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Passive nighttime warming facility for forest ecosystem research

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Summary A nighttime warming experiment is proposed. Over the last four decades a significant rise in nighttime minimum temperature has been determined from analysis of meteorological records from a global distribution of locations. The experiment involves nighttime deployment of infrared (IR) reflecting curtains around four sides of a forest canopy and across the top of the forest to mimic the top-down warming effect of cloud cover. The curtains are deployed with cable and pulley systems mounted on a tower and scaffolding structure built around the selected forest site. The trunk space is not enclosed except as an optional manipulation. The curtains reflect long-wave radiation emitted from the forest and ground back into the forest warming the trees, litter, and soil. Excellent infrared reflection can be obtained with commercially available fabrics that have aluminum foil bonded to one side. A canopy warming of 3 to 5 °C is expected on cloudless nights, and on cloudy nights, a warming of 1 to 3 °C is anticipated relative to a control plot. The curtains are withdrawn by computer control during the day and also at night during periods with precipitation or excessive wind. Examples of hypothesized ecosystem responses to nighttime warming include: (1) increase in tree maintenance respiration (decreasing carbon reserves and ultimately tree growth), (2) increase in the length of the growing season (increasing growth), (3) increase in soil respiration, (4) increase in litter decomposition, (5) increase in mineralization of N and other nutrients from soil organic matter, (6) increase in nutrient uptake (increasing growth), and (7) increase in N immobilization in litter. Hypothesis 1 has the opposite consequence for tree growth to Hypotheses 2 and 6, and thus opposite consequences for the feedback regulation that vegetation has on net greenhouse gas releases to the atmosphere. If Hypothesis 1 is dominant, warming could lead to more warming from the additional CO_2 emissions. Site-specific meteorological, ecophysiological, and phenological measurements are obtained in the warming treatment and in a carefully selected control plot to investigate site-specific hypotheses. Measurements made on both plots for a baseline period and during the period of curtain deployment provide data to test the hypotheses statistically by the "before-after-control-impact" method applicable to unreplicated experiments. The enclosure has a modular design that can be adapted and combined with other forest-scale manipulation experiments such as free air CO_2 enrichment and throughfall displacement.

Keywords: carbon dioxide, decomposition, forest ecosystem manipulation, infrared reflection, mineralization, respiration, temperature, tree growth.

Introduction

Nighttime warming—a global trend over recent decades

The proceedings from an international workshop (Kukla et al. 1994) have confirmed and expanded the earlier analysis of Karl et al. (1984) showing significant decreases in the daily range of maximum and minimum air temperatures. Records obtained over the last few decades from a wide distribution of global monitoring stations show decreasing temperature ranges. About 40% of global land area has been evaluated. The reductions in daily temperature ranges are largely caused by elevated minimum air temperatures (i.e., nighttime) which are often associated with increased cloud cover. A warming trend of 2.5 °C per 100 years is reported for mainland China, similar to the trend of 2 to 3 °C per 100 years found for Canada and the USA (Kukla et al. 1994).

Increasing concentrations of greenhouse gases and atmospheric aerosols may contribute to these trends (Charlson et al. 1992, Kiehl and Briegleb 1993). Anthropogenic aerosols from industrial and combustion sources have a cooling influence on the global energy budget during the daytime through backscattering of incoming short-wave radiation and by increasing the albedo of clouds. Increases in both cloud cover and cloud longevity induced by aerosols have a warming effect, particularly at night. The combined effects of these atmospheric processes may explain the observations of Kukla et al. (1994) of preferential nighttime warming (greenhouse gas warming reinforced by aerosol warming) and the relatively small global increases in daytime temperature (greenhouse gas warming countered by aerosol cooling). Dai et al. (1997) do not attribute significant warming to the direct effects of aerosols. They suggest that changes in cloud types and cloud cover are the major contributors to the decrease in the daily temperature range.

Terrestrial vegetation emits infrared (IR) radiation as a function of the fourth power of its absolute temperature, and at night the vegetation receives a small amount of irradiance from the sky as a result of the low temperature of the upper atmosphere. On a clear night, about 100 W m^{-2} of long-wave radiation is the net energy loss from the earth's surface, and empirical investigations have shown that this loss is about the same under both cold winter (–10 °C) and warm summer (30 °C) conditions (Figure 1, Monteith and Unsworth 1990). The lack of seasonal changes in the maximum energy loss on clear nights results from the parallel changes in the seasonal temperatures of the earth's surface and the upper atmosphere. More sky irradiance is received on the ground during cloudy nights than clear nights because clouds are warmer than the upper atmosphere.

We propose that structures with retractable IR-reflecting curtains be constructed for passive nighttime warming of forest trees and associated litter and soil. The passive warming approach provides higher nighttime temperatures as an ecosystem scale manipulation, and this warming has variability that is similar to natural conditions.

Preliminary analyses—canopy modeling and results from a crop study

About 100 W m^{-2} of IR energy is the net loss of heat from terrestrial surfaces on a clear night, and this is an upper limit value for the net long-wave energy flux that could be retained in a forest by IR reflection. Computer simulations conducted by Dennis Baldocchi (personal communication, National Oceanic and Atmospheric Administration, Oak Ridge, TN) with his CANOAK model (Baldocchi 1993) show that the upper canopy of an oak–hickory forest is warmer (+4.5 °C) and the lower canopy (+1 °C) receives less warming than the upper canopy from a gain of 100 W m^{-2} of IR irradiance during a summer night. A 10% increase in nighttime canopy respiration is projected as a result of the additional 100 W m^{-2} of energy input. Some soil warming is also predicted although this is small because of screening by foliage. We note that, during winter, soil warming should be relatively enhanced in deciduous forests with IR-reflecting curtains because of the absence of foliar interception of the reflected IR radiation.

Zeiher et al. (1994) manually deployed aluminum-based IR-reflecting curtains above a cotton crop for 42 consecutive nights during reproductive development. The influence of IR reflection on canopy temperature was quickly established with curtain deployment, and the effect was rapidly dissipated with removal of the curtain, as shown in diurnal measurements from the cotton study (Figure 2a). Foliar temperatures were increased by 1 to 6 °C with the curtain treatment, and an average canopy warming of +3.5 °C was obtained relative to the control (Figure 2b). Less warming (+1 to 3 °C) occurred on cloudy nights than on cloud-free nights. The warming treatment caused significant reductions in stem weight (31%), plant height (22%), and lint and seed yield (> 40%). The photosynthetic responses of cotton in the warming and control plots were not significantly different, suggesting that higher respiration is responsible for reduced plant performance with nighttime warming (Zeiher et al. 1994).

These investigations demonstrate the feasibility of nighttime warming by infrared reflection even on cloudy nights.

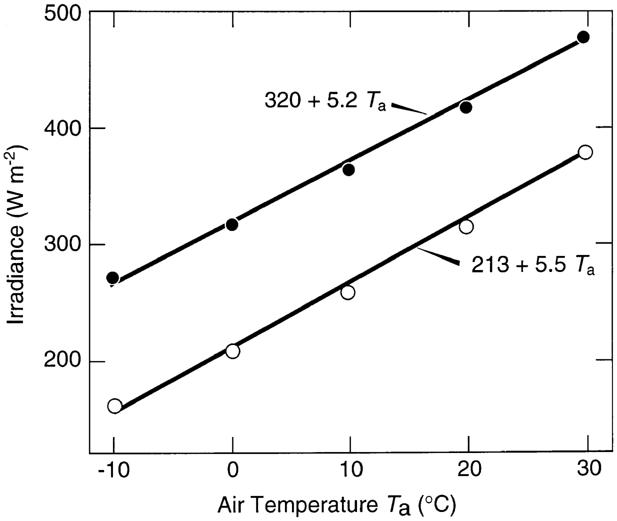

Figure 1. Long-wave radiation from a black body (●) for a range of air temperatures (T_a) and the long-wave irradiance received from a clear sky (○) over the same air temperature range. The straight lines are approximations given by the formulae shown (from Monteith and Unsworth 1990).

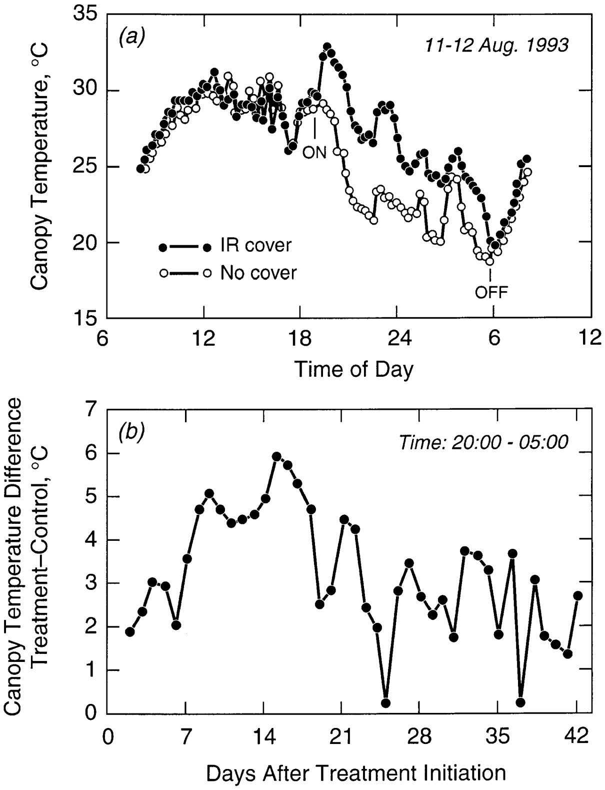

Figure 2. Diurnal temperatures of (a) a cotton canopy in nighttime warming and control plots obtained for two days in summer, and (b) mean nighttime temperature increase in a cotton canopy receiving warming by infrared reflection relative to a control plot for 42 days during summer (from Zeiher et al. 1994).

The average nighttime cloud cover for the southeastern United States during the decade 1982–1991, obtained from the database of Hahn et al. (1994), is 66, 66, 65, and 74% for the quarterly periods: December–February, March–May, June–August, and September–November, respectively. On a mean annual basis the nighttime cloud cover for this region is 68%. Thus, the IR reflection treatment is expected to raise canopy temperatures in the 3 to 5 °C range for about one-third of the nights, and during cloudy periods, canopy temperatures may be elevated in the 1 to 3 °C range. These ranges of nighttime warming are expected to be similar in all seasons and latitudes, particularly on clear nights (Figure 1), and this is favorable for the proposed comparative research from a global network of sites. The database of Hahn et al. (1994) provides nighttime cloud cover data that can be examined for any region of the globe. A feature of the proposed warming treatment is that top-down warming is expected to have greater relative effects on canopy processes than on litter and soil processes. Additionally, natural variation in the increment of nighttime warming may reduce any tendency for homeostatic adjustment as has been found with some constant temperature treatments (Gifford 1993).

Responses to warming—effects on respiration and growth

Tissue-specific respiration has been shown to increase exponentially with increasing temperature, often doubling in response to a 10 °C temperature increase (Q_{10} = 2) (Amthor 1984, 1989, Ryan 1991). Recent studies for hardwood forest stems (Edwards and Hanson 1996) and the forest floor (Hanson et al. 1993) show increasing respiration rates with temperature. Greco and Baldocchi (1996) showed an increase in canopy respiration with air temperature (Q_{10} = 1.6) from eddy covariance measurements obtained over an eastern deciduous forest. Because respiratory processes can consume a large percentage of total photosynthate (Sprugel and Benecke 1991, Paembonan et al. 1992), disproportionate increases in respiration resulting from climate warming are of serious concern. Gifford (1994) expresses a different viewpoint and cites evidence that respiratory responses of tissues may not exhibit simple temperature functions when integrated at the whole-plant and forest-stand scales.

Respiration of plant tissues will increase with increasing temperature; however, with time, these tissues may show acclimation to warming (Gifford 1993). Direct extrapolation of current tissue-specific respiration rates to warmer climate scenarios indicate the potential for decreased net carbon gain and reduced plant productivity. Nevertheless, physiological acclimation of plants or plant tissues to ambient temperature regimes has been suggested as a mechanism whereby plants might alter their temperature optima for photosynthesis and respiration, thus maintaining consistent carbon gain. A study evaluating metabolic acclimation with increasing temperature (Gunderson et al. 1995) has shown that the photosynthetic maximum of sugar maple (*Acer saccharum* Marsh.) seedlings increased and there was a slight depression of foliar respiration rate in an elevated temperature environment. It is not known if there will be any residual effects of nighttime warming on photosynthesis and transpiration during the following photoperiod; however, a null hypothesis may be a reasonable expectation.

Uncertainties about the expected response of respiratory processes to warming may arise from interactions with increasing atmospheric CO_2 concentrations. Respiration may be reduced in the presence of increasing atmospheric CO_2 concentrations (Reuveni and Gale 1985, Amthor 1991, Qi et al. 1994, Wullschleger et al. 1994), but studies remain to be conducted on large trees in the field. Results from a field investigation of sugar maple responses to combined elevated CO_2 and temperature treatments in open top chambers suggest reductions in aboveground growth with elevated temperature treatments (Norby et al. 1995) and effects on foliar senescence (Hartz and Norby 1995).

Schmidtling (1994) evaluated long-term growth data from provenances of loblolly pine (*Pinus taeda* L.) and Norway spruce (*Picea abies* (L.) Karst.) established along regional climate gradients and found that a 5 to 10% reduction in height growth was associated with a 4 °C increase in mean annual temperature. Matyas (1994) conducted similar analyses that suggested warming climates could have beneficial effects on some species if precipitation was adequate, but near the southern limits of current species' distributions in the northern hemisphere, the impacts of a warming climate were anticipated to be negative.

Root elongation rates are known to increase with increasing temperature for some species in a temperature range of 10 to 20 °C (Barney 1951, Shepperd 1981, Joslin and Henderson 1987, Kaspar and Bland 1992). As soil temperatures are raised, root growth is expected to occur earlier in spring and continue longer into autumn provided that soil water is adequate. Whether total annual root production will increase as a result of warming is not clear. We cannot confidently extrapolate our knowledge of tissue and plant respiration responses to forest ecosystem scales with data currently available. Warming of up to 5 °C could increase respiration rates by 35% or more, having a large cumulative impact on ecosystem processes (McGuire et al. 1992, Luxmoore et al. 1993). A mean annual temperature increase of 4 °C could have a major impact on tree, litter, and soil organic matter processes of deciduous forests because of the high temperature sensitivity of respiration and decomposition processes.

Warming effects on litter and soil—decomposition and mineralization

Large quantities of carbon and nutrients are stored in the litter and soil organic matter of temperate forests. For example, on Walker Branch watershed in eastern Tennessee, about half of the ecosystem carbon (Edwards et al. 1989) and over 90% of the nitrogen, phosphorus, potassium, and sulfur (Johnson and Henderson 1989) occur in the litter and soil. Warming could have a significant impact on soil respiration and decomposition processes. Schleser (1982) showed that elevated soil temperature increased soil respiration rates, and Raich and Schlesinger (1992) summarized the Q_{10} values for soil respiration from a wide range of sites and obtained a mean value of

2.4. They also estimated the turnover time of soil carbon in temperate forests to be about 29 years; turnover times are expected to decrease with warming. Globally, Jenkinson et al. (1991) estimated that about twice as much carbon exists in the top meter of soil as in the atmosphere; thus, the potential impact of increased soil respiration (i.e., CO_2 emissions) with warming of soil could have further impacts on atmospheric CO_2 concentrations.

Organic matter decomposition is the primary process controlling carbon turnover and nutrient mineralization (Oades 1988). Accordingly, decomposition is a critical component for understanding how climate change may affect the soil processes that determine ecosystem functioning. Although increased soil temperatures are expected to increase organic matter decomposition rate, it is uncertain how net nutrient mineralization, nutrient uptake by vegetation, and nutrient leaching will respond as a whole. Because nitrogen is generally the limiting nutrient for biological activity in many forests, the effect of increased soil temperature on microbially driven processes, like decomposition, will depend in large part on the availability of nitrogen.

Fluxes of nitrogen in forest soils depend on competition among microorganisms, vegetation, and abiotic processes (Johnson 1992). Fundamentally, nitrogen is cycled rapidly and conservatively between the microbial community and soil organic matter pools (Binkley and Hart 1989). Excess nitrogen, beyond microbial demand, released during decomposition (net mineralization) is available for plant uptake, leaching, or further microbial processing (e.g., nitrification, denitrification). Nitrogen loss in denitrification is sensitive to soil water status and landscape position (Groffman and Tiedje 1989); the process occurs in anaerobic microsites in soil, and increases with temperature (Nommik and Larsson 1989, Malki et al. 1990).

A positive relationship between net nitrogen mineralization and soil temperature has been established in several studies (Stanford et al. 1973, Kladivko and Keeney 1987), including some recent soil warming investigations (Joslin and Wolfe 1993, Mitchell et al. 1995, Rustad and Fernandez 1995, Simmons et al. 1995). Although temperature increases seem to result universally in increased release of CO_2 from belowground sources, the effect on nitrogen dynamics seems to vary with substrate (Schimel et al. 1994). Although the detrital pools (i.e., forest floor plus woody debris) account for, on average, 35% of the CO_2 evolved from litter and soil sources, these pools generally have high initial C/N ratios (average $\approx$ 140). This means that forest floor decomposition typically requires the immobilization of N from surrounding sources in order for an initial release of CO_2 to occur. This prediction was recently borne out in soil warming studies showing temporary increases in N immobilization in the forest floor layer with warming (Rustad and Fernandez 1995, Lockaby et al. 1998).

In contrast to the forest floor, Schimel et al. (1994) note that temperate and boreal zone forests have soil organic pools with C/N ratios averaging about 25 and although these pools decompose slowly, they still account, on average, for 30% of soil CO_2 efflux. These pools are large potential sources for increases in both CO_2 efflux and N mineralization with rising soil temperatures. A third important soil pool of C and N is the recalcitrant soil organic matter. Schimel et al. (1994) point out that recalcitrant organic matter will probably change very little with soil warming because of its structural resistance to decomposition.

Although several studies have noted temperature effects on N mineralization, warming effects on net nitrification or nitrate leaching, or both, have only been noted in the studies of Joslin and Wolfe (1993) and Mitchell et al. (1995). Both of these studies were conducted on forest ecosystems at or near N saturation, where high N deposition rates were combined with relatively low plant uptake requirements for N. In contrast, most temperate forests are N-limited, and any additional N mineralized is likely to be utilized rapidly by plants or microorganisms, or both. Nitrogen leaching may occur during the winter months when rates of biological activity and uptake are slow.

Gas fluxes from soil reflect metabolic activity, and Crill (1991) has shown that both CO_2 emission and CH_4 oxidation increase with soil temperature. Ongoing soil warming studies, conducted as part of the Southern Global Change and the Northern Global Change Programs of the United States Department of Agriculture Forest Service, have shown that soil warming increases litter decomposition rates (Mitchell et al. 1995, Rustad and Fernandez 1995, Lockaby et al. 1998) and increases CO_2 efflux from the forest floor (Mitchell et al. 1995, Rustad and Fernandez 1995, Simmons et al. 1995). Mitchell et al. (1995) also noted increased effluxes of methane and nitrous oxides from the forest floor with increasing temperature. Production and consumption of CH_4 are important processes in forest soils (Yavitt et al. 1990).

Van Cleve et al. (1990) conducted a soil warming experiment in a black spruce (*Picea mariana* (Mill.) BSP) stand using lead-shielded heating tape threaded through the organic soil at 15 cm depth below the surface of the moss layer. Soil heating caused an increase in decomposition, reducing the mass of the O21 layer. Soil heating also increased the amount of extractable N and P in the forest floor as a result of enhanced decomposition, and increased N, P, and K concentrations in the black spruce needles. In addition, soil heating increased the N concentration of the soil solution. Such responses are likely to be short-term (several years), because any decrease in soil carbon and nutrient pools will eventually diminish subsequent rates of CO_2 and mineral nutrient release. Thus, long-term warming experiments that emphasize the interaction of belowground and aboveground responses are needed at the forest ecosystem scale.

Research hypotheses

Nighttime warming facilities will contribute to resolution of an important global change issue. Will nighttime warming cause forests to become a net source or sink for atmospheric CO_2? There are several hypotheses about warming effects on forest ecosystem processes that can be derived from the foregoing review. The following hypotheses are offered as examples for consideration and are not intended for testing at specific sites without consideration of local site characteristics. We hypothesize that nighttime warming will:

(1) increase respiration of trees (decreasing carbon reserves and ultimately tree growth);

(2) increase the length of the growing season (increasing growth);

(3) increase soil respiration;

(4) increase litter decomposition;

(5) increase mineralization of N and other nutrients from soil organic matter;

(6) increase nutrient uptake (increasing growth of trees); and

(7) increase N immobilization in litter.

The hypothesized increase in a particular ecophysiological process with warming may be a result of a direct effect of temperature on the rate of the process or to an indirect effect through a change in the mass of tissue or material involved in the process. Research on these hypotheses has important implications for the feedback regulation between forest ecosystems and climate (Figure 3). Increased plant respiration and reduced tree growth with warming (Hypothesis 1) contribute to positive feedback and further warming. This may be offset by a longer growing season with warming (Hypothesis 2). Small percentage changes in decomposition of the large soil reserves of carbon and nutrients could have either significant positive or negative feedback effects on global warming. Positive feedback would occur if warming results in a net increase in CO_2 release from the litter-soil system (Hypotheses 3 and 4). Conversely, enhanced nitrogen mineralization (Hypothesis 5) may lead to increased nutrient uptake and growth of vegetation (Hypothesis 6) resulting in a net increase in CO_2 fixation and a negative feedback to global warming.

Soil organic matter has a much lower C/N ratio than forest vegetation (approximately 12–25 versus 140) and a small amount of nitrogen release by mineralization could support a relatively large increase in woody biomass (Figure 4). Alternatively, if enhanced rates of nutrient mineralization persist during the dormant period, then the potential for leaching and nutrient depletion could increase. Research is needed to determine whether warming will escalate nutrient deficiency in forest ecosystems because of possible increases in N immobilization in litter (Hypothesis 7) or N leaching losses, or both.

The top-down passive warming provided by IR reflection will greatly enhance our ability to examine these hypotheses because the proposed method mimics the warming effects from increased cloudiness and warmer nighttime air masses. Our warming approach complements the bottom-up warming provided by soil heating methods. Soil warming experiments directly address Hypotheses 3–7, whereas the proposed warming enclosure is expected to effect a forest ecosystem through Hypotheses 1 and 2.

Passive nighttime warming facility

A passive nighttime warming facility for forest ecosystem scale research is outlined for cooperative research. Features of the design and construction are described as a basis for new research initiatives. Physical and biological measurements evaluate facility performance. The structure should be installed at a field site in a secure area with electric power and vehicle access. The following description gives initial design concepts that will be changed as improvements in fabrication and operation are developed.

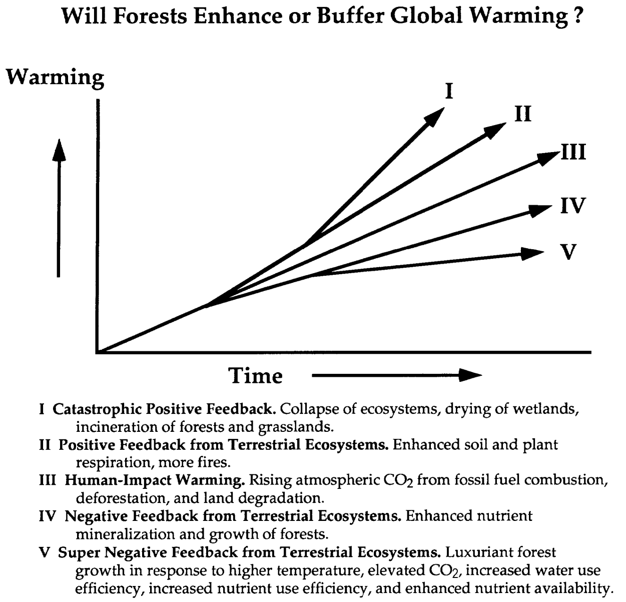

Figure 3. Curves showing positive (I, II) and negative (IV, V) feedback to global warming relative to the warming induced by human impact (III). Factors contributing to the various responses are suggested.

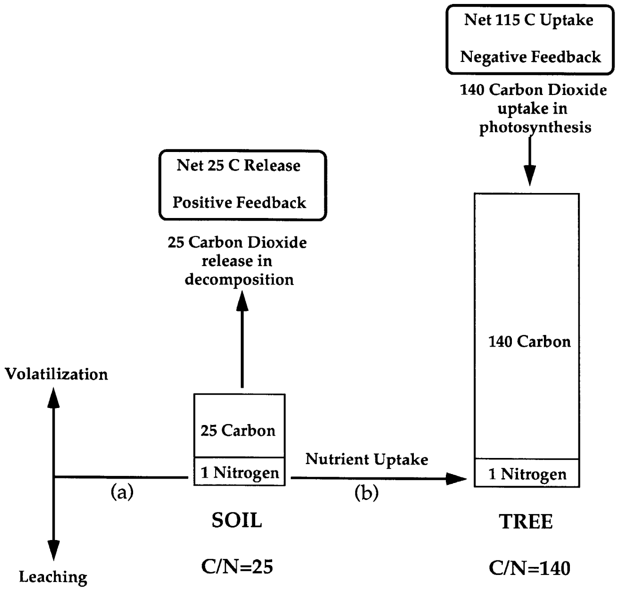

Figure 4. Loss of nitrogen from mineralization of soil organic matter (C/N = 25) by leaching or volatilization (a) is associated with a net release of CO_2, whereas nitrogen uptake by forests (b) (C/N = 140) is accompanied by net CO_2 fixation. Warming effects on these soil and plant processes contribute positive or negative feedback to global warming.

Facility design concept

Four (triangular) towers, stabilized with guy wires, are installed at the corners of a square plot of forest selected for the nighttime warming treatment. Four additional towers are installed at the mid-position between each of the corner towers (Figure 5). Each of the eight towers, positioned on a small concrete base, exceed the forest height by at least 1 m. Reinforced trusses are secured to the top of each tower to form a largely self-supporting framework for curtain deployment. The towers are suitable for climbing and supporting small work platforms needed for canopy access. Each tower is fitted with a lightning rod.

Plastic coated (tiller) wire cables and a pulley system are used to deploy each curtain with a reversible gearmotor. Each curtain may be held in a roll, like a window shade, in a housing close to ground level, and is pulled up at night by the cable and pulley system. An alternative curtain design employs lightweight frames (e.g., 2 × 2 m) connected with hinges so that a stack of frames at ground level is pulled by the cable system into place. Each frame has IR-reflecting curtain material attached. This latter design should withstand higher wind stress and may better protect the IR reflecting surface than the roll approach. The number and sizes of curtains are adapted to local conditions. For example, a structure that is 24.4 × 24.4 m in area and 24.4 m high (Figure 5), is designed with four curtains (each 6 m wide) on each of three sides of the enclosure to screen the forest canopy (upper 12 m). On the fourth side, four long curtains (6 m wide × 37 m long) pass over an upper roller to cover both the side canopy and top of the forest. Curtain deployment provides almost complete IR reflection to the canopy and provides some warming to the trunks, litter, and soil. Optional side curtains in the trunk space may be installed to reduce lateral heat loss at night. This additional manipulation is expected to enhance IR reflection back to the litter and soil; however, a build up of humidity and CO_2 may develop even though the curtains are not sealed along the sides. Measurements are made to evaluate environmental conditions at the warming site and on a nearby control plot with similar vegetation and soil conditions.

Reversible gearmotors, activated by computer with a motor controller, open and close curtains in response to changes in light, precipitation, and wind. A light sensor activates curtain deployment at dusk and rewinding at dawn. A raingauge linked to the computer control system is used to rewind the curtains at night during periods of precipitation so that there is minimal disturbance of soil water distribution. The raingauge is heated slightly during winter if necessary for detection of precipitation as snow or ice. Curtains will also be rolled down during periods with excessive wind as determined by an anemometer linked to the computer control system. Fortunately, some areas, like eastern Tennessee, are not very windy (Eckman et al. 1992), and additionally, wind speeds are generally reduced at night, particularly within a forest environment. The loss of the nighttime warming treatment during windy and rainy periods is to be expected.

Curtain materials and fabrication

Commercially available radiant energy barriers, used to reduce heat loss or gain in buildings and used on ducting for heating or cooling fluids, are evaluated for suitability in the forest application. The curtain material selected for the facility will require high tensile strength, light weight, high IR reflectance, and weather resistance. An initial survey of commercial products has identified suitable candidate materials. One example is a woven fiberglass and polyester blend fabric with laminated aluminum foil on one side. This material is very strong (high bursting strength, high puncture resistance, high tensile strength), has excellent IR reflective properties (shown by a low emissivity of 0.03), and costs about $3US per m^2. This material comes in a 54-inch width, and may be sewn with

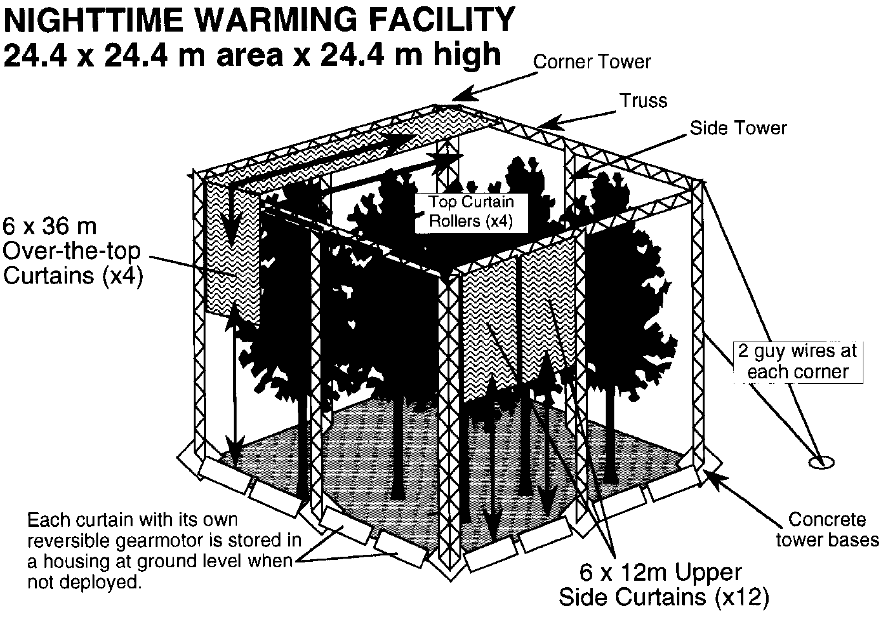

Figure 5. Sketch of a passive nighttime warming facility concept. A framework, formed from eight towers connected by trusses, support a cable tracking system for deployment of IR-reflecting curtains. Each curtain is installed near ground level in a protective housing. Reversible gearmotors deploy and rewind curtains under computer control.

double stitching to form large curtains. Guidance from sail makers and tent manufacturers should be helpful in curtain fabrication. A suitable design should be determined with a candidate curtain material in ground-based deployment and rewinding tests of a curtain tracking system. Reinforcing strips (6 m long × 3 cm wide) are attached across the outside of each curtain at suitable spacings (e.g., 2.4 m) along the curtain length to prevent excessive curling and creasing during deployment and rewinding, particularly for the roll-type deployment system. Following successful ground testing of the curtain deployment and rewind system, all curtains are installed at the field site.

Computer control and data acquisition

Environmental data acquisition and curtain positioning are computer-controlled. All data collected should be time-stamped and archived for statistical analysis of results. Lightning protection is included in the computer design specifications, and the whole system is housed in a weather-proof enclosure.

Environmental monitoring

Meteorological sensors linked to the data acquisition system provide measurements of (1) temperature (soil, litter, trees, and air ± 0.1 °C), (2) net infrared radiation (± 10 W m^{-2}), (3) humidity ± 1%, (4) wind speed (± 0.3 m s^{-1}), (5) solar irradiance (± 10 W m^{-2}), and (6) precipitation (± 1 mm). One instrument for each of sensors 4, 5, and 6 at the field site controls curtain deployment. A large number (e.g., 48) of thermocouples are used to monitor temperature in tree trunks, branches, foliage, air, litter, and the mineral soil at depths of 5, 10, and 30 cm (e.g., 24 in each plot). Periodically, intensive spatially distributed temperature measurements (e.g., 48 locations) are obtained in air, trunk, and litter positions to evaluate the uniformity of passive nighttime warming. All meteorological measurements, including net infrared radiation and humidity, are monitored within the warming enclosure and the carefully selected control plot. Hourly mean meteorological data are archived.

Although the curtains do not form a gas-tight seal, air exchange around the canopy is somewhat restricted. Buildup of humidity, CO_2, and perhaps other gases (e.g., methane), is not expected because of natural ventilation through the open trunk space; however, measurements should assess these effects. Nighttime buildup of gas concentrations within the warming plot could occur with the optional deployment of trunk space curtains. These effects are expected to dissipate quickly once the curtains are withdrawn. Effects of any nighttime buildup of CO_2 on photosynthesis during the following day is expected to be negligible, but there may be some effect of elevated CO_2 on nighttime respiration of plant tissues (Amthor 1991, Wullschleger et al. 1994). The effect of elevated CO_2 on nighttime respiration in the warming plot should be determined.

Statistical data analysis

Methods of data analysis for unreplicated experiments have been developed. One of these is the "before-after-control-impact" (BACI) method of analysis (Stewart-Oaten et al. 1986, Smith et al. 1993), in which measurements are obtained at treatment and control plots for periods before and after the treatment. This approach is frequently used for impact assessment investigations and is suitable for unreplicated experiments. In our use of the BACI method, paired observations at given sampling times from control and enclosure sites, over extended pre-impact and impact periods, are used to evaluate nighttime warming effects on ecosystem properties of interest. Although the BACI method has limitations related to confounding effects and additivity concerns, these can be addressed with appropriate experimental design or data transformation (see Smith et al. 1993). The utility of BACI is enhanced when: (1) the control site is closely similar to the soil, vegetation, and landscape attributes of the enclosure site; (2) the time and frequency of sampling at both sites are similar; and (3) the length of the baseline observation period is sufficient to allow for meaningful comparisons of the reference and impacted site observations. In an additional analysis, the temperature differences between control and warming plots are compared for the periods before and after curtain deployment. Air, trunk, and litter temperature data, obtained periodically on a regular grid with additional randomly placed measurements, are used in geostatistical analyses to evaluate spatial correlation of temperature values in the warming and control plots.

Ecological measurements

Measurements are needed to establish biological measures of facility performance. Access to the canopy is from the eight towers of the enclosure and from ladder-scaffolding secured within the forest stand. Additional towers may be installed in the control plot for canopy access. Suitable ecophysiological methods to measure tree, litter, and soil responses to nighttime warming should be adopted as appropriate for the ecosystem under investigation.

Temperature increase may have a wide range of effects in forest ecosystems. Measurement of variables, in addition to aboveground tree responses and respiration from litter and soil, may be useful in nighttime warming research. For example, root growth, soil organic matter decomposition, and nutrient uptake by vegetation may change with warming as suggested in some of the hypotheses presented. Research at specific sites should be based on the most relevant hypotheses for testing and should apply measurements needed to evaluate these hypotheses.

Discussion

Small-scale warming facilities with short vegetation or only litter may be constructed for specific investigations; however, our objective was to develop a method suitable for use in research at the forest-stand scale. The nighttime warming method has already been shown to work at a small scale in the cotton study of Zeiher et al. (1994). The forest-scale design has fabrication challenges that need to be addressed. Large trees maintain a higher ratio of maintenance tissues to photosynthetic tissues than seedlings, and warming effects on the large trees is expected to yield quantitatively different results from tree seedlings. Additionally, lower soil warming may occur with taller vegetation as a result of canopy screening of the litter, limiting warming effects on litter decomposition and nutrient mineralization. Assessment of forest ecosystem responses to global change requires that much more information be gained at the forest ecosystem scale. We anticipate that results from various forest ecosystem manipulations can be used in models to provide a synthesis of the combined effects of changing water, CO_2, and temperature conditions on forest ecosystems.

Passive nighttime warming at the forest scale could also be combined with other ecosystem scale manipulations such as free air carbon dioxide enrichment (FACE) experiments (Hendrey 1992) and throughfall displacement (Hanson et al. 1995). The structure is fabricated with a modular design, based on 6.1 m units that can be readily adapted to other applications. A factorial study of CO_2 enrichment, throughfall modification, and nighttime warming effects on forest ecosystem processes should be technically feasible.

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