Carbon and nitrogen losses from undisturbed soil columns under short-term flooding conditions

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Wang, F. L. and Bettany, J. R. 1995. **Carbon and nitrogen losses from undisturbed soil columns under short-term flooding conditions.** Can. J. Soil Sci. **75**: 333–341. Short-term flooding (few days to several weeks) of usually well-drained soils — often occurring after snowmelt in spring and after heavy precipitation in summer — is a natural event in many regions of the world. Using incubation-leaching and gas sampling techniques in the laboratory, we examined the impact of flooding on the loss of carbon and leaching of nitrogen from five undisturbed soil columns. The soils varied in management, salinity and carbon content. After 8 wk of incubation, the amounts of soluble organic carbon leached by 0.001 M $CaCl_2$ solution from flooded soils ranged from 153 to 630 mg C kg^{-1}. In contrast, only 28-107 mg C kg^{-1} was leached from nonflooded soils. The amounts of soluble organic nitrogen leached from the flooded soils ranged from 10 to 30 mg N kg^{-1} compared with 5.9-12 mg N kg^{-1} from nonflooded soils. In the flooded soils, ammonium nitrogen dominated the total inorganic nitrogen leached (99.5-99.9%) whereas in nonflooded soils leachable N was mainly nitrate and nitrite (97.4-99.9%). Methane was emitted from the flooded soils (10-138 mg C kg^{-1} over 8 wk). The rate of carbon dioxide evolution in flooded soils increased linearly with time and total evolution ranged from 72 to 552 mg C kg^{-1}, whereas CO_2 evolution in the nonflooded soils was steady with total evolution ranging from 159 to 1279 mg C kg^{-1} after 8 wk.

Key words: Prairie and forest soils, short-term flooding, C and N losses, methane emission

Wang, F. L. et Bettany, J. R. 1995. **Déperditions de carbone et d'azote dans des colonnes de sol non perturbé en conditions de submersion de courte durée.** Can. J. Soil Sci. **75**: 333–341. Des submersions de courte durée (quelques jours à quelques semaines) dans les terres habituellement bien drainées sont des phénomènes naturels dans de nombreuses régions du monde, souvent à la fonte des neiges au printemps et après de fortes précipitations en été. Au moyen de techniques d'incubation-lixiviation et de prélèvement de gaz en laboratoire, nous avons examiné l'effet de la submersion sur les déperditions de carbone et sur la délavage de l'azote dans cinq colonnes de sol non perturbé. Les sols variaient selon le degré de salinité et la teneur en C, ainsi que selon le régime d'exploitation. Au bout de 8 semaines d'incubation, les quantités de carbone organique soluble lixivitées dans les sols submergés par une solution de $CaCl_2$ 0,001 M se situaient entre 153 et 630 mg C kg^{-1}, contre seulement 28 à 107 mg dans les sols non submergés. Les quantités d'azote organique soluble lixiviées dans les sols submergés allaient de 10 à 30 mg N kg^{-1}, contre 5,9 à 12 mg dans les sols non submergés. Dans les sols submergés, NH_4 était la forme dominante de N minéral (99,5 à 99,9%), tandis que dans les sols non submergés le N délavable était principalement sous forme de nitrates et de nitrites, soit 97,4 à 99,9%. Les sols submergés dégageaient du méthane (10 à 138 mg C kg^{-1}) sur une période de 8 semaines. Dans ces sols, le taux de dégagement de CO_2 augmentait en fonction linéaire du temps, le dégagement total au bout de 8 semaines allant de 72 à 552 mg C kg^{-1}, tandis que dans les sols non submergés le dégagement était constant, les quantités totales dégagées au bout de cette période allant de 159 à 1279 mg C kg^{-1}.

Mots clés: Sol de prairie, sol forestier, submersion de courte durée, déperditions de C et de N, émission de méthane

The loss of carbon (C) and nitrogen (N) from soil is both an agricultural and environmental problem. Long-term sustainability of agricultural systems depends on maintaining the level of soil organic matter and associated nutrients. Losses of soluble organic compounds through leaching and run-off contribute to the pollution of groundwater and streams. Losses of organic matter through gas emission contribute to the global load of greenhouse gases, in particular, carbon dioxide, methane and various nitrogen oxides. Next to CO_2, CH_4 accounts for approximately 20% of the supposed greenhouse warming in the past 100 yr and affects tropospheric ozone levels (Schutz et al. 1990). Methane emitted from soils contributed more than 50% of the estimated total atmospheric CH_4 (Schutz et al. 1990). Although the contribution of rice paddy soils and wetlands to the global CH_4 pool has been recognized (Aselmann and Crutzen 1989; Windsor et al. 1992), little is known concerning the significance of CH_4 emission from usually well-drained soils subjected to short-term flooding conditions.

The dynamics of inorganic C and N have been investigated in rice fields which are submerged for several months (Ponnamperuma 1972; Stevenson 1986). Few studies, however, have addressed the impact of flooding on the loss of C and N, from usually well-drained soils. Short-term flooding, varying from a few days to several weeks, occurs after snowmelt in spring and after heavy precipitation in summer, especially in the prairie and boreal regions of Canada.

Previous studies in our laboratory with a disturbed Orthic Black Chernozemic soil showed that flooding enhanced evolution of CO_2 and the leaching of **water soluble organic carbon (SOC)** and **water soluble organic nitrogen (SON)** (Wang and Bettany 1993, 1994). These experiments posed many questions as to what kind of soil properties affected the loss and whether these results would be as apparent in undisturbed soil columns in the laboratory and in the field.

The cycles of C and N in an ecosystem should be partly governed by the nature and properties of the soil. An assessment of the loss of C and N from different soils may lead to knowledge about the soil factors affecting the dynamics of C and N. This knowledge is essential if we are to model CO_2 and CH_4 emission from the landscape.

The objective of our study, therefore, was to examine the effects of short-term flooding on the loss of C and N from variety of usually well-drained cultivated and native soils using undisturbed soil columns and an incubation-leaching technique in the laboratory.

MATERIALS AND METHODS

Five soils were selected which contrasted in management, salinity, carbon content and physical properties: **Orthic Black Hoey (OBH-orth.), Calcareous Black Weirdale (CBW-calc.), Calcareous Black Blainie-Lake, saline (CBB-saline), cultivated Orthic Gray Luvisol Waitville (OGLW-cult.)**, and **native Orthic Gray Luvisol Waitville (OGLW-nat)** (Tables 1 and 2). These soils occupy considerable land area in the northern agricultural-forest boundary regions of western Canada. Undisturbed soil columns were taken, by gently pressing PVC cylinders (25 × 10.4 cm) into the soil surface using hydraulic pressure from a punch equipment. The A horizons (13-16 cm deep) were sampled in the autumn from fields in the northern agricultural area of Saskatchewan near the towns of Melfort and Prince Albert. The sampling cylinders were then cut from the bottom such that the soil columns inside were 11 ± 0.5 cm in height, with exception of the native Luvisol. The soil column of the native Luvisol was kept 18 ± 1 cm in length to accommodate the loosely packed LFH layer (litter layer (7 ± 1 cm). The soil columns were stored at field moisture contents (Table 1) at 4°C prior to the start of the experiment.

Soil Incubation and Leaching

Duplicate soil columns together with the PVC cylinders were placed in sealed jars and incubated under flooding conditions (flooded system) or at field capacity moisture contents (nonflooded system) for 8 wk at 23 ± 0.5°C (Fig. 1). The soil columns were flooded with 0.001 mol L^{-1} $CaCl_2$ solution (1:2 wt/vol ratio) and maintained under about 1-2 cm of the solution during the incubation. The dilute $CaCl_2$ solution kept the soil flocculated. An additional flooding treatment was set up for only the litter layer of the native Luvisol (i.e. excluding the Ae layer) in the same way as the soil since the layer has distinctive chemical and physical properties (Table 2). Acid-washed Ottawa sand (0.53-0.80 mm, Fisher Scientific No S-23) was put in dupli-

Table 1. Descriptions of the soil sites[z]

Soil	Location	Vegetation or surface coverage	Slope position
Calcareous Black Weirdale (CBW-calc.)	53° 27' N, 105° 28' W	Fallow	Lower
Orthic Black Hoey (OBH-orth.)	52° 52' N, 105° 47' W	Wheat stubble	Middle
Calcareous Black Blainie-Lake, saline (CBB-saline)	52° 47' N, 105° 46' W	Cultivated grass	Lower
Orthic Gray Luvisol Waitville, cultivated (OGLW-cult.)	53° 29' N, 105° 20' W	Flax stubble	Upper
Orthic Gray Luvisol Waitville, native (OGLW-nat.)	53° 29' N, 105° 19' W	Aspen forest	Middle

[z] The moisture content of the soil at the sampling in g kg^{-1} was 157 (CBW-calc.), 113 (OBH-orth.), 168 (CBB-saline), 47 (OGLW-cult.), 45 (Ae horizon of OGLW-nat.), and 483 (the litter layer of OGLW-nat.).

Table 2. Selected physical and chemical properties of the soils

Soil	Soil properties[z]									
	pH	EC (mS cm^{-1})	FC (g kg^{-1})	Bulk density (g cm^{-3})	SAR	Inorganic C	Organic C (g kg^{-1})	Organic N	NO_3-N	NH_4-N (mg kg^{-1})
CBW-calc.	7.9	0.52	201	1.02	0.13	1.2	60	5.18	7	13
OBH-orth.	7.1	0.36	174	1.15	0.13	0.2	43	3.78	10	10
CBB-saline	8.1	4.2	247	1.06	0.72	1.6	42	3.98	6	12
OGLW-cult.	7.1	0.25	98	1.26	0.12	0.4	22	1.59	7	5
OGLW-nat. (Ae)	5.7	0.18	72	0.82	0.11	0	13	0.79	0.5	6
OGLW-nat. (litter)	6.7	0.82	635	0.12	na	0.22	313	21.2	1	99
OGLW-nat.[y]	na[x]	na	na	na	na	0.02	42	2.75	0.6	15

[z] pH (soil:water = 1:1); EC (electrical conductivity) was determined in filtered solutions of soil suspensions (soil:water = 1:2); FC (field capacity moisture content) (Klute 1986); Bulk density was obtained by measuring the volume and weight of the soil column (oven-dry basis); SAR (sodium adsorption ratio) (Rhoades 1982); Inorganic and total soil C (Tiessen et al. 1981, 1983); Organic C was calculated as the difference between the total and inorganic C; 2 M KCl extractable NH_4-N and NO_3-N (Technicon Industrial Systems 1973, 1978); Organic N was calculated as the difference between organic N (2 M KCl extractable NH_4-N, NO_3-N + NO_2-N) and total soil N (Thomas et al. 1967; Technicon 1978).

[y] Average values for the native Orthic Gray Luvisol Waitville. The soil column of the native Luvisol had two parts, a litter layer (litter) and a layer of Ae horizon (Ae). The litter layer made up 10 ± 0.5% of the total mass of the column.

[x] Not applicable.

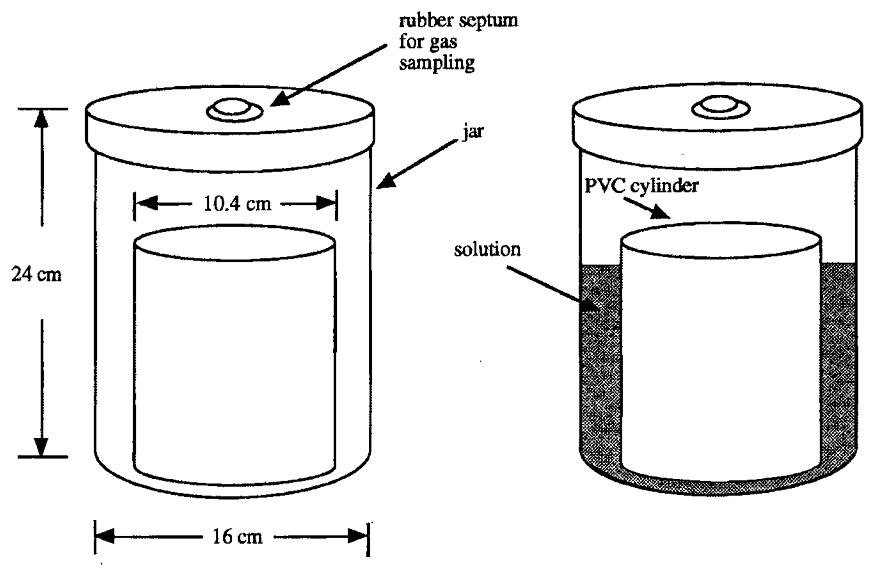

Fig. 1. The incubation systems for nonflooded and flooded soils. The soil column is inside the PVC cylinder and not visible from the figure.

cate to PVC cylinders (13 × 10.4 cm) to reach a height of 10 cm and flooded as checks for the flooded treatments. The litter layer and Ottawa sand were not treated at various field capacity moisture contents because the water could not be held uniformly in these materials.

At the end of incubation, nonflooded soils were leached by adding 0.001 M $CaCl_2$ solution to the soil surface at a solution to soil ratio of 2:1 (wt/vol). For the flooded soils, the flooding solutions in the jars were used in the leaching. The cylinders that contained soil columns were placed on Buchner funnels (6 × 12.5 cm) and when necessary, vacuum was applied to keep a leaching rate of about 8 mL min^{-1} kg^{-1}.

Gas Sampling, and pH, EC and Eh Measurements

Gases emitted from the incubated soils were sampled weekly through a rubber septum in the jar lid using plastic syringes. After sampling, the jars were placed in a fumehood and opened to the atmosphere for 2 h before resealing to assure that the concentrations of CO_2 and CH_4 of air-occupied space in the jars were the same as those of the atmosphere (380 ± 30 µL CO_2 L^{-1}air and 1.8 ± 0.3 µL CH_4 L^{-1}air).

For the flooded treatments, changes in pH and **electrical conductivity** (**EC**) of the flooding solution were also determined after gas sampling. The determinations were made for solutions on top of the soil column inside the cylinder and also for solutions in which the cylinder was standing using a pH (Fisher Model 825 MP) and an electrical conductivity meter (Horiba Model ES-12). The averaged pH and EC values of the two solutions were reported. The errors of pH and EC determinations were less than ± 0.05 pH and ± 0.01 mS cm^{-1}, respectively.

The redox potentials (Eh) of the soils were measured immediately after sampling the gas using a combined platinum/AgCl electrode attached to the pH meter. The electrode was inserted 4 cm into the soil column. Field observations in submerged rice soils have shown that the Eh at this depth may represent an average redox potential of the top 10 cm soil profile (Yu 1985). The electrode was calibrated by a standard Eh solution which contained 0.1 M $Fe(NH_4)_2(SO_4)_2$, 0.1M $FeNH_4(SO_4)_2$ and 1 M H_2SO_4 (Light 1972). In each measurement, the emf was recorded for at least 10 min so that a relatively steady (Δ emf/Δt ≤ 3 mV min^{-1}) reading was obtained. The errors of the measurement were less than ± 11 and ± 5 mV for the nonflooded and flooded soils, respectively. The measured Eh is a mixed potential of the soils — a weighted average of the potentials of all the redox couples present (Bohn 1968).

Leachate Analysis

Soil leachates were analyzed immediately after being filtered through 0.45-µm membrane filters. Total and inorganic C were determined by a carbon analyzer (Beckman Industrial, Model 915B Tocamaster). Water soluble organic C leached was calculated as the difference between the total and inorganic C in the leachates. Total N in the filtered soil leachates was determined using persulfate oxidation (Reveh and Avnimelech 1979). NH_4-N and NO_3-N + NO_2-N in the leachates were measured by AutoAnalyzer methods (Technicon Industrial Systems 1973, 1978). Water soluble organic N was calculated as the difference between the total and inorganic N in the leachates.

Carbon dioxide carbon (CO_2-C) evolved from the soils was measured by a Gas Partitioner (Fisher-Hamilton Model 29) with a thermal conductivity detector. A two column combination system, Porapak Q (50/80 mesh) and molecular sieve 13X (42/60 mesh), was equipped with the Partitioner and operated at 25°C. Methane carbon (CH_4-C) was determined by a HP 5890 SERIES II Gas Chromatograph equipped with a HP Porapak Q column (80/100 mesh) and a flame ionization detector. The temperatures for the column and detector were set at 50 and 250°C, respectively.

Statistical Analysis

The means of the observations were reported for soil treatments. The significance of the difference between the flooded and nonflooded treatments was identified for each soil by a *t* test. One factor ANOVA analysis was conducted separately for the flooded and nonflooded systems. The ANOVA analysis was followed by a LSD multiple comparison (Steel and Torrie 1980) to indicate the significance of the difference between the means. A correlation analysis also was done for studying the relationship between CO_2 emission and incubation time.

RESULTS

Leachable C and N

Four to ten times more total C was leached ($P < 0.01$) from the flooded than from the nonflooded soils (Table 3). Soluble organic C accounted for 50-97% of the total leached C from the flooded soils. For the nonflooded treatments, the largest loss of total C was from the CBB-saline followed by the CBW-calc. (Table 3). It was not the case for the flooded treatments, in which the CBW-calc., followed by the OGLW-nat., lost more total C than the other soils due to a larger loss of SOC.

In contrast to total carbon losses, total leachabe N from the flooded soils was up to four times less than from the nonflooded soils, with the exception of the native Luvisol (Table 4). However, flooding enhanced the loss of SON ($P < 0.01$) from all the soils studied. Negligible NO_3- and NO_2-N were found in the leachates of the flooded soils (≤ 0.07 mg kg^{-1}) and the same is true for NH_4-N for the nonflooded soils (≤ 1.5 mg kg^{-1}). Nitrate and nitrite accounted for 97.4-99.9% of the inorganic N leached from the nonflooded soils whereas ammonium nitrogen made up 99.5-99.9% of the inorganic N leached from the flooded soils. Furthermore, NO_3-N and NO_2-N made up at least 88% of the total leachable N from the nonflooded soils whereas NH_4-N made up less than 63% of the total N leached from the flooded soils.

In addition to the N leached from the Ae layer of the soil, the litter layer contributed 23 mg N kg^{-1}, accounting for 29% of the total leached N from the native Luvisol.

CO_2-C and CH_4-C Evolution

Total gaseous C loss from the flooded soils was lower ($P < 0.01$) than from the nonflooded soils (Table 5). Over the 8-wk incubation, more CO_2-C was evolved from the nonflooded soils ($P < 0.01$) than from the flooded soils. For the flooded native Luvisol, approximately 69% of the total CO_2-C evolved was from the litter layer which released CO_2-C at a rate of 3802 (mg kg^{-1}) during the incubation. Flooding caused CH_4 evolution from the soils. In contrast, for the nonflooded soils, the CH_4 concentration in the air-occupied space of the container was lower than the atmospheric CH_4 level after incubation, leading to a negative CH_4 flux. After each week of incubation, 80-95% of the atmospheric methane in the container was absorbed.

There was a significant linear relationship between the incubation time and the rate of CO_2-C evolution from the flooded soils during the period of 1-8 wk (Fig. 2). In con-

Table 3. Amount of carbon leached from the flooded and nonflooded soils after 8 wk of incubation[z]

Soil	Organic C		Inorganic C		Total C[y]	
	Nonflooded	Flooded	Nonflooded	Flooded	Nonflooded	Flooded
	(mg kg^{-1})					
CBW-calc.	62	354	17	353	79	707
OBH-orth.	28	177	0.4	220	29	398
CBB-saline	107	153	33	412	139	565
OGLW-cult.	29	140	0.5	172	29	313
OGLW-nat.	59	630	0.4	20	59	650
LSD (0.01)	4	10	1	7	4	19

[z] Carbon leached from the flooded litter layer of the native Luvisol in mg kg^{-1} was 44 (inorganic), 760 (organic) and 804 (total).
[y] Total C = sum of leached organic and inorganic carbon.

Table 4. Amounts of nitrogen leached from the flooded and nonflooded soils after 8 wk of incubation[z]

Soil	Organic N		NO_2-N+NO_3-N		NH_4-N		Total N[y]	
	Nonflooded	Flooded	Nonflooded	Flooded	Nonflooded	Flooded	Nonflooded	Flooded
	(mg kg^{-1})							
CBW-calc.	12	15	107	0.02	0.08	11	119	26
OBH-orth.	6.0	10	49	0.07	0.05	17	55	27
CBB-saline	5.9	10	84	0.04	0.1	9	90	19
OGLW-cult.	5.9	22	46	0.05	0.1	21	52	43
OGLW-nat.	6.5	30	57	0.02	1.5	49	65	79
LSD (0.01)	2	3	4	0.03	0.1	3	7	6

[z] Cumulative nitrogen leached from the flooded litter layer of the native Luvisol in mg kg^{-1} was 58 (organic), 0.04 (NO_3-N+NO_2-N), 174 (NH_4-N) and 232 (total).
[y] Total N = sum of leached organic, NO_3-N+NO_2-N and NH_4-N.

Table 5. Cumulative carbon evolved from the flooded and nonflooded soils during 8 wk of incubation[z]

Soil	CO_2-C		CH_4-C		Total C evolved[y]	
	Nonflooded	Flooded	Nonflooded	Flooded	Nonflooded	Flooded
	(mg kg^{-1})					
CBW-calc.	159	87	-0.03	10	159	97
OBH-orth.	283	138	-0.02	16	283	154
CBB-saline	295	168	-0.02	112	295	280
OGLW-cult.	189	72	-0.02	13	189	85
OGLW-nat.	1279	552	-0.03	138	1279	690
LSD (0.01)	8	7	0.02	2	10	10

[z] Cumulative CO_2-C and CH_4-C evolved from the flooded litter layer of the native Luvisol was 3802 and 459 mg kg^{-1}, respectively.
[y] Total C = sum of CO_2-C and CH_4-C.

trast, the rate of CO_2-C evolution from the nonflooded soils varied little with time and the average rates (mg kg^{-1} d^{-1}) were 22.8 (OGLW-nat.). 3.4 (OGLW-cult.). 5.1 (OBH-orth.), 2.8 (CBW-calc.) and 5.3 (CBB-saline).

The initial CH_4-C evolution (0.286 mg kg^{-1} d^{-1} on average) occurred in the Black saline soil during the 3rd week of flooding (Fig. 3). No detectable CH_4 in other flooded soils was found until the 4th week and the average rates of CH_4-C evolution (mg kg^{-1} d^{-1}) during the week were 0.229 (OGLW-nat.), 0.049 (OGLW-cult.), 0.003 (OBH-orth.), and 0.006 (CBW-calc.). The rate for OGLW-nat. was lower than that for the CBB-saline in the first 5 wk, but increased rapidly after 5 wk and became the highest at the end of the incubation. The rate for the OBH-orth, was also initially lower, but eventually became higher ($P < 0.01$) than those for the OGLW-cult. and CBW-calc.

EC, pH and Eh

A rise of ionic strength of the flooded soils was indicated by a continuous increase in the solution EC values during the incubation. At the end of 8-wk incubation, the EC was 1.40 (CBW-calc.), 1.11 (OBH-orth.), 1.87 (CBB-saline), 0.98 (OGLW-cult.) and 1.13 mS cm^{-1} (OGLW-nat.), which more than tripled the values at the beginning. The corresponding ionic strength data for these EC values may be obtained by a linear relationship: Ionic strength (mol L^{-1}) = 0.013 × EC (mS cm^{-1}) (Griffin and Jurinak 1973).

The pH of the solution of the flooded soils increased to a maximum between the 3rd and 5th weeks, then decreased, and remained relatively constant between the 6th and 8th weeks during the incubation. The pH of flooded treatments was lower at the end than that at the beginning of the experiment: 7.66 vs. 8.03 (CBW-calc.), 7.11 vs. 7.25 (OBH-orth.), 7.59 vs. 7.97 (CBB-saline), 7.44 vs. 7.61 (OGLW-cult.) and 6.87 vs. 7.15 (OGLW-nat.).

The Eh of the flooded soils dropped quickly from 318 to about 150 mV 1 d after flooding and then decreased gradually to attain a relatively constant level between the 6th and 8th weeks: -232 (CBW-calc.), -226 (OBH-orth.), -261 (CBB-saline), -212 (OGLW-cult.) and -272 (OGLW-nat.) (Fig. 4). In contrast, the Eh of the nonflooded soils varied little (± 10 mV for each soil) and was above 290 mV throughout the incubation period.

DISCUSSION

Losses of Water-soluble Carbon

In all soils, flooding enhanced the loss of SOC and inorganic C, regardless of variations in original soil properties such as pH, electrical conductivity, field capacity moisture content, bulk density and **sodium adsorption ratio (SAR)**. The loss of soluble C results from the interaction of several biological and chemical processes. Production of SOC in soils

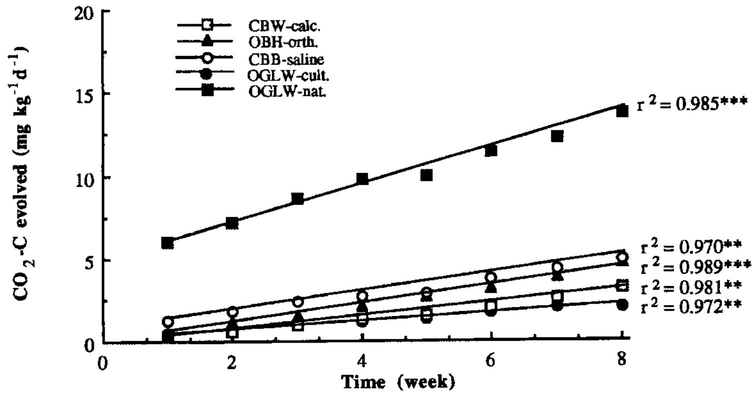

Fig. 2. The rate of CO_2-C evolution from the flooded soils as a function of time.

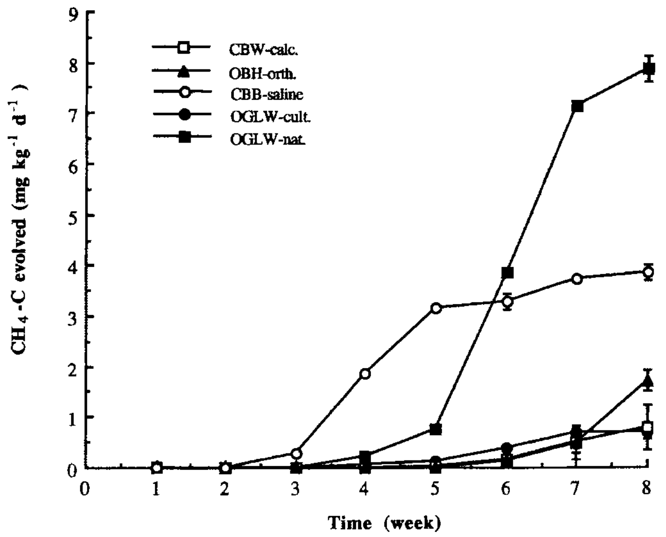

Fig. 3. The rate of CH_4-C evolution from the flooded soils. Bars indicate standard deviation of the mean. The error bars are not visible when their size is smaller than the data point.

involves processes of fragmentation, depolymerization and solubilization of soil organic components and the intensity of these processes depend on the nature of the soil and associated conditions (Reid et al. 1982; Beckwith and Butler 1983). Work in submerged rice fields showed a substantial production of low-molecular-weight SOC such as ethanol, butanol, 2-propanol, acetic, malonic and formic acids through fermentation (Ponnamperuma 1972).

The low redox conditions in the flooded soils may have played a role in promoting SOC production since for much of the incubation time, the Eh of the flooded soils was below -150 mV, a redox potential low enough to cause fermentation in some soil systems (Bohn et al. 1985).

The increase in ionic strength of solution observed during flooding may have weakened the solubilization of SOC. A high ionic strength changes the structure of organic coatings on soil particles and makes them less easy to be desorbed (Ghosh and Schnitzer 1980), depressing the amount of SOC leached (Evans 1985; Evans and Sorensen 1986). Although a substantial increase of ionic strength of the flooded soils was observed during the incubation, the depressing effect of a high ionic strength apparently did not outweigh other processes that enhanced the SOC production. The increase in the ionic strength may also be a transitory phenomenon. Studies on submerged rice soils showed that electrical conductivities of the soils increased to a maximum initially, and then decreased close to their original values after 10 wk of flooding (Ponnamperuma 1972).

The larger amount of inorganic C leached from the flooded compared with nonflooded soils was mainly attributed to organic acid production caused by flooding. Compared with nonflooded soils, a much larger quantity of soil carbonates will be dissolved in flooded soils due to the presence of organic acids produced under flooding conditions (Ponnamperuma 1972). The enhanced solubilization of carbonate may have had an effect on the CO_2 evolution because of the equilibrium between CO_2 and $CaCO_3$ in the solution.

Differences in soil properties can be used to explain differences in amounts of C leached among the various soils. The depressing effects of a high electrical conductivity (or ionic strength) on SOC leaching can be seen in CBB-saline soil. Only 1.5 times more SOC was leached under flooded than nonflooded conditions compared to 4 to 10- fold increase for the other soils. The greater amount of SOC in the nonflooded saline soil (CBB-saline) compared with other soils was partially attributed to its higher pH. A high pH enhances the solubilization of organic matter through hydrolysis (Stevenson 1982). More inorganic C was leached from the CBW-calc. and CBB-saline than other soils because of the larger amount of total inorganic C in these soils. Similarly, the amount of SOC leached from the flooded soils followed the same order as the total organic C content of the soils. For the nonflooded soils, however, less

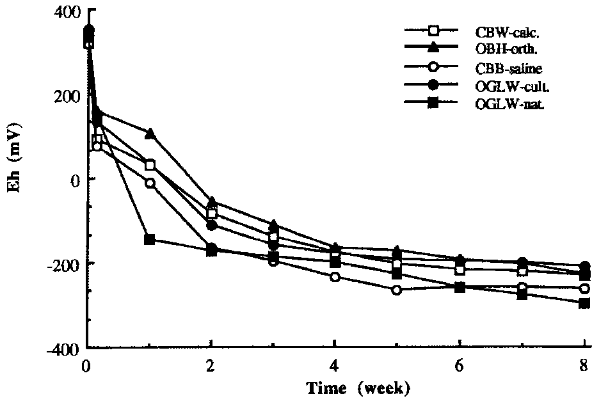

Fig. 4. Changes in redox potentials of the flooded soils. The error of the Eh measurements was ±5 mV.

SOC was leached from the CBW-calc. than from the CBB-saline, although the CBW-calc. had a larger amount of total organic C. Although the pH of the two soils is similar there is a difference in both the amount and type of salts present. The CBW-calc. soil had a low salt and a high Ca content which favors bonding of organic matter to the soil surfaces and formation of strong aggregates. The CBB-saline with a higher salt content and higher SAR, on the other hand, would favor weaker bonding of organic matter to surfaces and dispersion of aggregates.

Losses of Water Soluble Nitrogen

The enhanced leaching of SON by flooding was similar to results from a disturbed Orthic Black soil (Wang and Bettany 1994). The enhancement of both leachable SOC and SON in the flooded system suggested that some flooding-generated SOC may contain N.

The quantity and form of inorganic N leached varied with redox conditions and soil type. Nitrate was dominant in the nonflooded system. The reducing condition in the flooded soils inhibited the formation of NO_3- and NO_2-, and so favored the presence of NH_4+. Nitrification can be inhibited when Eh of a soil system is below 200 mV (Patrick and Jugsujinda 1992), a condition observed in the flooded soils only 2 d after flooding. The Eh dependence of type and amount of leachable inorganic N was consistent with the work on disturbed soils under similar flooding conditions (Larson et al. 1991; Wang and Bettany 1994) and with data obtained from long-term flooded rice soils (Ponnamperuma 1972; Stevenson 1986). Denitrification no doubt occurred, and reduced a portion of nitrate and nitrite in the flooded soils. Nitrate is the first substrate that disappears from the soil following O_2 depletion (Reddy and Patrick 1983).

The larger amount of total N leached from the nonflooded soils resulted from the large quantity of NO_3- + NO_2-N in the leachates. The highest amounts were found in the CBW-calc. leachates — typical of many Black soils that have been summerfallowed. The observation that more total N was leached from the flooded native Luvisol than the nonflooded was due to the influence of flooding on the litter layer. Compared with the soils, the flooded litter layer released similar amounts of NO_3- and NO_2-N, but a much larger quantity of NH_4-N and SON. Flooding allows for the extraction of SON from plant debris which becomes leachable along with NH_4-N. Some transformation of SON to NH_4-N probably occurred in the flooded litter layer as shown by a great difference between the amounts of SON and NH_4-N leached. Although this difference for the flooded native Luvisol was not as great as that for the flooded litter layer, it is possible that, for the soil, part of the NH_4-N derived from the litter layer was adsorbed and/or fixed by the mineral components of the Ae layer below.

Unlike organic C, the amount of organic N leached from both flooded and nonflooded soils was not consistent with the soil organic N content. In particular, the amounts of SON leached from the two flooded Luvisols was higher than those from the other soils, suggesting the highly labile nature of SON in the Luvisols under flooding conditions.

Losses of Carbon Dioxide

The weaker CO_2-C evolution from the flooded soils compared with the nonflooded soils probably reflects differences in soil organic matter decomposition. Under anaerobic conditions, the oxidation of organic substrates is incomplete and soil organic matter ferments; in the process the intermediate products including fatty acids and CO_2 can be reduced to CH_4 (Stevenson 1986). The initially low CO_2-C evolution could be further attributed to a temporarily depressed respiration of the soil microbes. However, the higher CO_2-C evolution in the latter period could also be due to the increased dissolution of carbonates as organic acids accumulated under flooding.

There was a linear relationship between the rate of CO_2-C evolution and incubation time for the flooded soils. No such correlation was found when a disturbed Orthic Black soil was flooded for 12 wk (Wang and Bettany 1993). Whether it was a transient phenomenon or not remains unclear because only an 8-wk incubation was conducted. The disturbed Orthic Black soil showed a larger flux of CO_2-C, which reached a maximum in the first 10 wk, in flooded compared with nonflooded systems. The disturbance of the soil (destroying soil structure, air-drying soil sample, etc.) together with the flooding effect (solubilization, fermentation, etc.) may have made substrates more available in the disturbed system during the initial incubation period.

The increased CO_2 evolution in the flooded soils should have increased the concentration of CO_2 dissolved in the soil solution and was partially responsible for depressing the soil pH in the later part of the incubation. By generating more H_3O^+ and HCO_3^- in solution, the increased CO_2 evolution, together with flooding-induced dissolution of carbonates (Table 3) and Mn and Fe compounds (Larson et al. 1991), also contributed to higher electrical conductivity of the soil solution as the incubation progressed.

There was no discernible relationship between the total soil organic C and CO_2-C evolved, probably due to the presence of carbonate which was also involved in CO_2 equilibrium in the solution. However, in the native Luvisol, the litter layer seemed to play a dominant role in generating CO_2-C, which was suggested by the low carbonate content and large quantity of CO_2 evolution of the flooded litter layer.

Losses of Methane

Methane emission from the flooded soils may be expected because of the strong reducing conditions. However, the nonflooded soils absorbed CH_4 from the air-occupied space in the incubation jar, as indicated by the negative values of CH_4-C evolution and unexpected absorbing strength of the soils. This result supports the claim that soil acts as both a sink and source for atmospheric CH_4 (Schutz et al. 1990).

The production of CH_4 in paddy soils requires a strong anaerobic environment (Ponnamperuma 1972). Few studies, however, have given attention to the redox conditions when CH_4 fluxes were studied. Methanogenesis takes place when Eh of a homogeneous system is below -244 mV (pH 7) (Stevenson 1986). In our flooded soils, the Eh required for CH_4 emission to be observed was close to -200 mV. A further decrease in Eh was clearly associated with an increase in CH_4 evolution. The observation that more CH_4-C evolved from the CBB-saline and OGLW-nat. than from the other soils may be also in part explained by the lower redox potentials of the two soils during the incubation.

The rate of CH_4-C evolution did not appear to be related to the total organic carbon content of the soil and the amount of SOC leached. Furthermore, the CH_4-C evolved from the litter layer of the native Luvisol made up approximately 33% of the total CH_4-C evolution from the soil. Hence, the nature of the substrate in the system may have affected the production of CH_4. Methane emissions of up to 200 mg CH_4 m^{-2} d^{-1} are reported for northern peatlands (Moore and Knowles 1990) and from 2.3 to 350 mg CH_4 m^{-2} d^{-1} for subarctic fens (Windsor et al. 1992). It is difficult to extrapolate our results to field conditions, but if we convert the data (Table 5) to an area basis we find the emission rate in the range of 27 (CBW-calc.) to 324 mg CH_4 m^{-2} d^{-1} (OGLW-nat.) over 8 wk. In the field, these rates would probably be reduced substantially because of lower temperatures and shorter flooding intervals.

Although transient kinetics of the CH_4 evolution was evident, one might still expect measurable CH_4 emission in the field. In the spring and early summer, soils in low slope positions and many potholes may remain saturated for several weeks after snowmelt. In the present study, only the top 11 cm soil was studied and the reducing condition was developed in aerobic systems. In the field, CH_4 emission may also originate from deeper soil layers where reducing conditions are stronger and are more permanent, and there may be adequate substrates due to downward movement of SOC (Xiao et al. 1991). Sufficient reducing conditions probably will be achieved quickly even in top soils after flooding in the spring, since the micropores of the soil already have a O_2 deficiency during the winter due to presence of frozen soil moisture retarding air exchange. Nevertheless, the significance of CH_4 emission from usually well-drained soils should be finally judged by field experiments.

CONCLUSIONS

Flooding substantially enhanced the leaching of SOC and evolution of CH_4 from the usually well-drained soils, but decreased the loss of CO_2. The amount of SOC leached from the flooded soils appeared to be related to soil organic C content. Compared with other soils, the greater loss of SOC from the Calcareous Black (saline) at field capacity moisture content was likely attributed to high alkalinity and sodium content of the soil, whereas a relatively small quantity of SOC leached under flooded conditions was partly due to a high solution ionic strength. Soil properties such as pH, SAR and EC may be useful in interpreting SOC data for saline soils.

The majority of N leached from the nonflooded soils was NO_3- and NO_2-N. In contrast, flooding enhanced solubilization of N-containing organic matter and inhibited nitrification, leading to the dominance of NH_4-N and SON in the total N leached. The quantity of SON leached from the flooded soils was not consistent with soil organic N content. The N-rich litter layer of the native Luvisol, however, was an important source of leachable SON in the flooded soil.

While there was a linear correlation between the amount of CO_2 evolved and incubation time for the flooded soils, the relationship between soil organic C and CO_2 emission was not found, probably due to the complication of enhanced dissolution of carbonates (an abiotic source of CO_2) under flooding conditions. Apparently, a low redox potential (approximately -200 mV) was required for the generation of measurable CH_4 emission from the soils and the quantity of CH_4 emitted was not necessarily related to soil C and SOC leached. Although the calculated flux of CH_4 evolution from the Calcareous Black (saline) and native Gray Luvisol was well above those observed in northern peatlands, the result of this laboratory study can not be directly extrapolated to the field. Field investigations are required to assess the regional impact of episodic events such as snowmelt and precipitation on the loss of C and N from prairie and forest soils.

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