

Degradation of monoethanolamine in soil

Anne W. Ndegwa, Ron C.K. Wong, Angus Chu, Laurence R. Bentley, and Stuart R.D. Lunn

Abstract: Monoethanolamines (MEA) are commonly used by the natural gas industry to remove acid gases from the natural gas stream. A series of pan studies was conducted to examine the biodegradability of MEA in soil recovered from a gas plant site under various environmental conditions. Experimental results indicate that MEA was successfully biodegraded or transformed into other compounds under both aerobic and anaerobic conditions even at concentrations greater than 1500 mg/kg. Ammonium, acetate, and nitrogen gas were the dominant by-products in these experiments. The generation of nitrogen gas suggests that simultaneous nitrification and denitrification occurred because of the existence of anoxic zones resulting from diffusion limited oxygen transport into the soils. Cold temperatures (5 °C) reduced the biodegradation rates significantly compared to rates at room temperature.

Key words: bioremediation, monoethanolamine, ammonia, acetate, pan study, cold temperature.

Résumé: Les monoéthanolamines sont fréquemment utilisées par l'industrie du gaz naturel pour retirer les gaz acides des courants gazeux. Une série d'études en laboratoire a été menée pour examiner la biodégradabilité des monoéthanolamines, dans les sols récupérés d'un site de raffinerie de gaz, sous différentes conditions atmosphériques. Les résultats expérimentaux indiquent que les monoéthanolamines ont été biodégradées avec succès ou transformées en d'autres composés sous des conditions aérobies ou anaérobies, même à des concentrations supérieures à 1500 mg/kg. L'ammoniac, l'acétate et le gaz azoteux étaient les sous-produits dominants lors de ces expériences. La génération de gaz azoteux suggère que la nitrification et la dénitrification surviennent simultanément en raison de l'existence de zones anoxiques qui résultent de la diffusion limitée du transport d'oxygène dans les sols. La basse température (5 °C) a réduit considérablement les vitesses de biodégradation par rapport aux vitesses à la température ambiante.

Mots clés: biorestauration, monoéthanolamine, ammoniac, acétate, étude en laboratoire, basse température.

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Introduction

Monoethanolamine (MEA) is commonly used by the natural gas industry to remove acid gases from natural gas (e.g., H₂S and CO₂) in a process called "sweetening". Monoethanolamine belongs to the group of chemicals known as alkanolamines. Alkanolamines are bifunctional molecules with amine and alcohol functional groups occurring in the same compound. As a result, they undergo a wide variety of useful reactions common to amines and alcohols (Dow 1980). The chemical identity and physical and chemical properties of ethanolamine are summarized in Table 1.

Few studies have been done on biodegradation of MEA in

water (Chong 1994; Emtiazi and Knapp 1994; Stepan et al. 1997) and soil (Gallagher et al. 1995; Sorensen et al. 1997, 2000; Lee and Portier 1999). Many of these studies have been conducted on demonstration sites. The objective of this study is to elucidate degradation pathways of MEA in soil under aerobic and anaerobic conditions.

Biodegradation of ethanolamine

The biodegradability of MEA (Verschueren 1996) is not surprising since it is a common biological product (i.e., constituent of phospholipids). The ability of microorganisms to degrade ethanolamine has been studied in several bacteria and different metabolic pathways have been suggested (Narrod and Jakoby 1964; Kaplan and Stadtman 1968; Scarlett and Turner 1976; Tchobanoglous and Burton 1991; Frings et al. 1994; Knapp et al. 1996).

Ethanolamine in soil is biodegraded by a process that involves hydrolysis to ammonium and acetaldehyde (Fig. 1). Under aerobic conditions, ammonium can be oxidized to nitrite and then nitrate. The acetaldehyde in a hydrolysis reaction degrades to ethanol and acetic acid. In aerobic conditions, acetic acid and ethanol are readily consumed by bacteria.

In Fig. 1, the acetic acid is shown as the electron donor for denitrification of nitrate, however, ethanol or other organic carbon can also act as the electron donor. The degradation of MEA is carbon rich in the sense that more ethanol and acetic acid is

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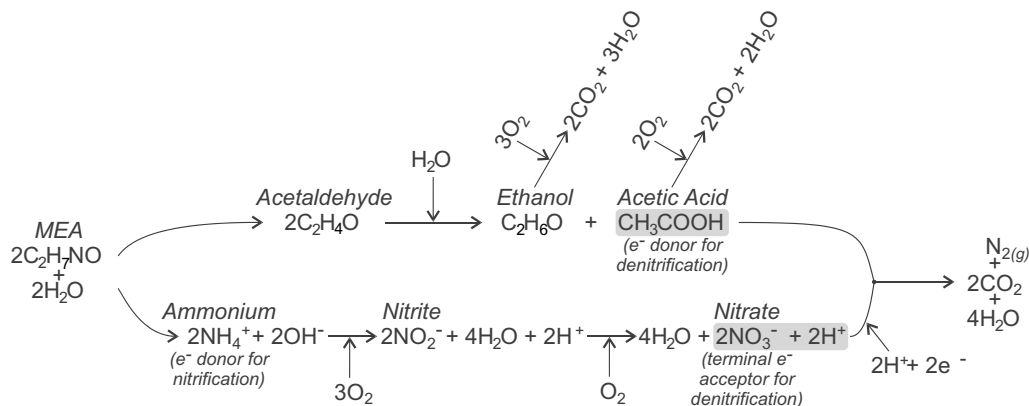
A.W. Ndegwa, R.C.K. Wong, and A. Chu. Department of Civil Engineering, The University of Calgary, Alberta, AB T2N 1N4, Canada.

L.R. Bentley.¹ Department of Civil Engineering and the Department of Geology and Geophysics, The University of Calgary, Alberta, AB T2N 1N4, Canada.

S.R.D. Lunn. Imperial Oil Resources Ltd., Calgary, Alberta, AB T2P 3M9, Canada.

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¹Corresponding author (e-mail: lbentley@ucalgary.ca).

Fig. 1. Biodegradation of monoethanolamine.**Table 1.** Properties of monoethanolamine.

| Characteristic | Property data |
|--------------------|--|
| CAS No. | 141-43-5 |
| Common synonyms | Monoethanolamine; MEA; 2-aminoethanol; ethylolamine; beta or 2-hydroxyethylamine; beta-aminoethyl; glycinol; colamine; olamine, thiofalco. |
| Molecular formula | C_2H_7NO |
| Chemical structure | $OH - \begin{array}{c} H & H \\ & \\ C & - & C \\ & \\ H & H \end{array} - NH_2$ |
| Physical state | Viscous colorless liquid with a mild ammonia-like odor. |
| Molecular weight | 61.08 |
| Boiling point | 170.8 °C at 760 mmHg |
| Water solubility | Completely miscible |
| pH | 12.6 at 25 °C for 25% (w/w) aqueous solution; 12.1 (0.1 N aqueous solution) |
| Specific density | 1.012 |

produced than required for denitrification. Both compounds are easily degraded by bacteria in aerobic conditions, producing a large biochemical oxygen demand.

Ammonia has a boiling point of -33.3 °C (Montgomery 1991) and therefore is volatile at room temperature. Ammonium (DeSimone and Howes 1998) and MEA (Sorenson et al. 1997) sorb to soil materials such as clay minerals, organic matter, hydroxides and oxides.

Nitrification and denitrification require different redox conditions and are traditionally regarded as essentially separate processes in either time or space. However, studies have suggested that nitrification and denitrification can occur simultaneously at the micro-scale with no major build up of NO_3^- (Rittmann and Langeland 1985; Gupta 1997; Xie et al. 1999; Abbasi and Adams 2000). The precise location and kinetics of the two processes has not been established (Arts et al. 1995; Madigan et al.

1996). The hypothesis is that oxygen is consumed more rapidly than it can diffuse into soil peds greater than 4 mm in diameter producing anoxic centers. Using readily biodegradable carbon as an electron donor, denitrification can then occur in the center of the peds.

Methods and materials

Test material

A former gas processing plant located in northwestern Alberta, Canada, was the source of soil for this laboratory study (Wong and Alfaro 2001). The site has been known to contain high concentrations of monoethanolamine and degradation by-products. A drilling program determined that the chemicals are found up to 6 m below ground level. The soil stratigraphy at the site consists of a few centimetres of fill overlying a 5–6 m thick layer of glacial till. The glacial till can be classified as clay with low plasticity. This clayey till consists of 20%–42% silt, 24%–41% clay, with the remainder being sand. Its in situ density is about 2.02 g/cm³. Water level data from piezometer installations show that the near-surface water table fluctuates up to 2 m with the seasons. However, neutron probe data show that the fine grained glacial till remains near saturation except in the upper 0.5 m. The in situ hydraulic conductivity of intact till is typical of low-conductivity soils and is approximately 10^{-7} – 10^{-8} m/s.

The gas plant soil used in the pan tests was removed by hand excavation, and was stored in a cold room at 1 – 2 °C prior to starting the bench- scale experiments.

Bench-scale pan study

A series of pan studies were conducted to examine the biodegradability of MEA and MEA-related materials in the soil under various environmental conditions. Disposable aluminum pans were used to hold approximately 1 kg of soil. Each soil pan was 21.5 cm in diameter and 3.5 cm in depth and held a shallow layer of the soil.

Glass desiccators 25 cm in diameter with a volume of 3 L sealed with silicon high vacuum grease were used as gas tight

Table 2. Summary of pan test details and results.

| Pan test details | Run label | Temp (°C) | pH range | Initial extractable MEA concentration (mg/kg of soil) | Average removal time (days) |
|---|--------------|-----------|----------|---|-----------------------------|
| Aerobic soil batch 1 | R1-SOIL-1,2 | 21–22 | 8.6–9.2 | 1250 | 10 |
| Aerobic soil batch 2 | R2-SOIL-1,2 | 21–22 | 8.9–9.2 | 0 | — |
| Aerobic soil batch 3 | R3-SOIL-1,2 | 21–23 | 8.6–9.1 | 267 | 3 |
| Aerobic soil batch 3; MEA added | R4-MEA-1,2 | 23–24 | 8.8–9.3 | 1533 | 11 |
| Aerobic soil batch 3; cold temp | R3-COLD-1,2 | 5–10 | 8.6–9.1 | 267 | 20 |
| anaerobic soil batch 3; MEA added | R4-ANA-1,2 | 23–24 | 8.6–9.3 | 1533 | 9 |
| Aerobic/nitrification inhibited soil batch 3 | R3-NITIN-1,2 | 21–23 | 8.7–9.0 | 150 | 3 |
| Aerobic/nitrification inhibited soil batch 3; MEA added | R4-NITIN-1,2 | 23–24 | 8.8–9.2 | 1413 | 10 |

containers to hold the soil pans. To minimize moisture losses from the soil, 100 mL of distilled deionized water was placed at the bottom of each desiccator to reduce the evaporation of soil moisture. The pan weight was regularly monitored for moisture losses. The gas port of each desiccator was modified so that gas samples could be taken from the headspace and the atmospheric pressure inside the gas tight desiccator could be measured.

Test matrix

A total of 16 pan tests (8 aerobic, 4 nitrification-inhibited, 2 cold room, and 2 anaerobic tests) in 4 separate runs were conducted on 3 soil batches of approximately 45 kg from the gas plant site (Ndegwa 2001). In addition, two control pan studies (e.g., autoclaved control and a sodium azide amended control) were monitored to investigate abiotic processes.

The independent variables examined in this study were oxygen, nutrients, nitrification inhibition (i.e., by the addition of nitrapyrin to the soil), temperature, and MEA. Refer to Table 2 for a detailed list of the conditions examined in the pan experiments. Duplicate experiments were conducted and the results were consistent (Figs. 2 and 3). Given the reproducibility between duplicates, in some cases only the data from one duplicate is shown. A detailed description of each variable can be found on the following list:

- **Oxygen:** Aeration was implemented by loosening and spreading the soil evenly over the pan in the aerobic experiments. Anaerobic condition was created by purging the desiccators with a gas mixture of 10% carbon dioxide (v/v), 5% hydrogen (v/v), and 85% nitrogen (v/v). Alumina pellets (3.2 mm) coated with a 0.5% (by weight) palladium catalyst were placed inside the desiccator to scavenge for any remaining oxygen.
- **Nutrients:** This run studied the effect of nutrient on the biodegradation rate of MEA and degradation products in the soil.

Based on total carbon measurements on the soil, approximately 1.35 g of KH_2PO_4 was added to 1 kg of soil to ensure that the soil had adequate phosphorus for biodegradation. The addition of KH_2PO_4 had no effect on the results.

- **Nitrification inhibitor:** To verify the presence of nitrification activity, nitrapyrin (2-chloro-6-trichloromethyl-pyridine) and sodium sulfate were applied in solution to the soil at a concentration of 240 mg/kg of soil (APHA 1998).
- **Temperature:** Effect of cold temperature on reaction rates were investigated by placing desiccators in a cold room set at 5 °C. Other pan tests were conducted under ambient room temperature conditions of between 20 °C and 25 °C.
- **MEA:** Approximately, 2000 mg of MEA per kg of soil was added to the remaining soil from Run 3, in a mixed solution of one part distilled deionized water and one part MEA.

Test and analytical procedures

A 20-L concrete mixer was used to homogenize the soil with admixtures. Then, the soil was placed in the aluminum pan inside the desiccator. Soil from the pan studies were sampled regularly and analyzed for moisture content, pH, anions, and cations. Headspace gases were also collected and analyzed.

Gas sampling

Gas samples were taken from the desiccator headspace using a 10-mL gas tight glass syringe. Headspace pressure measurements were also made and incorporated into gas production calculations. Gas composition was analyzed using a Hewlett-Packard 5880A gas chromatograph (GC) equipped with a thermal conductivity detector. A 60/80 carboxen-1000 molecular sieve column with a length of 4.75 m and an inner diameter of 2.1 mm was used (Supeclo Chromatography Ltd.). Dräger™

Fig. 2. Evolution of extractable MEA under aerobic and anaerobic conditions at ambient temperature.

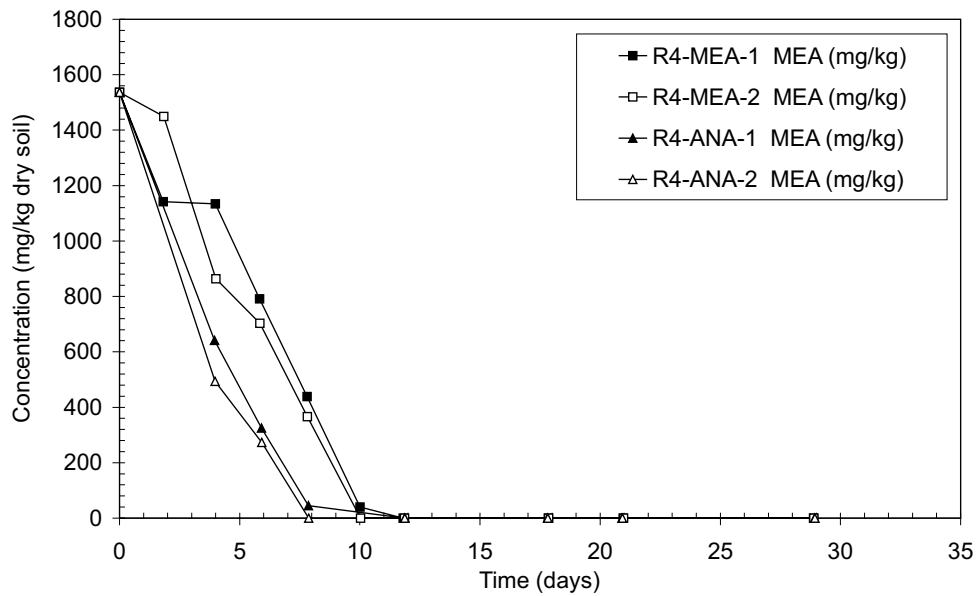
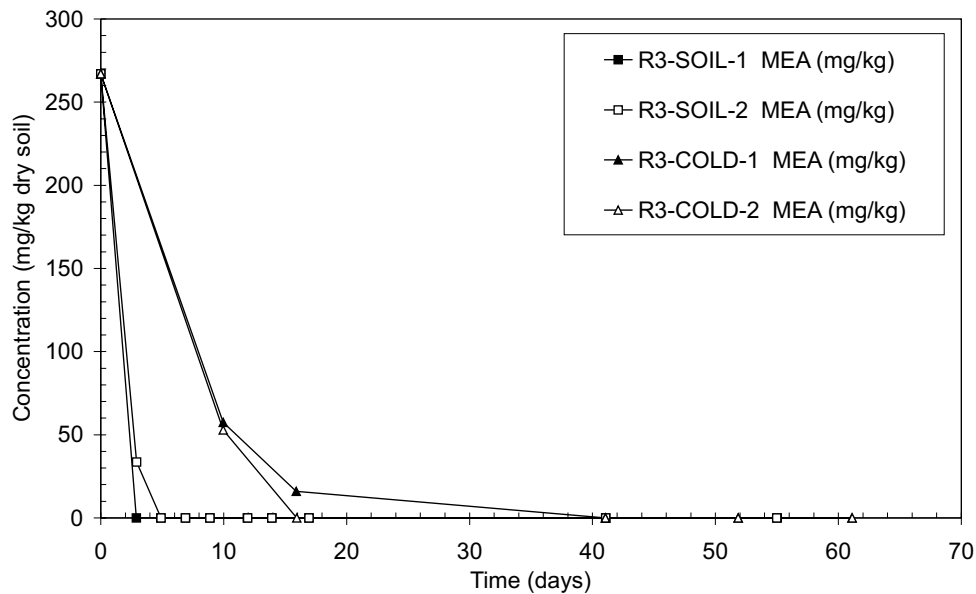


Fig. 3. Evolution of extractable MEA under aerobic conditions at ambient and 5 °C temperature.



gas detection tubes were used to determine ammonia concentrations in the desiccator headspace. This method has a detection limit of 0.5% (v/v).

Moisture content

The moist soil was air dried in an oven at 105 °C for 24 h, and weighed to determine its moisture content.

Soil extracted for analysis

A soil–water slurry was prepared using one part soil and one part distilled deionized water. These extracts were used for the

determination of a number of analytes including MEA, ammonia, acetate, and pH. The volume of distilled water was corrected for the initial moisture content of the soil. The slurry was mixed using a mechanical shaker for approximately 60 min to allow sufficient time for extraction. The slurry was then centrifuged for 45–60 min to separate particulates from the liquid fraction. The supernatant was drained off and filtered through a sterile 0.45- μ m membrane filter to complete the extraction procedure.

Because the absolute and relative amounts of various solutes are influenced by the soil–water ratio at which the extract is made (Reitemeier 1946), the ratio used to obtain the extract

was kept constant to obtain consistent results. However, some of the MEA and ammonium remained sorbed on the solid fraction, so a total accounting of the nitrogen in the system is not possible using the soil water extract. Consequently, the following analysis uses the trends in the soil extract concentrations with time.

Ion chromatography (IC)

Ion chromatography was used in this study because of its well documented application for the analysis of alkanolamines (Mrklas 2002; Gallagher et al. 1995). Cation analysis, including MEA and ammonium, was done using a cation exchange column (Dionex™ IonPac CS15, 4 mm in diameter, 250 mm in length). An analytical temperature of 44 °C was used. An eluent of 6 mM methansulfonic acid and a regenerant of 20 mM tetrabutylammonium hydroxide were used at a flow rate of 0.6 mL/min and 1.2 mL/min, respectively. Anion analysis, including acetate, was conducted using a carbonate selective exchange column (Dionex™ IonPac AS4A-SC, 4 mm in diameter, 250 mm in length). The eluent consisted of 1.8 mM sodium carbonate and 1.7 mM sodium bicarbonate at a flow rate of 2 mL/min. The regenerant consisted of 25 mM sulfuric acid at a flow rate of 4 mL/min.

Results

Results of the study are presented in Figs. 2–6 and Table 2. Soil water extract indicates that MEA was completely removed in approximately 10 d in the aerobic case and 12 d in the anaerobic case (Fig. 2). In the aerobic cold room case the MEA was gone in about 18–20 d compared to 4–5 d for the same soil at room temperature (Fig. 3). The initial extractable MEA concentrations were as high as 25 000 mg/kg of soil. In addition, 2000 mg/kg of soil was added to the native soil in Run 4. However, the extractable MEA was only about 1500 mg/kg of soil indicating that a significant amount of MEA sorbed onto the clay fraction of the soil consistent with the observations of Sorenson et al. (1997).

In the aerobic cases, soil extract ammonia concentration initially declines and then reaches a fairly constant value after 12 d in the room temperature studies and somewhat longer in the cold room study (Fig. 4). In the anaerobic case, ammonia concentrations increase with time and possibly level out after about 12 d. Although ammonia concentrations declined, nitrate accumulations were not observed and the concentrations were consistently less than 6 mg/kg of soil (Ndegwa 2001). The addition of nitrapyrin did not seem to affect the results and no accumulation of ammonia was observed. Small amounts of ammonia gas were measured in the headspace, but they can only account for 0.1% to 1% of the measured loss of ammonia and MEA from the soil extract.

Nitrogen gas is produced in all of the aerobic experiments (Fig. 5) with production still occurring over 70 d after the commencement of experiment R1-SOIL-1. However, after an initial small amount of gas production, the anaerobic case shows no

nitrogen gas production and the cold room experiment shows low rates of production. In addition carbon dioxide (data not shown) was also produced in the aerobic experiments. The autoclave experiments showed no nitrogen gas or carbon dioxide production.

In the aerobic cases, acetic acid rapidly declines in concentration, but remains at measurable concentration for the remainder of the experiments. In the anaerobic experiment, acetic acid concentrations continue increasing with time. pH ranged from 8.6 to 9.3, with the low pH values associated with the anaerobic experiments and the accumulation of acetic acid.

Discussion

Degradation of monoethanolamine

Sorensen et al. (1997) observed degradation lag times of 4.5–33 d depending on temperature and aerobic or anaerobic conditions in bio-slurries with MEA sludge. Since the pan study soil came from a site that had been exposed to MEA for many years, the microorganisms present in the soil were probably well acclimated and therefore, no observable lag phase was detected in either aerobic or anaerobic experiments (Fig. 2). The results show rapid MEA degradation in the soil under both aerobic and anaerobic conditions. Sorensen et al. (1997) found that biodegradation rates were strongly influenced by the concentration of ethanolamine and concentrations greater than 1500 mg/kg were found to inhibit microbial growth. However, this pan study showed that MEA concentrations above 1500 mg/kg of soil were rapidly degraded, and the addition of MEA to the soil had no observable impact on the degradation rate.

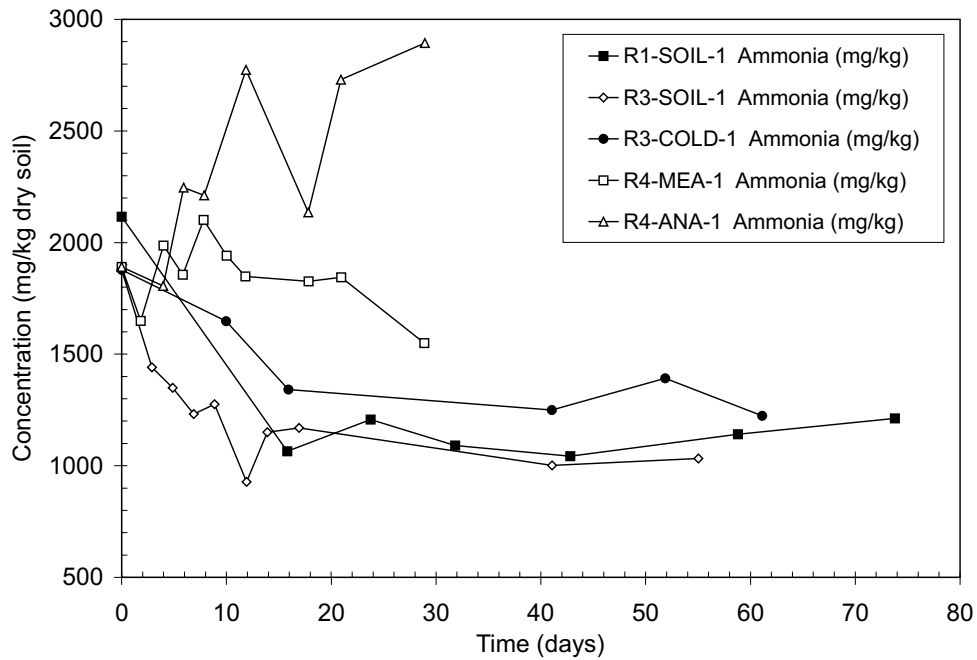
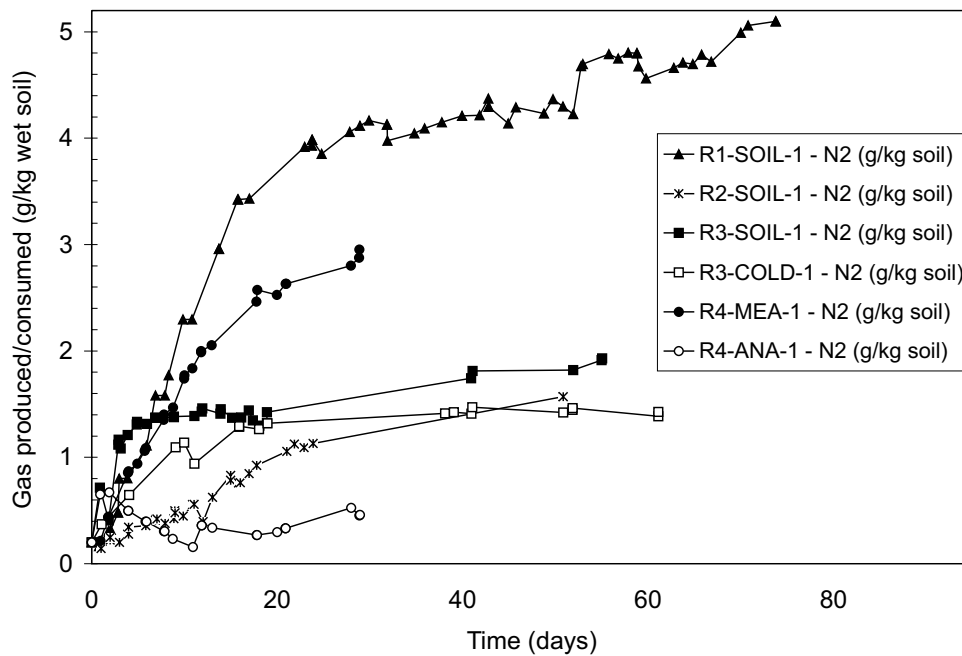
Knapp et al. (1996) showed that amines could be degraded under anoxic conditions and that its degradation was more rapid than under aerobic conditions. However, Sorensen et al. (1997) found that anaerobic degradation rates in soil were about one-tenth of those found under aerobic conditions. Our results indicate similar degradation rates for the aerobic and anaerobic conditions

Sorensen et al. (1997) also found that MEA degradation rates at 6 °C were approximately one-third of the degradation rate observed at 25 °C. Monoethanolamine degradation rates were also found to decrease with a decrease in temperature in the pan study soil. Total degradation of MEA at 5 °C, took twice as long as at ambient temperature conditions (Table 2 and Fig. 3).

The initial extractable MEA concentrations of soil samples from the site varied significantly and were as high as 25 000 mg/L. This indicates that the in situ degradation rates in some locations are very slow. This observation is inconsistent with the rapid degradation rates observed in the pan tests under both aerobic and anaerobic conditions.

In pan tests of Run 4, fresh MEA was observed to sorb onto the solid fraction. Consequently, a reservoir of MEA exists in the solid phase as well as the liquid phase.

Initial extractable ammonia concentrations of the in situ contaminated soil were high, in a range of 1400–2100 mg/kg of soil. These ammonia concentrations were likely the result of in

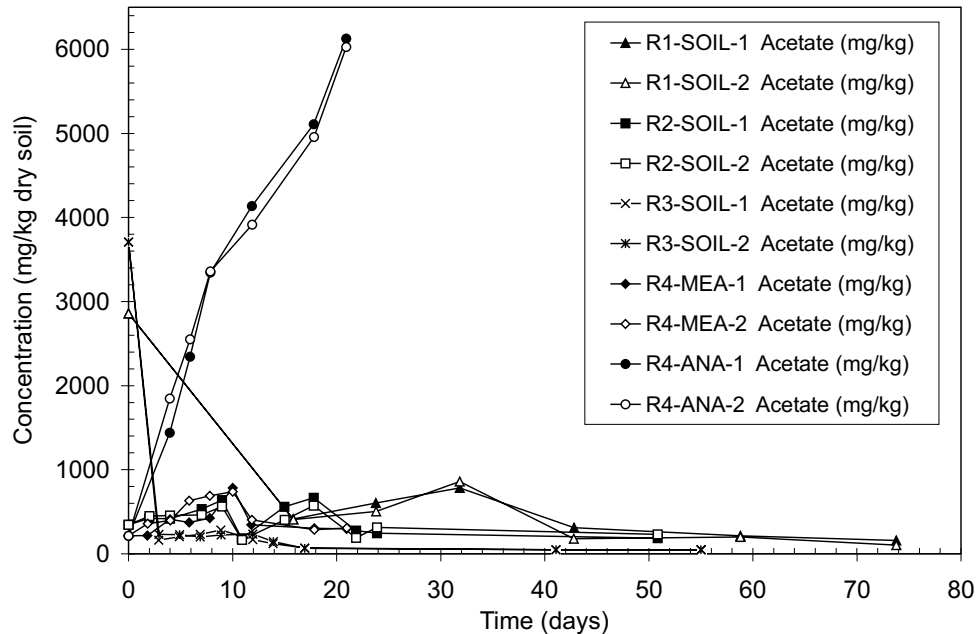
Fig. 4. Evolution of extractable ammonia.**Fig. 5.** Cumulative nitrogen gas production.

situ MEA biodegradation activities in the soil prior to starting the pan study experiments. Extractable ammonia decreased, but then remained fairly constant in the soil water extract. However nitrogen gas production continued throughout the experiments indicating that nitrogen was being converted to gas. These results suggest that a large reservoir of ammonia exists as sorbed ammonium and that ammonium desorbs to replace any declines in ammonium concentrations in the pore water.

Consequently, MEA degrades under aerobic and anaerobic conditions creating a large reservoir of ammonium, ethanol, and

acetic acid. A portion of the ammonium will sorb to the clay fraction producing a large reservoir in addition to the liquid phase concentrations. In the anaerobic case, the reaction stops at this point, because, as is seen in Fig. 1, oxygen is required to oxidize the acetic acid and ethanol or to create nitrate. Stopping the reactions at this point accounts for the lack of nitrogen gas production and the accumulation of acetic acid and ammonia in the anaerobic pan experiments.

Acetate is typically degraded fairly quickly by aerobic bacteria (Verschueren 1996), and, consequently, the continued pres-

Fig. 6. Evolution of extractable acetate.

ence of acetic acid indicates that some locations within the aerobic pan experiments remain anaerobic. In addition, the production of nitrogen gas is evidence of denitrification and, consequently, anaerobic sites. On the other hand, the initial rapid decline of acetate and the implication that ammonium must oxidize to nitrate prior to denitrification is consistent with the obvious existence of oxygen in the aerobic pan experiments. The clay till is fine grained and the diffusion of oxygen from the margins of peds that are exposed to headspace gas will be slow. Given the abundance of acetic acid and ethanol that is produced by the degradation of MEA and slow oxygen diffusion rates, the center of the peds are likely anaerobic. The margins and surface of peds are aerobic or transition zones from aerobic to anaerobic.

One inconsistent result is that the addition of nitrapyrin did not change the results. One explanation is that nitrification, and therefore denitrification, did not occur in any of the experiments. The other possibility is that, for whatever reason, nitrapyrin was not effective in suppressing nitrification. The second explanation seems most likely, because nitrogen gas production was observed in all aerobic pan experiments (Fig. 5). The amount of nitrogen gas produced was correlated to the MEA and ammonium concentrations of soil water extract at the beginning of the experiments. Runs 1 and 4 had the highest concentrations of MEA and ammonia and these pan tests also produced the highest masses of nitrogen gas. Nitrogen gas volumes produced in cold room experiments were lower than room temperature experiment volumes, consistent with the expected lower kinetic rates for both nitrification and denitrification. The anaerobic experiments showed by far the lowest rates of nitrogen gas gen-

eration, since nitrification is suppressed under anaerobic conditions. The production of nitrogen gas was confirmed to be a biotic process, since abiotic controls showed no nitrogen gas production (data not shown).

Assuming that the production of nitrogen gas is due to denitrification, the lack of nitrate accumulation implies that simultaneous nitrification and denitrification was occurring in the aerobic experiments. Dissolved oxygen concentrations above 1 mg/L are cited as optimum for nitrification to occur and if dissolved oxygen levels drop below this value, oxygen becomes limiting and nitrification slows or ceases. Dissolved oxygen concentrations greater than 0.2 mg/L can suppress denitrification in activated sludges (Tchobanoglous and Burton 1991). On the other hand, dissolved oxygen concentrations about 0.5 mg/L were found to be suitable to produce nitrification rates equal to the denitrification rates (Pochana and Keller 1999). Although nitrification and denitrification appear to be occurring simultaneously, our data does not provide evidence to distinguish the locations of the reactions. One possibility is that the reactions are occurring in a transition zone between the oxic exteriors of soil peds and the anoxic interiors. A second possibility is that ammonia is nitrified in the oxic exteriors of the peds and, due to the resultant nitrate concentration gradient, the nitrate then diffuses into the anoxic interior where it is denitrified (Abbasi and Adams 2000). As the ammonia is nitrified, it is replaced by ammonium that desorbs from the clays explaining the relatively constant soil water extract concentrations of ammonia during the production of nitrogen gas. The abundance of acetic acid and ethanol provides electron donors for the denitrification and oxygen sinks to keep the ped centers anoxic.

Conclusions

The experimental results from this study are qualitatively consistent with the proposed MEA degradation pathways seen in Fig. 1. The soils from the field site contained MEA in both the soil water phase and sorbed onto the clay fraction. In addition, the soils contained large reservoirs of ammonium in the soil water phase and sorbed onto the clay fraction, acetate and, presumably, ethanol from in situ degradation of MEA. The residual and added MEA degraded by hydrolysis to ethanol and acetic acid via acetaldehyde and ammonium in both the aerobic and anaerobic experiments. The degradation occurred even at high concentrations of MEA. The degradation rates were similar for the aerobic and anaerobic conditions.

In the anaerobic experiments, the chemical evolution ceased because mineralization of the ethanol and acetic acid and the nitrification of ammonium require oxygen. Acetate and ammonia soil water extract concentrations increased as a result of the degradation of MEA. Without nitrate, denitrification does not occur, explaining the lack of nitrogen gas accumulation.

In the aerobic case, the acetate concentrations in the soil water extract decreased rapidly, but remained measurable throughout the experiments. It is interpreted that the residual acetic acid and presumably ethanol resided at the anoxic interiors of fine grained peds. The exterior of the peds remain oxic due to the contact with the head space gas. In this exterior zone, or a transition zone between the oxic exteriors and anoxic interiors, acetic acid and ethanol are oxidized contributing to carbon dioxide accumulation and ammonium is oxidized to nitrate. The nitrate is then denitrified in the transition zone or in the anoxic interior after diffusion from the nitrification site, contributing to accumulating carbon dioxide and nitrogen gas and explaining the lack of accumulation of nitrate. The nitrification causes an initial reduction in concentration of soil water extract ammonium, but the rate of decline slows as the aqueous phase ammonium is replaced by ammonium desorbing from the clay fraction. Volatilization of ammonia played a minor role. Acetic acid or ethanol (the ethanol pathway is not shown in Fig. 1) act as the electron donor for denitrification of nitrate. MEA degradation produces twice as much organic carbon than required for denitrification. Slow oxygen diffusion through the fine grained peds and the excess biochemical oxygen demand keeps the center of the peds anoxic.

The evidence for simultaneous nitrification and denitrification includes

- A decrease in total ammonia was observed in all aerobic experiments.
- Carbon dioxide gas was produced indicating that biological activity was occurring in the soil.
- An accumulation of nitrogen gas was observed and the amounts of gas produced were correlated to the initial amounts of MEA and ammonia present in the soil water extract.
- Nitrogen gas was not produced in sterile controls indicating that nitrogen gas production was due to biological activity in the soil.
- The presence of acetate in the aerobic pan studies suggests that the three prerequisite conditions necessary for simultaneous nitrification and denitrification existed in the pans. Namely, the existence of an anoxic mass fractions in the soil, the provision of readily biodegradable carbon, and oxic zones.
- Some losses of volatile ammonia to the headspace were observed, but cannot explain the reduction in nitrogen due to measured losses in the soil water extract of MEA and ammonium.

Monoethanolamine degraded completely within 20 d even in the cold room experiment. However, residual MEA is found in the plant site soil many years after closure. Certainly, the conditions in the lab were different, because the soils were broken up and spread out and the temperature conditions were different. On the other hand, high concentrations of ammonium and acetic acid in the field site soils indicate that large quantities of MEA had degraded in situ. Although it is not clear what inhibited the in situ degradation of some of the MEA, the pathways demonstrated by the lab studies will be useful in interpreting the geochemical conditions at this and other sites.

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