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EFFECT OF FREQUENT CHANGES IN AEROBIC AND ANAEROBIC CONDITIONS ON REDOX POTENTIAL AND NITROGEN LOSS IN A FLOODED SOIL

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Summary—The effect of frequent changes in aerobic and anaerobic conditions on redox potential and N loss in a flooded soil was investigated under laboratory conditions. Increasing the frequency of changing from aerobic to anaerobic conditions from 48 h aerobic–48 h anaerobic to 6 h aerobic–6 h anaerobic increased N loss. A separate experiment showed that losses were somewhat less when the frequency was increased from 6 h aerobic–6 h anaerobic to 3 h aerobic–3 h anaerobic, but the loss of N again increased when the frequency was further increased to 1.5 h aerobic–1.5 h anaerobic. N losses were due to alternate nitrification (aerobic period) and denitrification (anaerobic period), possibly coupled with chemical decomposition of nitrite at the greater aerobic–anaerobic frequencies.

INTRODUCTION

Alternate aerobic and anaerobic conditions in a flooded soil provide a favorable environment for N loss. NH_4^+–N is nitrified during the aerobic period and undergoes denitrification during the anaerobic period. In a recent study (Reddy and Patrick, 1975) we found that increasing the frequency of alternate aerobic and anaerobic conditions increased N loss. A greater loss was determined in a 2-day aerobic–2-day anaerobic cycle, the shortest cycle studied, than in longer cycles. It was anticipated in the design of the experiment that such a short cycle of aerobic–anaerobic conditions would result in less loss than in longer but fewer cycles (all of the incubations were carried out for 128 days). Since the shortest cycle resulted in the greatest loss, the present study was designed to measure the effect of even more frequent aerobic–anaerobic changes on N loss.

MATERIALS AND METHODS

A Crowley silt loam from the Rice Experiment Station, Crowley, Louisiana was used in this study. The soil had a total C content of 0.7%, total N content of 0.08%, and a pH of 5.6. The soil was thoroughly mixed and ground to pass a 0.4-mm mesh sieve. An energy source of 0.5% finely ground rice straw (48% C) and 100 $\mu g\,N.g^{-1}$ of soil as $(NH_4)_2SO_4$ or KNO_3 containing 10.146 or 10.077 atom % excess ^{15}N, respectively, was thoroughly mixed with the soil.

The experimental setup was similar to the one described by Reddy and Patrick (1975), with few modifications. Alternate aerobic and anaerobic conditions were established by passing either air (21% O_2) or Ar (O_2 free) through a three-way solenoid valve attached to a timer as shown in Fig. 1. The timers were set at selected intervals (Table 1), and air and Ar were supplied automatically. There was a rapid turnover of gas in the flask with a displacement time of 2 min. Redox potential measurements were made using a Pt electrode and a saturated calomel half cell. The redox potential was detected with a mV meter connected to a strip chart recorder.

The study was carried out for two different incubation periods. In Experiment I total incubation was 128 days with the treatments varying from 6 h aerobic and 6 h anaerobic to 48 h aerobic and 48 h anaerobic. In Experiment II total incubation was 64 days with the treatments, varying from 1.5 h aerobic and 1.5 h anaerobic–6 h aerobic and 6 h anaerobic. All treatments are listed in Table 1. In Experiment I, the samples were analysed at the end of incubation for NH_4^+–N, NO_3^-–N, and organic–N. In Experiment II samples were removed during incubation at 0, 4, 8, 16, 32 and 64 days, and analyses were carried out for NH_4^+–N, NO_3^-–N, NO_2^-–N and organic–N. NO_3^-–N and NO_2^-–N were analysed by the phenoldisulfonic acid and the Griess-Ilosvay methods, respectively. NH_4^+–N was analysed using steam distillation and nesslerization and organic–N by the modified Kjeldahl method (Bremner, 1965a). Labelled N was determined in both organic and inorganic fractions using a Dupont Model 21-614 mass spectrometer with an isotope ratio attachment (Bremner, 1965b).

RESULTS AND DISCUSSION

Redox potential of the soil during frequent changes in aerobic and anaerobic conditions in flooded soil

The effect of frequent changes in aerobic–anaerobic conditions on redox potential are shown for the first 10 days of each treatment of Fig. 2. The redox potential decreased to approximately +300 mV during the anaerobic period and increased to approximately +600 mV during the aerobic period for the 6 and 6 h treatment. The minimum redox potential recorded was less than +300 mV during the anaerobic period for the 12 and 12, 24 and 24, and 48 and 48 h treatments. Redox potential values below approximately

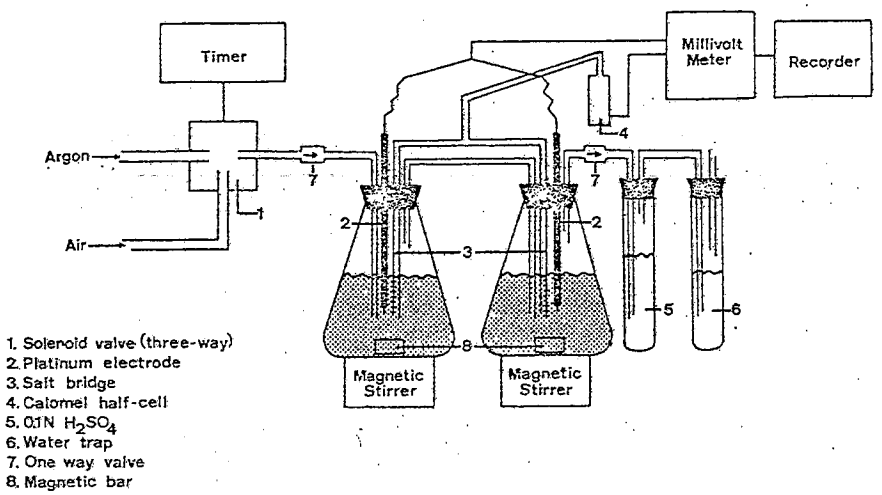

Fig. 1. Diagram of the apparatus used to study the effect of frequent changes in aerobic and anaerobic conditions on redox potential and nitrogen loss in a flooded soil.

+340 mV have been reported to be favorable for denitrification (Pearsall and Mortimer, 1939; Patrick, 1960). The maxima and minima of redox potentials at the end of each aerobic period and each anaerobic period are presented in Figs. 3a and 3b for the 128-day incubation. The redox potential recorded at the end of each aerobic period was about +640 mV for all treatments, whereas the redox potential at the end of each anaerobic period was as low as +300 mV during the early part of incubation, but increased to about +500 mV during the latter part in the 6 and 6 h treatments probably as a result of energy depletion. Similar trends were observed for other treatments having frequent changes in aerobic and anaerobic conditions.

The redox potential measured during alternate aerobic and anaerobic conditions for 64 days in Experiment II are presented in Fig. 4. In the treatment where the change from aerobic to anaerobic conditions was made every 1.5 h, the redox potential reached maxima of approximately +640 mV during the aerobic periods. The minimum redox potential values reached at the end of the 1.5 h anaerobic period was approximately +400 mV during the early part of incubation and approximately +550 mV during the latter part. Similar trends in the redox potential were also obtained for the 3 and 3 h treatment.

At the beginning of each aerobic period the redox potential increased rapidly when air (21% O_2) was introduced, and the potential remained relatively stable during the aerobic period. When Ar was bubbled into the soil suspension at the beginning of each anaerobic period, however, the redox potential decreased very slowly and was somewhat erratic. These results indicate rapid oxidation of reduced components upon introduction of O_2 into the anaerobic soil and slow reduction of oxidized components upon introduction of Ar in the aerobic soil. It is possible

Table 1. Changes in total nitrogen as influenced by frequent changes in aerobic and anaerobic conditions in flooded soil

Length of Aerobic period (21% O_2) (h)	Length of Anaerobic period (Ar) (h)	Number of complete cycles during incubation period	Total Nitrogen ($\mu g.g^{-1}$)			
			At beginning of experiment	At end of experiment	Net Loss	Loss (%)
EXPERIMENT I						
6	6	256	936.0 ± 32.1	588.2 ± 9.8	347.8	37.2
12	12	128	936.0 ± 32.1	636.5 ± 38.9	300.0	32.1
24	24	64	936.0 ± 32.1	702.7 ± 38.8	233.5	24.9
48	48	32	936.0 ± 32.1	695.8 ± 9.8	240.2	25.7
EXPERIMENT II						
1.5	1.5	512	962.0 ± 30.1	780.6 ± 29.3	181.4	18.9
3	3	256	962.0 ± 30.1	808.8 ± 9.7	153.2	15.9
6	6	128	962.0 ± 30.1	793.8 ± 19.4	168.2	17.5
6*	6*	128	962.0 ± 30.1	726.4 ± 29.3	235.6	24.5

*NO_3^--N (100 $\mu g.g^{-1}$) was added instead of NH_4^+-N at the beginning of the experiment.

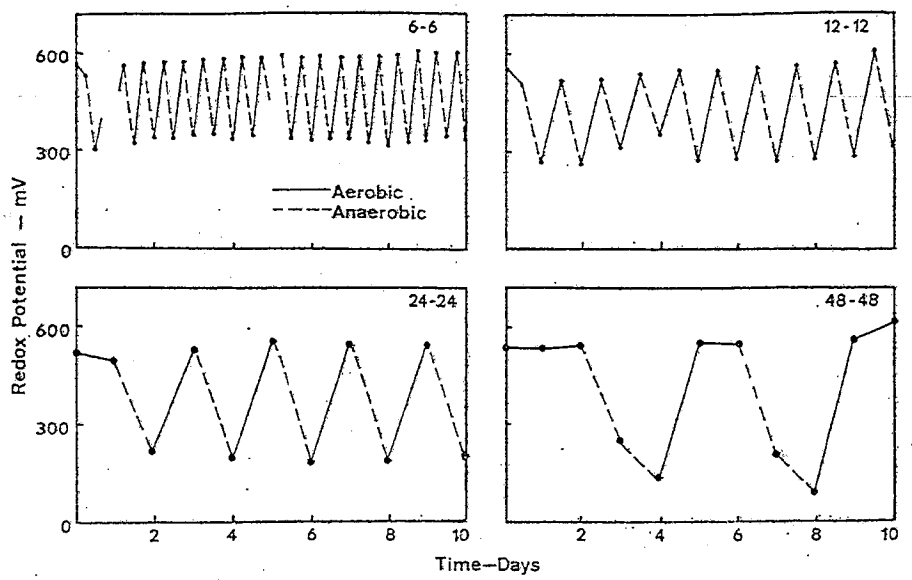

Fig. 2. Changes in redox potential for 10-day period as influenced by frequent changes in aerobic and anaerobic conditions in Experiment I.

that the oxidation processes were largely chemical, such as oxidation of Fe^{2+} to Fe^{3+} by O_2, while the reduction processes were biological and therefore somewhat slower. Also, NO_3^--N produced in the soil during the aerobic period tends to keep the redox potential at a high value and results in a slow decrease in redox potential.

Loss of native and added N as a result of frequent changes in aerobic and anaerobic conditions

Loss of total N (native + added) as influenced by frequent changes in aerobic and anaerobic conditions for two different incubation periods are presented in Table 1. The N losses were as high as 37.2% of the total N in short-term cycles of 6 h alternate aerobic

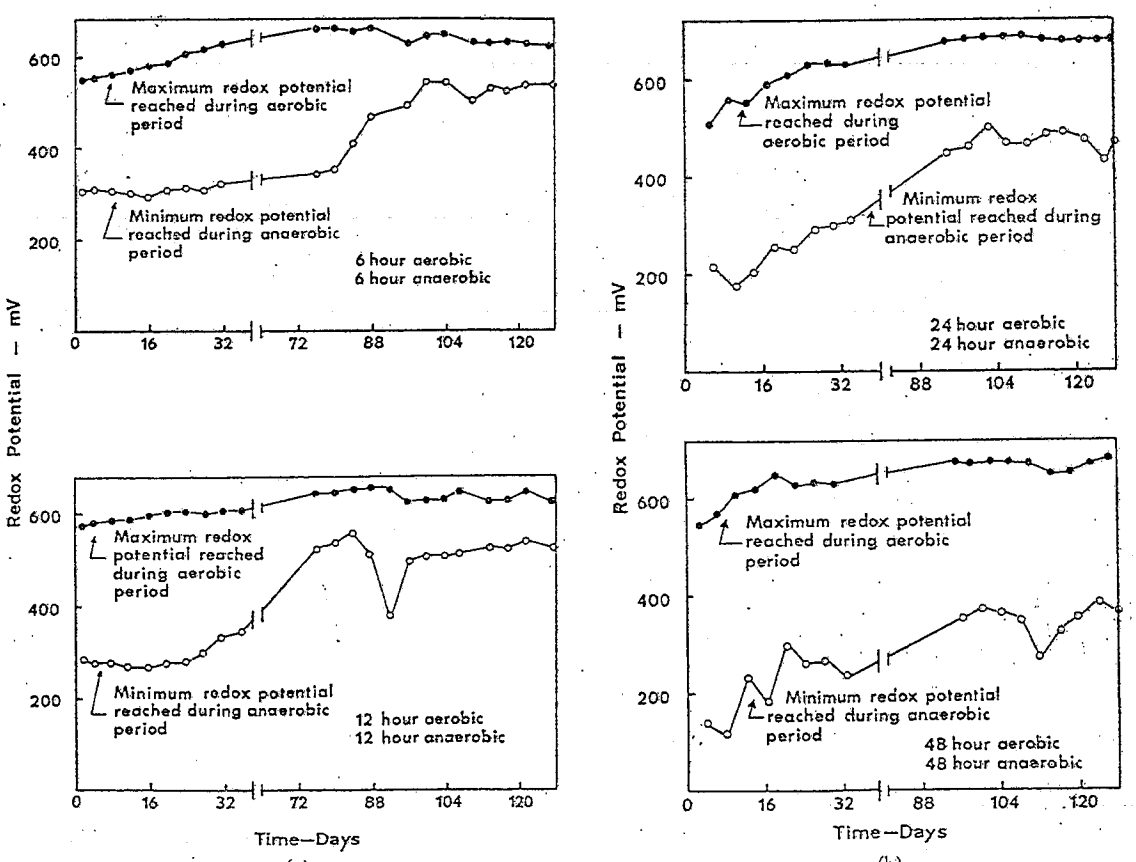

Fig. 3a, b. Maxima and minima of redox potential values reached at the end of each aerobic and anaerobic period during 128-day incubation in Experiment I.

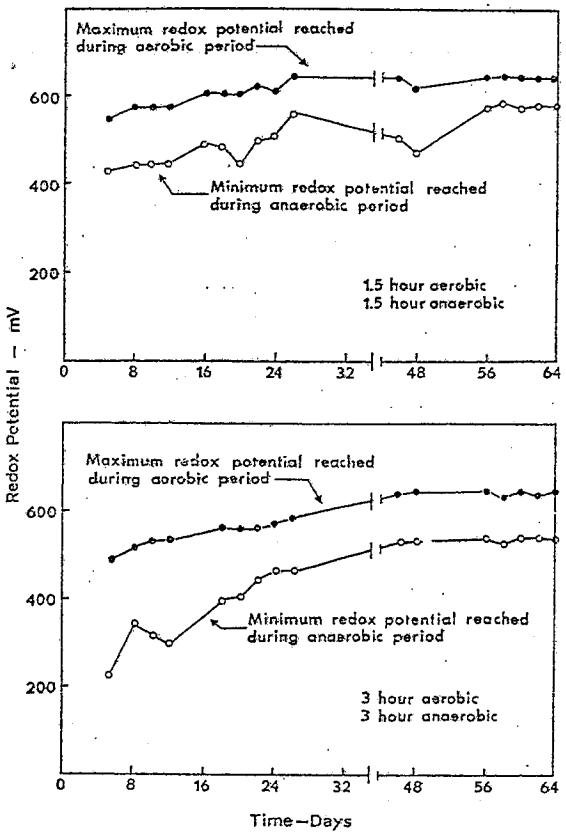

Fig. 4. Maxima and minima of redox potential values reached at the end of each aerobic and anaerobic period during 64-day incubation in Experiment II.

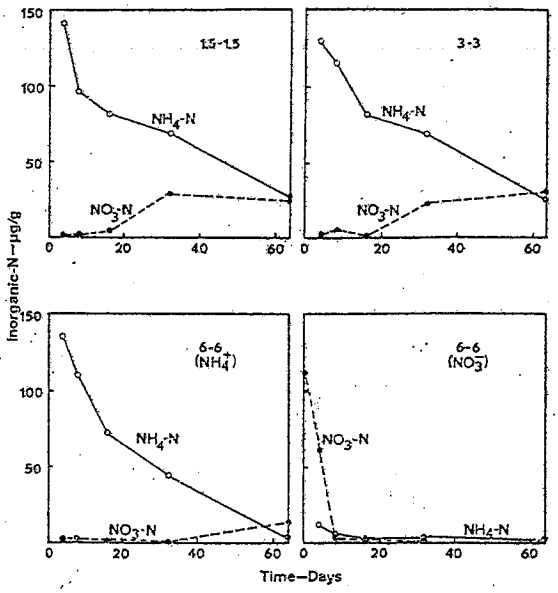

Fig. 5. Changes in inorganic nitrogen as influenced by frequent changes in aerobic and anaerobic conditions during 64-day incubation in Experiment II.

and anaerobic conditions, followed by 32.1, 24.9, and 25.7% for 12 h, 24 h and 48 h alternate aerobic–anaerobic cycles, respectively for a period of 128 days (Experiment I). In all the treatments no inorganic N (NH_4^+–N or NO_3^-–N) was recovered at the end of incubation, showing that part of the added N plus mineralized NH_4^+–N was lost as a result of nitrification (aerobic period) and denitrification (anaerobic period) and that the remaining N was incorporated into microbial tissue. The redox potential fell below approximately +340 mV during the anaerobic period during the early part of incubation, indicating favorable conditions for denitrification.

Large losses of native and added N were also encountered in Experiment II, where short-term cycles were as frequent as 1.5 h aerobic and 1.5 h anaerobic. The losses were 18.9, 15.9 and 17.5% of total N for 1.5 h, 3 h, and 6 h alternate aerobic and anaerobic conditions respectively, during 64 days. For the 6 h treatment where NO_3^--N was used instead of NH_4^+–N, the loss of total N was 24.5%. Changes in inorganic N (unlabelled + labelled N) at several incubation times are presented in Fig. 5 for these treatments. NH_4^+–N disappeared rapidly from the soil suspension. There was a slight buildup of NO_3^--N, especially in the 1.5 h and 3 h treatments, but not enough to compensate for the NH_4^+-N decrease. NO_3^-–N was apparently being formed and lost from the system. For the treatment with 6 h aerobic–anaerobic periods, NO_3^-–N was probably lost be denitrification. Denitrification may have been responsible for N loss in the soils subjected to shorter aerobic–anaerobic periods, although the fact that the redox potential did not decrease below about +500 mV suggests that some other mechanism may have been involved. NO_2^-–N formed during the nitrification process may have undergone chemical decomposition. The maximum NO_2^-–N concentration found in the treatments, however, was 0.5 $\mu g.g^{-1}$ of soil.

The amount of added labelled N remaining in the soil at the end of the 128-day incubation (Experiment I) is shown in Table 2. For all treatments no labelled N was recovered in the inorganic fraction at the end of incubation. The net loss of added labelled N (not recovered in either organic or inorganic fractions) was high, 71.2, 66.3, 65.0 and 61.3% of added labelled N for 6 h, 12 h, 24 h and 48 h alternate aerobic and anaerobic conditions, respectively. The added labelled N was subjected to nitrification during the aerobic period and denitrification during the anaerobic period.

The amount of labelled N recovered at the end of the 64-day incubation for Experiment II is shown in Table 3. The net loss of labelled N was 38.8, 24.5,

Table 2. Fate of applied $^{15}NH_4$–N (100 $\mu g.g^{-1}$ soil) in various treatments following frequent changes in acrobic and anaerobic conditions in a flooded soil during 128-day incubation

N-Fraction	Treatments (h)			
	6–6	12–12	24–24	48–48
	Labelled N $\mu g.g^{-1}$			
Organic N	28.8 ± 0.85	33.7 ± 1.05	35.0 ± 0.50	38.7 ± 0.45
Inorganic N	—*	—	—	—
N-Unaccounted for	71.2	66.3	65.0	61.3

*Samples did not contain enough total inorganic N (<1.2 $\mu g.g^{-1}$) for labelled N analysis in the mass spectrometer.

Table 3. Fate of applied $^{15}NH_4$–N (100 $\mu g.g^{-1}$ soil) in various treatments following frequent changes in aerobic and anaerobic conditions in a flooded soil during 64-day incubation

N-Fraction	Treatments (h)			
	1.5–1.5	3–3	6–6	6–6*
	Labelled N $\mu g.g^{-1}$			
Organic-N	41.90 ± 2.31	46.40 ± 0.77	45.4 ± 1.18	6.6 ± 3.0
NH_4^+–N	12.72 ± 0.76	16.61 ± 0.76	---**	---
NO_2^-–N + NO_3^-–N	6.60 ± 1.74	12.53 ± 1.40	---**	---
N-Unaccounted for	38.78 ± 0.20	24.46 ± 0.13	54.60 ± 1.18	93.40 ± 3.0

*NO_3^-–N (100 $\mu g.g^{-1}$) was added instead of NH_4^+–N at the beginning of the experiment.

**Samples did not have enough NH_4^+–N or NO_3^-–N (<0.36 $\mu g.g^{-1}$) for labelled N analysis in the mass spectrometer.

and 54.6% of applied N for the 1.5 h, 3 h and 6 h treatments, respectively. Under complete aerobic conditions for 128 days, 18% of applied NH_4^+–N was not recovered, indicating that mechanisms other than denitrification were probably involved in N loss. No NH_3 was recovered in the traps provided, showing that NH_3 volatilization was not responsible.

The results of this study show that increasing the frequency of changing from aerobic to anaerobic conditions from 48 h aerobic and 48 h anaerobic to 6 h aerobic and 6 h anaerobic increased the loss of total N and labelled inorganic N. In an additional experiment where even more frequent changes in aerobic–anaerobic conditions were made, losses were less for a 3 h aerobic–3 h anaerobic treatment than for the 6 h treatment. Increasing the frequency of change of aerobic–anaerobic conditions to 1.5 h, however, resulted in greater N loss than for the 3 h treatment. Nitrogen loss was apparently due to nitrification during the aerobic period followed by denitrification during the anaerobic period. NO_2^-–N formation and chemical decomposition of NO_2^-–N may also have been involved in N loss, especially for the more frequent changes in aerobic–anaerobic conditions.

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