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Influence of Red Imported Fire Ants on Greenhouse Gas Emissions from a Piedmont Plateau Pasture

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ABSTRACT

Researchers have previously attempted to relate the influences of many ant species to the nitrogen (N) and carbon (C) cycles. However, the gaseous phases of these cycles have been neglected. A field study was conducted near Auburn University (32°52′N, 85°30′W) in a bermudagrass [*Cynedon dactylon* (L.) Pers] pasture to determine the influence of the red imported fire ant [*Solenopsis invicta* (L.) Buren] on soil emission of three greenhouse gases from April 1999 to April 2000. A completely random design was used with three replications. Treatments consisted of ant influenced soil (mounds) and non-ant influenced control soil. Surface emission rates of N_2O-N, CH_4-C, and CO_2-C were measured bi-weekly using a closed chamber technique. Soil collection to a depth of 100 cm

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was used to determine soil moisture, pH, and status of soil N and C. While the red imported fire ant significantly influenced greenhouse gas fluxes from mound soil, it was concluded that for a bermudagrass pasture in Alabama, the increase of annual emissions of N_2O-N, CH_4-C, and CO_2-C was only 6.95 $g\,N\,ha^{-1}$, 0.16 $g\,C\,ha^{-1}$, 0.92 $kg\,C\,ha^{-1}$, respectively. It is speculated that regional and global budgets of these greenhouse gases may be underestimated when the influence of soil macro-organisms, such as ants, are not taken into account. However, this underestimation may only be slight.

Key Words: Red imported fire ants; Nitrous oxide emission; Carbon dioxide emission; Methane emission; Soil carbon; Soil nitrogen.

INTRODUCTION

There are presently 9,500 identified species of ants around the world, and it is estimated that nearly 20,000 more species have yet to be identified.[1] It has also been estimated that, with an extensive range from tropic to temperate zones, the mass of the nearly ten trillion ants on earth equals that of all humans.[1] The force of these insects greatly influences the general area in which their colonies are found, and there currently exists a large body of research describing these localized effects. However, the impact of these organisms on the global environment through contributions to the greenhouse effect has not yet been addressed.

During an intact core field study of greenhouse gas emissions from swine waste amended soils, evidence seemed to indicate that the red imported fire ant, *Solenopsis invicta*, could increase N_2O-N emissions considerably from a Norfolk loamy sand (fine, loamy, siliceous, thermic, Typic Kandiudult) (unpublished data). It was discovered that the mean N_2O-N emission rate from one control core disturbed by an established fire ant colony was 232 $\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$, as compared to a mean rate of 12 $\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$ from all undisturbed control cores. There is currently a lack of research to substantiate these accidental findings, however, a large body of research addressing the effects of ants on soil N is available.

Ant colony soil typically has higher rates of N mineralization, and contains greater concentrations of NO_3-N and NH_4-N than soil not influenced by ants.[2–4] These foraging insects are capable of significantly redistributing N in their environment. In a study of plant–ant mutualism, Treseder et al.[5] reported that a species of epiphyte (*Dichidia major*) derived 29% of its N from organic material deposited by ants of the genus *Philidris*. Similarly, Soyunov[2] reported that the mounds of three ant species (*Cataglyphis setipes*, *Messor varabilis*, and *M. aralocaspius*) in Russia contained nearly double the amount of N as surrounding soil.

Increased N mineralization rates found in ant mounds may be explained by the gathering and mixing of large quantities of organic material in colonies by ants. Mixing stimulates microbial activity in soil, which in turn, increases degradation of organic material brought into the mounds.[6–8] Higher rates of mineralization and nitrification could possibly lead to an increase of N_2O-N production via denitrification. The rate of denitrification follows Michaelis-Menten kinetics, therefore N_2O-N fluxes increase with increasing concentrations of soil NO_3-N to a point in which emission becomes constant regardless of NO_3-N concentration.[9] However, denitrification rates are also influenced by other factors, such as soil structure and moisture content, which is also be affected by ants.[10]

As with the relationship between ants and N_2O-N emission, there is no documentation of the influence of ants on either the emission or oxidation of CH_4-C. However, there exists a great deal of research describing the production of CH_4-C by many species of termites.[11,12] Termite released CH_4-C, which is produced by symbiotic microorganisms found in the hindgut, contributes approximately 5% of the annual global flux of CH_4-C.[12] If it is found that CH_4-C is emitted from fire ant mounds, the emission may be a product of a metabolic process within the ant, or caused by soil microbial activity as influenced by ants.

Dauber and Wolters[13] observed CO_2-C evolution rates 1.7 to 2.7 times greater from the mounds of three ant species (*Myrmica scabrinodis, Lasius niger*, and *L. flavus*) versus non-ant influenced soil. However, Lenoir et al.[4] observed that CO_2-C evolution from ant mounds was only significantly greater than the forest floor at higher water holding capacities. At a water holding capacity of 60%, Lenoir et al.[4] reported that ant mound soil increased CO_2-C evolution as great as 1.5 times that of forest floor soil.

Solenopsis invicta is one of the common fire ant species inhabiting the southern United States, and it can often be found in fields, pastures, and occasionally wooded areas. First introduced to Mobile, AL from South America around 1930, red imported fire ant populations have steadily increased, and can currently be found in 11 U.S. states.[14] The objective of this study was to quantifying suspected greenhouse gas emissions from soil influenced by this species of ant. By doing so, contributions of N_2O-N, CH_4-C, and CO_2-C emissions made by ants around the world might be estimated in an effort to improve global greenhouse gas budgets.

MATERIALS AND METHODS

A 12-month study of greenhouse gas emissions from red imported fire ant mounds was conducted in a bermudagrass pasture near Auburn, Alabama, USA (32°41′N, 85°30′W) on a Hiwassee sandy loam (fine, koaolinitic, thermic Typic Rhodudult). Treatments consisted of ant influenced soil (mounds) and non-ant influenced control soil. The experiment was arranged in a completely randomized design having three replications.[15]

Three ant mounds were chosen at random within the bermudagrass pasture during each bi-weekly collection time from April 1999 to April 2000. Control sites were not chosen closer than 5 m to any mound. Measurements of N_2O-N, CH_4-C and CO_2-C from the soil surface were made using a closed chamber method.[16] Chambers were constructed from PVC pipe (20 cm dia. × 16 cm headspace), and were fitted at the top with a vent (5 mm dia. × 25 cm length), and a sampling port. Chambers were colored white to minimize temperature variation of air within the chambers. Using a syringe, gas samples were collected from the chamber headspace at 0, 30, and 60-minute intervals, and stored in 3 ml vials. Gas samples were analyzed using a Varian star cx gas chromatograph (Varian, Walnut Creek, CA). Nitrous oxide concentrations were determined using a 4 m Haysep R column and a ^{63}Ni electron capture detector (ECD). Detector temperature was 350°C, carrier gas was N_2, and carrier gas flow was $17\,\mathrm{mL\,min^{-1}}$. Carbon dioxide concentrations were determined using a 4-m Haysep R column and a thermal conductivity detector (TCD). Detector temperature was 200°C, carrier gas was N_2, and carrier gas flow was $17\,\mathrm{mL\,min^{-1}}$. Methane concentrations were determined using a 3 m Porapak N column and a flame ionizing detector (FID). Detector temperature was 350°C, carrier gas was N_2, and carrier gas flow was $30\,\mathrm{mL\,min^{-1}}$.

Soil samples were collected at 5 cm increments to 20 cm, and at 10 cm increments from 20 to 100 cm depth from ant influenced and control soils. Soil samples were stored at 5°C until analysis. Soil pH, moisture, NH_4-N, NO_3-N, total N, and organic C were measured. Soil moisture was measured gravimetrically. Soil was extracted with 2 *M* KCl, and NH_4-N, and NO_3-N concentrations were determined using a microplate reader.[17] Soil organic C and total N were determined with a LECO CHN-600 analyzer (LECO Corp., St. Joseph, MI) (Table 1).

In an effort to quantify greenhouse gas fluxes from fire ant influenced soil, a survey of mound numbers and sizes was conducted every 3 months. Three plots (30 × 30 m) within the pasture were established, and counts of mounds and measurements of mound diameters were made.

Table 1. Initial and final control soil characteristics from fire ant study site near Auburn, AL from April 1999 to April 2000 (0–20 cm).

	pH		Soil N		Soil C	
	Initial	Final	Initial ($g\,kg^{-1}$)	Final ($g\,kg^{-1}$)	Initial ($g\,kg^{-1}$)	Final ($g\,kg^{-1}$)
Bermudagrass pasture soil	5.92	5.99	0.29	0.34	19.7	19.6

Statistical analyses consisted of analysis of variance and least significant difference. Statistical significance was set at the $\alpha = 0.05$ level.

RESULTS

Nitrous Oxide

During our study, a sampling date × treatment interaction occurred for T2 N_2O-N data ($P \leq 0.0001$) (Table 2). Eighteen of the 23 sampling dates showed no significant differences between N_2O-N emissions from ant influenced and control soils ($LSD_{0.05} = 46\ \mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$). Differences between treatments were only observed between May 19 and July 14, and in F1 each case, ant influenced soil emitted more N_2O-N than control soil (Fig. 1).

The mean flux of N_2O-N across all sampling dates was 9 and 149 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$ for control and ant influenced soils, respectively. Much of the cumulative emissions observed from ant influenced soil was explained during

Table 2. Analysis of variance for effect of sampling date and treatment on N_2O-N emission ($\mu g\ N\ m^{-2}\ h^{-1}$), CH_4-C emission ($\mu g\ C\ m^{-2}\ h^{-1}$), and CO_2-C emission ($mg\ C\ m^{-2}\ h^{-1}$) for control and ant influenced soils near Auburn, AL from April 1999 to April 2000.

	$P > F$		
Source of variance	N_2O-N	CH_4-C	CO_2-C
Date	0.0001	0.2579	0.0001
Treatment	0.0028	0.0211	0.0001
Date*treatment	0.0001	0.0924	0.0001

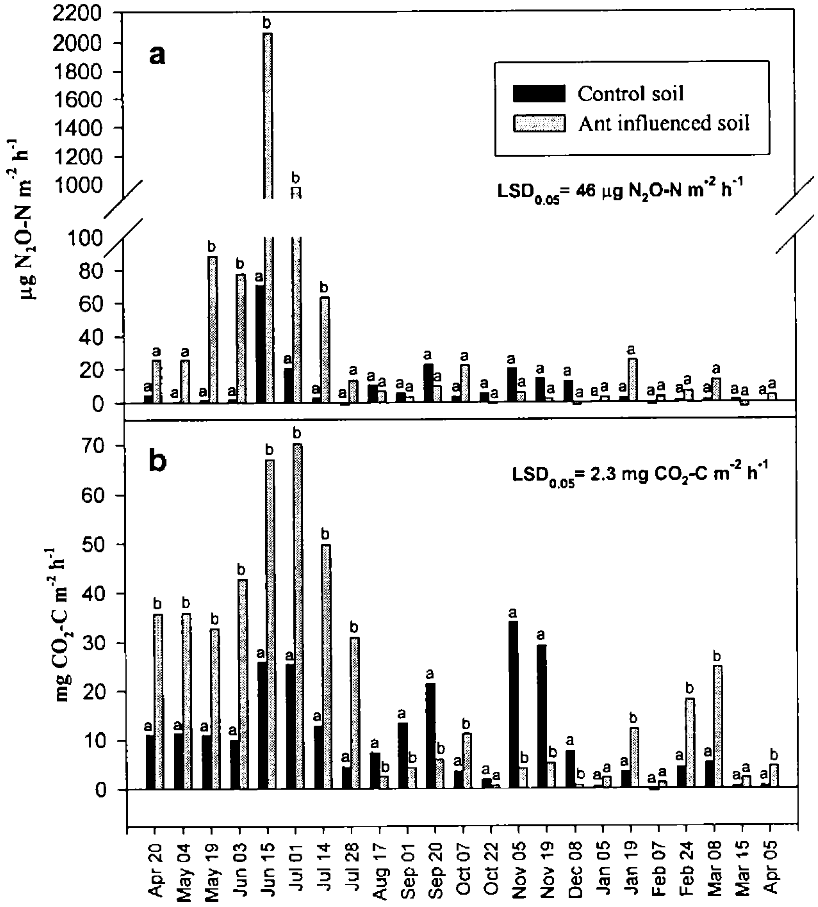

Figure 1. Emission of N_2O-N (a) and CO_2-C (b) as affected by fire ant influence. For each sampling date, values followed by the same letter are not significantly different by $LSD_{0.05}$. A break occurs on the Y axis of N_2O-N graph between 100 and 1000 µg N_2O-N m^{-2} h^{-1}.

the period between May 19 and July 14. The mean rate of emission from ant influenced soil during this period was 654 µg N_2O-N m^{-2} h^{-1} per sampling date. The highest rate of emission (2060 µg N_2O-N m^{-2} h^{-1}) was observed on June 15. The rate during this day was twice that of the second highest rate of emission found on July 1. Following July 14, mean emission rates of N_2O-N from ant influenced soil dropped to 7 µg N_2O-N m^{-2} h^{-1}.

Table 3. Analysis of variance for effect of sampling date, treatment and soil depth on soil C ($\mathrm{g\,C\,kg\,soil^{-1}}$), soil N ($\mathrm{g\,N\,kg\,soil^{-1}}$), soil NH_4-N($\mathrm{mg\,N\,kg\,soil^{-1}}$), and soil NO_3-N ($\mathrm{mg\,N\,kg\,soil^{-1}}$) for control and ant influenced soils near Auburn, AL from April 1999 to April 2000.

	$P > F$			
Source of variance	Soil C	Soil N	Soil NH_4-N	Soil NO_3-N
Date	0.0001	0.0001	0.0001	0.0001
Treatment	0.0001	0.0946	0.0001	0.0001
Depth	0.0001	0.0001	0.0202	0.0001
Date*treatment	0.0029	0.0001	0.0001	0.0001
Date*depth	0.0001	0.0001	0.9145	0.9892
Treatment*depth	0.0001	0.0001	0.0271	0.0001
Date*treatment*depth	0.0001	0.0001	0.7225	0.9995

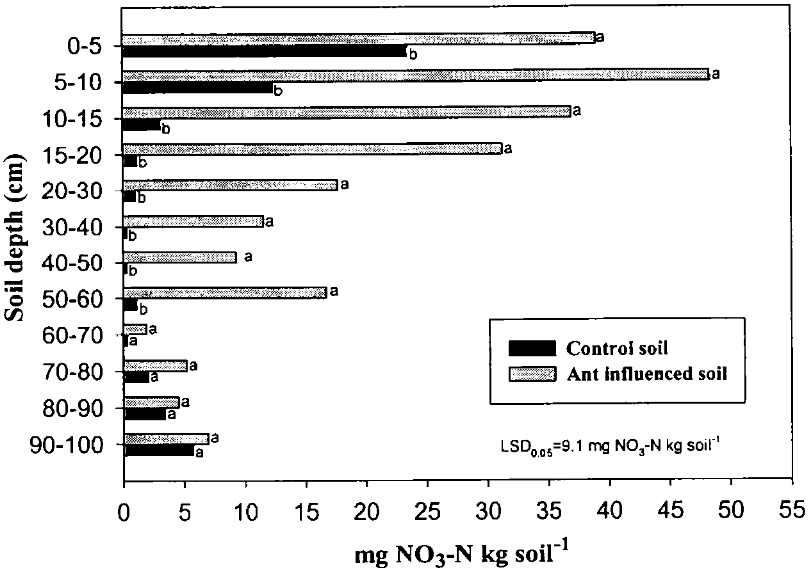

Figure 2. Soil NO_3-N by depth as affected by fire ant influence across all sampling dates. For each soil depth, values followed by the same letter are not significantly different by $LSD_{0.05}$.

As with rates of emission from ant influenced soil, the highest N_2O-N emission rates from control soil were also observed during the period between May 19 and July 14. The rates of emission from control soil during this period averaged 20 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$, and the rate of emission found on June 15 was nearly 3.5 times greater than the sampling date with the next highest rate of emission (July 1). Following July 14, mean emission rates of N_2O-N from control soil dropped to 6 $\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$; a rate quite comparable to that of ant influenced soil following July 14.

Other factors that influence N_2O-N fluxes, such as soil NO_3-N and NH_4-N, and soil pH, were also documented during this study. Significant sampling depth × treatment interactions were observed for soil NO_3-N ($P \leq 0.0001$) and soil NH_4-N ($P \leq 0.0271$) (Table 3). Ant influenced soil had significantly higher concentrations of soil NO_3-N and NH_4-N for all depths between 0–60 cm (Figs. 2 and 3). Mean NO_3-N concentrations from 0–60 cm were 4.8 and 23.6 $mg\ NO_3\text{-}N\ kg\ soil^{-1}$ for control and ant influenced soils, respectively. Mean NH_4-N concentrations from 0–60 cm were 3.78 and 18.5 $mg\ NH_4\text{-}N\ kg\ soil^{-1}$ for control and ant influenced soils, respectively. Also observed was a significant

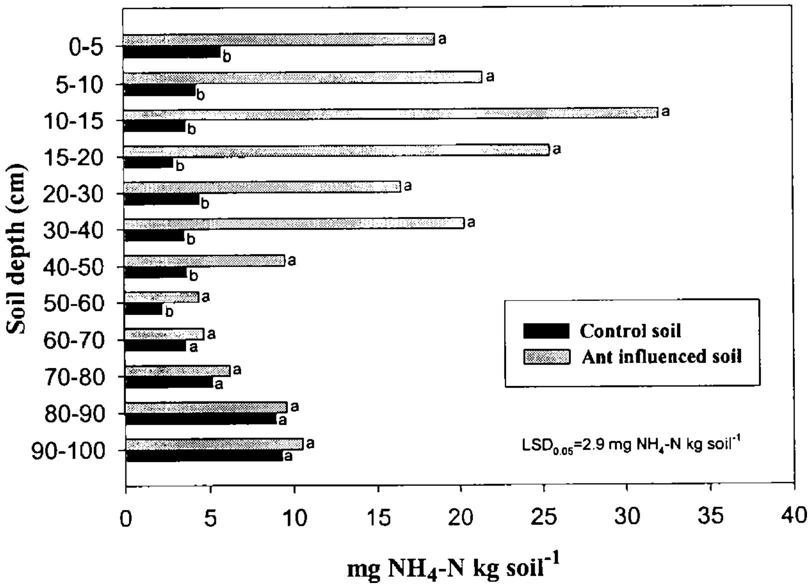

Figure 3. Soil NH_4-N by depth as affected by fire ant influence across all sampling dates. For each soil depth, values followed by the same letter are not significantly different by $LSD_{0.05}$.

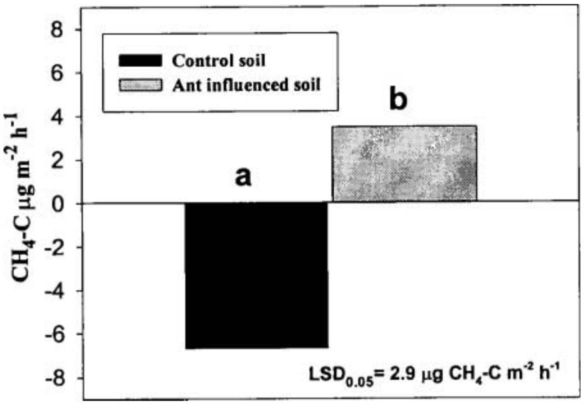

Figure 4. Emission of CH_4-C as affected by fire ant influence across all sampling dates. Values followed by the same letter are not significantly different by $LSD_{0.05}$.

treatment effect for soil pH ($P \leq 0.013$). The mean soil pH of control soil during this study was 5.9, as compared to 5.6 for ant influenced soil.

Methane

A significant treatment effect ($P \leq 0.0211$) occurred for CH_4-C emission data during this study (Table 2). Unlike the N_2O-N data, a definable seasonal pattern of higher rates of CH_4-C emission or oxidation was not observed. The flux of CH_4-C was quite variable throughout the study, with a range of emissions for each treatment over all sampling dates between -39 to 17 $\mu g\,CH_4\text{-C}\,m^{-2}\,h^{-1}$, and -24 to 39 $\mu g\,CH_4\text{-C}\,m^{-2}\,h^{-1}$ for control and ant influenced soils, respectively. Across all sampling dates, ant influenced soil emitted an average of 3.5 $\mu g\,CH_4\text{-C}\,m^{-2}\,h^{-1}$, while control soils oxidized an average of 6.7 $\mu g\,CH_4\text{-C}\,m^{-2}\,h^{-1}$ ($LSD_{0.05} = 2.9\,\mu g\,CH_4\text{-C}\,m^{-2}\,h^{-1}$) F4 (Fig. 4).

Carbon Dioxide

During our study, a sampling date × treatment interaction ($P \leq 0.0001$) was observed for CO_2-C emissions (Table 2). The pattern of CO_2-C emissions for the duration of this study was similar to that of N_2O-N emissions. However, only four of the 23 sampling dates showed no significant differences between CO_2-C emissions from control and ant influenced soils

($LSD_{0.05} = 2.3\,mg\,CO_2\text{-}C\,m^{-2}\,h^{-1}$). When differences were observed, ant influenced soil emitted more CO_2-C than control soil on 13 sampling dates, whereas control soil emitted more CO_2-C, as compared to ant influenced soil, on only six sampling dates (Fig. 1).

The mean flux of CO_2-C across all sampling dates was 11 and 20 $mg\,CO_2\text{-}C\,m^{-2}\,h^{-1}$ for control and ant influenced soils, respectively. Much of the cumulative emissions observed from ant influenced soil was explained during the period between April 20 and July 28. The mean rate of emission from ant influenced soil during this period was 48 $mg\,CO_2\text{-}C\,m^{-2}\,h^{-1}$ per sampling date. Following July 28, the mean rate of emission of CO_2-C dropped to 7 $mg\,CO_2\text{-}C\,m^{-2}\,h^{-1}$.

Similarly, much of the cumulative emissions observed from control soil also occurred during the period between April 20 and July 28. During this period, the mean rate of CO_2-C emission was 15 $mg\,CO_2\text{-}C\,m^{-2}\,h^{-1}$; nearly double the mean rate of emission observed after July 28.

In addition to CO_2-C emissions, soil C was another index of ant activity observed during this study. For soil C, a significant sampling date × depth × treatment interaction ($P \leq 0.0001$) was observed (Table 3). Within each sampling date, soil C decreased with depth for both treatments, however, there appeared to be greater loss of soil C from ant influenced soil as compared to control soil. Mean soil C concentrations, across all depths and sampling dates, was 9.9 and 7.8 $g\,C\,kg\,soil^{-1}$ for control and ant influenced soils, respectively.

DISCUSSION

Nitrous Oxide

The mean N_2O-N emission rate observed from control soil (8.6 $\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) was similar to the mean emission rate of 10 $\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$ from an unfertilized pasture reported by Mosier and Schimel,[18] and within the range of emissions reported by Ambus and Christensen[19] from an unfertilized coastal grassland. However, rates of N_2O-N emission from ant influenced soil often exceeded peak rate values shown in these studies, and were more analogous to rates seen following soil applications of highly mineralizable organic wastes.[20,21]

It also appeared there was a seasonal influence on N_2O-N emissions for both control and ant influenced soils. Between the period of May 19 and July F5 14, temperatures ranged from 23°C to 33°C (Fig. 5). This temperature range was within the optimum range for nitrification, as well as denitrification.[22,23] Soil moisture content was between 90–180 $g\,water\,kg\,dried\,soil^{-1}$ for

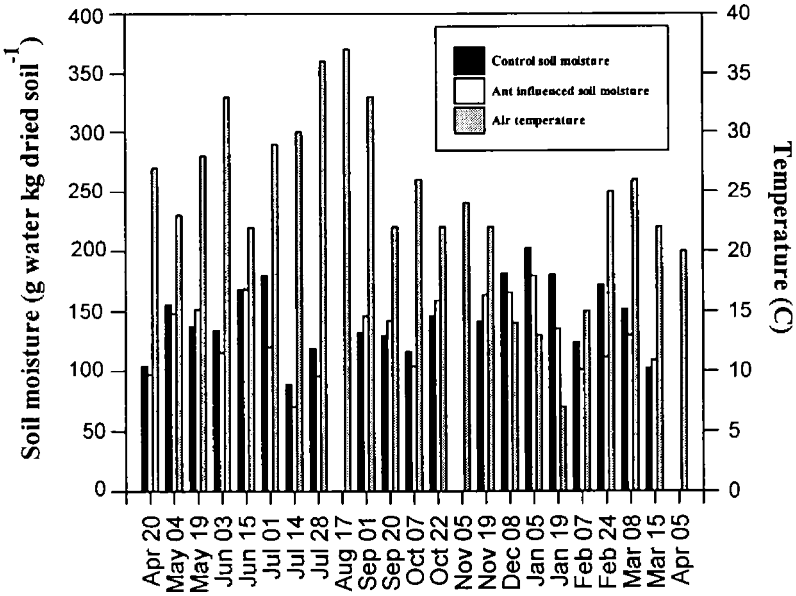

Figure 5. Air temperature, and soil moisture for control and fire ant plots (0–20 cm) near Auburn, AL from April 1999 to April 2000.

control soil, and 80–150 g water kg dried soil^{-1} for ant influenced soil from a 0–20 cm depth.

Increased emission rates during the summer months, when soil retains adequate moisture, has been reported by others.[9,24,25] In unfertilized soil, Bremner et al.[24] found 55–83% of the annual emission of N_2O-N occurred between the summer months of June and August. However, it was concluded that temperature and soil water content could not explain all of the seasonal variation, and that nitrifiable N content also played a role in this seasonal flux.

The content of nitrifiable N may explain the large flux of N_2O-N observed in ant influenced soil during the period of May 19 and July 14. It is possible that high amounts of organic materials brought into the mound by foragers may have increased nitrifiable N. Red imported fire ants utilize a wide variety of animal, plant, fungal, and bacterial food.[26] In warm months, fire ants favor proteins over carbohydrates,[27] and during these warmer months, the average colony consumes nearly 454 g of insects and sugar a week.[28]

Higher concentrations of soil NO_3-N and NH_4-N to a depth of 60 cm were found in ant influenced soil, and it has been reported by others that higher concentrations of both NO_3-N and NH_4-N can increase emissions of N_2O-N.[29,30] The soil NO_3-N concentration that yields maximum rates of N_2O-N emission via denitrification is variable, however, Limmer and Steele[30] reported the maximum denitrification rate for a range of soils occurred when the NO_3-N concentration was approximately 25 mg NO_3-N kg soil^{-1}. This concentration value was close to the mean concentration of NO_3-N found across all depths in ant influenced soil (23.6 mg NO_3-N kg soil^{-1}).

Higher concentrations of NH_4-N may also stimulate N_2O-N emissions by increasing nitrification. Mosier et al.[29] found that for cropped and native soils, emissions of N_2O-N increased with concentrations of NH_4-N between 1 and 6 mg NH_4-N kg soil^{-1}. Emissions of N_2O-N from nitrification became constant when NH_4-N concentrations exceeded 10 mg NH_4-N kg soil^{-1}. At a mean concentration of 18.5 mg NH_4-N kg soil^{-1} for ant influenced soil across all depths, it is likely that significant contributions to N_2O-N emissions were made via nitrification. Another indicator that considerable nitrification was occurring was the lower soil pH value observed from ant influenced soil, as compared to control soil.

Soil pH may also influence N_2O-N emissions from soil. However, this influence is often complex, and its effects may be unclear. When soil pH ranges from <5 to 6, N_2O-N emissions tend to decrease with increasing pH when denitrification is the main source of N_2O-N.[9] However, when soil pH ranges from 7 to 8, denitrification increases with pH.[31] When nitrification is the main source of N_2O-N, emissions tend to increase with increasing pH from a range of 6 to 8. However, in acid soils (up to pH 5), autotrophic nitrification decreases with increasing pH.[9] The mean soil pH of control soil during our study was 5.9, whereas the mean soil pH for ant influenced soil was 5.6. Though both of these pH values were slightly less than that required for optimum denitrification and nitrification, and while soil pH was shown to be significantly different between treatments, it is doubtful there was enough difference in pH to account for differences in N_2O-N emissions observed between control and ant influenced soils.

It is possible that the seasonal fluxes observed between May 19 and July 14 were associated with activities relating to the brood production or even preparation for mating (nuptial) flights. While broods of red imported fire ants are produced year around in warmer regions of the U.S., Lofgren et al.[32] reported May as the peak month for brood production. It is possible that the higher emissions seen in late spring and early summer are related higher brood production. Another possibility may be mating flights. While mating flights can occur between spring and fall in the U.S., the peak months for this behavior occur at the same time as our observed peak emission rates.[26] However, without further investigation, definite correlation between these ant colony behaviors and increased N_2O-N emissions cannot be made.

Methane

Though CH_4-C emissions were found to be highly variable during this study, there seemed to be evidence that ants influence CH_4-C uptake and emission. Increased net CH_4-C emission ($3.5\,\mu g\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) by ant influenced soil may be due to higher NH_4-N concentrations observed in ant influenced soil. Tlustos et al.[33] reported CH_4-C oxidation decreased in inverse proportion to the amount of N added as fertilizer. This was supported by Hütsch,[34] who found when NH_4CL, $(NH_4)_2SO_4$, and urea were applied to a silty loam soil at a rate of $40\,mg\,N\,kg\,soil^{-1}$, oxidation of CH_4-C decreased by 96%, 80%, and 84%, respectively, soon after application. Across all sampling dates for ant influenced soil, the concentration of NH_4-N from 0 to 100 cm ranged from 4.4 to $32.0\,mg\,NH_4\text{-}N\,kg\,soil^{-1}$, and averaged $18.5\,mg\,NH_4\text{-}N\,kg\,soil^{-1}$ across all depths. Ammonium found in these concentrations likely had a profound influence on the ability of ant influenced soil to oxidize CH_4-C.

Another possibility for increased net CH_4-C emission by ant influenced soil may be related to the biological function of the ants themselves. It has been shown that termite associated CH_4-C is produced by symbiotic microorganisms found in the hindgut.[11,12] However, it cannot be concluded that this was the case for the red imported fire ant. More research would have to be directed toward the study of digestive functions of this species of insect to determine if CH_4-C emission is a by-product of their metabolism.

Carbon Dioxide

Respiration by ants and bacteria within the colonies likely accounted for the greater CO_2-C emissions observed from ant influenced soil, as compared to control soil. Surface emission rates of CO_2-C during the spring and summer were often three to five times greater from ant influenced soil than control soil, and the overall mean of CO_2-C emission rates throughout the study from ant influenced soil was double that from control soil. The substantially higher rates of CO_2-C emissions from ant influenced soil was thought to be due, not only to respiration by the ants, but also to increased microbial activity within the colonies. Czerwiński et al.[6] reported greater population sizes of bacteria and fungi within ant hills as compared to non-ant influenced meadow soil. The development of these bacterial and fungal communities, as well as their increased activity, was a response to the highly mineralizable organic matter deposited in the nests by ants. It was concluded by Dauber and Wolters[13] that this increase in microbial activity within the mound was primarily responsible for increases observed in C mineralization. Dauber and Wolters[13] reported that CO_2-C evolution from the mound soil of three ant species was between 1.7 and 2.7 times greater than that from non-ant influenced soil. Similarly, Lenoir et al.[4] reported that when soil moisture was sufficient enough to stimulate microbial activity (60% water holding capacity), CO_2-C evolution rates were as high as 1.5 times greater than non-ant influenced forest floor soil.

Estimation of Greenhouse Gas Flux

To determine the influence red imported fire ants have on greenhouse gas fluxes from soil, an estimate was made of the amount of land affected by their colonies. From surveys conducted between April 1999 and April 2000, it was estimated that an average of 49 fire ant mounds ha^{-1} existed on this pasture throughout the year. While mound densities vary greatly throughout the southern U.S., this estimation was lower than numbers of red imported fire ant mounds reported by Porter et al.,[35] Diffie and Bass,[36] and Macom and Porter.[28] The average area of ant mounds surveyed in our study was $0.12\,m^2\,mound^{-1}$, which was similar to the mean area ($0.14\,m^2\,mound^{-1}$) reported by Porter et al.[35] From these estimates, it was calculated that ant influenced soil comprised $6.1\,m^2$ of each ha of land.

The calculated annual flux of N_2O-N from this Piedmont Plateau bermudagrass pasture, without emissions from fire ant mounds, was $7.0\,kg\,N_2O\text{-}N\,ha^{-1}$. When emissions from fire ant mounds were considered, it was estimated that an additional $6.95\,g\,N_2O\text{-}N\,ha^{-1}$ was supplied. Ant influenced soil increased N_2O-N emissions from this bermudagrass pasture by 1.0%.

A discernable influence by fire ants on CH_4-C flux was most difficult to detect. When annual flux of CH_4-C was calculated, it was determined that this Piedmont Plateau bermudagrass pasture oxidized $0.58\,kg\,CH_4\text{-}C\,ha^{-1}$. When the influence of fire ant mound emissions was taken into account, it was concluded that only an additional 160 mg CH_4-C was emitted per ha. While ant influenced soil was estimated to have decreased CH_4-C oxidation by 0.03%, this change in CH_4-C flux was rather insignificant, and was likely within our error of measurement.

The estimated annual flux of CO_2-C from this Piedmont Plateau bermudagrass pasture, without emissions from fire ant mounds, was calculated to be $821.9\,kg\,CO_2\text{-}C\,ha^{-1}$. When emissions from fire ant mounds were considered, it was estimated that an additional $0.9\,kg\,CO_2\text{-}C\,ha^{-1}$ was supplied. Ant influenced soil increased CO_2-C emissions from this bermudagrass pasture by only 0.1%.

It can be speculated that regional and global budgets of N_2O-N, CH_4-C, and CO_2-C emissions may be underestimated when the influence of soil macro-organisms, such ants, are not taken into account. However, the underestimation may only be slight given the data presented here.

REFERENCES

1. Hölldobler, B.; Wilson, E.O. *Journey to the Ants*; Harvard University Press: Cambridge, 1994; 2–8.
2. Soyunov, O.S. *Problems of Desert Development (Translated from Problemy Osvoeniya Pustyn)*; Allerton Press: New York, 1988; 85–90.
3. Segal, D.S.; Jones, R.H.; Sharitz, R.R. Release of NH_4-N, NO_3-N, and PO_4-P from litter in two bottom land hardwood forests. Am. Midl. Nat. **1990**, *123*, 160–170.
4. Lenoir, L.; Persson, T.; Bengtsson, J. Wood ant nests as potential hot spots for carbon and nitrogen mineralisation. Biol. Fertil. Soils **2001**, *34*, 235–240.
5. Treseder, K.K.; Davidson, D.W.; Ehleringer, J.R. Absorption and ant-provided carbon dioxide and nitrogen by a tropical epiphyte. Nature **1995**, *375*, 137–139.
6. Czerwiński, Z.; Jakubczyk, H.; Petal, J. Influence of ant hills on the meadow soils. Pedobiologia **1971**, *11*, 277–285.
7. Briese, D.T. The effects of ants on soil of a semi arid saltbush habitat. Insectes Soc. **1982**, *29*, 375–386.
8. Ikan, R., Haber, O., Ofer, J., Schallinger, K.M., Eds. *Proceedings of the Second International Symposium: Peat in Agriculture and Horticulture*; Hebrew University of Jerusalem: Ehovot, Israel, 1983; 131–139.
9. Granli, T.; Bøckman, O.C. Nitrous oxide from agriculture. Norw. J. Agric. Sci. **1994**, *12*, 2–24.
10. Lobry de Bruyn, L.A.; Conacher, A.J. The role of termites and ants in soil modification: a review. Aust. J. Soil Res. **1990**, *28*, 55–93.
11. Rasmussen, R.A.; Khalil, M.A.K. Global production of methane by termites. Nature **1983**, *301*, 700–702.
12. Martius, C.; Wassmann, R.; Thein, U.; Banderia, A.; Rennenberg, H.; Junk, W.; Seiler, W. Methane emission from wood-feeding termites in Amazonia. Chemosphere **1993**, *26*, 1–4.
13. Dauber, J.; Wolters, V. Microbial activity and functional diversity in the mounds of three different ant species. Soil Biol. Biochem. **2000**, *32*, 93–99.

14. Callcott, A.M.A.; Collins, H.L. Invasion and range expansion of imported fire ants (Hymenoptera: Formicidae) in North America from 1918–1995. Fla. Entomol. **1996**, *79*, 240–251.
15. Gomez, K.A.; Gomez, A.A. *Statistical Procedures for Agricultural Research*, 2nd Ed.; Wiley: New York, 1984; 8–25.
16. Hutchinson, G.L.; Mosier, A.R. Improved soil cover method for field measurement of nitrous oxide fluxes. Soil Sci. Soc. Am. J. **1981**, *45*, 311–316.
17. Sims, G.K.; Ellsworth, T.R.; Mulvaney, R.L. Microscale determination of inorganic nitrogen in water and soil extracts. Commun. Soil Sci. Plant Anal. **1995**, *26*, 303–316.
18. Mosier, A.R.; Schimel, D.S. Influence of agricultural nitrogen on atmospheric methane and nitrous oxide. Chem. Ind. **1991**, *23*, 874–877.
19. Ambus, P.; Christensen, S. Spatial and seasonal nitrous oxide and methane fluxes in Danish forest-, grassland-, and agroecosystems. J. Environ. Qual. **1995**, *24*, 993–1001.
20. Watanabe, T.; Osada, T.; Yoh, M.; Tsuruta, H. N_2O and NO emissions from grassland soils after application of cattle and swine excreta. Nutr. Cycl. Agroecosyst. **1997**, *49*, 35–39.
21. Chadwick, D.R.; Pain, B.F.; Brookman, S.K.E. Nitrous oxide and methane emissions following application of animal manures to grassland. J. Environ. Qual. **2000**, *29*, 277–287.
22. Haynes, R.J. Nitrification. In *Mineral Nitrogen in the Plant–Soil System*; Haynes, R.J., Orlando, F.L., Eds.; Academic Press: New York, 1986; 127–165.
23. Paul, E.A.; Clark, F.E. *Soil Microbiology and Biochemistry*; Academic Press, Inc.: San Diego, CA, 1989; 159.
24. Bremner, J.M.; Robbins, S.G.; Blackmer, A.J. Seasonal variability in emission of nitrous oxide from soil. Geophys. Res. Lett. **1980**, *7*, 641–644.
25. Cates, R.L.; Keeney, D.R. Nitrous oxide production throughout the year from fertilized and manured maize fields. J. Environ. Qual. **1987**, *16*, 443–447.
26. Taber, S.W. *Fire Ants*; Texas A & M University Press: College Station, TX, 2000; 25–57.
27. Stein, M.B.; Thorvilson, H.G.; Johnson, J.W. Seasonal changes in bait preference by red imported fire ant, *Solenopsis invicta* (Hymenoptera: Formicidae). Fla. Entomol. **1990**, *73*, 117–123.
28. Macom, T.E.; Porter, S.D. Food and energy requirements of laboratory fire ant colonies (Hymenoptera: Formicidae). Environ. Entomol. **1995**, *24*, 387–391.

29. Mosier, A.R.; Parton, W.J.; Hutchinson, G.L. Modelling nitrous oxide evolution from cropped and native soils. Environ. Biogeochem. Ecol. Bull. **1983**, *35*, 229–241.
30. Limmer, A.W.; Steele, K.W. Denitrification potentials: measurement of seasonal variation using a short-term anaerobic incubation technique. Soil Biol. Biochem. **1982**, *14*, 179–184.
31. Bremner, J.M.; Shaw, K. Denitrification in soil. II. Factors affecting denitrification. J. Agric. Sci. **1958**, *51*, 377–380.
32. Lofgren, C.S.; Banks, W.A.; Glancey, B.M. Biology and control of imported fire ants. Ann. Rev. Entomol. **1975**, *20*, 1–30.
33. Tlustos, P.; Willison, T.W.; Baker, J.C.; Murphy, D.V.; Pavlikov, A.D.; Goulding, K.W.T.; Powlson, D.S. Short-term effects of nitrogen on methane oxidation in soils. Biol. Fertil. Soils **1998**, *28*, 64–70.
34. Hütsch, B.W. Methane oxidation in arable soil as inhibited by ammonium, nitrite, and organic manure with respect to soil pH. Biol. Fertil. Soils **1999**, *28*, 27–35.
35. Porter, S.D.; Fowler, H.G.; MacKay, W.P. Fire ant mound densities in the United States and Brazil (Hymenoptera: Formicidae). J. Econ. Entomol. **1992**, *85*, 1154–1161.
36. Diffie, S.; Bass, M.H. Densities of monogynous red imported fire ant (Hymenoptera: Formicidae) colonies in Georgia pastures. J. Entomol. Sci. **1994**, *29*, 367–369.