CHAPTER 13

Soil Warming

A Major Consequence of Global Climate Change

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Rationale and Overview

Current models of climate change predict that as human activity increases the amounts of greenhouse gases such as CO_2, methane (CH_4), and nitrous oxide (N_2O) in the atmosphere, global mean temperature will rise over the twenty-first century, perhaps by as much as 1.4° to 5.8°C. Rising sea level, alterations of agricultural production, and gradual changes in the distributional ranges of animals and plants are among the many potential ecological consequences of temperature increases in this range. Some of the most important effects would be changes in a suite of soil processes that influence ecosystem function but also have critical linkages to atmospheric and global processes. Temperature-dependent belowground processes that are of particular interest include plant root respiration, organic matter decomposition, CH_4 production and oxidation, nitrogen mineralization, nitrification and denitrification, and phosphorus availability. These processes are involved in the fluxes of greenhouse gases and/or in ecosystem production. Understanding the direction, magnitude, and duration of their responses to temperature increases is important. Among the key questions concerning the effect of climate change on the soil environment are the following:

- What are the types and magnitudes of ecosystem responses?
- Are responses transient or persistent?
- Are there important feedbacks between these responses and global climate change?

There are many approaches to estimating ecological responses to global change, including simulation modeling, microcosm or closed-system experiments, and reductionist studies on individual organisms.

One of the most promising for studying the responses of belowground processes is carefully controlled and long-term manipulation of the soil temperature environment. Such studies seek to manipulate one component of intact ecosystems—the soil—generally using buried heating cables to maintain the temperature at a certain level above ambient conditions.

Soil-warming experiments in a number of ecosystems have shown a range of responses to increased temperatures, including increased fine root mortality in a yellow birch stand in New England and increased decomposition, nutrient availability, and foliar nutrient concentrations in an Alaskan black spruce stand. The warming of cores containing both plants and soil from a wet coastal area of the tundra of northern Alaska resulted in reduced ecosystem carbon storage, whereas the warming of an adjacent wet sedge area caused increases in concentrations of inorganic nitrogen, phosphorus absorption, and plant growth. Overall, these studies reinforce the interpretation that elevated soil temperatures from global warming have the potential to dramatically alter the carbon, nitrogen, and phosphorus cycles of ecosystems.

As a result of feedbacks among soil and ecosystem and atmospheric processes, soil warming may also have global effects, but the net effect of these interactions on a global scale is unclear. On one hand, faster decomposition of soil organic matter may enhance global warming substantially by increasing the release of CO_2 from soil to the atmosphere. On the other, this increase in organic matter decomposition may increase the availability of nitrogen for plant growth, increasing carbon storage in plants and litter.

To explore this complex set of interactions within the soils, we initiated a soil-warming experiment at the Harvard Forest in 1991. The purpose of this experiment was to determine the response of soil processes in a typical mixed deciduous forest to elevated soil temperatures, with special emphasis on soil processes that could substantially alter ecosystem function, atmospheric chemistry, and global climate. We were interested in considering warming as a stress that, like nitrogen deposition or logging and wind disturbance, would initiate forest ecosystem responses, but also sought to link those responses with broader processes. The initial ten years of the experiments generated some very interesting insights on both.

Experimental Design

The soil-warming experiment was established on the Prospect Hill tract in an even-aged, mixed deciduous forest dominated by black oak, red maple, paper birch, and striped maple that was quite similar to the forests in the other experiments. The soil profile and historical records indicate that the site underwent historical uses that are typical

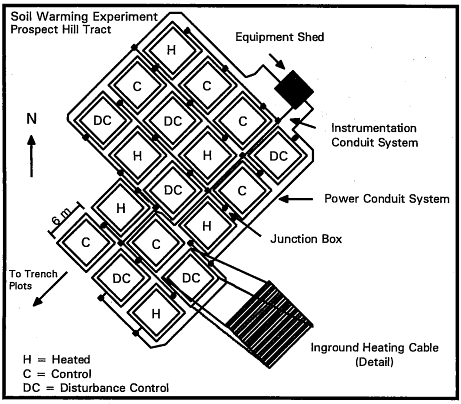

Figure 13.1. Design and layout of the soil-warming experiment at the Harvard Forest. The experiment had six replicates of three treatments: control plots where no manipulation occurred, disturbance-control plots where heating cables were installed but not turned on, and heated plots where buried heating cables maintained a 5°C temperature differential above the control plots through continuous monitoring by buried thermistors and a data logger. Modified from Peterjohn et al. 1994, with permission from the Ecological Society of America.

for the region. After deforestation the area was pastured, though not plowed, until the late 1890s, when it was abandoned and reforested naturally. Since that time, the regrowing forest was cut for firewood once.

In April 1991, we established eighteen 6-by-6-meter plots assigned to one of three treatments: (1) heated plots in which the average soil temperature at 5 centimeters was elevated 5°C above ambient using buried heating cables; (2) disturbance control plots that had buried heating cables identical to heated plots but that received no electric power; and (3) control plots that were left in their natural state (Figures 13.1 and 13.2). In the heated and disturbance control plots, heating cables were buried at a depth of 10 centimeters in rows spaced 20 centimeters apart. Electrical current was supplied only to the cables in the six heated plots. Application of the current was controlled by computers connected to an array of thermistors buried at a depth of 5 centimeters in all of the plots. These served to maintain the 5°C temperature difference between the heated plots and the others. The technology for heating soils is very well-developed and has many applications. In fact, the cables that we used are similar in design to those used in Mile High Stadium, where the Denver Broncos play football. Nonetheless, to develop an effective system to ensure closely controlled temperatures, we had to undertake considerable engineering and field experiments. Among the results from a study that we undertook on Cape Cod before establishing the soil-warming experiment at the Harvard Forest, we learned that soil temperatures

Figure 13.2. Several snow-free heated plots in late winter. In addition to raising soil temperatures and altering ecosystem processes, soil warming lengthened the growing season and decreased the duration of snow cover. Photograph by H. Lux.

were consistently lower near the edges of a heated area. Therefore, to avoid places where the temperature difference is less than 5°C, we made all of our measurements in a 5-by-5-meter area in the center of each plot.

Over the course of the study, we measured trace gas fluxes, various indices of nitrogen availability, and soil water content. Taken together, these measurements allowed us to quantify key biogeochemical responses of this forest ecosystem to soil warming. The three gases that we chose to measure—CO_2, CH_4, and N_2O—can accumulate in the Earth's atmosphere and trap enough heat radiating from the surface to cause global warming. As discussed extensively in the previous chapter, nitrogen is thought to be the nutrient that most limits forest growth in New England. Soil water affects both the carbon and nitrogen cycles in terrestrial ecosystems.

Soil Responses to the Treatment

Soil Temperature

Our soil-heating approach successfully and consistently elevated soil temperatures 5°C above ambient soil temperature throughout the ten years of the experiment (Figure 13.3). Although most of our measurements of soil temperature came from the upper 20 centimeters of the

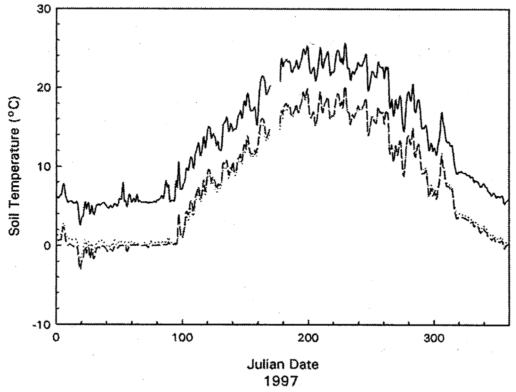

Figure 13.3. Daily soil temperatures in heated (solid line), disturbance control (broken line), and control (dotted line) plots over the course of one year (1997). The array of heating cables was capable of maintaining a sustained 5°C increase in heated plots over a wide range of temperatures and environmental conditions.

soil profile, we were able to verify that heating does affect soil temperatures to a depth of at least 1 meter. We also confirmed that the soil disturbance associated with the installation of heating cables had no effect on soil temperatures and only minor and variable effects on soil moisture.

Interannual Variability in Soil Respiration

Carbon dioxide flux from soils, which reflects respiration of both plant roots and soil microorganisms, exhibited substantial interannual variability across treatments. The highest annual emission rate of CO_2 was 1,090 grams per square meter from the heated plots during 1994 (Table 13.1). Interannual variability in climate parameters, temperature, and precipitation, all of which influence decomposition rates, appear to be responsible for these year-to-year variations. A warm and extremely dry period between May and August 1995 resulted in the lowest absolute fluxes for each of the treatments for the field measurement period, April through November.

Q_{10} Relationships between Temperature and CO_2

Over the course of our study, we observed a strong exponential relationship between soil temperature and CO_2 flux for each treatment (Figure 13.4). Initially, the Q_{10} values, which represent the change in respiration associated with a 10°C change in temperature, were very similar for all treatments. However, through time the Q_{10} value for the heated plots declined (mean of 2.4), while the annual Q_{10} values for the

Table 13.1. Cumulative Yearly CO_2 Flux by Treatment

Year	Control	Distrubance Control	Heated
1991	480	550	770
1992	660	730	870
1993	730	790	970
1994	900	870	1,090
1995	590	570	720
1996	640	610	740
1997	730	710	780
1998	890	880	940
1999	760	780	770
2000	720	730	780

Note: 1991 is a partial year (July through November). Values are grams carbon per square meter per year.

control and disturbance control plots remained similar (means of 2.8 and 3.0, respectively) (Figure 13.5). The Q_{10} values derived from these measurements on the three treatments bracket the median value of 2.4 calculated from an extensive review of the literature.

For each of the treatments, we observed substantial year-to-year variability in Q_{10} values. Annual Q_{10} values for the control plots ranged from 2.0 to 3.7, whereas those for the disturbance control plots ranged from 2.1 to 4.0 and for the heated plots from 1.7 to 3.4. The lowest Q_{10} values for all of the plots occurred during the very dry late spring and summer of 1995. There is a strong linear relationship between summer precipitation for the months of June, July, and August and Q_{10} values for the ten full years of soil respiration measurements (Figure 13.6).

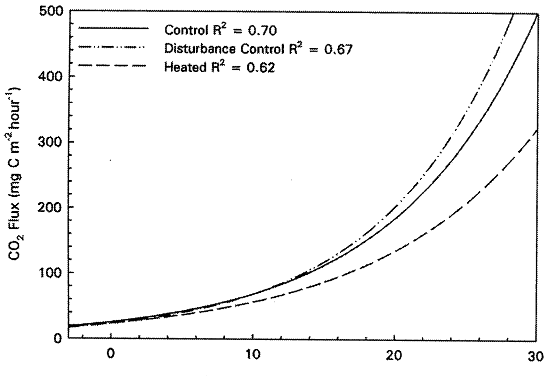

Figure 13.4. CO_2 flux as a function of soil temperature for each treatment over the period 1991–2000. Heating altered the exponential relationship of soil CO_2 flux with temperature, showing less sensitivity over time.

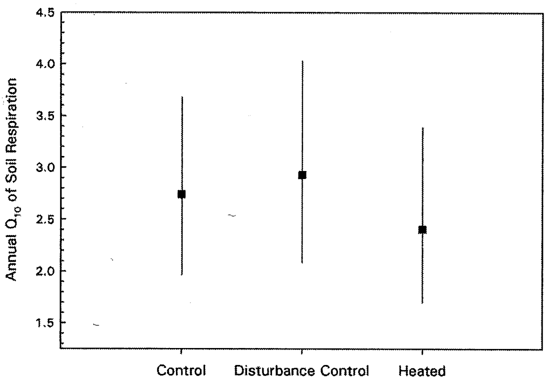

Figure 13.5. The mean and range of Q_{10} values calculated for soil respiration in the soil-warming experiment over the ten years of the study.

CO_2 Fluxes: Patterns Change through Time

Soil warming dramatically increased the CO_2 flux from soils, but this response changed over time (Figure 13.7). In this part of the chapter, we report results from the disturbance control plots as the reference plots, since they are most analogous in treatment to the heated plots. Over the first six years, soil respiration increased on average by about 28 percent. By year ten there was no measurable difference between the CO_2 emissions from the heated and disturbance control plots.

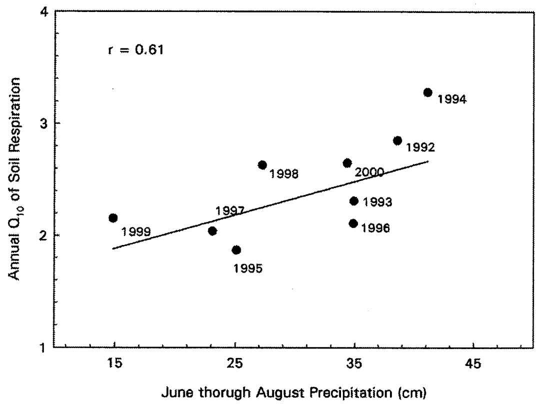

Figure 13.6. The relationship between Q_{10} values calculated for soil respiration each year from 1992 to 2000 for all three treatments and the precipitation for June, July, and August for these years in the soil-warming experiment.

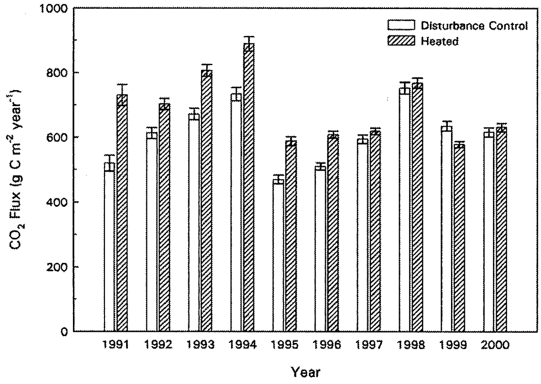

Figure 13.7. Soil respiration by treatment and year on the soil-warming experiment for the field measurement period of April through November. Soil respiration was measured using syringes to draw a time series of gas samples from closed-top chambers (static chamber technique). Samples were analyzed in the lab using an infrared gas analyzer, and rates were calculated from changes in concentration observed over time. Error bars represent the standard error of the mean ($n = 6$ plots) for each treatment. Based on Melillo et al. 2002.

This lack of a difference likely reflects the fact that warming had exhausted an easily decomposed carbon pool.

To estimate the size of this easily decomposed carbon pool we had to partition the two components of soil respiration—microbial respiration and root respiration. We carried out a second field experiment adjacent to the soil-warming experiment that involved trenched plots to exclude roots and a soil-warming treatment, in a full-factorial design in which there were three plots per treatment. We estimated that root respiration is about 20 percent of the total soil respiration, with microbial respiration accounting for the remaining 80 percent (Figure 13.8).

Combining the soil respiration data from the warming study with the data from the partitioning study, we estimate that carbon loss stimulated by warming for the entire ten-year period was 944 grams per square meter. This amounts to about 11 percent of the soil carbon found in the top 60 centimeters of the soil profile.

These results underscore the importance of long-term experiments. The large initial response, if extrapolated, would produce a large overestimate of the potential efflux of CO_2 from soils in a warmer environment.

Evidence for Exhausting the Labile Soil Organic Matter Pool

The overall decrease in the Q_{10} values in the heated plots over ten years suggests that there has been a reduction in the size of the car-

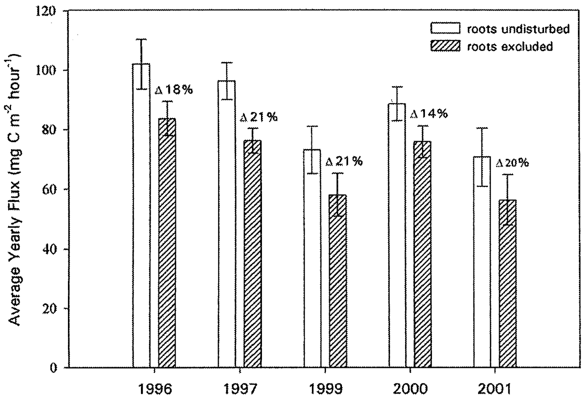

Figure 13.8. Average yearly fluxes at the trenched-plot experiment. Data represent average yearly CO_2 fluxes from unheated plots only, as measured by the static chamber technique. Percent values represent the contribution of roots to total soil respiration. Error bars represent the standard error of the mean ($n = 3$ plots) for each treatment. The same relative patterns were observed in the treatments that included heating and trenching. Modified with permission from Melillo et al., *Science* 298:2173–2176 (copyright 2002, American Association for the Advancement of Science).

bon pool that is readily available for decomposition. The narrowing of the differences between soil respiration rates in the heated and disturbance control plots is consistent with this interpretation. Thus, available evidence suggests that the CO_2 flux response to increased global temperatures in temperate forest soils will be short-lived unless carbon inputs are also increased. Inputs could be increased if temperature increases (or concomitant environmental changes associated with global climate change) elevate the production of leaf or root inputs to the soil organic pool.

Effects of Treatment on Methane Fluxes

Methane fluxes represent the net result of the activities of both CH_4-producing and CH_4-consuming soil microorganisms. Between 1991 and 1995, the average net uptake rate of CH_4 from the atmosphere in the heated plots was about 20 percent higher than in the control and disturbance control plots (Figure 13.9). Interestingly, we found that water-filled pore space, an index of soil water content, is a good predictor of CH_4 flux (Figure 13.10). Therefore, as soil temperatures increase, soil water content decreases, CH_4 uptake in the soil increases, and concentration of CH_4 in the atmosphere declines. This response further complicates the global change interpretation, because two major greenhouse gases (CO_2 and CH_4) respond in different directions to soil warming.

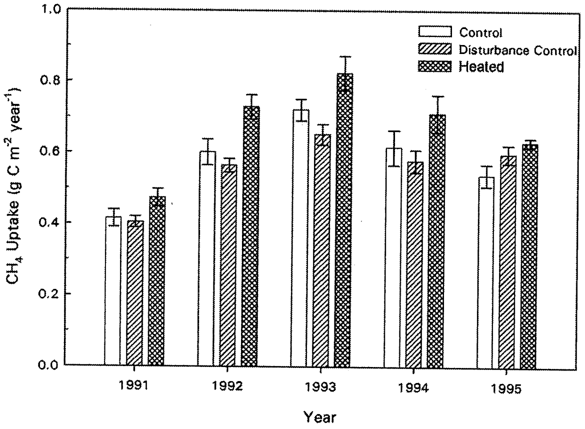

Figure 13.9. Methane uptake by treatment and year in the soil-warming experiment for the field measurement period of April through November. Uptake rates in the heated plots were generally 20 percent higher than those observed in the disturbance control plots. Error bars represent the standard error of the mean ($n = 6$ plots) for each treatment.

Effects of Treatments on Soil Nitrogen Fluxes

Nitrogen is a key limiting nutrient in forest ecosystems of New England (see Chapter 12). We therefore focused on three aspects of the nitrogen cycle:

- Net nitrogen mineralization and nitrification
- Concentration of inorganic nitrogen in soil water
- Nitrous oxide fluxes between the soil and the atmosphere

Net nitrogen mineralization and net nitrification were measured for the first eight years of the study. In this part of the chapter, we again report results from the disturbance control plots as the reference plots, since they are most analogous in treatment to the heated plots. Warming increased net nitrogen mineralization throughout this period (Figure 13.11). Overall, net nitrification rates were low in all plots and years, and in no year was it more than about 5 percent of net nitrogen mineralization (Figure 13.12). We observed neither large amounts of nitrogen (inorganic or organic) moving through the soil profile below the rooting zone nor large N_2O fluxes from the soil in any treatment (Figures 13.13 and 13.14). Presumably, this is due to the fact that these soils, like others at the Harvard Forest, have an ammonium economy with low rates of nitrification, low concentrations of nitrate, and very efficient immobilization of mineralized nitrogen. With little nitrate being produced, there is minimal leaching of inorganic nitrogen. Nitrate is also the primary form of nitrogen used by denitrifying organisms, the producers of N_2O, and so the lack of nitrate production leads to low N_2O production.

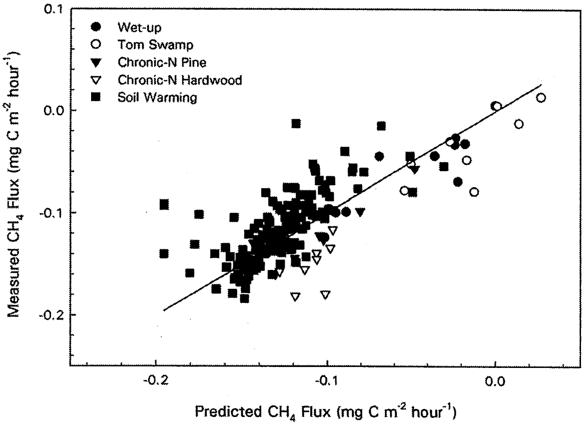

Figure 13.10. Relationship between the observed CH_4 fluxes on a number of field and experimental sites and those predicted with a simple regression model: CH_4 consumption = [0.00175 × (% water-filled pore space) − 0.1957], $R^2 = 0.74$. Modified from Castro, Melillo et al. 1995, with permission from NRC Research Press.

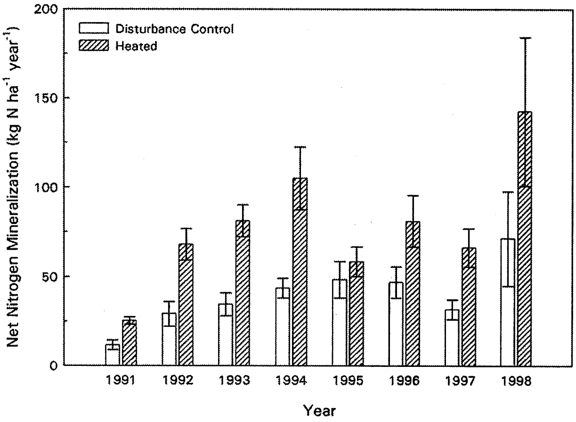

Figure 13.11. Annual rates of net N mineralization for the organic horizon plus the top 10 centimeters of mineral soil for the disturbance control and heated plots in the soil-warming experiment. Soil cores were incubated in situ and extracted in the lab using 2N KCl (buried bag technique). Error bars represent the standard error of the mean ($n = 6$ plots) for each treatment. Modified with permission from Melillo et al., *Science* 298:2173–2176 (copyright 2002, American Association for the Advancement of Science).

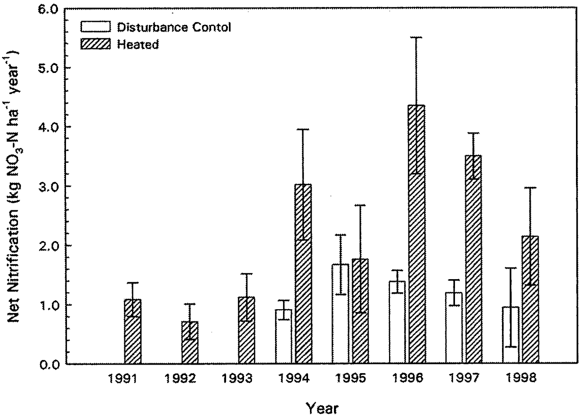

Figure 13.12. Annual rates of net nitrification for the organic horizon plus the top 10 centimeters of mineral soil for the disturbance control and heated plots in the soil-warming experiment. Nitrification was consistently a small contribution to net mineralization in all of the soil-warming plots. Error bars represent the standard error of the mean (*n* = 6 plots) for each treatment.

Since we measured minimal leaching or gaseous losses of nitrogen associated with this accelerated nitrogen mineralization rate, the "excess" inorganic nitrogen released through mineralization appears to have remained in the system. This result, which parallels the observations in the chronic nitrogen experiment (Chapter 12), raises an important set of questions:

- What is the mechanism for the capture of the "excess" nitrogen, and what is its fate?
- Is it transferred to deeper portions of the soil profile and stored there?
- If yes, what is the storage mechanism?
- Is it taken up by trees and shrubs?
- If yes, is it stored in woody tissue?

Answers to these questions will give us insight into the diverse ways in which warming and nitrogen deposition will affect carbon storage in terrestrial ecosystems. The observations and questions reflect the way in which identical fundamental biological processes can emerge as central issues in studies like chronic nitrogen and soil warming that initially were quite independent.

Global-Scale Consequences of Accelerated Carbon and Nitrogen Cycles in a Warmer World: Some Preliminary Evidence

Our results indicate that warming generally increases soil respiration. A number of scientists have argued that in many ecosystems the

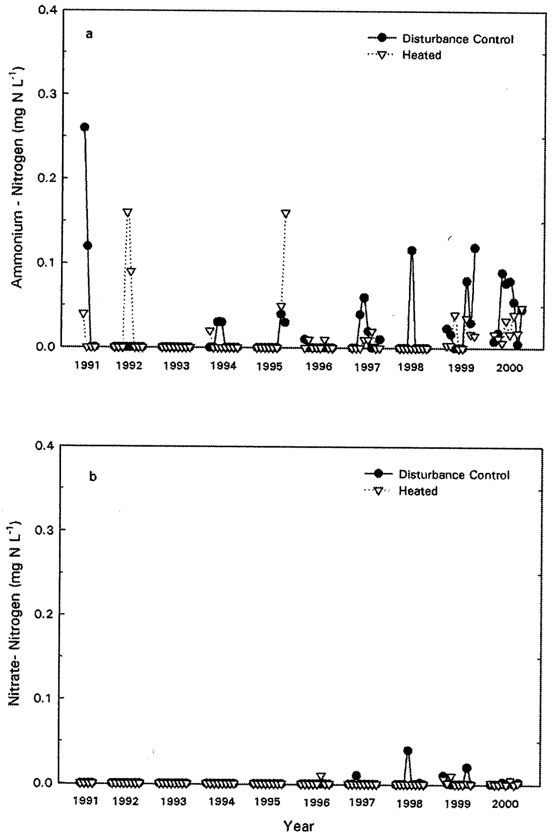

Figure 13.13. Soil solution ammonium (a) and nitrate (b) collected from tension lysimeters placed below the rooting zone at 50 centimeters in the soil-warming experiment. Nitrogen is largely retained in this system, in all treatments. Note low maximum concentrations.

increase of soil respiration with temperature is steeper than any increase of net primary production stimulated by the temperature increase, so that the net effect of warming is to reduce carbon storage and increase atmospheric CO_2. But warming may not always lead to a reduction of carbon storage in terrestrial ecosystems. In nitrogen-limited forests, particularly in cold climates, warming may increase carbon storage through a two-part mechanism. First, warming may increase the decay rate of labile soil organic matter with a low C:N ratio. This may release nitrogen into the soil solution and some CO_2 into the atmosphere. Subsequently, trees may take up this nitrogen from the soil solution and store it in woody tissues with a high C:N ratio (Figure 13.15). Thus, the transfer of nitrogen from the soil to the trees may lead to an increased net carbon storage in the ecosystem.

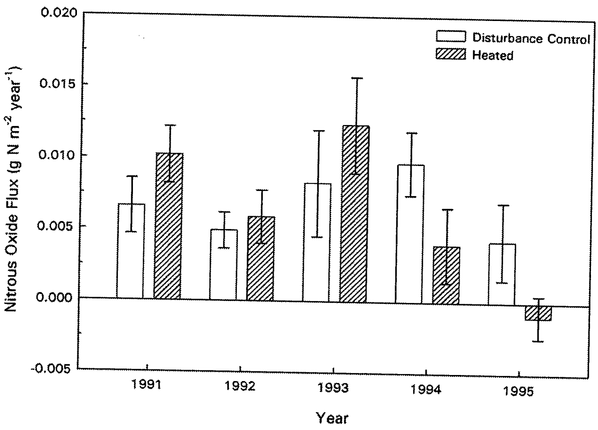

Figure 13.14. Nitrous oxide flux by treatment and year for the field measurement period of April through November in the soil-warming experiment. Nitrous oxide losses from the soil were consistently low. Error bars represent the standard error of the mean ($n = 6$ plots) for each treatment.

We have some early evidence that this nitrogen transfer may be happening in the heated plots. Our measurements of ^{15}N natural abundances in the soil-warming plots suggest that elevated temperatures have altered the pattern and rates of nitrogen cycling in the ecosystem. Nitrogen in fine roots, in soil microbes, in soil solutions, and in both the bulk and acid-insoluble (refractory) forest floor all show trends of in-

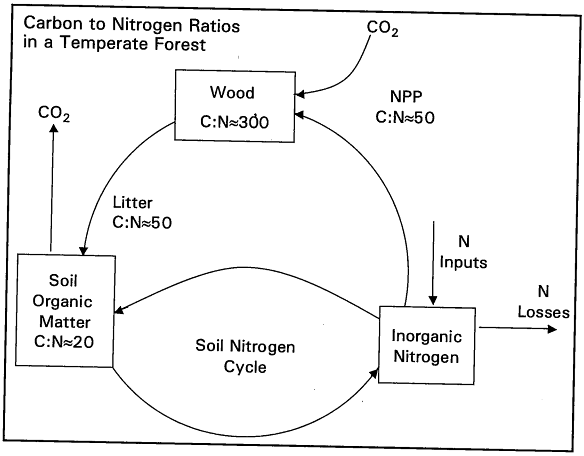

Figure 13.15. A model of the soil N cycle. Carbon-to-nitrogen mass ratios in net primary production (NPP), vegetation, litter, and soil organic matter for a temperate deciduous forest ecosystem.

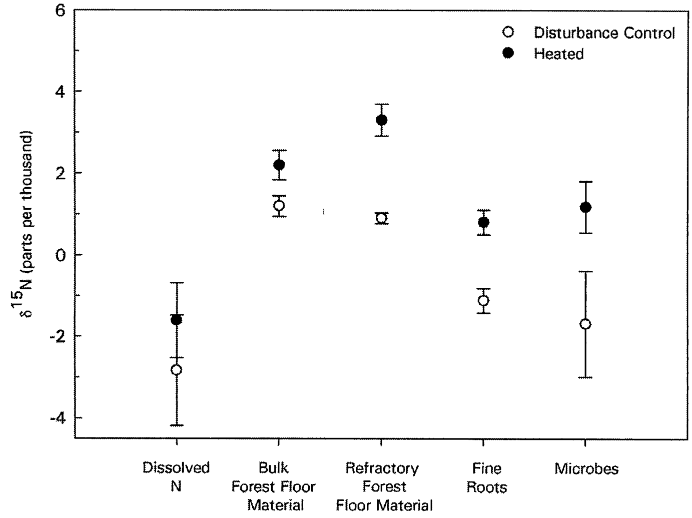

Figure 13.16. The $\delta^{15}N$ in fine roots, microbes, and soil N pools for the disturbance control and heated plots in 1992. Higher (more positive) $\delta^{15}N$ values indicate higher ratios of ^{15}N to ^{14}N for nitrogen in a sample. Trends suggest that N turnover from more recalcitrant pools is being accelerated in the warmed plots. Error bars represent the standard error of the mean ($n = 3$ plots) for each treatment. From Nadelhoffer et al., unpublished.

creasing ^{15}N abundances with warming (Figure 13.16). These patterns suggest that warming has increased turnover rates of relatively old, stable, ^{15}N-enriched soil organic matter, thereby transferring nitrogen from slow to rapidly cycling pools. This could lead to greater fluxes of nitrogen from soil to woody vegetation and to increased carbon sequestration, as noted above.

How much carbon might be sequestered at the ecosystem level through this "nitrogen transfer" mechanism? We can begin to address this question by using the results of our long-term nitrogen fertilization study at the Harvard Forest (Chapter 12). In that study we have been adding almost 5 grams of nitrogen per square meter per year for more than a decade to a hardwood forest stand very similar to the one we have been using for the soil-warming study. At the end of nine years we estimated that 12.7 percent of the total amount of nitrogen fertilizer added (approximately 41 grams of nitrogen per square meter) ended up in the woody tissue of the stand's trees. If we assume that 12.7 percent of the increased amount of nitrogen made available by warming ended up in woody tissue, we estimate that this would result in an additional 1,560 grams per square meter of carbon storage in the vegetation over the decade of warming. Combining this vegetative storage estimate with our estimate of soil carbon loss due to warming, we calculate that for this forest ecosystem, warming could have stimulated at least 600 grams per square meter of carbon storage over the decade, thereby creating a negative feedback to the climate system. The magnitude of this type of negative feedback in a climate-changed world would depend on more than soil warming. Carbon storage in woody tissue would also be affected by other factors related to aspects of climate change, including the availability of water, the effects of increased temperature on both plant photosynthesis and aboveground plant respiration, and the atmospheric concentration of CO_2.

Despite these uncertainties, there is some direct field evidence that supports this kind of negative-feedback mechanism. One example comes from a soil-warming study in a Norway spruce forest at Flakaliden in northern Sweden. Using a soil-warming design based on our Harvard Forest study, Linder and colleagues warmed large (10-by-10-meter) forest plots in a long-term study. After five years they found that there was a significant (more than 50 percent) increase in stem-wood growth of the trees on the heated plots relative to the controls.

The Harvard Forest warming study demonstrates the potential importance of understanding how microbial respiration in soils responds to global warming and how temperature-driven changes in the nitrogen cycle in forest ecosystems will affect their capacity to store carbon. If climate change leads to a net carbon loss from an ecosystem, the feedback to the climate system is positive, whereas if climate change leads to a net carbon gain for the ecosystem, the feedback to the climate system is negative. In addition, this study shows that warming can increase the capacity of soil microbes to oxidize the powerful greenhouse gas CH_4, thus leading to a negative feedback to the climate system. The possibility that warming can lead to both positive and negative feedbacks to the climate system suggests that it is essential that we accurately represent these feedback mechanisms in integrated global systems models designed to project possible future climates.