Soil warming and trace gas fluxes: experimental design and preliminary flux results

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Received: 13 March 1992 / Accepted: 12 August 1992
Abstract. We conducted several experiments to determine a procedure for uniformly warming soil 5°C above ambient using a buried heating cable. These experiments produced a successful design that could: 1) maintain a temperature difference of 5°C over a wide range of environmental conditions; 2) reduce inter-cable temperature variability to ca. 1.5°C; 3) maintain a temperature difference of 5°C near the edges of the plot; and 4) respond rapidly to changes in the environment. In addition, this design required electrical power only 42% of the time. Preliminary measurements indicate that heating increased CO₂ emission by a factor of ca. 1.6 and decreased the C concentration in the O soil horizon by as much as 36%. In addition, warming the soil accelerated the emergence and early growth of the wild lily of the valley (Maianthemum canadense Desf.). The relationship between CO₂ flux and soil temperature derived from our soil warming experiment was consistent with data from other hardwood forests around the world. Since the other hardwood forests were warmed naturally, it appears that for soil respiration, warming the soil with buried heating cables differs little from natural, aboveground warming. By warming soil beyond the range of natural variability, a multi-site, long-term soil warming experiment may be valuable in helping us understand how ecosystems will respond to global warming.

Key words: Global change - Temperate forest - Forest soils - Biogeochemistry - Global warming

The global mean annual temperature increased 0.5°C during the last century (Jones et al. 1986; Jones and Wigley 1990), and it is expected to increase 2-5°C during the next century due to an enhanced greenhouse effect (Houghton et al. 1990). Although we are uncertain about the timing, magnitude and extent of global warming, we are more uncertain about how ecosystems may respond to increased temperature (Metillo et al. 1990). Warming entire terrestrial ecosystems, especially forests, is difficult. Fortunately, warming entire ecosystems may be unnecessary if their response depends strongly on changes in soil processes. The results of several ecosystem models suggest that this is the case. For example, the response of grassland and forest ecosystem models to simulated climate change is largely determined by decreases in belowground C storage and changes in soil nutrient availability (Schimel et al. 1990; Rastetter et al. 1991). Thus, although it may not always be practical to experimentally warm entire ecosystems, significant insights may still be gained by more feasible soil warming experiments.

Early soil warming experiments in natural ecosystems have shown dramatic results. These include: high mortality of fine roots in a northern hardwood forest (Redmond 1955); a 50% reduction in net C storage by intact cores of Arctic tundra (Billings et al. 1982); and increased decomposition, nutrient (N and P) availability, and foliar nutrient concentrations in an Alaskan black spruce forest (Van Cleve et al. 1990).

Soil warming experiments in agricultural systems have also shown dramatic results. For example, when Rykbost et al. (1975) warmed soils 10°C, yields increased by 19-100% and seedling growth was accelerated. A multi-site soil warming experiment was identified as a "flagship" project by the Long-Term Ecological Research network due to its feasibility and potential for providing valuable information (Long-Term Ecological Research Network Office 1989). Important questions that can be addressed by soil warming experiments include: the effects of soil warming on biogeochemical processes (e.g. decomposition, rock weathering, N cycling, and trace gas emission); and the feedback that changes in these processes may have on atmospheric chemistry and climate change. The potential for climatic feedback is shown by recent predictions that increased global temperatures may increase CO₂ emissions from

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soils to the extent that they will further enhance global warming (Jenkinson et al. 1991).

This paper describes a series of experiments we conducted to determine an appropriate design for a soil warming instrument. We were especially interested in a design that would allow us to determine how warming a forest soil would affect the exchange of trace gases between the land and atmosphere.

Methods
We conducted 6 experiments to determine a procedure foruniformly warming soil 5°C above ambient using a buried heating cable. In these experiments we altered: the plot size; cable spacing; depth of cable burial; and the position of control thermistors within each plot. The specific conditions for each experiment are summarized in Table 1. We evaluated each experiment by measuring the inter-cable temperature variability, and the ability of each plot to maintain the temperature at 5°C above ambient. The inter-cable temperature variability was measured at a depth of 5 cm and is defined as the difference between the soil temperature above and midway between the heating cables.

Plot establishment
The soil in each plot was warmed using 4 buried heating cables (Smith-Gates Easy Heat, Inc.). The cables contained a nickel-chromium resistance wire with an output of 11.5 W/m at 120 V. The heating cables extended the length of each plot and were spaced either 20 or 30 cm apart depending on the desired power density. Heating cables were placed at the bottom of narrow cuts that were created using a flail-bulled shovel. The shovel was inverted to the desired depth and then rocked back and forth to widen the cuts. After the cables were positioned, the soil was compacted back into place by stepping on both sides of the opening. When a buried obstacle was encountered, the cable was buried to the depth of the obstacle. When emergent obstacles were encountered (e.g. trees), the cable was fastened around or over the object.

To measure temperature we used a total of 12 thermistors: 9 in each heated plot; 2 in unheated soil outside each plot ("reference thermistor"); and 1 at a height of ca. 2 m to measure air temperature. A subset of the thermistors in each plot ("control thermis-
tors") were used to maintain the temperature at 5°C above amb-
temperatures. The inter-cable temperature variability was burried to a depth of 5 cm, and measurements from all thermistors were recorded every 15 min by a Campbell CR10 datalogger. To maintain the temperature in the heated plots at 5°C above ambient, the datalogger compared the average temperature of the control and reference thermistors. If the difference in temperatures was <5°C, then a relay switch was opened and power was supplied to the heating cables. If the difference in temperature was ≥5°C, then the relay was closed. Thus, the temperature in a given plot was controlled by evaluating the difference in temperature between heated and unheated soil at 15-mn intervals, and supplying electric power when needed.

Trace gas measurements
We measured the flux of trace gases (CO₂, CH₄, and N₂O) once in January and March, and at least once a month from June through November, 1991. In total we measured trace gas flux on 11 separate occasions. On 8 occasions, we made 3–4 flux measurements per treatment (heated and unheated soil) at midday. On 7 occasions, we measured both early morning and midday fluxes. Fluxes were measured by placing static chambers over the sur-
face of the soil for 30 minutes and measuring the change in trace gas concentrations by gas chromatography. Detailed accounts of these procedures have been previously published (Bowden et al. 1990; Raith et al. 1990; Steidler et al. 1989).

Soil measurements
After 316 days of heating, 5 soil cores were taken from heated (plot A) and unheated soil at 3 m intervals into 3 genetic horizons (O, Ae, and Bhs) and analyzed for C and N. Total C and N were measured by Dumas combustion procedures using a Perkin-Elmer 2400 elemental analyzer (Seibert and Sommer 1982).

Table 1. Summary of the conditions for the prototype soil warming experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Plot Vegetation</th>
<th>Size (m)</th>
<th>Duration (days)</th>
<th>Cable Spacing (cm)</th>
<th>Cable Depth (cm)</th>
<th>Power Density (W/m²)</th>
<th>No. of Control Thermistors</th>
<th>Inter-cable Temperature Variability (°C)</th>
<th>Average Temperature Difference (°C)</th>
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*Placement of control thermistors: 1 = several across inter-cable gradient in center of plot; 2 = over cable and 1 midway between cables in center of plot; 3 = midway between cables in center of plot; 4 = midway between cables at stratified random positions in plot; 5 = midway between cables in corners of plot; 6 = midway between cables insert from corners 3/13 the radius.
Results
Experiments to achieve uniform heating

When heating cables were spaced 30 cm apart and buried at a depth of 5 cm (experiment 1), the inter-cable temperature variability was >3°C. In addition, the average temperature of one of the replicate plots (plot 2) was only 4.23°C above ambient soil temperature. Altering the position of the control thermistor (experiment 2) had little effect on either the inter-cable temperature variability or the ability of plot 2 to maintain its temperature at 5°C above ambient. When control thermistors were positioned midway between the heating cables (experiment 3), plot 1 failed to maintain a temperature difference of 5°C. Thus, plots with a power density of ca. 46 W/m² had considerable inter-cable temperature variability and failed to maintain the desired temperature difference (Fig. 1).

When heating cables were spaced 20 cm apart and buried at a depth of 10 cm (experiment 3) the inter-cable temperature variability was ≤1.6°C and both replicates (plots 3 and 4) had temperatures that were very close to 5°C above ambient soil temperatures. When the control thermistors in these plots were dispersed throughout the plot (experiment 4), the inter-cable temperature variability remained low and the average temperature difference close to 5°C. Thus, plots with a power density of ca. 67 W/m² had a low inter-cable temperature variability and successfully maintained the desired temperature difference (Fig. 2).

During experiments 3 and 4, the lower inter-cable temperature variability in plots 3 and 4 probably resulted from the higher power density and the greater depth of the heating cables relative to the depth of the thermistors. The ability of plots 3 and 4 to maintain the desired temperature difference was due solely to the increased power density.

The spatial variability of the temperature difference (heated – unheated) was measured at 200 random locations in plots 3 and 4 during experiment 4. In both
Fig. 5. The difference in soil temperature maintained in plot 3 during experiment 4

Fig. 6. Temperature difference in plot 3 following a heavy rainstorm. Storm is the one highlighted in Fig. 5

Fig. 7. Temperature at different depths in prototype plot 5 and unheated soil during experiment 6

Heating cables in each corner of the plot (i.e., in the coldest spots). With control thermistors in these positions (experiment 5), both replicates were unable to maintain their temperature at 5°C above ambient. In a second effort, we created a 5 x 5 m plot (plot 5) that was nested within a 6 x 6 m heated area. We also increased the power density of this plot to 79 W/m² by using heating cable with a higher power output (14.8 W/m). Under these conditions (experiment 6) the inter-cable temperature variability was ca. 1.5°C, the temperature was close to 5°C above ambient, and there was no zone of low temperature near the edge of the 5 x 5 m plot (Table 1; Fig. 4).

Performance of heated plots

With power densities ≥ 67 W/m², the soil temperature in the prototype plots could be maintained 5°C above ambient over a wide variety of air temperatures (Fig. 5). Heavy rainstorms often depressed the temperature difference (ca. 1.5°C) but recovery usually occurred within 10 hours (Fig. 6).

On several occasions we compared the temperature at different depths in heated and unheated soil. In March, the temperatures measured in the upper 20 cm of plot 5 were 3-6°C higher than those measured in the upper 20 cm of unheated soil (Fig. 7). In July, more extensive measurements in plot 5 revealed that the temperature at a depth of 1 m was 5°C higher than the temperature at the same depth in unheated soil (Pers. Comm. Pat Megonigal, Duke University). Thus, by heating the soil at a depth of 10 cm, we elevated soil temperatures ca. 5°C above ambient to at least a depth of 1 m.

By directly heating a 6 x 6 m area we also warmed some of the surrounding soil. To determine the extent of this indirect warming, we measured the temperature gradient surrounding plot 5. Soil temperatures surrounding plot 5 decreased 3°C over the first 20 cm and then declined gradually to an asymptote at a distance 50 cm from the perimeter of the plot (Fig. 8). Thus, measurements in soil adjacent to a heated plot should be unaffected.

replicates, 30% of the area had temperatures that were <4°C above ambient, and 70% of the area had temperatures that were between 4 and 6°C above ambient. In addition, the temperature difference was lowest near the edges of each plot (Fig. 3). Attempting to heat the entire plot more uniformly, we positioned the control thermistors midway between the
ed by the heating treatment if they are made at distances that are >50 cm away from the edge of the 6×6 m heated area.

The efficiency and operating cost of our experimental design is largely determined by the amount of time that electricity is supplied to the heating cables. During >900 h of operation, power was supplied to plot 5 only 32% of the time (Fig. 9). At this supply rate the monthly (30-day) power usage was ca. 860 kW.h. The price of electricity varies but it cost us ca. $0.5/month to supply power to plot 5.

In designing long-term experiments, the lifetime of any mechanical components should be considered. The only mechanical components in our soil-warming experi-

ment are the power relays that control the supply of electricity to the heating cables. These switches have an expected lifetime of ca. 2 million operations. During 917 h of operation there was an average of 0.59 switch operations/h in plot 5, so at this rate the relays will last for over 300 years.

Preliminary trace gas measurements

The efflux of CO₂ increased exponentially with increasing soil temperature (Fig. 10A). A linear regression of temperature and the natural logarithm of CO₂ flux explained 72% of the variability and is in agreement with the Arrhenius equation. The estimated activation energy for this process is 78 kJ/mol and the Q₁₀ is 3.1. The efflux of CO₂ was always higher in the heated plots (Fig. 11A) and the average flux of CO₂ from the heated plots (X±SE = 129±11 mg C/m²·h) was ca. 1.6x the average flux from the control plots (78±7 mg C/m²·h).

Methane can be both produced and consumed by soil microbes. In this experiment there was a net uptake of CH₄ by the soil. Methane uptake increased slightly with increasing soil temperature (Fig. 10B) and a linear regression of temperature and methane uptake explained 19% of the variability. The uptake of methane was not consistently or substantially higher when soils were heated (Fig. 11B). The average CH₄ uptake by the heated plots (X±SE = -0.076±0.006 mg C/m²·h) was almost identical to the uptake by the control plots (0.086±0.006 mg C/m²·h).

The flux of N₂O was highly variable and low (<10 μg N/m²·h) which agrees with measurements from other hardwood forests in Massachusetts (Bowden et al. 1990). There was no correlation between soil temperature and N₂O flux (Fig. 10C), and heating the soil did not consistently increase or decrease N₂O flux (Fig. 11C).

Vegetation response

Wild lily of the valley (Mertensia candelaria Desf.) growing in heated soil (plot 5) had fully expanded leaves ca. 2 weeks before individuals growing in unheated soil. The plants were dispersed throughout the plot which created a conspicuous 6×6 m green square in a background of brown-colored leaf litter. To quantify this response, we counted the number of individuals with fully expanded leaves in 4 circular quadrats (0.065 m² each) located both within and outside the heated plot. In early April, the number of plants with fully expanded leaves averaged 44.5 plants/m² in the heated plot and only 11.6 plants/m² in the unheated soil.

Soil response

In the 0 horizon, the average C concentration in the heated soil (X±SE = 22±3.8%) was 36% less than the C concentration in unheated soil (35±1.9%). Carbon
concentrations in both the AE and Bhs horizons (ca. 1.5%) were substantially lower than those in the O horizon, and there was little difference between heated and unheated soil.

The relative differences in N concentrations were similar to those of C. In the O horizon, the average N concentration in the heated soil (8.5 ± 0.83%) was 30% less than the N concentration in unheated soil (1.20 ± 0.09%). Nitrogen concentrations in both the AE and Bhs horizons (ca. 0.05%) were substantially lower than those in the O horizon, and there was little difference between heated and unheated soil.

Discussion

The experiments we conducted produced a successful design for a soil warming experiment at our site. The final design (plot 3) was able to: 1) maintain the average soil temperature at 5°C above ambient over a wide range of environmental conditions; 2) reduce inter-cable temperature variability to ca. 1.5°C; 3) maintain a temperature difference of 5°C near the edges of the plot; and 4) respond rapidly to changes in the environment.

In addition, this design required electrical power only 42% of the time. To achieve this degree of performance we recommend: 1) a power density of 0.67 W/m²; and
2) testing experimental plots within a larger heated area. We also recommend that future soil warming ex-
periments have a replicated design that includes control plots that incorporate the disturbance caused by installing the electrical cables (i.e. culturing roots, soil compaction, etc.).

Preliminary measurements indicate that our final de-
sign is suitable for studying the effects of warming on soil processes. For example, the relationship between CO2 flux and soil temperature derived from our soil warming experiment is consistent with data from other hardwood forests around the world (fig. 12). Since the other hard-
wood forests were warmed naturally, it appears that for soil respiration, warming the soil with buried heating cables differs little from natural, aboveground warming.

By warming soil beyond the range of natural variability, soil warming experiments can provide a unique and valuable data set. Such data will be especially useful for calibrating and testing ecosystem models. If coupled to ecosystem models, we feel that a multi-site, long-term soil warming experiment will be invaluable in helping us understand how ecosystems will respond to global warm-

Acknowledgments: For field and laboratory assistance we thank K. Newkirk, M. Mejufsky, J. Chapman, A. Reza, and M. Caudle. This research is being supported by funds from the United States Environmental Protection Agency (Cooperative agreement CR817734-010, Agency Environmental Research Laboratory) and from the Department of Energy's National Institute for Global Environmental Change (Northeast Regional Center, subagreement 901204-HAR).

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