Oecologia (1993) 93:18–24

Oecologia

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

William T. Peterjohn, Jerry M. Melillo, Francis P. Bowles, Paul A. Steudler

The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543, USA

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 CO_2 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 CO_2 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 forests – 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 (Melillo 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 CO_2 emissions from

Correspondence to: W.T. Peterjohn

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 experiment. 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 for uniformly 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 flat-bladed shovel. The shovel was inserted to the desired depth and then rocked back and forth to widen the cuts. After the cables were positioned, the soil was compressed back in 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 thermistors"); and 1 at a height of ca. 2 m to measure air temperature. A subset of the thermistors in each plot ("control thermistors") were used to maintain the temperature at 5° C above ambient. All thermistors measuring soil temperatures were buried 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 temperature was $< 5°$ C, then a relay switch was opened and power was supplied to the heating cables. If the difference in temperature was $\geq 5°$ 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-min intervals, and supplying electrical power when needed.

Trace gas measurements

We measured the flux of trace gases (CO_2, CH_4, and N_2O) 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 surface 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; Raich et al. 1990; Steudler et al. 1989).

Soil measurements

After 316 days of heating, 5 soil cores were taken from heated (plot 5) and unheated soil. The soil from each core was separated 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 (Nelson and Sommers 1982).

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

Experiment[a]	Plot	Vegetation	Size (m)	Duration (days)	Cable Spacing (cm)	Cable Depth (cm)	Power Density (W/m²)	No. of Control Thermistors	Inter-cable Temperature Variability (°C)	Average Temperature Difference (°C)
1	1	None	3×3	14	30	5	46	4	4.25	4.98
1	2	None	3×3	14	30	5	46	4	3.25	4.23
2	1	None	3×3	4	30	5	46	2	4.75	4.97
2	2	None	3×3	4	30	5	46	2	3.48	4.49
3	1	None	3×3	8	30	5	46	3	5.12	4.09
3	3	Woods	2×3	26	20	10	67	3	0.44	4.98
3	4	Woods	2×3	26	20	10	67	3	1.56	4.98
4	3	Woods	2×3	46	20	10	67	5	0.50	4.95
4	4	Woods	2×3	46	20	10	67	5	1.00	4.89
5	3	Woods	2×3	18	20	10	67	4	0.70	4.23
5	4	Woods	2×3	18	20	10	67	4	0.75	3.81
6	3	Woods	2×3	47	20	10	67	4	N.D.	4.91
6	4	Woods	2×3	47	20	10	67	4	N.D.	4.14
6	5	Woods	6×6	>47	20	10	79	4	1.52	5.05

[a] Placement of control thermistors: 1 = several across inter-cable gradient in center of plot; 2 = 1 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 inset from corners 1/3 the radius

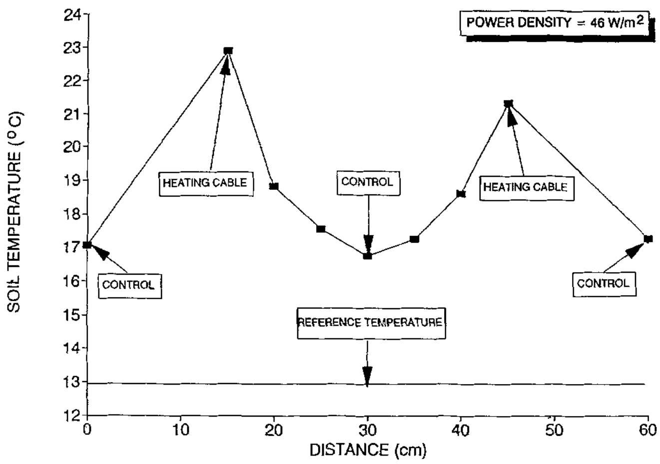

Fig. 1. Variability of inter-cable temperatures in prototype plot 1 during experiment 3. Thermistors were positioned along a transect in the center of the plot that was perpendicular to the lengths of heating cable. The locations of control thermistors and the heating cables are indicated. Reference soil temperature was measured in unheated soil. All thermistors were buried to a depth of 5 cm

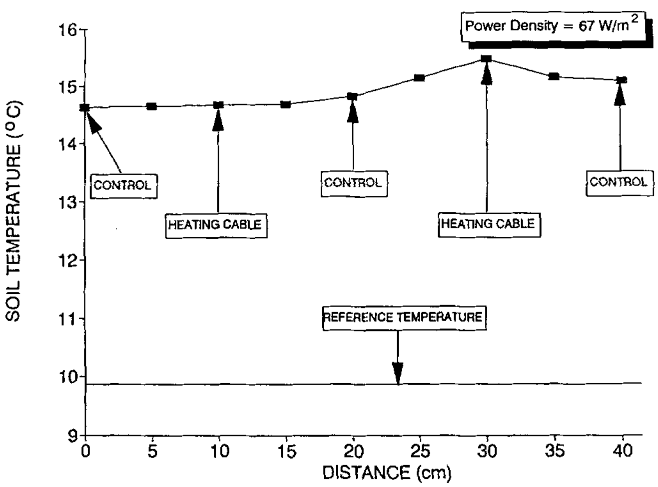

Fig. 2. Inter-cable temperature variability for prototype plot 3 during experiment 3. Thermistor placement as in Fig. 1

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 in one of the replicate plots (plot 2) was only 4.23° C above ambient soil temperature. Altering the position of the control thermistors (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/m^2 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/m^2 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

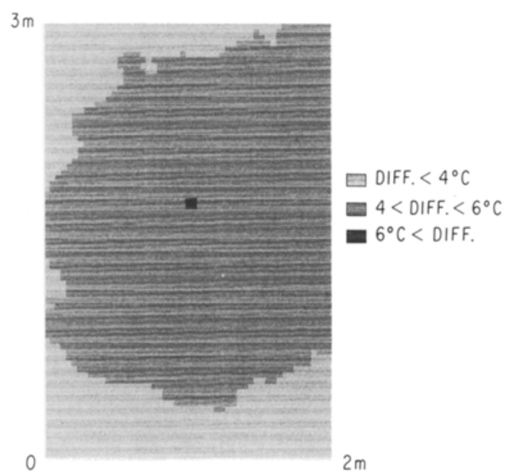

Fig. 3. Spatial variability of the temperature difference between plot 3 and unheated soil during experiment 4

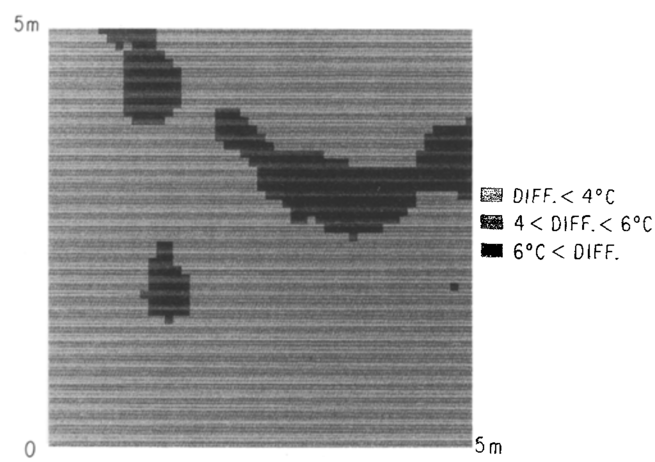

Fig. 4. Spatial variability of the temperature difference between plot 5 and unheated soil during experiment 6

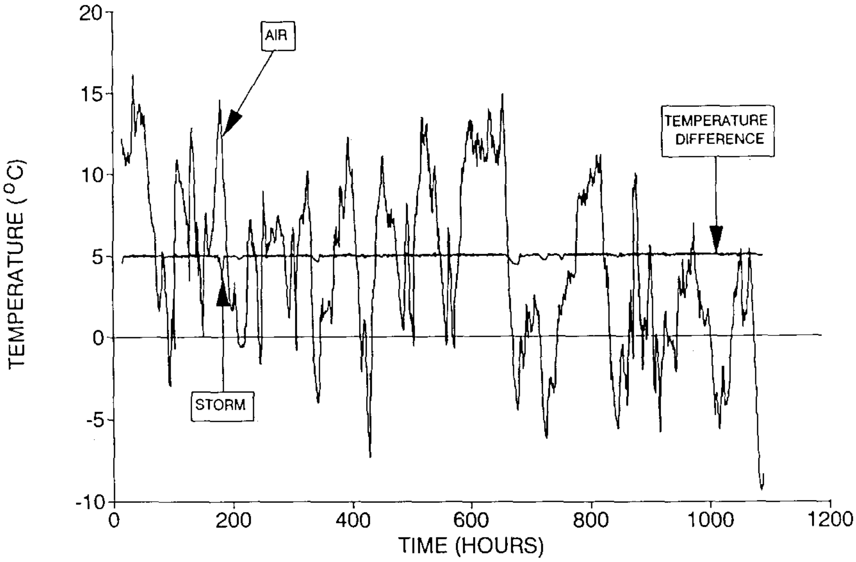

Fig. 5. The difference in soil temperature maintained in plot 3 during experiment 4

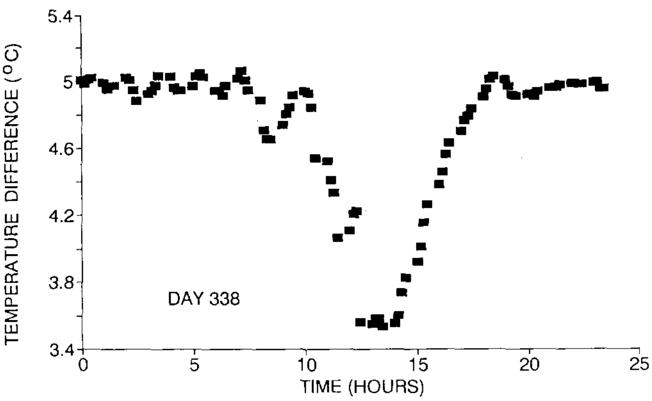

Fig. 6. Temperature difference in plot 3 following a heavy rainstorm. Storm is the one highlighted in Fig. 5

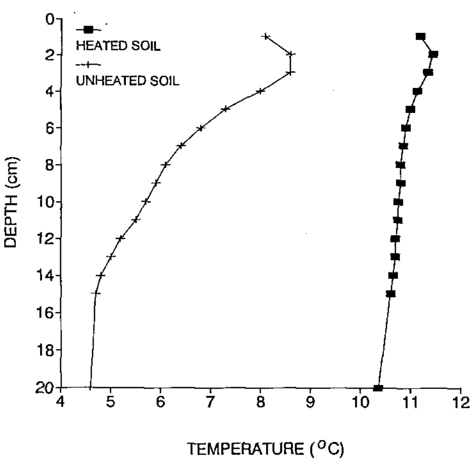

Fig. 7. Temperature at different depths in prototype plot 5 and unheated soil during experiment 6

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 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 × 5 m plot (plot 5) that was nested within a 6 × 6 m heated area. We also increased the power density of this plot to 79 W/m^2 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 × 5 m plot (Table 1; Fig. 4).

Performance of heated plots

With power densities ≥67 W/m^2, 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 × 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 unaffect-

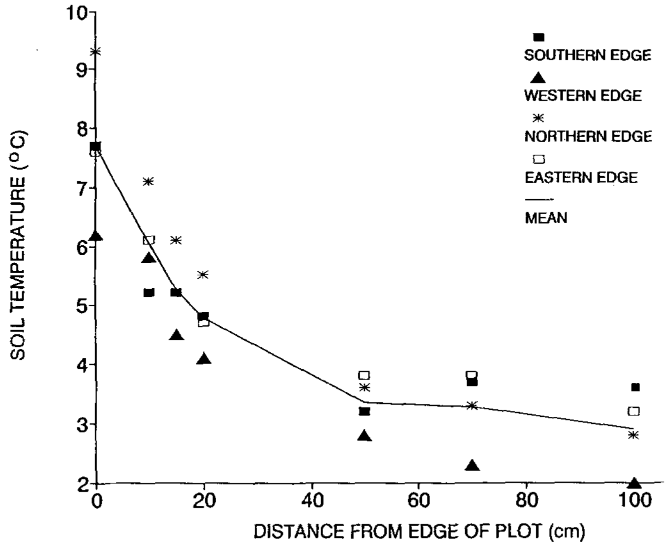

Fig. 8. Temperature gradient surrounding prototype plot 5 during experiment 6. Measurements begin at edge of the heated area

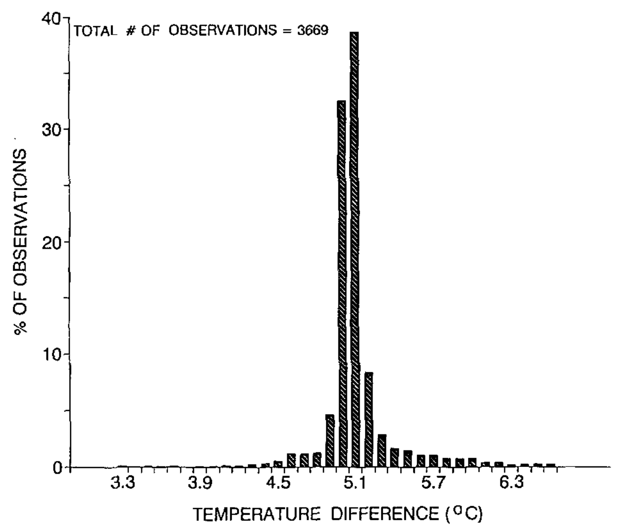

Fig. 9. Frequency distribution of the temperature difference between plot 5 and unheated soil during experiment 6. Power was supplied to the heating cables when the difference in temperature was $<5°$ C

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 42% 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. $85/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 experiment 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 CO_2 increased exponentially with increasing soil temperature (Fig. 10A). A linear regression of temperature and the natural logarithm of CO_2 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 Q_{10} is 3.1. The efflux of CO_2 was always higher in the heated plots (Fig. 11A), and the average flux of CO_2 from the heated plots ($X \pm SE = 129 \pm 11$ mg C/m^2 · h) was ca. 1.6x the average flux from the control plots (78 ± 7 mg C/m^2 · h).

Methane can be both produced and consumed by soil microbes. In this experiment there was a net uptake of CH_4 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 CH_4 uptake by the heated plots ($X \pm SE = 0.076 \pm 0.006$ mg C/m^2 · h) was almost identical to the uptake by the control plots (0.086 ± 0.006 mg C/m^2 · h).

The flux of N_2O was highly variable and low (<10 µg N/m^2 · h) which agrees with measurements from other hardwood forests in Massachusetts (Bowden et al. 1990). There was no correlation between soil temperature and N_2O flux (Fig. 10C), and heating the soil did not consistently increase or decrease N_2O flux (Fig. 11C).

Vegetation response

Wild lily of the valley (*Maianthemum canadense* 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 m^2 each) located both within and outside the heated plot. In early April, the number of plants with fully expanded leaves averaged 444.5 plants/m^2 in the heated plot and only 11.6 plants/m^2 in the unheated soil.

Soil response

In the O horizon, the average C concentration in the heated soil ($X \pm SE = 22.3 \pm 2.8\%$) was 36% less than the C concentration in unheated soil ($35.1 \pm 1.9\%$). Carbon

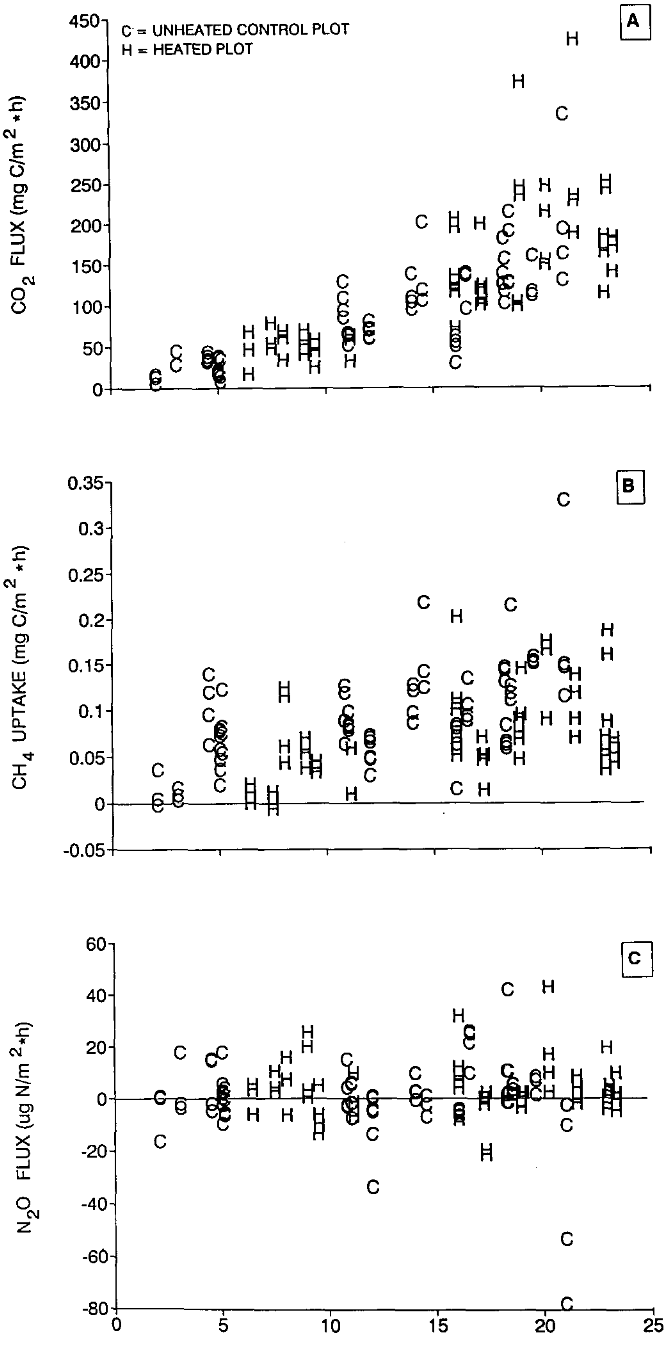

Fig. 10A–C. Relationship between soil temperature at 4 cm and trace gas fluxes for all sampling times

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 (X ± SE = 0.85 ± 0.11%) 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

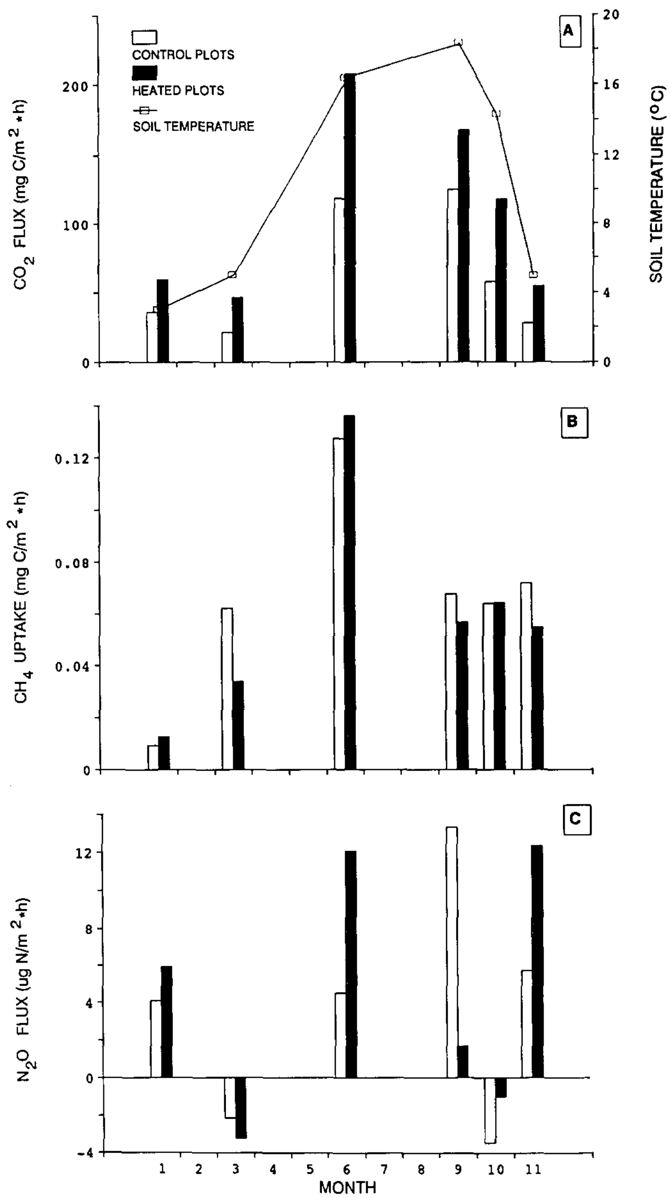

Fig. 11A–C. Average midday fluxes of trace gases from control and heated plots for times when both treatments were sampled

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 5) 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 ≥67 W/m^2; and

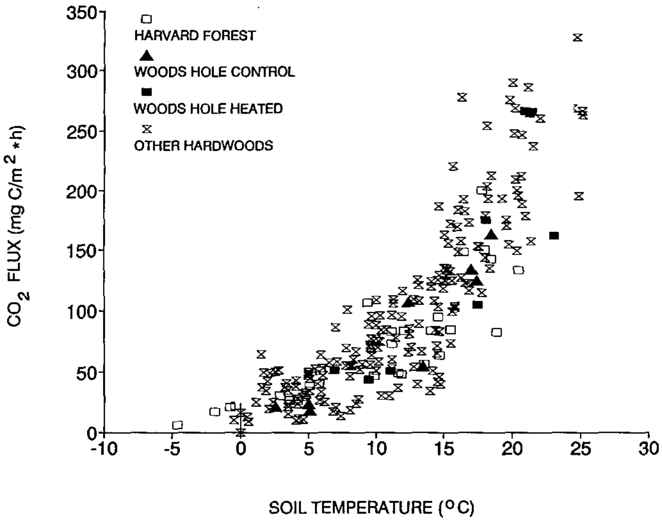

Fig. 12. Relationship between CO_2 flux and soil temperature for hardwood forests around the world. Woods Hole data from this study. Harvard Forest data from Melillo et al. (unpublished data). Values for other hardwood forests include data from: Minnesota (Reiners 1968); Tennessee (Edwards 1975); Missouri (Garrett and Cox 1973); United Kingdom (Anderson 1973); Italy (Virzo De Santo et al. 1976); and Japan (Nakane 1980)

2) nesting experimental plots within a larger heated area. We also recommend that future soil warming experiments have a replicated design that includes control plots that incorporate the disturbance caused by installing the electrical cables (i.e. cutting roots, soil compaction, etc.).

Preliminary measurements indicate that our final design is suitable for studying the effects of warming on soil processes. For example, the relationship between CO_2 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 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, 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 warming.

Acknowledgements. For field and laboratory assistance we thank K. Newkirk, M. Miliefsky, J. Chapman, A. Ricca, and M. Castro. This research is being supported by funds from the United States Environmental Protection Agency (Cooperative agreement CR817734–010, Athens Environmental Research Laboratory) and from the Department of Energy's National Institute for Global Environmental Change (Northeast Regional Center, subagreement 901214–HAR).

References

Anderson JM (1973) Carbon dioxide evolution from two temperate, deciduous woodland soils. J Appl Ecol 10:361–378

Billings WD, Luken JO, Mortensen DA, Peterson KM (1982) Arctic tundra: a source or sink for atmospheric carbon dioxide in a changing environment? Oecologia 53:7–11

Bowden RD, Steudler PA, Melillo JM, Aber JD (1990) Annual nitrous oxide fluxes from temperate forest soils in the northeastern United States. J Geophys Res 95:13997–14005

Edwards NT (1975) Effects of temperature and moisture on carbon dioxide evolution in a mixed deciduous forest floor. Soil Sci Soc Am Proc 39:361–365

Garrett HE, Cox GS (1973) Carbon dioxide evolution from the floor of an oak-hickory forest. Soil Sci Soc Am Proc 37:641–644

Houghton JT, Jenkins GJ, Ephraums JJ (eds) (1990) Climate change: the IPCC scientific assessment. Cambridge University Press, New York

Jenkinson DS, Adams DE, Wild A (1991) Model estimates of CO_2 emissions from soil in response to global warming. Nature 351:304–306

Jones PD, Wigley TML (1990) Global warming trends. Sci Am 263:84–91

Jones PD, Wigley TML, Wright PB (1986) Global temperature variations between 1861 and 1984. Nature 322:430–434

Long-Term Ecological Research Network Office (1989) 1990's global change action plan utilizing a network of ecological research sites. Long-Term Ecological Research Network Office, Seattle

Melillo JM, Callaghan TV, Woodward FI, Salati E, Sinha SK (1990) Effects on ecosystems. In: Houghton JT, Jenkins GJ, Ephraums JJ (eds) Climate change: the IPCC scientific assessment. Cambridge University Press, New York, pp. 285–310

Nakane K (1980) Comparative studies of cycling of soil organic carbon in three primeval moist forests. Jpn J Ecol 30:155–172

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Page AL (ed) Methods of soil analysis. Part 2. American Society of Agronomy and Soil Science Society of America, Madison, pp. 539–579

Raich JW, Bowden RD, Steudler PA (1990) Comparison of two static chamber techniques for determining carbon dioxide efflux from forest soils. Soil Sci Soc Am J 54:1754–1757

Rastetter EB, Ryan MG, Shaver GR, Melillo JM, Nadelhoffer KJ, Hobbie JE, Aber JD (1991) A general biogeochemical model describing the responses of the C and N cycles in terrestrial ecosystems to changes in CO_2, climate, and N deposition. Tree Physiol 9:101–126

Redmond DR (1955) Studies in forest pathology. XV. rootlets, mycorrhiza, and soil temperatures in relation to birch dieback. Can J Bot 33:595–627

Reiners WA (1968) Carbon dioxide evolution from the floor of three Minnesota forests. Ecology 49:471–483

Rykbost KA, Boersma L, Mack HJ, Schmisseur WE (1975) Yield response to soil warming: agronomic crops. Agron J 67:733–738

Schimel DS, Parton WJ, Kittel TGF, Ojima DS, Cole CV (1990) Grassland biogeochemistry: links to atmospheric processes. Clim Change 17:13–25

Steudler PA, Bowden RD, Melillo JM, Aber JD (1989) Influence of nitrogen fertilization on methane uptake in temperate forest soils. Nature 341:314–316

Van Cleve K, Oechel WC, Hom JL (1990) Response of black spruce *(Picea mariana)* ecosystems to soil temperature modification in interior Alaska. Can J For Res 20:1530–1535

Virzo De Santo A, Alfani A, Sapio S (1976) Soil metabolism in beech forests of Monte Taburno (Campania Apennines). Oikos 27:144–152