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Appropriate experimental ecosystem warming methods by ecosystem, objective, and practicality

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ABSTRACT

The temperature of the Earth is rising, and is highly likely to continue to do so for the foreseeable future. The study of the effects of sustained heating on the ecosystems of the world is necessary so that we might predict and respond to coming changes on both large and small spatial scales. To this end, ecosystem warming studies have been performed for more than 20 years using a variety of methods. These warming methods fall into two general categories: active and passive. Active warming methods include heat-resistance cables, infrared (IR) lamps and active field chambers. Passive warming methods include nighttime warming and passive field chambers. An extensive literature review was performed and all ecosystem warming study sites were compiled into a master list. These studies were divided by latitude and precipitation, as well as the method type used and response variables investigated. The goals of this study were to identify: (1) the most generally applicable, inexpensive and effective heating methods; and (2) areas of the world that are understudied or have been studied using only limited warming methods. It was found that the most generally applicable method, and the one that is most true to climate change predictions, is IR heating lamp installation. The least expensive method is passive chambers. The extreme lower and upper latitudes have been investigated least with ecosystem warming methods, and for the upper-mid-latitudes (60–80°) there have been limited studies published using methods other than passive chambers. Ecosystem warming method limitations and recommendations are discussed.

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1. Introduction

The rising trend of greenhouse gas concentrations in the atmosphere, and the subsequent temperature increase on the Earth's surface, is an accepted phenomenon (IPCC, 2007). Increased air temperatures are predicted to cause a series of macro-organismal ecological changes, including changes in forest and rangeland productivity (Aber et al., 2001), changes in plant water use and nutrient demand (Shaver et al., 2000), increases in insect, disease and wild fire damage, and shifts in plant and animal distributions (Dale et al., 2000). In addition, ecosystem warming is increasingly being seen influencing microorganism-mediated biogeochemical cycles of various temporal and spatial scales and with a range of ecosystem consequences.

Important biogeochemical affects have been seen in several research studies, including strong relationships between increasing soil temperature and increasing soil nitrogen mineralization and nitrification (Hart, 2006; Rustad et al., 2000), and organic matter decomposition (Rustad and Fernandez, 1998b; Rustad et al., 2000), and indirect relationships with methanogenesis and methanotrophy via temperature-driven changes in soil moisture (Bowden et al., 1998). As soil organic matter decomposes, carbon dioxide is released back into the atmosphere, which could further exacerbate additional global warming (Carney et al., 2007). Given sufficient moisture, soil decomposition is fastest in the summer and slowest in the winter. This relationship between air temperature, soil moisture and decomposition is relatively well understood and predictable in various environments over the short-term (Shaver et al., 2000). However, much less is known about the impact of long-term air and soil temperature increase on soil decomposition, though a number of such studies are being conducted at high latitudes, with results not yet published (F. P. Bowles, *personal communication*).

It is imperative that researchers investigate the direct and indirect effects of a warmer climate on all above and belowground aspects of ecosystems. This knowledge has led to the first generations of climate models and, as experimental warming studies are performed in more locations and for longer time scales, this information will continue to inform ever-better climate

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models and global change predictions. The need for this data is gaining notice in the scientific community. In fact, a recent editorial by *New Phytologist* Editor-in-Chief F.I. Woodward proposes that though we have learned much about the potential results of climate change to various ecosystems from elevated CO_2 experiments, scientific necessity now calls for more elevated temperature studies (Woodward, 2007). Such studies are most beneficial if they employ a small number of standardized methods, in order to facilitate the comparison and contrast of results from different ecosystems and research efforts.

The potential consequences of the Earth's changing air and soil temperature regimes are being experimentally evaluated in several countries and ecosystems to better understand soil temperature/process relationships (Shaver et al., 2000; Rustad et al., 2001). There are a several methods that can be used to warm forest soils, each method has advantages and disadvantages. In addition to experimental and logistical limitations, some ecosystem warming methods are more costly to establish and maintain than others. Many least studied ecosystems occur in underdeveloped nations. Practical cost constraints limit these countries' options for assessing climate change impacts on forest soil processes. Therefore, this paper examines which form of ecosystem warming may be most appropriate given the question of interest, and methodological and practical (i.e., as a function of human and capital resources) limitations.

There exist vast differences in the funding level of studies carried out around the world that may affect the types of warming experiments that are possible in different ecosystems. In addition to cost limitations, the appropriate heating method may also be a function of the ecosystem studied and the responses to be measured. It is of interest to the scientific community to understand the potential consequences of increased soil and air temperatures on above and belowground processes across ecosystems at all latitudes and precipitation levels. It has been shown that within ecosystem types, a variety of environmental factors influence the local impact of warming on responses of interest. Thus, there is a need for multiple small-scale studies as opposed to a more limited number of large-scale studies, which are then interpreted to represent an entire biome (Rustad et al., 2001). Efforts to prescribe the best methods to perform this important type of experiment are necessary in order to improve predictions of global climate change and related consequences.

Warming methods range widely in their disruption of the ecosystem and replication of predicted conditions of global warming (Kennedy, 1995). One of the goals of this paper is to identify the best available ecosystem warming methods for all ecosystems in terms of various levels of funding, locations, and study objectives. Our review pairs the experimental methods currently in use with complexity, cost and labor requirements for each, as well as ecosystem- or hypothesis-specific applicability. Warming methods should be economically and environmentally appropriate, as well as scientifically accountable for the intended hypothesis tests.

2. Review methods

Rustad et al. (2001) completed a meta-analysis of available forms of ecosystem warming, and Shaver et al. (2000) reviewed the results of several ecosystem warming experiments. We have supplemented these works with an updated literature review and different type of analysis. In addition to looking at the types of warming, we have also assessed the ecosystem warming methods as a function of comparability between ecosystems as well as installation and maintenance costs. The dataset includes source, country, latitude, precipitation, ecosystem, method type, warming methods, monitoring methods, companies used, number of experimental and control replicates, heating duration, average temperature increase compared to control, variability in that increase in terms of reported temperature differential range, response type, measured responses, and response trends.

Studies were not included if the effects of a natural temperature increase were being evaluated (e.g. Alward et al., 1999), if average temperature increase was consistently less than 1 °C or less than the sensitivity of the temperature measurement apparatus (McGeoch et al., 2006), or if the paper did not report temperatures with enough detail to assess accuracy. Similarly, any studies that did not provide adequate controls for warming treatments (Delille et al., 2004) were not included in the analysis. Studies with a lack of experimental replication were not included (Hillier et al., 1994). Further, the dataset was limited to *in-situ* methods with the one exception of large "mesocosms" which keep the native vegetation completely intact in the soil column and held the ecosystem in a confined, regulated chamber (Bridgham et al., 1999). Therefore, though a study involving mesocosms is included in the analysis, this method is not strictly a field method and is not discussed in detail. To avoid overestimation of the representation of various method types, where one site and timepoint of manipulations was described in more than one article, the results were combined to form one line of data (e.g. Chapin et al., 1995; Shaver et al., 1998; Schmidt et al., 2004). In total, 64 studies were used to assess the ecosystem warming appropriateness.

2.1. Variable creation

In addition to the variables mentioned above, which were taken directly from the texts, four other, more subjective variables were created. These include an approximate "method complexity", "ecosystem applicability limits", "ecosystem disturbance", "and level of replication of natural heating" (outlined below). To assign relative values to each, there were a number of factors considered.

2.1.1. Method complexity

The method complexity evaluates the installation and maintenance cost, technical expertise and automation that the methods require a well-engineered complex system will require regular maintenance by skilled technicians, such as electrical engineers, who are trained to respect the inherent dangers inherent to the exposure of a complex electrical system to the environment. Nevertheless, when properly maintained, these systems have proven to be very reliable. Generally these systems are expensive to install, but can be inexpensive to maintain if mechanical breakdowns are minimal. A less complex study may require frequent human supervision and maintenance, although in both cases, it is common to have research technicians to perform regular maintenance, in addition to sampling of research effects. We assessed method complexity using cost data derived from funded research proposals, published literature, commercial ecosystem warming equipment retailers and personal communications with scientists who have performed ecosystem warming impact studies.

2.1.2. Ecosystem applicability limits

Not all ecosystem warming methods can be universally applied. Some methods are only effective or feasible in certain ecosystems. Most active ecosystem warming methods have been found to work in most locations, while passive methods have limits to their application.

2.1.3. Replication of natural heating level

Natural ecosystem heating is in the form of greater infrared (IR) radiation incidence on organisms and the Earth surface from an atmosphere that is holding more of this radiation with increased levels of greenhouse gasses in comparison with pre-industrial levels. An ecosystem heating method that replicates nature would ideally use the same form of heat (i.e., radiation as opposed to conduction or convection), as well as replicating predicted heating levels, although this may not be a possible result of a single heating method.

2.1.4. Ecosystem disturbance

Each ecosystem warming method creates some (lesser or greater) degree of ecosystem disturbance. For example, the process of burying cables throughout a treatment plot exhibits high disturbance through physical disruption of the soil, although allowing the soil time to settle has resulted in minimal cable effects (Rustad and Fernandez, 1998a). Conversely, more passive ecosystem warming methods exhibit lower initial disturbance.

3. Methods of ecosystem warming

Methods of ecosystem warming can broadly be defined as passive or active. Passive ecosystem warming is a slight misnomer, as these systems do not warm the soil but generally slow down the relative heat loss as air temperature drops or protect the soil from boundary layer disruption (Marion et al., 1997). Unlike passive systems, active systems apply an external heat source to the system within, at the surface, or above the soil and vegetation. Active systems require temperature sensitive regulation, which monitors temperature and turns the heat on and off to maintain a constant temperature differential from the control (Peterjohn et al., 1994). This limits the extent that these methods can be used in remote areas, such as the Arctic, or in studies with limited budgets. The most common active heating apparatus are heating cables and IR lamps, with the latter becoming more prevalent in recent years.

3.1. Passive nighttime warming

Air temperature is generally greater during the day than at night; this class of ecosystem warming methods uses this principle to retain daytime heat to increase nighttime soil temperatures relative to untreated control plot soil temperatures. Historic air temperature data, and most of the general circulation model GCM) scenarios suggest that the much of the global warming increase will occur during the nighttime hours (Luxmoore et al., 1998). Therefore, this type of passive ecosystem warming is ideally suited for replicating a potentially relevant form of climate change in particular, even though overall temperature increases have begun and are expected to continue over the entire diel cycle. The replication of natural heating from this method is quite high, in terms of only using radiative heat transfer. The amount of ecosystem (i.e., soil, animals, and plants) disturbance associated with this method is minimal.

Passive nighttime warming usually involves an IR reflective nighttime shade covering the soil and low-lying vegetation to trap the IR that has accumulated inside the soil and on the soil surface over the course of the daylight hours (Emmett et al., 2004). A variety of materials can be used as an IR-reflecting curtain, such as woven fabric composed of fiberglass and polyester blends with a laminated aluminum foil on one side of the curtain (Llusia et al., 2006a). There are several advantages to using this type of curtain material including high puncture resistance, high bursting strength, and excellent IR reflective properties (i.e., emissive of 0.03). The width of the material varies, but in almost all cases, multiple strips of fabric need to be sewed together with double stitching to create the curtain. Tent and sail makers routinely join large sections of heavy weight cloth, and are an excellent choice for constructing the IR-reflective curtain. The IR-reflective curtain material is relatively inexpensive (i.e., \$4 m^{-2}). Additional costs associated with this form of ecosystem warming include the construction of the curtain support structure, photo, rain, and wind sensors integrated with an automated curtain deployment system. These costs and system complexities can all be reduced with increased manual labor and monitoring.

The shade is usually automated to move over the soil after there is a threshold decrease in light levels, signifying that the sun has set. The shade can also be moved manually. These options make this ecosystem warming method either of high or low complexity, depending on how one chooses to maintain it. The curtains are impermeable to water so they need to be removed at the onset of a precipitation event, unless drought impacts on ecosystems structure and function is also part of the experiment. A moisture sensor can be used to retract or deploy the curtain as precipitation begins. As with day and nighttime curtain placement, humans could also be used to remove the curtains during rain events.

There are a few possible limitations to the use of this method. In forest ecosystems, tree canopy height can exceed 20 m, therefore the use of IR curtains would require a truss system over the canopy to suspend top and sides, a method that has been proposed but not implemented (Luxmoore et al., 1998). In addition to canopy height issues, there is a potential latitudinal limitation to this system is the necessity for sun in daytime hours. In higher latitudes, where days, weeks or months pass in the winter without sunshine, this method is useless. With passive nighttime warming, the daytime insolation is the source for the nighttime IR re-radiation, and therefore heat. Without this input there could be no difference between covered and uncovered plots during the winter months.

3.2. Field chambers

Field chambers for ecosystem warming include field-style greenhouses, tents and open top chambers (OTCs) of various shapes and sizes. The use of this warming technique developed out of experiments not concerned with elevating ecosystem temperature. Active OTC studies were used extensively in the 1980s and 1990s in association with various forms of fumigation including ozone and carbon dioxide inputs. In general, these chambers were created by open-topped cylindrical frames covered in plastic, with a fan and inlet hose secured to the base of the chamber to circulate air and to mix contributed gases. The top of the chamber was open to allow for gas exchange with the atmosphere, and to allow precipitation to enter. As the plastic sheeting allowed short wave radiation in, but prevented IR from escaping, it became very difficult to control the gas concentrations at a desired level while also minimizing air temperature increases, and was severely criticized (Kennedy, 1995). This has led to a shift towards "free air carbon dioxide experiment" (FACE) sites for more recent studies on increased CO_2 (Canadell et al., 1996). However, ecosystem warming experiments began to be run using partially open A-frame greenhouses, tents and OTCs, adapted from the chambers that had previously been used for fumigation experiments.

There is a wide range of shapes and sizes used for passive OTCs, ranging from small four-sided chambers such as were used for the International Tundra Experiment (ITEX corners) to larger hexagonal chambers (Marion et al., 1997). The relative surface area to interior space directly regulates the amount of interior chamber air and soil temperature increase. The smaller the hole relative to the height of the chamber, the higher the temperature increase. The hole diameter to chamber height ratio also impacts other environmental parameters such as lower light and precipitation inside the chamber (Marion et al., 1997).

Field chambers in their most basic form are the least costly to construct and maintain. A fan can be used to both regulate and homogenize the internal air temperature, or ecosystem warming can be made more fully regulated through the conversion to an active chamber, by passing heated air through the chamber (Norby et al., 1997). However, the system is most often used in remote locations where electrical applications are problematic, and therefore run without the fan. Unlike IR-reflective curtains, which must be deployed and retracted, the open top field chamber or A-frame greenhouse is not modified once in place.

However, this system has several limitations. Even with a fan to circulate the air, the range of temperatures, as well as the variability of the temperature difference between control and treatment chambers, can very large (Marion et al., 1997). The greatest differences in absolute and relative temperatures occur when the chamber is exposed to full sunlight. Although not as efficient at retaining heat as a curtain, the chambers will reduce soil heat loss at night. Therefore, this system will heat the air and soil during both day and night (provided it is a sunny day), but the majority of the warming will occur during the day. In addition to the chamber design, solar angle and degree of cloud cover will influence the amount of chamber heating (Marion et al., 1997).

3.3. Overhead IR lamps

To maintain constant heat differentials, active methods must be used. The active method that may require the highest energy flow is that of overhead IR lamps. These lamps function to provide energy in the form of heat to the soil and overlying vegetation (Harte et al., 1995). Generally, these lamps (also called heaters) are suspended within 3 ft. of the soil surface, and block relatively little (often <2%) of the sun's electromagnetic radiation of all levels (Price and Waser, 2000). The IR lamps are also usually in the center of curved reflective materials, which are designed to spread the radiation evenly across the plots. The lights can be connected to a temperature monitoring system within the plots that maintains a constant temperature increase by turning the lamps on and off in response to the measured differential between the temperature of the experimental and control plots. This is a high cost study method, as well as a difficult one logistically, due to the heavy energy requirement. To decrease the energy necessary, the lamps can be run with timers instead of in response to temperature. This method creates very little ecosystem disturbance and there are few ecosystem limitations. These limitations are similar to those of passive nighttime heating, in that the height of vegetation canopy is inhibitory of heating lamp suspension. Similarly, dense ground cover may impede heat reaching the soil surface, though this has not been established.

3.4. Heat-resistance cables

Another common method of ecosystem warming involves heating cables placed above, laid on top of or buried in the soil. Regardless of placement, this type of ecosystem warming method is losing favor, due to perceived decoupling between the above and belowground ecosystem components. When placed on top of the soil surface, the relationship to the above ground vegetation must be considered, as plant structure and function can be adversely impacted by direct heat conductance. Researchers have devised some methods to limit contact with vegetation, such as by lacing a thin heating cable through a wire mesh that is laid on top of very low lying vegetation, while allowing some vegetation through (Fitter et al., 1999).

For use in the soil, the topsoil or humus layer is usually cut, and cables laid down under the top $\sim$5 cm of soil, humus or debris (Bergh and Linder, 1999). In this form of installation, the belowground biota are most heavily disturbed, and the cutting of vegetation mats or roots increases the chances that aboveground vegetation is impacted. Often the effects of these disruptive actions are replicated using cabled control plots (Peterjohn et al., 1994). This disruption has been shown to have no noticeable affect after 6–12 months, which is therefore the recommended lag time between cable implementation and activation.

Temperature monitors are usually linked to an automated, computer-based regulation system (Grime et al., 2000), as discussed in relation to IR heating lamps above. A distinction between the two active ecosystem warming methods (i.e., IR and cable) is that in cable monitoring, the temperature sensors are usually dispersed through the soil strata, and the temperatures very close to the cables are obviously always higher than those further away. The need for computer regulation of cable warming along with the energy demand of heat-resistance cables increases the cost of this experimental method. A labor-based monitoring system would not be as responsive, and is inappropriate in this system. The disturbance level is high, due to heat conductance through the soil, which can significantly affect biota in and above the soil. The replication of natural heating is low, also due to the point specific nature of the applied heat and the variability of soil heat conductance. The main advantage of this system is the ability to generally keep the soil within a very small temperature range.

3.5. Temperature measurement

In most cases, measurement of temperature was conducted in the air as well as at and below the soil surface, often at several heights and depths (Lukewille and Wright, 1997). Temperature is measured most often using thermocouples or thermistors, and only occasionally with reflectivity instruments, as these are known to have very low temperature accuracy. Both thermocouples and thermistors are used often in ecosystem warming experiments, with thermocouples having the advantage of being cheaply and easily made, although thermistors have the advantage of being the easiest to maintain in the field.

4. Discussion

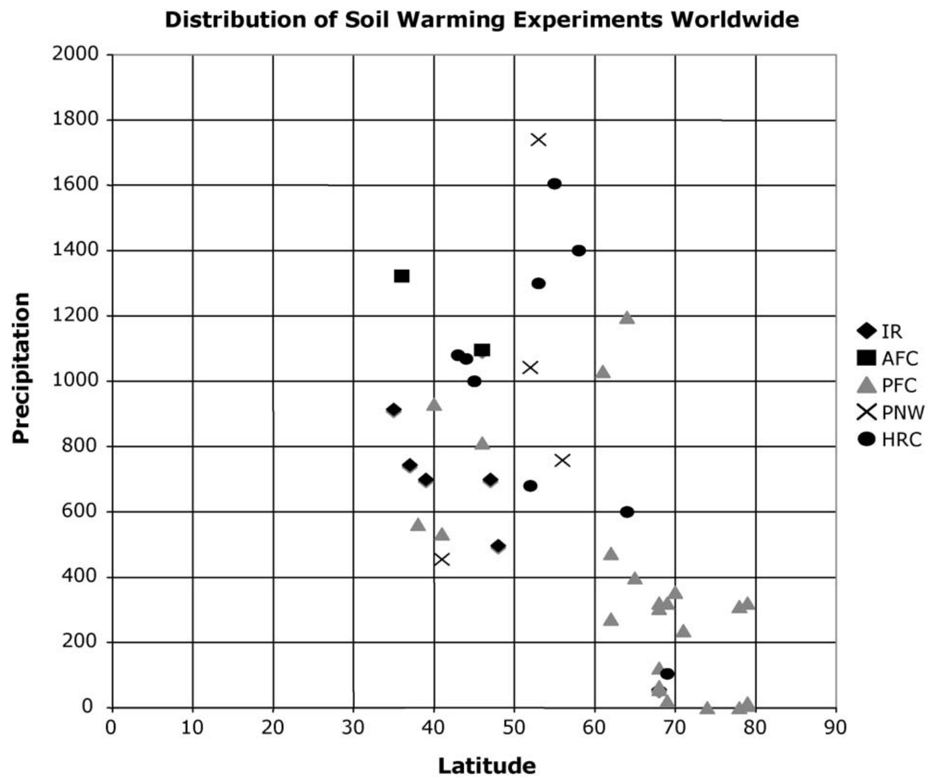
4.1. Previous use of ecosystem warming methods

The majority of ecosystem warming experiments utilized the passive field chamber and IR warming methods. A literature search revealed that there is a concentration of ecosystem warming studies in the mid to higher latitudes across the middle to high range of precipitation gradients (see Fig. 1). Almost all published studies above latitude 60 were conducted with passive OTCs, many in the ITEX design (Marion et al., 1997), which are method 3 in Fig. 1. There are a number of studies being conducted at the Abisko field station in Sweden that compare various methods of warming, but little of the data has been published from these comparison experiments (F. P. Bowles, *personal communication*). Ecosystem warming experiments in the mid-latitudes have used a wide variety of methods, and there have been very few experiments of any kind conducted at equatorial latitudes (Fig. 1).

4.2. Response variables across method types

The response variables tested by ecosystem warming experiments show interesting trends (see Table 1). Regardless of study method, soil moisture and evapotranspiration were often the first response variables investigated in early soil warming studies. This concerns measurements of how the heating treatments affect soil water balance, and was monitored in relatively few, mostly early studies (i.e., 25% of the total 64 studies). Once the effects of the treatment type on moisture regulation had been established for each method, it appears that it was not investigated again.

Approximately 25% of the ecosystem warming studies investigated only general soil parameters, such as nutrient status and



*Northern and Southern latitudes are not distinguished. Where precipitation information was not included in the text, it was estimated from other references and nearby weather stations using worldclimate.com.

Fig. 1. Worldwide distribution of ecosystem warming studies, with respect to latitude and precipitation.*IR addition (IR); active field chamber use (AFC); passive field chamber use (PFC; passive nighttime warming (PNW); and; heat-resistance cables (HRC).

pH, without respect to the biota. However, studies measuring these inorganic soil responses were more evenly spread between the ecosystem warming method types than those that measured soil moisture relationships. Over 50% of the 64 total studies investigated microbial and macro-biota responses to ecosystem warming. In some cases total soil biota response was investigated through total soil respiration (Jones et al., 1998), while others observed changes in microbial biomass (Schmidt et al., 2002). Studies with more specific aims included those concerned with fungal diversity (Tosi et al., 2005) or certain species of micro-arthropods (Webb et al., 1998). Ecosystem warming effects on plant function, whether on a local or ecosystem scale, was the most common response type investigated, and was measured in more than 67% of the studies in the dataset. The aims of these studies range from plant diversity and vegetation cover to examining changes in foliar N and C concentrations. Plant response studies largely used the passive field chamber method, but plant response was a commonly measured variable within all ecosystem warming methods.

4.3. Comparing cost of experimental establishment and maintenance

In addition to the various applications and limitations of each ecosystem warming method, the costs of establishment and operation vary considerably. Even within the same basic method costs can vary depending on the level of automation. For example, curtain material is relatively inexpensive (i.e., \$4 m^{-2}, Luxmoore et al., 1998) to purchase. However, if the curtain is placed on a canopy scaffold that retracts and opens in response to photoperiod and precipitation, then the cost of installation and operation can rise considerably. Based on the cost survey, open top chambers (even some that included fans for thermostatic air temperature control) were the cheapest to install and operate (less than \$65 m^{-2} $year^{-1}$), followed by IR lamps (\$80–260 m^{-2} $year^{-1}$), while buried warming cable were most costly (>\$500 m^2 $year^{-1}$). There was a lack of information regarding the complete installation and operational cost of reflective curtains, but as previously discussed, the cost of this ecosystem warming method could vary considerably.

Table 1
Summary table of warming methods and the associate type of ecosystem variable being measured.

Method type	Plant responses	Soil biota responses	Soil nutrients	ET/moisture	Total response types per method type
Active field chamber	1	1	0	1	3
Cables	7	6	4	2	19
Infrared	9	6	4	4	23
Night warming	5	4	4	0	13
Passive field chamber	21	17	4	9	51
Totals*	43	34	16	16	109

* All studies were counted for every category that was investigated, which leads to overestimation of total studies across methods.

In addition to equipment costs, labor costs can also vary considerably. In developed nations initial costs associated with long-term automated ecosystem warming systems may be cost effective as labor costs are high. Conversely, developing and under-developed nations generally have low to very low labor costs. In these areas, manual maintenance may be most cost effective over time, especially as electrical supplies are lacking or undependable. However, in all countries, the amount of research performed by students and interns dramatically lowers the cost of labor, potentially affecting the most cost effective ecosystem warming methods in more developed countries.

4.4. Comparison of methods using subjective variables

In reviewing past experiments, it became apparent that the passive methods, including nighttime warming and OTCs, actually test two of the factors important to climate change: increased temperature and increased variability of temperature. In both these ecosystem warming methods there is not a constant temperature differential between treated and control plots, but rather a fluctuating, variable differential. Well-maintained active methods regulate experimental plots to a constant temperature increase relative to control plots. Therefore, active warming systems test the impact of increased heat, but not increased variability of temperature. Climate is predicted to be more erratic as the surface air temperature increases around the world (Diffenbaugh et al., 2005). Therefore, both types of experiments are of interest, especially in comparison. However, published comparative studies (i.e., those that compare different methods of experimental heating apparatus) are lacking, even 12 years after a review was published criticizing the lack of comparative studies (Kennedy, 1995). Some of the largest increases in global warming to date have occurred across the northern tundra (Serreze et al., 2000). It would be interesting to compare the commonly used passive treatments with IR lamps or cables, thereby investigating how increased temperature but not increased temperature variability, affects measured ecosystem variables. A series of experiments are being carried out at the Abisko scientific station that may fill this gap in information (F.P. Bowles, *personal communication*).

Passive methods are good at minimizing soil disturbance. However, disturbance and temperature above control both increase with more enclosure of the chamber (Marion et al., 1997). The affects of OTC ecosystem warming, both passive and active, on plant physiological or structural changes are often investigated, although the affects of partial enclosures and decreased light penetration in the photosynthetic range on vegetation cannot be determined separately. Vegetation impacts, such as photosynthesis and herbivory level, may be confounded by this warming method. Therefore, studies focusing on ecosystem warming impacts on plant factors may benefit from using methods other than OTCs. Nighttime warming (i.e., heat retention) methods are useful for most study objectives, but test a more limited hypothesis by investigating only the effects of increased nightly temperatures.

Heat-resistance cables, in tandem with multiple thermistors or thermocouples and an automatic temperature control system, likely provide the most homogenous warming throughout the soil strata (Rustad and Fernandez, 1998a). However, this form of ecosystem warming greatly disturbs the soil regardless of whether the apparatus is buried or left on the soil surface. Cables also unevenly distribute the temperature increase across the soil. Cables at the soil surface might be more useful to study processes lower down in the soil profile, while buried cables might be more useful to study soil surface phenomenon and vegetation effects.

Infrared lamps are the best method for replicating natural conditions ecosystem warming conditions. As global mean temperature continues to increase, there will be an increase in IR from the atmosphere that holds more energy at low frequencies. The IR lamp warming method causes minimal disturbance, has moderate temperature variability, and can be applied across a broad range of environmental conditions. However, as the most complex, costly and high-energy system, the IR lamp ecosystem warming methods can only be used for very well funded ecosystem warming studies.

5. Conclusions and recommendations

Based on the metadata set collected, recommendations can be made for response variables appropriate to various ecosystem warming methods (as summarized in Table 2). Across study objectives and sites, the most effective ecosystem warming methods, in terms of realistic global warming impacts, are IR lamps and passive night warming. Of these two methods, IR lamps are more difficult to install and are more costly to operate compared to nighttime warming (i.e., heat retention) methods. Although less costly to install and maintain, the system limitations restrict the type of questions that could be addressed with nighttime warming technology. Heat-resistance cables are the easiest to regulate, but may confound above or belowground responses by exposing some biota to high heat conductivity, as well as increasing soil disturbance. Active and passive field chambers may affect the vegetation in ways that may confound a heating study, but are ideal for studying of temperature increase and variability on belowground biotic and abiotic processes.

Marion et al. (1997) predicted that freeze and thaw date changes and the length of growing season would be most pronounced within the far Northern and Southern latitudes. This has led to a disproportionate number of ecosystem warming studies in high latitude environments. Unfortunately, comparisons of ecosystem warming methods have only been published on in the Northern temperate zone, with unpublished comparison studies currently underway in higher latitudes (F.P. Bowles, *personal communication*). There will likely be different methodological ecosystem warming impacts in tropical and subtropical areas. The tropics should be investigated, especially in human-altered settings, such as crop and pasture land. There are many indications that multiple anthropogenic modifications of an area can work together to change the soil and vegetation in ways that are beyond

Table 2
Recommendations by method and response variable types.

Method type	Plant responses	Soil biota responses	Soil nutrients	ET/moisture
Active field chamber	With caution of confounding	Yes	Yes	Should be included in every study
Cables	With caution of confounding	With caution of confounding	With caution of confounding	Should be included in every study
Infrared	Yes	Yes	Yes	Should be included in every study
Night warming	Yes	Yes	Yes	Should be included in every study
Passive field chamber	With caution of confounding	Yes	Yes	Should be included in every study

prediction based on what is known of each variable on its own (Ineson et al., 1998).

Elevated temperature effects across ecosystems is an important factor to be understood in global change research, as climate models predict that worldwide temperatures will increase by at least 2 °C during the 21st century (IPCC, 2007). Investigating temperature increase effects *in situ* across latitudes and precipitation gradients is necessary to understand the complexity of ecosystem responses above and belowground. Before such a study is implemented, careful consideration is necessary regarding how the proposed methods will affect the ecosystem processes to be studied. In addition, the framework proposed by Shaver et al. (2000) for analysis of ecosystem responses to warming, based on complexity and various responses, should be considered when developing warming experiments. Only by understanding how climate change can alter ecosystems structure and function, will policy makers and land managers be better able to cope with a changing environment. Ecosystem warming studies can significantly contribute to that improved understanding, but only if the limitations and applications of these studies are properly applied.

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Appendix A. References used in database, those that were also references in the paper appear only in the references section, with an asterisk "*"

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