

Assessing Forest Soil Disturbance through Biogenic Gas Fluxes

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ABSTRACT

Soil damage from wet-weather timber harvests may persist after some physical and chemical properties have been restored through tillage and fertilization. This study's objective was to determine if the gaseous products of aerobic and anaerobic soil biological activity could reveal harvest-damage effects, even after applying costly mitigation treatments. Fluxes of CO₂, CH₄, and N₂O across the soil surface were measured in Ultisols of a Coastal Plain pine flat damaged during timber harvest, then mitigated by bedding and fertilization (100 kg ha⁻¹ N, P, and K). Gas fluxes were measured with large static chambers (0.5 by 1.0 m sampling area) to compensate for high microsite variability and the presence of coarse debris on the forest floor. Carbon dioxide evolution was a robust and consistent indicator of residual damage, declining an average of 34% in planting beds on damaged vs. undamaged soils. For example, in a late summer reading, efflux of CO₂-C from beds installed over former skid trails was 143 mg m⁻² h⁻¹ vs. 258 mg m⁻² h⁻¹ from undamaged beds and 231 mg m⁻² h⁻¹ from undisturbed forest floor. Methane and N₂O fluxes were ephemeral and, thus, generally unreliable as indicators of harvest damage – though bedding produced scattered high peaks in both. Carbon dioxide was also the only gas flux that responded significantly to fertilization, with an average 26% increase up to 4 mo after fertilization. These results suggest that suppression of gross soil biological activity by harvest damage was not restored by intensive mitigation in the next rotation's establishment phase.

IN PINE FLATS of the southeastern Coastal Plain, skid trails and log decks typically occupy 32 to 36% of areas harvested with ground-based machinery (Aust et al., 1993; Hatchell et al., 1970). Compaction in these areas persists up to 40 yr (Dickerson, 1976; Hatchell and Ralston, 1971). The most successful strategy for repairing skid-trail damage and avoiding long-term reductions in forest productivity has been a combination of tillage and fertilization (Berg, 1975; Hatchell, 1981).

Compaction, rutting, loss of soil structure, and displacement of topsoil may affect the productivity of both plants and soil organisms and, thus, the production of their respiratory metabolites. The gases CO₂, CH₄, and N₂O arise from many pathways, under the full range of oxidation–reduction potentials that occur in soils. While CO₂ is produced through both aerobic and anaerobic pathways (Howes et al., 1984; Valiela, 1984), N₂O and

CH₄ are primarily anaerobic metabolites, and biological methanogenesis occurs only in the strict absence of O₂ (Conrad, 1989).

Carbon dioxide evolution may be the most robust and consistent biological indicator of soil condition. Most investigators (e.g., Behera et al., 1990) regard gaseous CO₂ evolution to be representative of most metabolic activity in the soil. Other routes of metabolite export from uplands, such as CO₂ dissolved in groundwater, are thought to be negligible (Schlesinger, 1977). In wetlands, even high rates of CH₄ production are an order of magnitude less than that of CO₂ (Baker-Blocker et al., 1977; Smith et al., 1982). Plants and heterotrophic organisms both contribute significantly to CO₂ evolution from forest soils, where estimates of root respiration vary from 22 to 62% of total soil respiration (Behera et al., 1990; Ewel et al., 1987b). The interrelated contributions from these two sources are not readily partitioned, however, and in situ CO₂ efflux measurements have been used primarily to estimate gross soil metabolic activity.

In contrast to CO₂ evolution, N₂O and CH₄ arise under more limited ranges of conditions and should provide greater specificity in assessing soil condition. High rates of N₂O production, for example, suggest adequate NO₃⁻ availability, reducing conditions, and a means for N₂O–N to escape from the soil before it is metabolized further (Firestone and Davidson, 1989). Methanogenic bacteria can metabolize only a limited range of simple organic compounds, which must be sufficiently available under strong reducing conditions for methanogenesis to occur (Conrad, 1989). Moreover, CH₄ must elude biological oxidation in aerated zones in order to escape from the soil (King et al., 1990). In well-aerated upland soils, net consumption of atmospheric CH₄ occurs commonly through biological oxidation (Keller et al., 1990; Steudler et al., 1989).

Several experiments on agricultural soils have suggested that biogenic gas fluxes are sensitive to trafficking and compaction and useful in impact assessments. Torbert and Wood (1992) observed reduced CO₂ evolution and increased N loss with increasing bulk density in intact cores. Nitrogen loss was determined from soil pools, rather than gas fluxes, and attributed to microbial denitrification. Using 17-cm-diam. chambers placed over the soil, Bakken et al. (1987) found that tractor traffic imposed experimentally under wet conditions increased N loss by denitrification three- to fourfold vs. controls. Also using soil covers, Hansen et al. (1993) observed a 52% reduction in CH₄ uptake due to compaction.

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No comprehensive, in situ evaluation of biogenic gas fluxes to assess mechanical disturbance of forest soils was found in the literature. The objectives of this study were to: (i) determine the degree to which biogenic gas fluxes were affected by harvest damage after mitigation by bedding and fertilization; and (ii) compare commonly used measures of soil condition — such as bulk density, total organic C, and macronutrient concentrations — with biogenic gas fluxes.

MATERIALS AND METHODS

Study Location

The study was conducted in the South Carolina Coastal Plain, at two locations in the Francis Marion National Forest. One site is located on a Bethera series soil (clayey, mixed, thermic Typic Paleaquilt) and the other on a Goldsboro series (fine-loamy, siliceous, thermic Aquic Paleudult). Both sites were previously occupied by stands of merchantable longleaf pine (*Pinus palustris* Miller). Annual rainfall averages 120 cm and is evenly distributed throughout the year.

Treatments and Experimental Design

Treatments, previously described by Aust et al. (1995), represented three levels of mechanical disturbance: (i) none, (ii) bedding over an undisturbed area, and (iii) bedding over a former skid trail. Skid trails were formed during timber salvage operations following Hurricane Hugo, which struck

the forest in 1989. Three plots, one for each disturbance level, comprised a block. There were two blocks per site, for a total of four blocks. Each plot was split into fertilized and nonfertilized halves.

Treatment differences were analyzed in a randomized-block, split-plot design, with three levels of mechanical disturbance in whole plots. Each plot was split by two levels of fertilization. For measures that were repeated temporally, time was regarded as a second split. Means were compared by analysis of variance and separated with an *F*-test protected Duncan's multiple-range test at $\alpha = 0.05$, using SAS statistical software (SAS Institute, 1990).

The bedding treatment involved two mechanical passes: disking to a depth of 20 cm, and bedding with a fire plow at close spacing (1.2 m). The use of a fire plow resulted in A horizon material with litter and herbaceous vegetation being stripped from the interbed rows, inverted, and deposited into beds. Bed surfaces were initially devoid of vegetation. The Bt horizon was exposed in interbed rows. Planting beds were about 40 cm from furrow to crest. Nitrogen (in urea), P (in triple super phosphate), and K (in muriate of potash) each were applied to fertilized areas at the rate of 100 kg ha⁻¹ in May of 1992, 5 mo after bedding.

In analyzing the main treatment effects, gas fluxes were compared at the field level, integrating across a variety of microsite conditions within each plot. For silvicultural interpretations, however, examination of soil condition in the planting beds alone was desirable — as well as comparison of planting beds with other microsite types. Hence, four microsite types were recognized and compared: (i) undisturbed forest floor, (ii) beds over former skid trails, (iii) beds over previously undisturbed soil, and (iv) interbed rows. No distinction was drawn between the presence or absence of residual skid-trail damage in the interbed rows, as they were sheared and compacted by the plow regardless of the area's previous condition. Moreover, the interbed rows were frequently submerged due to high water tables, resulting in minimal gas flux rates.

In each block, two permanent sampling microsites had been randomly located in both the fertilized and nonfertilized areas occupied by each microsite type. Thus, there were 64 sampling microsites, 16 per block. Means among microsite types were compared in a two-way ANOVA, with four levels of microsite type and two levels of fertilization. Means were separated with an *F*-test protected Duncan's multiple-range test at $\alpha = 0.05$.

Gas Fluxes

Gas fluxes were measured with large static chambers (Fig. 1) adapted for use in forest soils strewn with coarse debris. Temporal changes in gas concentrations in the chamber were attributed to exchange across the soil surface. The stainless steel base was installed the day before sampling by hammering it into the ground so that the walls extended 3 to 8 cm below the surface. The base was leveled and the trough filled with about 2 L of water. Because microtopography influenced the volume of the chamber headspace, the elevation of the soil surface relative to the base rim was determined for a grid of 48 points over the sampled area. Microtopography was measured with a profiler placed at eight intervals along the installed chamber base and containing six graduated drop pins. Vegetation was clipped to a height even with the rim.

At the start of an incubation, the chamber was lowered onto the base and covered immediately with a radiation shield. The sampling port was left open, permitting air to escape until pressure in the chamber had equilibrated with that of the atmosphere. Thirty-five milliliters of air were then withdrawn from the chamber into a 50-mL gas-tight syringe (Hamilton

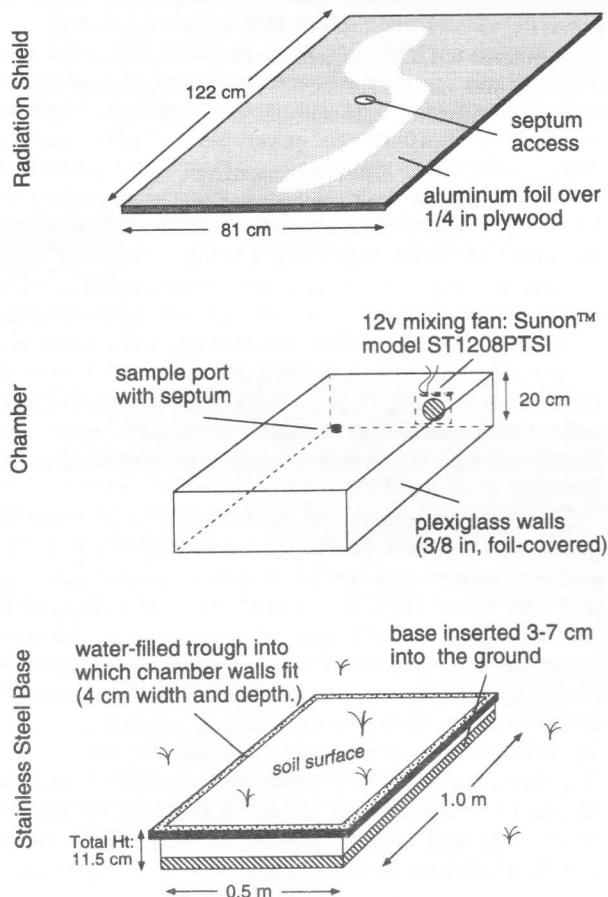


Fig. 1. Static chamber used for sampling forest-floor gas fluxes.

Co., Reno, NV) and injected into a 10-mL crimp-top vial, with a minimally reactive, butyl-rubber septum (West Company, Phoenixville, PA). A small (22-gauge) needle was used to minimize the size of puncture holes in the vial septa. Additional gas samples were withdrawn at 40 and 120 min, after activating a mixing fan for 30 s before each sampling. In about 10% of the incubations, up to 10 sequential samples were withdrawn to aid in determining whether evolution was temporally linear. Air temperature and barometric pressure were recorded before and after each set of incubations. Before the chamber base was removed, the corners were marked with pin flags for precise relocation.

Gas concentrations were determined by analysis on a Shimadzu GC-14A gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD), using a 10-port valve with a sample loop of fixed volume. The same column arrangement was used for all analyses: a 91-cm Poropak N with 80/100 mesh, in series with a 305-cm Poropak Q with 100/120 mesh. The 10-port valve allowed backflushing of the first column after the substances to be analyzed had eluted, preventing extraneous peaks from reaching the detectors. Carbon dioxide concentration was determined using a thermal conductivity detector, a He carrier gas at a flow rate of 35 mL min⁻¹, a 50°C column, and 110°C detector. Methane concentration was determined using a flame ionization detector, a He carrier at 35 mL min⁻¹, a 50°C column, and 250°C detector. Nitrous oxide concentration was determined using an electron capture detector (Ni⁶³), a carrier-gas mixture of 95% Ar and 5% CH₄ at 40 mL min⁻¹, a 70°C column, and 340°C detector.

The mass of a particular gas in the chamber was calculated using the ideal gas law and Dalton's law of partial pressures. The flux rate was estimated by fitting a least-squares linear equation to mass vs. time. To estimate field-level fluxes in the bedded plots, rates from beds and interbed rows were averaged on an area-weighted basis. Interbed rows occupied 33% of the surface area in bedded plots. The additional relief created by bedding resulted in a 12% increase in surface area for gas exchange per hectare, which was accounted for in field-level flux estimates.

Gas fluxes were measured during four seasonally distinct periods in 1992. Analyses of variance and means separations were performed for each period. In Period 1, the Goldsboro site was sampled on 18 and 19 January and the Bethera site on 7 and 9 April. One of the four blocks was sampled on each date. Despite an unintended delay between sampling of the two sites in Period 1, temperatures and activity rates were distinctly lower than in the subsequent summer and fall measurements. The remaining dates were as follows: Period 2, Goldsboro site on 11 and 13 June and Bethera site on 2 and 7 July; Period 3, Goldsboro site on 9 and 11 September and Bethera site on 16 and 17 September; and Period 4, Goldsboro site on 6 and 8 October and Bethera site on 20 and 21 October.

Soil Characterization

After each set of incubations, the soil was sampled to a depth of 23 cm with a 2-cm-diam. push tube. Six samples were collected from the area of each chamber, composited in a polyethylene bag, and placed immediately into a cooler. Samples were stored at ambient soil temperature during transport and in the laboratory.

Nitrate and NH₄ were determined within 2 d of sampling by KCl extraction of well-mixed, field-moist soil samples and colorimetric analysis on a Technicon autoanalyzer (Technicon Industrial Systems, 1978). Nitrogen and P were also measured colorimetrically following a Kjeldahl digestion. Total organic

matter was determined by combustion of 10 g of oven-dry soil at 450°C for 4 h. Water-soluble organic C was determined 2 ds after sampling in Period 4 by cold-water extraction (Burdorf and Bremner, 1975) and analysis on a Shimadzu organic C analyzer. Samples for estimation of bulk density were collected with an impact corer that extracted a core of radius 3.81 cm and length 7.62 cm. A single core was collected from the surface soil of each sampling microsite immediately after Period 4. On each sampling date, soil temperature was measured in 12% of the incubations by inserting a dial thermometer (-15 to 105°C, Weksler, Freeport, NY) 23 cm vertically into the soil. Soil moisture was determined by time domain reflectometry (Topp et al., 1980), using two parallel, 22.9-cm stainless steel rods inserted vertically into the soil, 5 cm apart, at each sampling microsite. Porosity was calculated from bulk density, assuming a particle density of 2.65 g cm⁻³. Volumetric soil moisture was subtracted from total porosity to obtain air-filled pore space.

The rate of N₂ evolution relative to that of N₂O-N was estimated in a two-stage laboratory incubation within 5 d of sampling. In Stage 1, the rate of N₂O evolution from 30 g of field-moist soil placed in a 125-mL serum bottle was measured for 12 h. The headspace was sampled 1 and 12 h after the bottle was sealed. The bottle was opened, ventilated with fresh air, and resealed. In Stage 2, the procedure was identical, with the exception that the atmosphere was amended with acetylene to block the reduction of N₂O to N₂ (Tiedje, 1982). Evolution of N₂ was taken to be the second-stage N₂O evolution minus that of the first stage.

RESULTS

Gas Fluxes

At the field level, CO₂ evolution tended to be depressed in bedded areas, especially where the soil had been previously damaged during timber harvests (Table 1). A spring fertilizer application accelerated CO₂ production an average of 26% in two summer measurements (Table 2). There was no interaction between disturbance and fertilization. Unlike CO₂, CH₄ and N₂O were largely unresponsive to treatments, except for a short-term increase in N₂O evolution after fertilization in bedded areas with residual skid-trail damage (Table 2).

Flux rates of all three gases varied significantly with time ($\alpha = 0.05$), with no interactions between time and fertilization. In the case of CO₂, there was an interaction between time and mechanical disturbance ($P = 0.007$).

Table 1. Influence of mechanical disturbance on field-level gas fluxes, with area-weighted averages of activity in beds and interbed rows in bedded areas.

Gas	Treatment	January-	June-	September	October
		April	July		
mg m ⁻² hr ⁻¹					
CO ₂ -C	Undisturbed	52 a†	257 a	231 a	136 a
	Bedded	45 ab	161 b	218 a	95 ab
	Bedded over damage	34 b	118 b	120 b	65 b
CH ₄ -C	Undisturbed	0.00 a	0.13 a	0.10 a	0.07 a
	Bedded	0.15 a	0.40 a	0.32 a	0.39 a
	Bedded over damage	0.04 a	0.25 a	0.19 a	0.20 a
N ₂ O-N	Undisturbed	0.000 a	0.000 a	0.000 a	0.000 a
	Bedded	0.000 a	0.002 a	0.003 a	0.000 a
	Bedded over damage	0.001 a	0.007 b	0.000 a	0.000 a

† Within each measurement period, means with different letters are significantly different ($\alpha = 0.05$).

Table 2. Influence of fertilization on field-level gas fluxes, with area-weighted averages of activity in beds and interbed rows in bedded areas.

Gas	Treatment	January- April	June- July	September	October
		mg m ⁻² hr ⁻¹			
CO ₂ -C	Unfertilized	43 a†	154 a	174 a	92 a
	Fertilized	44 a	204 b	206 b	106 a
CH ₄ -C	Unfertilized	0.06 a	0.29 a	0.21 a	0.27 a
	Fertilized	0.07 a	0.22 a	0.19 a	0.17 a
N ₂ O-N	Unfertilized	0.000 a	0.002 a	0.001 a	0.000 a
	Fertilized	0.000 a	0.004 a	0.002 a	0.000 a

† Within each measurement period, means for with different letters are significantly different ($\alpha = 0.05$).

For all three disturbance levels, CO₂ evolution in the January to April period was significantly lower than in both summer periods. The two summer rates were statistically similar, except in the bedded plots without damage, where the September rate was elevated. October CO₂ evolution was also significantly lower than in both summer periods, regardless of mechanical disturbance. No time-related interactions occurred in CH₄ evolution. Averaged across all treatments, CH₄ evolution was relatively uniform in the last three measurement periods (0.26, 0.20, and 0.22 mg m⁻² h⁻¹, respectively), but significantly lower in January through April (0.07 mg m⁻² h⁻¹). Nitrous oxide evolution exhibited an interaction between time and mechanical disturbance ($P < 0.001$), as there was no measurable activity in undisturbed areas, but significant ephemeral activity in areas that were mechanically disturbed.

Differentiation of microsite types proved useful both in understanding these treatment effects and in assessing soil condition in the planting beds. Initial ANOVAs indicated strong differences in CO₂ evolution among some microsite types (Table 3). Means separation showed that rates of CO₂ evolution from undisturbed forest floor and beds without residual damage were similar (Fig. 2B). Thus, lower means in bedded vs. undisturbed plots were due mainly to depressed activity in interbed rows. Carbon dioxide evolution was depressed an average of 34% in planting beds with residual damage vs. undamaged beds. Shortly after fertilization in early summer, CO₂ evolution from damaged beds that were fertilized was about twice that of similar nonfertilized beds, re-

Table 3. Summary of significance levels from gas-flux ANOVAs in comparisons of microsite types.

Factor	Gas	P values			
		January- April	June- July	September	October
Mech. disturbance (4 levels)	CO ₂	0.000***	0.000***	0.000***	0.000***
	CH ₄	0.081	0.209	0.052	0.011*
	N ₂ O	0.568	0.000***	0.331	0.049*
Fertilization (2 levels)	CO ₂	0.658	0.003**	0.042*	0.158
	CH ₄	0.852	0.474	0.831	0.291
	N ₂ O	0.972	0.538	0.526	0.758
Interactions	CO ₂	0.991	0.094	0.912	0.382
	CH ₄	0.689	0.897	0.783	0.152
	N ₂ O	0.526	0.656	0.484	0.232

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

sulting in an interaction ($P = 0.09$) between microsite type and fertilization.

Undisturbed soils adhered closely to an exponential temperature function, which accounted for 85% of variation throughout 1992 (Fig. 3). This function defined a sharp upper bound on rates of CO₂ evolution for all microsite types. With increasing severity of disturbance, however, temperature accounted for less variation, suggesting that other factors had become limiting. Soil moisture was largely insignificant as a determinant of CO₂ efflux, probably because soil moisture at the study sites varied little during 1992—a year of above-average rainfall.

Spatial variation in CH₄ (Fig. 2C) and N₂O (Fig. 2D) fluxes was much greater. For both CH₄ and N₂O, scattered high peaks occurred exclusively in mechanically disturbed areas. However, a significant difference in CH₄ evolution occurred only in October, when evolution from undamaged beds was higher than undisturbed soils and interbed rows. Nitrous oxide evolution was significantly higher in beds with residual damage than all other microsite types in the June through July period only, shortly after fertilization. No N₂O evolution was observed from undisturbed soils during this study. In the assay for determining the N₂/N₂O-N ratio, N₂O evolution was detected in 29% of the incubations in either the first or second stage. Of the cases in which denitrification activity was detected, N₂ evolution averaged 4.1 times greater than N₂O-N, and the N₂/N₂O-N ratio varied from 0.23 to 16. These incubations suggested that only about 20% of gaseous N evolution was in the form of N₂O, the only N gas measured in the field.

Chamber Performance

A constant flux rate across the soil surface during sampling is desirable, as it indicates that effects sometimes associated with chambers (such as soil warming or decreased diffusion due to high concentrations of a gas in the chamber headspace) either did not occur or did not affect flux rates. For all gases, evolution remained temporally linear throughout the study, even on the warmest days ($\approx 40^\circ\text{C}$). Coefficients of determination were calculated for every rate calculation and were consistently near 1.0. Soil temperature beneath the chambers remained constant during incubations.

Soil Characteristics

Two soil characteristics were especially sensitive to mechanical disturbance. The concentration of water-soluble organic C was reduced 37% in beds with residual skid-trail damage vs. undamaged beds and was lowest in interbed rows where the A horizon had been removed (Fig. 4B). Compounding this potential labile C deficiency was an acute reduction in air-filled pore space in damaged beds (Fig. 2A) to a level where gas diffusion through soils and unconsolidated sands virtually ceases (Blake and Page, 1948; Wyckoff and Botset, 1936). There was little air-filled pore space in the interbed rows due to high water tables and frequent saturation and inundation.

Differences were smaller or non-existent among more

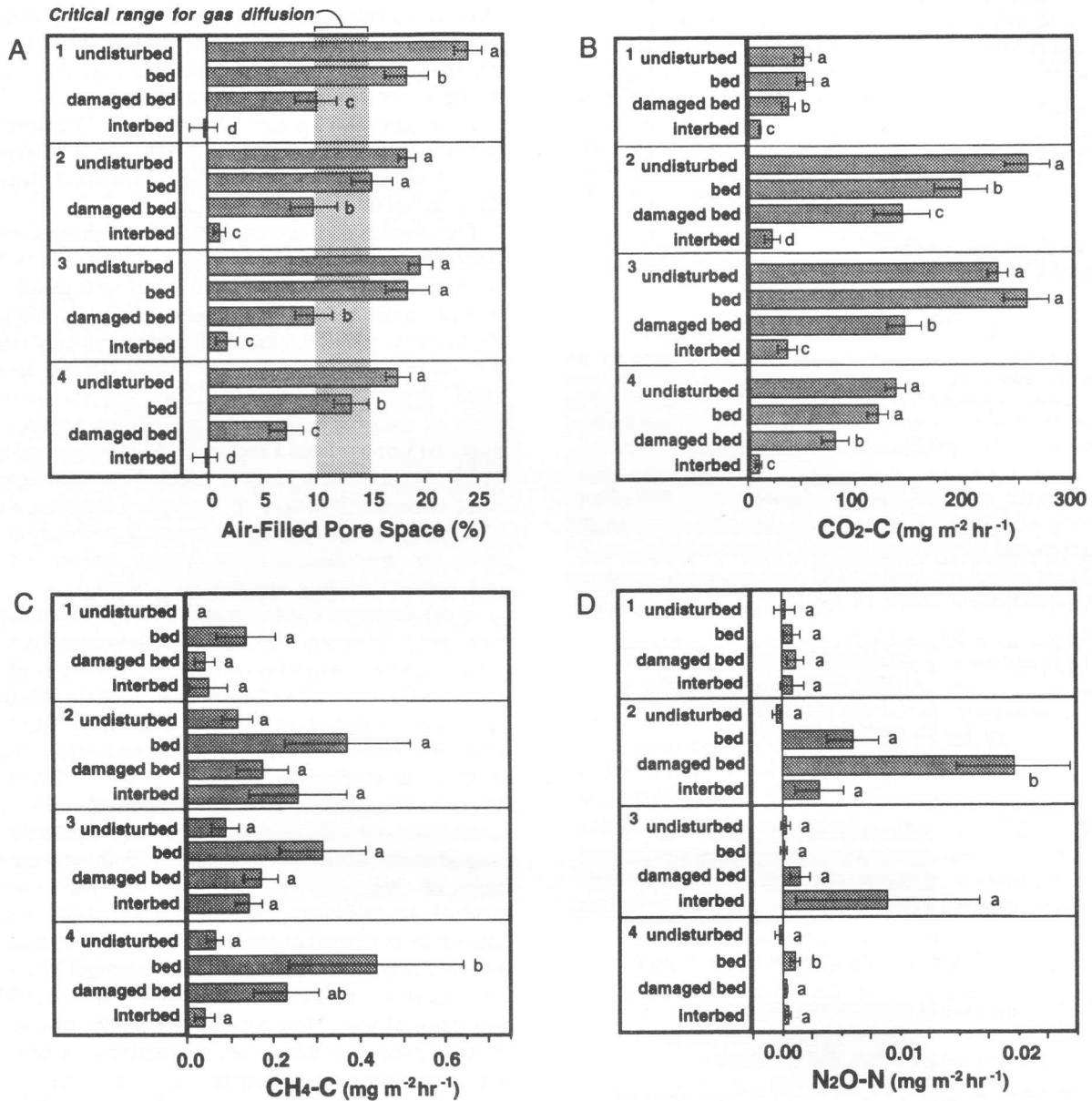


Fig. 2. Air-filled pore space (a) and evolution of the three gases studied (b, c, and d) on four microsite types. Numbers at the upper left of each graph indicate measurement periods in 1992. Period 1 measurements were in January and April, Period 2 in June and July, Period 3 in September, and Period 4 in October. Means with different letters are significantly different ($\alpha = 0.05$). Bars represent \pm one standard error of the mean ($n = 16$).

common measures of soil condition. Although air-filled pore space is calculated from bulk density (Fig. 4D) and soil moisture (Fig. 4E), differences in the latter two measures were smaller. Total organic matter was reduced significantly only in the interbed rows (Fig. 4A). Differences in Kjeldahl N (Fig. 4C) were smaller than those in water-soluble C, but the rankings of microsite types were similar. Ammonium and NO₃ were lowest in undisturbed soils, with no consistent ranking among the remaining microsite types. However, differences in these labile N measures were usually significant only at high probability values (0.08–0.11), possibly due to the difficulty of obtaining a well-mixed field-moist soil sample for KCl extraction. The range of microsite-type means

for NO₃ concentrations was 0.0013 to 0.0032 mg kg⁻¹, and 0.02 to 0.14 mg kg⁻¹ for NH₄.

DISCUSSION

Residual Harvest Damage

Carbon dioxide evolution, unlike that of CH₄ and N₂O, was a stable and consistent indicator of residual harvest damage and was among the most sensitive measures tested. Two measures rarely included in soil damage assessments, water-soluble organic C and air-filled pore space, proved particularly useful in interpreting biological responses.

The lower concentration of water-soluble organic C

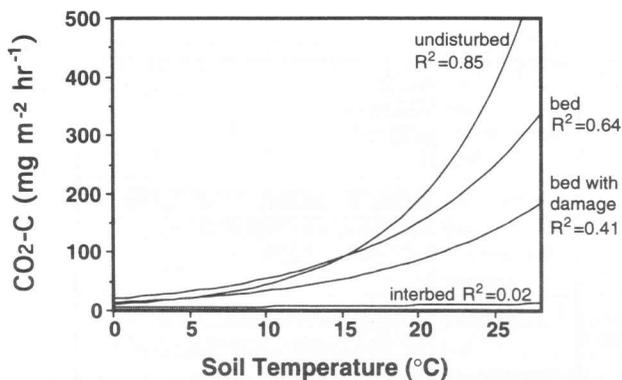


Fig. 3. Exponential regressions of $\text{CO}_2\text{-C}$ vs. temperature for the four microsite types ($n = 64$ for each type). Regression equations are as follows: undisturbed, $Y = 10.41 \times 10^{0.0585}$; beds, $Y = 19.75 \times 10^{0.0411}$; beds with damage, $Y = 13.07 \times 10^{0.0382}$; and interbed rows, $Y = 4.58 \times 10^{0.0141}$.

in soils with residual harvest damage provided direct evidence of a labile C deficiency. Displacement of the A horizon and forest floor during timber salvage had no significant effect on total soil C, but probably removed a disproportionate share of labile C in fresh detritus.

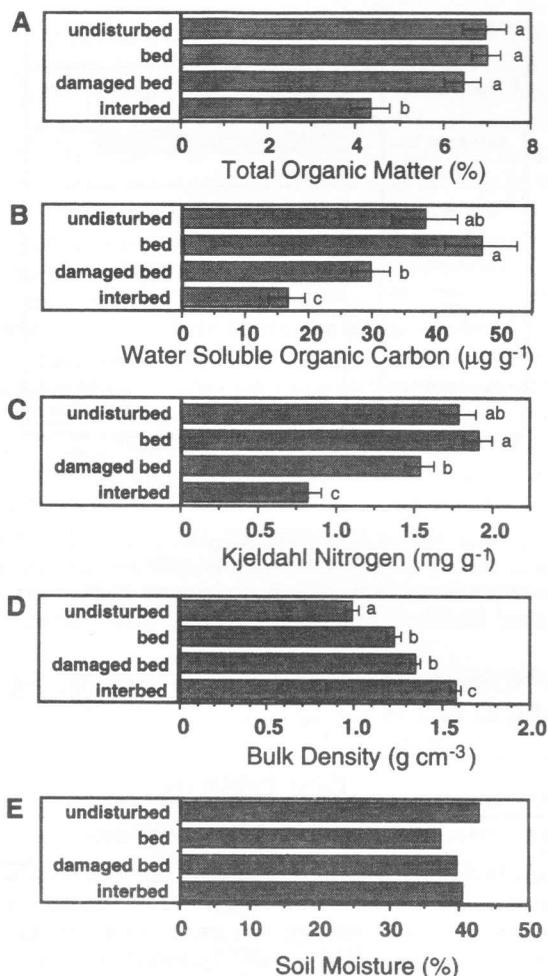


Fig. 4. Soil characteristics of four microsite types. Means with different letters are significantly different ($\alpha = 0.05$). Bars represent \pm one standard error of the mean ($n = 16$). Soil moisture is averaged across all four measurement periods.

Moreover, rutting from harvest machinery and subsequent tillage caused incorporation of Bt horizon material into the planting beds. Water-soluble organic C has been strongly correlated with mineralizable C, evolved as CO_2 , in laboratory assays (Burford and Bremner, 1975) and should be investigated further as a limitation to biological activity and microbially mediated nutrient cycling in harvest-damaged soils.

The results also demonstrated the importance of considering air-filled pore space in evaluation of wet soils, where critically low values can occur with small changes in soil moisture and bulk density. Below 10 to 15% air-filled pore space, most soils and unconsolidated sands are virtually impermeable to gases (Blake and Page, 1948; Wyckoff and Botset, 1936) and the growth and yield of many agricultural crops suffers appreciable reduction (Vomocil and Flocker, 1961; Grable and Seimer, 1968). Soils in planting beds created over damaged areas were consistently below this range. Likewise, the 10 to 15% range in air-filled pore space is probably a critical level for microbial activity, below which metabolism and nutrient cycling are radically altered.

In the absence of disturbance, CO_2 evolution appears to be largely a function of seasonal temperature fluctuations, even among dissimilar soils. Temperature alone accounted for 85% of variation in CO_2 fluxes from undisturbed soils in this study. Jurik et al. (1991) likewise observed remarkable similarity in soil respiration rates among undisturbed Michigan sites that differed widely in tree size, productivity, and soil fertility.

Methane and N_2O responded only intermittently to disturbance, which is consistent with the ephemeral natures of these gas fluxes. The 210% increase in N_2O evolution associated with residual damage, which occurred in the period following fertilization, was consistent with the earlier findings of Torbert and Wood (1992) in laboratory incubations and Bakken et al. (1987) in an agricultural soil. However, in our study, this effect was evident even after tillage as a corrective measure. Nitrous oxide evolution was absent on many sites where methanogenesis occurred, a process requiring a much lower redox potential. Denitrification was probably limited by NO_3^- , rather than redox state. Despite lack of differences in NO_3^- concentrations, lower overall biological activity in damaged beds may have led to lower assimilatory demand by plants, microorganisms, and fungi — leaving a greater share for dissimilatory reduction by anaerobic bacteria.

The average 54% decrease in CH_4 evolution associated with residual damage in planting beds was not significant, but the trend was consistent with results previously obtained by Hansen et al. (1993). Two mechanisms for attenuation of CH_4 efflux are plausible.

1. In addition to requiring virtually complete anoxia, methanogens utilize only a limited range of simple, labile, organic compounds (Conrad, 1989). A labile C deficiency could limit methanogenesis in harvest-damaged soils.
2. Methane is subject to rapid biological oxidation if its efflux from the soil is delayed (King et al.,

1990). Such a delay is likely in soils with reduced aeration and loss of soil structure due to puddling.

Bedding

Differences in flux rates among beds and undisturbed soils were minor or of marginal significance. In areas without previous soil damage, the composition of soil in beds was similar to that of an undisturbed A-horizon. Though aeration was reduced slightly as a result of bed formation (air-filled pore space was significantly lower in two of four periods), CO₂ evolution was largely unchanged. Scattered high peaks in CH₄ and N₂O, not seen in the undisturbed soils, did occur in the beds. These peaks rarely resulted in significantly higher means, but the trends' consistency suggests that differences could have existed. In the future, more intensive sampling or alternative approaches such as micrometeorological sampling, should be employed to better characterize tillage effects on CH₄ and N₂O fluxes.

Immediately after the planting beds were formed, and during the first measurement period, no plant cover was present. Though seasonal changes in the flora and fauna contributing to CO₂ efflux were not characterized, the consistency of treatment effects suggested that gross soil metabolic activity was governed by relatively stable factors associated with soil condition.

The interbed rows differed radically from other microsite types. This result was specific to the method of bedding employed, which exposed a Bt horizon in interbed rows. Other methods of bedding leave an intact forest floor in the interbed row, which differs little from an undisturbed soil. Low rates of CO₂ evolution from interbed rows contributed to reduced C efflux from bedded vs. undisturbed areas. Concentrating all of the A horizon material into beds further limited overall CO₂ efflux by reducing surface area for gas exchange between A horizon material and the atmosphere.

Fertilization

Carbon dioxide was the only gas flux for which a significant response to fertilization was observed. Fertilizer may have stimulated C mineralization or root respiration by increasing plant vigor, but these contributions were not partitioned. The only direct evidence that fertilizer ameliorated harvest damage was an interaction between mechanical disturbance and fertilization during the June to July period, in which CO₂ evolution from damaged beds that were fertilized was higher than similar unfertilized beds. Hatchell (1981) saw a similar interaction for seedling growth in pine flats of the Francis Marion National Forest, where a combination of bedding and fertilization was more effective than bedding alone. By accelerating biological activity, fertilization may eventually promote recovery of soil physical properties, in addition to directly supplementing tree nutrition.

There are several possible explanations for the apparent lack of N₂O production following fertilization.

1. Nitrous oxide evolution occurred but was not detected. Fertilization frequently results in short-

- term, pulsed releases of N gas. In this study, sampling was delayed about a month after fertilization.
2. There was little or no "nitrification link" for conversion of the applied NH₃ to NO₃.
3. Nitrogen evolved primarily as N₂ rather than N₂O and, thus, went undetected. In fact, laboratory incubations suggested that only about 20% of N evolved in the form of N₂O.

Because of the uncertainties in estimating N₂O efflux, interpretations concerning N-gas losses are limited.

Applications for Biogenic Gas Fluxes

Biogenic gas fluxes are composite indicators of soil condition that can integrate across a broad, but ill-defined, range of variables. Biogenic gas fluxes provide a way of discovering and documenting changes in ecosystem processes that may not be apparent through traditional measures such as bulk density, total organic matter, and macronutrient concentrations. Understanding changes in these soil processes facilitates the investigation of the specific chemical and physical properties altered by a disturbance.

Soil biological activity, through the products of respiration, can also reveal effects not apparent through other composite measures. For example, the growth and survival of trees are influenced by a broad range of factors and yield important information concerning commercial productivity. In some cases, fertilization could fully restore tree growth, while soil biological activity and mineralization remain limited by a labile C deficiency. Biogenic gas fluxes also permit instantaneous assessment of treatment effects, whereas measures such as tree performance require years of monitoring. The two approaches

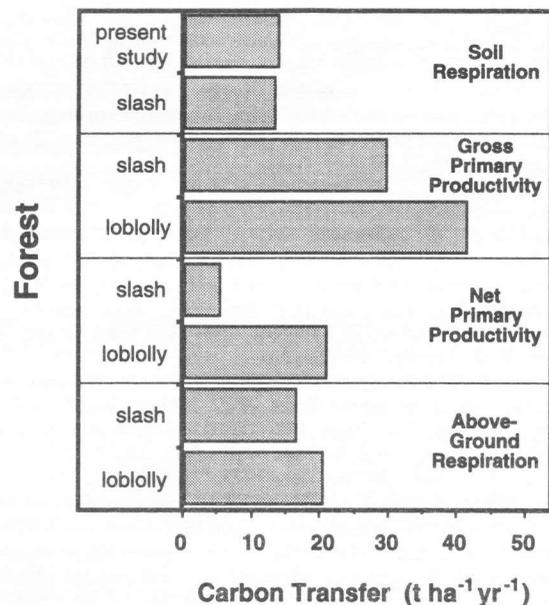


Fig. 5. Carbon transfer rates in three ecosystems. *Slash* indicates rates from a slash pine plantation in Florida (Ewel et al., 1987a). *Loblolly* indicates rates from a loblolly pine plantation in North Carolina (Kinerson et al., 1977). Soil respiration was not estimated in the North Carolina study.

complement one another by integrating across vastly different time scales.

Carbon dioxide evolution emerged as the most reliable indicator of residual harvest damage among the gas fluxes tested. It is also among the largest ecosystem processes, of the same order of magnitude as primary production (Fig. 5). Of the biological processes that are readily measured, soil respiration is exceeded in magnitude only by photosynthesis. Because fluxes of CH_4 and N_2O are highly ephemeral, they require more intensive sampling for accurate characterization and are of limited utility in assessing soil disturbances. Nevertheless, N_2O fluxes are informative in N-amended soils; and CH_4 may be useful under strong reducing conditions, especially where a labile C deficiency is suspected.

CONCLUSIONS

1. Soil damage from wet-weather logging persisted into the establishment phase of the next rotation, despite mitigation by bedding and fertilization.
2. The soil characteristics most strongly influenced by residual harvest damage were water-soluble organic C, reduced 37%, and air-filled pore space, reduced an average of 43% to a level below which gas diffusion through most soils virtually ceases.
3. Soil biological activity, as evidenced by CO_2 evolution, was a robust indicator of soil condition, declining an average of 34% in beds with residual skid-trail damage.
4. Methane and N_2O evolution were unreliable indicators of soil condition, though mechanical soil disturbances produced scattered high peaks in both.

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