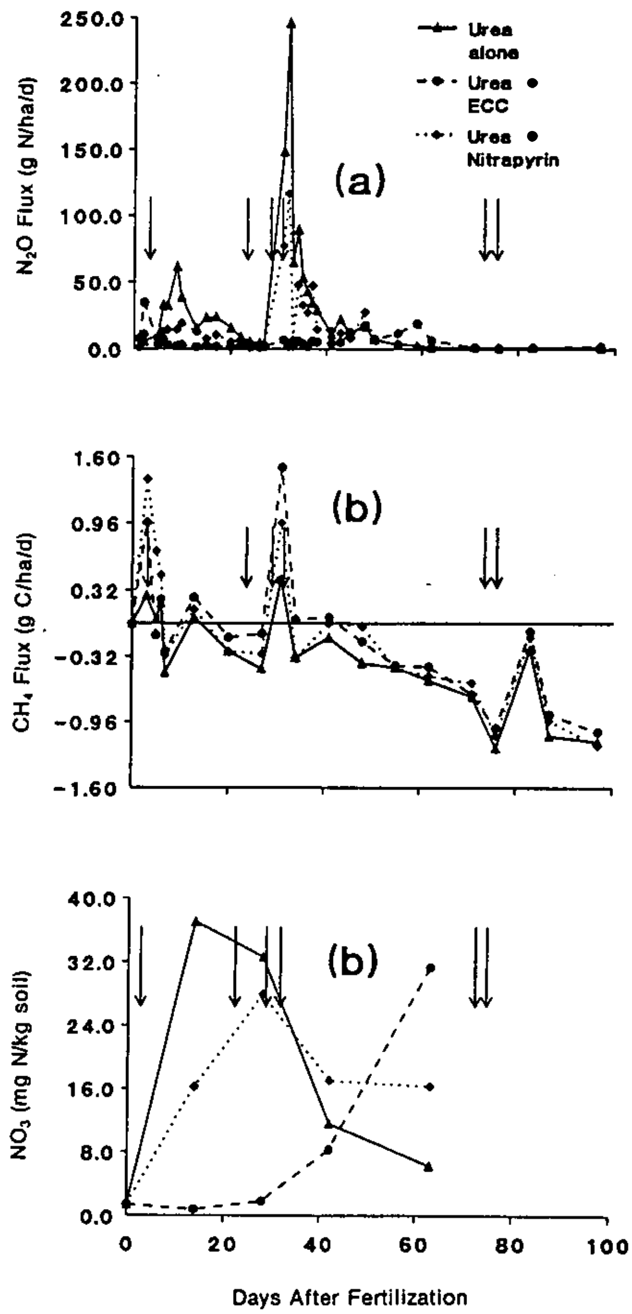

Fig. 9-3. Trace gas fluxes from irrigated corn as affected by urea with and without encapsulated calcium carbide (ECC) or nitrapyrin: (a) N_2O, (b) CH_4, and (c) soil NO_3 in surface 25 cm. Single arrows indicate an irrigation and double arrows indicate a rainfall >25 mm.

Nitrous oxide fluxes were positively correlated with NO_3-N in the surface 30 cm soil ($r = 0.38$, $P < 0.01$). By delaying and reducing NO_3 formation (Fig. 9-3c), the NIs indirectly reduced N_2O emissions from denitrification. Part of the N_2O emitted from urea in the absence of nitrification inhibitors was probably evolved during nitrification of NH_4 (Bremner & Blackmer, 1978). The NH_4-N levels in soil were not correlated with N_2O fluxes, ($r = 0.06$, $P > 0.05$), however.

Total denitrification measurements ($N_2 + N_2O$) (Bronson et al., 1992) indicated that when denitrification activity was high, the ratio of N_2O-($N_2 + N_2O$) was less than 0.3, and when activity was low, N_2O-($N_2 + N_2O$) was 0.5.

Methane Consumption

Methane emissions were observed for brief periods following irrigations on 3 and 29 DAF (Fig. 9-3b), but no significant treatment differences ($P > 0.05$) existed. Low rates of CH_4 consumption predominated during the rest of the growing season. Overall, rates of CH_4 consumption were about two-thirds those in the irrigated wheat field. The highest CH_4 consumption rates were observed from the unfertilized control and the urea-treated plots between the two irrigations. Only at 7 DAF was CH_4 consumption with urea alone significantly less than with the control plots ($P < 0.05$). After the second irrigation, CH_4 consumption with urea alone was similar to that of the unfertilized soils ($P > 0.05$). Nitrification and plant consumption depleted NH_4 by this time.

Acetylene significantly inhibited CH_4 consumption ($P < 0.05$) similar to the irrigated wheat (this paper). In agreement with Dalton's (1977) work in pure cultures of methanotrophic bacteria, nitrapyrin inhibited CH_4 consumption. Acetylene produced in the soil from ECC with or without N fertilizer (data for ECC alone not shown) inhibited CH_4 consumption (compared to control and urea alone) up to 62 DAF, after which no treatment differences in CH_4 consumption were observed. Nitrapyrin had an inhibitory effect on CH_4 consumption ($P < 0.05$), but not on as many sampling dates as C_2H_2 had. Methane consumption generally increased as the growing season progressed, probably due to the disappearance of N fertilizer and NIs.

Cumulative Fluxes of Nitrous Oxide and Methane

Dryland versus Irrigated Wheat

Cumulative emissions of N_2O from unfertilized dryland winter wheat were about one-fourth of that of the unfertilized irrigated wheat (Table 9-1). This is probably due to the lower amounts of inorganic N in the dryland soil.

During the growing season there is no statistical difference between the cumulative CH_4 consumed from the wheat-cropped vs. the fallow field ($P > 0.05$). The wheat-cropped soil did, however, consume more towards the end of the season (Fig. 9-1b; $P < 0.05$) when crop water use dried the soil

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Table 9-1. Cumulative fluxes of N_2O-N and CH_4-C in dryland wheat-fallow system†, irrigated wheat‡, and irrigated corn§.

System-treatment	N_2O		CH_4	
	Avg.	SD	Avg.	SD
	g N_2O-N ha^{-1}		g CH_4-C ha^{-1}	
Dryland wheat				
Wheat	101 a¶	15	−393 a¶	135
Fallow	112 a	18	−257 a	125
Irrigated wheat				
Urea alone	929 a#	150	−188 b#	22
Urea + ECC (20 kg ha^{-1})	509 b	67	−66 a	11
Urea + DCD (10% N)	437 b	71	−156 b	20
ECC alone (20 kg ha^{-1})	360 b	88	−75 a	6
Control	440 b	102	−185 b	21
Irrigated corn				
Urea alone	1651 a#	618	−43 b#	7
Urea + nitrapyrin (0.5 L ha^{-1})	980 b	593	−36 ab	9
Urea + ECC (20 kg ha^{-1})	483cc	128	−25 a	8
Control	108 c	29	−45 b	2

† Fluxes were measured from time of planting to just before harvest (329 d after planting).
‡ Fluxes were measured from time of fertilization (planting) to just before harvest (292 d after fertilization).
§ Fluxes were measured from time of fertilization (9 wk after planting) to just before harvest (97 d after fertilization).
¶ Means in a column followed by the same letter are not significantly different at P = 0.05 by T test.
# Means in a column followed by the same letter are not significantly different at P = 0.05 by Duncans Mean Range Test.

relative to the fallow field (Fig. 9-1c). Dryland wheat soil consumed twice as much CH_4 as unfertilized irrigated wheat ($P < 0.05$). This is probably a result of wetter conditions and the fertilization history of the irrigated wheat field, which would tend to suppress CH_4 consumption.

Urea fertilizer addition to irrigated wheat resulted in two times more N_2O-N emissions than the unfertilized control (Table 9-1). Severalfold increases of N_2O flux with N fertilizer application have been reported often (Mosier et al., 1986; Rolston et al., 1976). Cumulative N_2O emitted during the growing season was 929 g N_2o-N ha^{-1} from urea alone, or 0.3% applied fertilizer N (after subtracting the cumulative flux of the control). The NIs ECC and DCD reduced N_2O emissions 45 and 53%, respectively.

The clay soil under irrigated wheat acted as a small sink for atmospheric CH_4. Methane consumption averaged 186 g CH_4-C ha^{-1} in both unfertilized and urea-fertilized soil during the growing season. This result, that N fertilizer additions to a cropped system did not affect CH_4 consumption, differs from reports in forest soils (Steudler et al., 1989) and in grasslands (Mosier et al., 1991). Several years of N fertilization might have suppressed CH_4 consumption to the low levels observed in this study, such that the N additions in this experiment had no effect.

On average, the CH_4 consumption rates observed in the irrigated wheat field were about four times less than that measured in nearby grasslands that were plowed 50 yr ago, and about eight times less than nearby native grasslands that have never been plowed (Ojima et al., 1992). Cultivation itself might have a suppressive effect on CH_4 consumption in soils, as Keller et al. (1990) reported that cropped–cultivated tropical soils had CH_4 consumption rates four times less than that of tropical forest soils.

In the irrigated wheat, C_2H_2 produced from ECC inhibited cumulative CH_4 consumption 65% during the 300-d period. Dicyandiamide addition had no effect on CH_4 consumption ($P > 0.05$), but since it inhibited nitrification (Fig. 9–2c), it was found to be a differential inhibitor. At 168 DAF, DCD had inhibited nitrification 83%, but the cumulative CH_4 flux up to that time was inhibited only 8% (not significant at $P = 0.05$).

Irrigated Corn

Cumulative CH_4 and N_2O fluxes are presented in Table 9–1. This clay loam soil under irrigated corn acted as a small net sink for atmospheric CH_4. As in the irrigated wheat, addition of urea did not affect CH_4 consumption ($P > 0.05$). About 44 g CH_4–C ha^{-1} were taken up by unfertilized and urea-fertilized soil during the growing season. Although the growing season for irrigated corn was one-third of that for irrigated wheat, the cumulative CH_4 consumed in the irrigated corn was about one-fourth of that in the irrigated wheat.

Acetylene produced from ECC inhibited cumulative CH_4 consumption 43% during the 97-d period. Nitrapyrin addition to urea reduced cumulative CH_4 consumption 22% ($P < 0.10$), in agreement with the work of Topp and Knowles (1984) with pure cultures of methanotrophs.

Cumulative N_2O emitted during the growing season was 1480 g N_2O–N ha^{-1} from urea alone, or 0.7% applied fertilizer N. Dinitrogen is the main denitrification product in this clay loam soil (36% clay), but it produces more N_2O per NO_3 denitrified than does the clay soil planted to irrigated wheat. Encapsulated calcium carbide controlled N_2O emissions as effectively as nitrapyrin ($P > 0.05$). Urea fertilizer resulted in 13 times more N_2O–N emissions than the unfertilized control.

SUMMARY

Nitrous oxide emissions increased with increased soil moisture and N fertilization; however, potential for N_2O production from denitrification was limited in heavy clay soils because of enhanced N_2 production. Nitrification inhibitors reduced N_2O emissions in N fertilized, irrigated wheat and corn. Methane consumption was higher in unfertilized dryland wheat than in fertilized, irrigated systems. Urea fertilization in irrigated crops did not affect CH_4 consumption, but the nitrification inhibitors ECC and nitrapyrin generally had a repressive effect. Considering the 10- and 150-yr decay

times of CH_4 and N_2O, respectively, in the atmosphere (Rodhe, 1990), the emissions of N_2O contribute far more to the "greenhouse effect" than does the consumption of CH_4 in all of these cropping systems. Therefore, strategies to reduce N_2O emissions should be emphasized, especially in systems where CH_4 consumption rates are low.

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