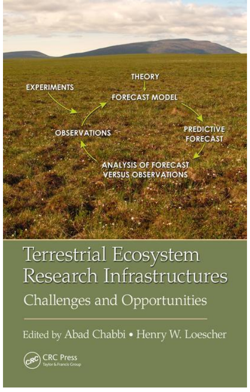

Terrestrial Ecosystem Research Infrastructures
Challenges and Opportunities

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9

Climate Warming Experiments: Selecting the Appropriate Technique

Hans J. De Boeck and Ivan Nijs

CONTENTS

Abstract

Experiments allow the testing of elaborate hypotheses to gain mechanistic understanding of how ecosystems respond to climate change. Establishing warming experiments is an integral part of this quest for knowledge. Many methods exist to increase temperatures, some of which use energy from the environment (passive warming) while others rely on electric power (active warming). We discuss strengths and weaknesses of each of the methods, also focusing on recent improvements. Passive warming methods are generally less costly and require less technological know-how compared to active methods, but this comes at the expense of control over the achieved temperatures. Active warming methods provide more control, but their reliance on electric power limits their use in remote locations. Weaknesses differ among the methods: asymmetric warming, unwanted co-occurring changes in other environmental variables, disturbances, etc. No warming method is free of flaws, yet every method also has distinct advantages. The fact that strengths and weaknesses differ among the methods also implies that researchers can pick the most optimal method for their specific experiment. This would avoid mismatches between the warming method and the study at hand and should thus lower the chances of conclusions being skewed by experimental artifacts.

Keywords: Active, artifacts, climate change, heating, passive, state-of-the-art, technology, temperature

9.1 Introduction

Experimental approaches are invaluable tools to promote better understanding of ecological processes in the context of a changing climate. They enable researchers to test specific hypotheses and elucidate unknown processes and the effects of their drivers (see Chapters 1 and 2), with the ultimate goal of gaining fundamental mechanistic knowledge, so that case-specific results can be extrapolated to other systems and situations (Beierkuhnlein and Nesshöver, 2006). One of the most pressing issues today is the impact of ongoing human-induced changes to the climate system. Several consequences of climate change have already been observed in ecosystems around the world, such as upward and poleward migration of species (Parmesan and Yohe, 2003), drying of tropical rainforests (Zhou et al., 2014), and earlier green-up of deciduous tree species (Menzel et al., 2006). These observations demonstrate that even small changes in the global climate can significantly alter the structure and functioning of ecosystems, with important potential feedbacks to the climate, primarily via changes in the carbon balance (e.g., Heimann and Reichstein, 2008). As deviations from the preindustrial climate are fast becoming more pronounced, an increasing number of studies that attempt to mimic certain aspects of (potential) future environmental conditions are being conducted, in order to gain understanding of likely impacts of further changes to the local and global climate.

As increases in surface temperatures are a key aspect of climate change, studies considering warming as an explicit experimental treatment are highly relevant in global change research. Warming studies may focus on various aspects of climate change. In some experiments, year-round temperature increases are considered, which ideally need to be imposed for a long time to avoid noise generated by natural interannual variability from obfuscating responses to the treatment (cf. Hollister and Webber, 2000; Norby and Zak, 2011). Other research endeavors are more concerned with the effect of temperature increases in certain seasons, such as warm winters

(Schuerings et al., 2014), or earlier onset of spring and the subsequent impacts on phenology and/or legacy effects in the rest of the year (e.g., Fu et al., 2014). Finally, some studies focus on large but short-lived deviations from normal temperatures (heat waves), which can have significant impacts on ecosystem structure and functioning both in the short and in the long term (Dreesen et al., 2015). Not all warming methods are suitable for every of such research goals, as will become apparent throughout this chapter.

Broadly, two categories of warming methods can be distinguished: those using passive mechanisms that harness energy from the environment and those where temperature is changed and controlled actively, relying mostly on electric power. In this chapter, we present an overview of widely used methods of either category and discuss the advantages and disadvantages of each technique (which often result from trade-offs between cost, control, practicality, and ecosystem disturbance). We also highlight recent developments that resolve some of the weaknesses or artifacts involved. The ultimate aim is to help researchers in selecting the most appropriate technique for each experiment.

9.2 Passive Warming Methods

9.2.1 Open-Top Chambers

Many of the first warming experiments made use of passive warming in closed chambers (e.g., Chapin and Shaver, 1985). Unfortunately, this approach came with a number of important concerns, chief of which were high-temperature peaks and significant, unwanted alteration of environmental variables such as humidity, light, and wind speed (Kennedy, 1995). Over the course of the years, open top chambers (OTCs) were increasingly preferred as these avoided the most excessive artifacts associated with their closed predecessors (Marion, 1996). The passive warming in OTCs is achieved by slowing heat dissipation, as the sides of the chamber reduce the influence of outside airflows (which carry away warmed air and cool down the canopy and soil). They have been used in different climates (e.g., De Frenne et al., 2010; Cavieres and Sierra-Almeida, 2012; Bokhorst et al., 2013), with the warming effect sometimes being an unintended side effect in early atmospheric CO_2 enrichment studies (Drake et al., 1989). The construction of OTCs requires no special technical skills, and the materials used (mostly transparent PVC plates and simple connections to keep these together) are commonly available and inexpensive. In accessible areas, more complex OTCs with active support via ventilated air in combination with heating and cooling systems (cf. Pelini et al., 2011) can be employed to increase control over the achieved temperatures, making them no longer strictly passive (see Section 9.3.2). OTCs that are only warmed by passive means have been used extensively especially in cool and remote regions such as the arctic (Wahren et al., 2005; Strebel et al., 2010) where their essentially power- and maintenance-free nature provides a major logistic advantage. Their appeal is therefore understandable, although already early on researchers acknowledged a number of weaknesses.

The achieved passive increases in air and soil temperature are generally modest in the regions and ecosystems where they are most employed (in the range of 0.5°C–1.5°C), and the amount of warming is also variable in time (Marion et al., 1997; De Frenne et al., 2010). Because the warming signal tends to be small in comparison to interannual variability (Hollister and Webber, 2000), experiments using passive OTCs are required to run for many years before being able to confidently attribute changes in ecosystem functioning or composition to the (small) increases in temperature (Hollister et al., 2005; Hudson and Henry, 2010). Nevertheless, a recent study demonstrated that at the level of the aboveground plant tissues, the daytime warming was more substantial than reported increases in air temperature because of significantly lower wind speeds (De Boeck et al., 2012a). Apart from increasing canopy temperatures, calmer conditions can also alter exchange of important gasses like CO_2 (Kimball et al., 1997) and can render wind pollination more difficult (cf. Molau and Shaver, 1997). Moreover, the decreased wind speeds inside the chambers also increase temporal variability of temperature, that is, they tend to increase maximum and decrease minimum temperatures (especially under clear-sky conditions), which differs from the general reduction in diurnal temperature range projected under climate change (Lindvall and Svensson, 2015). The variability of the achieved level of warming is also more pronounced between days and seasons, because the amount of warming is dependent on incoming energy, therefore leading to lower increases under cloudy conditions and in winter time.

Next to temporal variability of the achieved warming, spatial variation is also an issue inside OTCs, with substantial changes in surface temperature observed in the space of less than a meter (Figure 9.1). Another reported artifact is that snow tends to get trapped within the OTCs (Marion et al., 1997), which can change soil temperatures because snow cover serves as an insulation layer (cf. Wahren et al., 2005) and which can alter the growing season length if the date of snowmelt is affected. Finally, many of the commonly used passive OTCs are of a fairly small size (1–2 m across), meaning that island effects (cf. De Boeck et al., 2015), which tend to dilute experimentally imposed treatments, are likely. For example, soils will be cooler at the plot edge due to contact with the surrounding (unwarmed) soil, and roots are likely to grow outside of the chamber’s zone of influence.

The artifacts and drawbacks associated with passive OTCs can be avoided to an extent by taking known artifacts into account. Researchers could, for example, only consider plants from the central patch, as changes in the microclimate (radiation, air circulation, moisture, etc.) are less acute there. Also, acquiring data of variables such as snowmelt dates, tissue temperatures, and

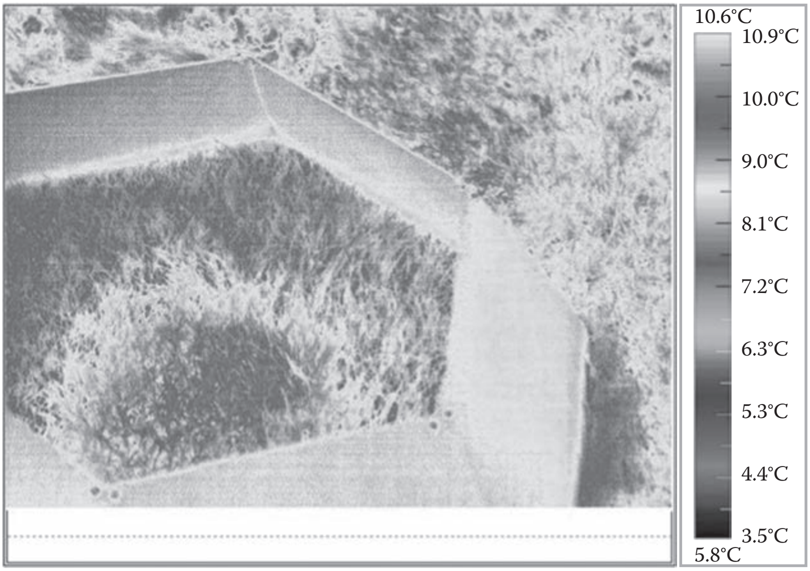

FIGURE 9.1
(**See color insert.**) Infrared image of a passive OTC covering a lawn, taken on a sunny day. (Copyright H.J. De Boeck.) Note the significant differences in surface temperature within the chamber.

irradiance would allow more precise linking of cause and effect, therefore increasing the mechanistic understanding of observed biotic responses to experimental warming, as illustrated by Bokhorst et al. (2013). Other technical improvements have also been proposed. For example, one of the most promising refinements is the use of thermally inert mass in the form of a liquid contained inside plastic pipes at the edge of the OTC (Godfree et al., 2011). This creates a more stable warming, topping off both hot and cold peaks by about 1°C, thus avoiding some of the reported increases in temporal variability in normal OTCs. Moreover, some of the island effects may also be decreased by introducing such a warm rim around the plots. Unfortunately, this improvement may in turn create new artifacts, such as increased shading. Although clearly not free of drawbacks, the major advantage of being nearly maintenance- and cost-free will ensure that passive OTCs will continue to be used, especially in remote and inhospitable environments.

9.2.2 Thermal Screens

A second method that utilizes energy from the environment to experimentally warm plots is the use of thermal screens. This method was developed in the 1990s, based on reducing the amount of net radiation lost from the land surface at night to reduce nighttime cooling. To that end, infrared reflective curtains (thermal screens) are suspended above the vegetation, which reflect a portion of the outgoing infrared radiation back to the vegetation and soil. In one of the first of such experiments, Zeiher et al. (1994) covered a cotton crop with thermal screens during 42 consecutive nights, which led to a 1°C–6°C increase in canopy temperatures compared to controls. Based on such early work, this method was used in the pan-European CLIMOOR project, where the reflective screens were applied using automated shelters, creating a modest 0.4°C–1.2°C increase in minimum air and soil temperatures (Beier, 2004).

A major advantage of using thermal screens is that there is no light attenuation (which causes a reduction of photosynthesis and can decrease surface temperatures; cf. De Boeck et al., 2012a). One aspect of the method that has been criticized is the asymmetric nature of the warming. Amthor et al. (2010) note that nighttime-only warming may be "of limited value to understanding effects of future warming on terrestrial ecosystems" as they argue that further reductions of the diurnal temperature range (i.e., more warming at night than during day) are uncertain and geographically varied. However, the most recent model projections still indicate that the diurnal temperature range is likely to decrease further (Lindvall and Svensson, 2015). Furthermore, applying the screens only at night actually also results in limited daytime warming because of lag effects via the warmer soils (Bruhn et al., 2013).

A more pertinent critique is that, like for passive OTCs, the achieved warming depends greatly on the accumulated radiation (Bruhn et al., 2013). This leads to similar issues of increased variability through time, as the weather conditions are so important in determining the realized temperature increase. An additional factor to be considered in the case of thermal screens (a horizontal surface, contrary to the more or less vertical plates in OTCs) is the more pronounced influence of wind speeds, which can again increase variation within a day and between days. On the other hand, the more natural wind environment reduces a number of artifacts linked to OTCs such as abnormal buildup of water vapor or other gasses. Indeed, Bruhn et al. (2013) reported that artifacts related to changes in air humidity or dew formation are generally minimal or insignificant. Another clear advantage compared to passive OTCs is that warming can be applied to much larger plots (20 m^2 in the case of the CLIMOOR project; Beier, 2004), so that artifacts associated with small plot sizes such as edge effects are likely to be reduced. On the downside, construction and maintenance is more complicated and costly than OTCs, and although the warming in itself is passive, automated screens require an external power source.

In order to remedy some of the weaknesses associated with this technique, several improvements were tested by Bruhn et al. (2013). Higher-temperature increases (adding a few extra tenths of degrees) were achieved by using screens with higher infrared radiation reflection and installing shields to reduce lateral wind speeds (although this could lead to other artifacts; see Section 9.2.1). The addition of thermal mass, much like in improved OTCs, was not effective, likely because of the large plot size. In spite of the limited temperature increases possible when using thermal screens (although this depends on the climate; cf. Zeiher et al., 1994), issues with asymmetric and variable changes in temperature, and the technical and logistical challenges involved, warming by thermal screens may be appealing in certain cases as it allows large plot sizes to be covered with no or minimal disturbance. Although the method has been used to cover short-statured vegetation, Luxmoore et al. (1998) developed a theoretical setup with thermal screens deployed with a cable and pulley systems mounted on a tower and scaffolding structure to warm forest sites. Such an experiment would require electric power to open and close the screens, however, and has to the best of our knowledge not been put into practice so far.

9.2.3 Translocation

A method that requires no outside power output to achieve warming but that allows more control is the translocation of monoliths (i.e., patches of vegetation with intact soil in containers or lysimeters) to a different climate zone. This can encompass relocating across hundreds of kilometers (especially to lower latitudes) or across mere kilometers (to lower elevations) when the landscape has suitable topography (hills or mountains). As an example of the former, Backhaus et al. (2014) moved *Fagus sylvatica* seedlings across more than 250 km, achieving an average air warming of 3.2°C. Regarding experiments in mountainous regions, there are studies that look into impacts of mild changes in temperature sustained for multiple years, like in Switzerland where monoliths were excavated from 2100 m a.s.l. and translocated to elevations ranging from 1680 to 2360 m a.s.l. (Seraina Bassin, pers. comm.). On the other hand, large vertical gradients have also been used in short-term studies on heat waves, for example, in the study of De Boeck et al. (2016), where an 1800 m vertical gradient led to average warming up to 11°C compared to the reference site (Figure 9.2). This illustrates that monolith translocation allows a wide range of warming. Moreover, the temperature increase is fairly predictable, especially if sites are not located too far apart and if the experiment lasts longer.

A major advantage is that a number of environmental parameters change in a manner that is realistic for a future climate. If site selection is carefully made, changes in air humidity, cloudiness, and wind speed can be consistent with climate projections. For example, relative humidity is expected to change little on average with climate warming, but if heat waves are the focus of the study, selecting a site with lower air humidity would improve realism as air humidity tends to decrease during heat waves (cf. De Boeck et al., 2010). Further “free” improvements of experimental realism using translocation compared to other warming methods are the increased percentage of precipitation as rainfall instead of snow and the change in partial pressure of CO_2 in studies using an elevational gradient. Indeed, warming by translocation encompasses a relative enrichment with CO_2, as a 100 m

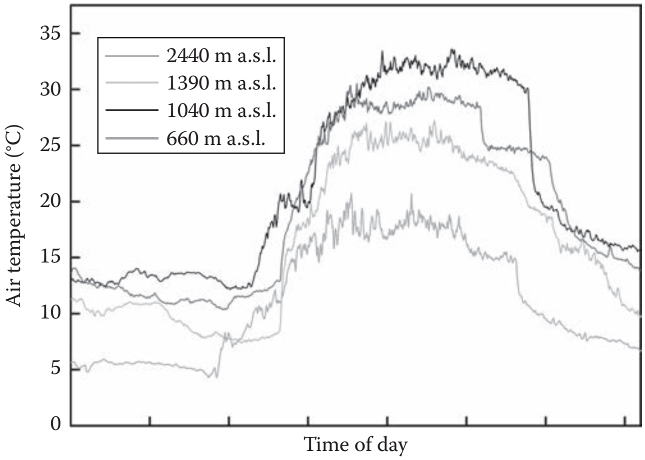

FIGURE 9.2
(**See color insert.**) Course of air temperatures during one day (July 31, 2013) measured at 40 cm height (just above the vegetation) at four sites used in a translocation experiment. Remarkably, the lowest site was not the warmest, due to specific local microclimates. (From De Boeck, H.J. et al., *New Phytol.*, 209, 531, 2016.)

difference (= ±0.7°C warming) in altitude approximately corresponds to a 1% change in the pressure of CO_2 (Körner, 2007). This amount of CO_2 fertilization is about an order of magnitude lower than what could be expected in a future environment, however.

Translocation also comes with a number of disadvantages. First, some conditions may change in an unwanted manner. Litter inputs (quantity and quality) originating from the environment can differ from the site of origin (e.g., when moving monoliths from above to below the tree line), as can radiation, pollution, herbivory, and pollination. Some of these artifacts, such as changes in pollution, could be mitigated by careful site selection, while others, such as those related to plant–animal interactions (e.g., with potential impacts on community composition), are largely unavoidable. Second, several issues are specifically associated with the use of monoliths. During the extraction of the soil blocks, some plant roots are inevitably cut, which can affect subsequent growth and induce additional edge effects (as roots from plants near the sides are trimmed to a larger extent than plants toward the center). As a minimal precautionary measure, data collection should be focused on plants in the center of the plot. Furthermore, the lysimeters containing the monoliths tend to warm up more than the outside soil, even when buried (Klaus Butterbach-Bahl, pers. comm.). To reduce this soil warming artifact, the lysimeter construction can be adapted, for example, by providing passive cooling (via evaporation of a water reservoir) at the bottom and by isolating the rim at the top. Third, the spatial separation of the warming treatments complicates measurements. To survey essential environmental variables such as temperature, humidity, and radiation, sensors and data loggers need to be installed at each site, which can imply a significant additional cost compared to when treatments are imposed at the same site. Furthermore, manual measurements cannot be carried out simultaneously, unless multiple collaborators and multiple precisely cross-calibrated measurement devices are available. As many variables of interest, such as gas exchange, differ within and between days, measurement schemes and data analyses have to be adapted to reflect the fact that individual data recordings cannot be compared one-on-one between two warming treatments. This encompasses spreading out measurements within one day to avoid intraday variability skewing results. For example, if stomatal conductance would only be measured before noon at site A and only in the afternoon at site B, this could affect the interpretation of the responses, as stomatal conductance is known to vary throughout the day (and to a larger extent in case of warming and/or drought; cf. Nijs et al., 1997). If data are acquired on many days during the experiment, data analysis can be focused on the general trends in time, which incorporate day-to-day variability so that the problem that not every measurement can be made at every site on each day is significantly reduced (e.g., De Boeck et al., 2016).

The spatial separation of treatments, which lies at the basis of the monolith translocation method, causes a number of difficulties, as discussed earlier. These may make precise attribution of cause and effect more difficult and can complicate logistics and data analysis. Yet in spite of this, using translocation as a warming method has the distinct advantage that it is very flexible (the amount of warming can be chosen relatively freely), open air (which avoids a number of artifacts), and relatively precise. A basic requirement is that sites are chosen carefully to avoid issues with locally differing conditions such as microclimate, litterfall, and pollution and that the measurement and data analysis protocols are designed with the specific characteristics of translocation studies in mind.

9.2.4 Geothermal Hot Spots

Harnessing the possibilities provided by natural anomalies is not new. Several studies have made use of locally increased levels of CO_2 (e.g., Tognetti et al., 2000). A similar approach also exists for temperature by using hot spots found in geologically active regions such as New Zealand (Burns, 1997) and Iceland (O'Gorman et al., 2014). Locally, gradients can be found where the soil is heated in different amounts without concomitant factors such as changes in pH and/or nutrients and pollutants interfering with straightforward comparisons along the warming gradient. Employing such a gradient and including extreme ranges brings the added benefit of being able to detect nonlinear trends and tipping points better (Kayler et al., 2015).

Because this type of passive warming is fully *in situ*, artifacts associated with excavation or shielding described earlier are avoided. The plots can often be chosen close to each other, with a gradient from +0°C (control) to

FIGURE 9.3
(**See color insert.**) FORHOT site in Iceland, where an earthquake in 2008 led to parts of the forest and grassland being exposed to marked increases in soil temperature. A gradient with plots warmed with 1°C–20°C at 10 cm depth was established here. (Copyright H.J. De Boeck.)

+20°C in soil temperature (at 10 cm depth) present within approximately 100 m at the Icelandic "FORHOT" grassland site (Figure 9.3). This allows measurements to be performed in rapid succession and under very similar conditions. One of the main other advantages of the use of hot spots is the fact that the warming is free and maintenance costs are mainly limited to loggers. Such loggers are evidently essential to keep track of temperatures during but also prior to the experiments. With good a priori quantification of isotherms, the desired warming levels can be chosen with relative confidence. Finally, interesting comparisons can be made between sites where the warming has been present for a long time and sites where soil warming is new. Such is the case in the FORHOT experiment in Iceland, where seismic shifts caused a grassland and forest to become affected by warming since 2008, while elsewhere in the area there is another grassland where the geothermal warming has been present for at least several decades (and likely for several centuries). By comparing responses to similar levels of warming, transient responses and long-term acclimation can be identified.

Of course, the warming is ultimately not controlled, so new geological activity may change the temperature gradient (or provide new opportunities). A more pronounced concern is that the warming originates from the soil, which implies that the aboveground part experiences temperatures that are close to ambient, especially in higher vegetation. This asymmetrical nature of the warming renders interpretation of its effects less straightforward, as important feedbacks exist between above- and belowground systems

(Van der Putten et al., 2009). Therefore, hypotheses have to be very well delineated to avoid extrapolation of trends that would change if the warming was symmetrical. As the heat source originates from deep within the soil, there is a vertical gradient of higher to lower temperatures in the direction of the soil surface, regardless of the season. In winter, such a situation is natural (soil temperature is fairly constant near the annual average in deeper soil layers), but in summer a reversed thermal profile would be expected under ambient conditions because of stronger irradiation and high air temperatures. Finally, even when having existed for hundreds of years, local hot spots still remain islands in a wider landscape that does not experience the same warming. As a result, mobile organisms may be attracted more to those warm patches than they would if the entire environment was warmed (De Boeck et al., 2015). This may affect, for example, pollination or grazing and hence alter processes and ecosystem characteristics down the line, such as community composition.

Such island effects are a phenomenon that occurs to some degree in all warming experiments and that is largely unavoidable, however. In general, making use of natural hot spots seems to provide some unique advantages. One is the relative ease with which gradients can be found where temperature changes while other environmental variables remain unaffected. Another important asset is the possibility of comparing locations where the temperature change is new with sites where the warming has been present for a considerable time. Nevertheless, hypotheses need to explicitly acknowledge the asymmetrical nature of the warming so that extrapolation of responses beyond the inherent limitations associated with soil-only warming is avoided.

9.3 Active Warming Methods

9.3.1 Soil Heating Cables

The use of soil heating cables is the least costly and the least technically demanding of the three active warming methods discussed here. Major studies applying this technique were started up in the 1990s (Peterjohn et al., 1993; Bergh and Linder, 1999), but heating cables have been used in ecological research even well before that (e.g., McBee et al., 1968). The method makes use of thin cables laid out in several rows (usually in one horizontal plane) with spacing and burial depth varying between experiments (Patil et al., 2013). The amount of warming is then controlled by modulation to preserve a constant difference between soil temperature sensors deployed in warmed and control plots. Usually, this control is precise and malfunctions are rare (Strömgren and Linder, 2002; Patil et al., 2013, but see Schindlbacher et al., 2009). Another major advantage is that the warming can be imposed also in forests, as the technical challenges of warming tall vegetation are not applicable here. The relative cost-effectiveness is a major advantage when performing research on long-living organisms such as trees, as responses found in short experiments may be especially misleading in such systems (cf. Norby and Zak, 2011). A prime example of a long-term warming study is found in Flakaliden (Sweden), where soil warming has been imposed for 18 consecutive growing seasons (Leppälammi-Kujansuu et al., 2013).

The temperature at Flakaliden was increased to simulate earlier soil thawing in spring, thus advancing the onset of the growing season by several weeks. Soil warming releases this boreal system from belowground cold limitation (due to the frozen soils) while cold limitation for the aboveground structures is largely absent in this season. Hence, the asymmetrical nature of the warming is less of a concern in this case. The relevance of the results when using soil heating cables depends very much on carefully developing assumptions that are well grounded in theory and avoiding a focus on processes that are highly dependent on aboveground warming, much like for soil warming through passive means (Section 9.2.4). In contrast with warming via passive methods, the installation of heating cables causes soil disturbance through the digging of slits (unless the cables are deployed at the soil surface), which cut through roots. Obviously, the same procedure needs to be followed in control plots so that the disturbance is similar. The system tends to recover from this fairly rapidly (Sune Linder, pers. comm.), implying that longer-term results should not be affected significantly by the initial perturbation. The technique creates both horizontal and vertical temperature gradients in the soil (as temperature decreases away from the cables), which is another drawback. These gradients differ from those found in naturally warmer soils especially if the cables are buried neither at the soil surface (e.g., Reth et al., 2009), which would be reminiscent of summer warming, nor in deep soil layers (Hanson et al., 2011), which would mimic winter warming. Finally, the increased soil temperatures inevitably increase evaporation, which can lead to drought. Depending on the study's goals, this drought effect may be part of the experimental design, or it can be avoided by providing irrigation (like was done in the Flakaliden experiment).

In general, soil warming provided via heating cables comes with a number of clear limitations and artifacts, of which asymmetric nature of the warming is the most important. Its major appeal is that it currently is the only technique that has been used to actively warm mature forests (not merely single trees). The relative cost-effectiveness allows for long-term warming experiments, which is an additional benefit when testing responses to temperature increases in long-lived ecosystems.

9.3.2 Climate-Controlled Chambers

Early CO_2 enrichment experiments made use of OTCs and were confronted with concurrent warming as an unwanted additional treatment (e.g., Drake et al., 1989). In response to this warming side effect, researchers added systems to dissipate warmer air by ventilation with outside air (e.g., Norris et al., 1996). Although this reduces the temperature increase measured within the OTCs, such an approach cannot keep temperatures close to those measured outside the chambers under all circumstances (Leadley and Drake, 1993), especially in late spring and summer when radiation loads on the system are very high. This is why active cooling systems were developed that are able to maintain the air temperature inside the chambers closer to ambient temperatures (e.g., Van Oijen et al., 1999) and that are often complemented with heaters so that warming could be included as an additional factor in a full-factorial design. Similar climate controls that cool or warm the air on demand have also been used in complete enclosures (e.g., Naudts et al., 2013).

Creating a fully climate-controlled environment places substantial demands on technology (sensors, control algorithms, etc.) and requires a high amount of external energy (cf. Pelini et al., 2011). A major benefit, apart from the tight control, is that the air is the medium that is warmed, which matches the characteristics of natural temperature increases. Nevertheless, some dampening may occur in the soil due to the influence of outside, unwarmed soil (another island effect). In complete enclosures, other climate variables such as atmospheric CO_2 concentrations and precipitation can be varied in a straightforward manner. Some setups also allow varying air humidity (Barton et al., 2010), which is highly relevant to avoid conditions that are drier than they would be in a future climate. Indeed, warming depletes the air of humidity in a relative sense while climate projections indicate that relative humidity would be generally unchanged in a warmer climate (IPCC, 2013). Installing air humidifiers can remedy this potential artifact and also increases the range of climate scenarios that can be imposed experimentally. The most sophisticated systems, sunlit ecotrons (e.g., Milcu et al., 2014), enable continuous sampling of gasses so that whole-system CO_2 and H_2O fluxes can be followed almost in real time. The size of climate-controlled greenhouses usually allows for experiments on short-statured systems (grassland, crops, heather, etc.) and young trees (Bauweraerts et al., 2013), but even single adult trees have been used (Medhurst et al., 2006).

Enclosing a plant or ecosystem offers some advantages, such as increased control and the possibility to measure gas fluxes continuously, but also leads to a number of artifacts. Because the radiation environment inside is different from outside (not only because of radiation reduction but also because the cover materials are usually warmer than the sky and therefore radiate more heat), there is the possibility that leaf temperatures would deviate. Results obtained using an energy balance model show that this different radiation environment does not lead to large leaf temperature changes (under ambient air temperatures) compared to outside (De Boeck et al., 2012a). The same model demonstrated that avoiding low wind speeds is crucial as these affect leaf temperatures substantially (by several degrees). Adjustable ventilation should therefore be a priority in the technical design of greenhouse experiments. Light attenuation is impossible to avoid, with reductions of 15% of photosynthetic active radiation commonly reported. This could be remedied by installing additional lighting, especially in climates where light reduction is expected to have important impacts. Another concern is that many materials block (part of the) UV wavelengths, which can additionally affect plant growth and functioning (Kittas et al., 2006). Proper material choice (Milcu et al., 2014) can avoid this. Finally, the (partially) enclosed nature of climate-controlled chambers also changes or blocks out interactions with many higher trophic groups (such as pollinators and herbivores). Apart from the targeted introduction of certain species (e.g., Stevnbak et al., 2012), no real solution exists (cf. De Boeck et al., 2015).

Climate-controlled chambers require a fairly big budget and technical know-how, and some of the downsides associated with enclosing ecosystems may mean that they are not the proper choice for certain studies (e.g., if a large spatial scale is required). Nevertheless, they provide unique research opportunities through their flexibility regarding potential treatments, their level of control, and the possibility to instantly measure whole-system gas exchange in the most sophisticated systems.

9.3.3 Infrared Heating Systems

The use of infrared heaters in ecological research was introduced in the 1990s to be able to warm ecosystems under free-air conditions, first by Harte et al. (1995) in a field experiment where commercially available IR lamps were suspended above montane meadow plots. The lamps were set to emit a constant flux, effectively increasing the amount of incoming radiation, resulting in temperature increases in vegetation and soil. Later, Nijs et al. (1996) adapted this technique by adding a modulator so that a constant difference between the surface temperatures of warmed and control plots could be maintained. Such modulation greatly decreases variability of the amount of warming caused by fluctuations in wind speed and other environmental variables that influence canopy temperatures.

However, maintaining a fixed temperature difference between plots also implies that normal physical and physiological feedbacks are negated. In reality, warmed plots tend to dry out more, and drought-stressed vegetation should warm up more than well-watered vegetation (Larcher, 2003), leading to potential differences in heat stress. Control systems that aim at a constant temperature difference between heated and unheated plots will eliminate this natural drought-associated heat by lowering the emitted infrared radiation, however. A control method was recently developed that takes this natural feedback into account while still allowing a great amount of control (De Boeck and Nijs, 2011). By using energy balance equations supported by instantaneous measurements of all the relevant environmental variables, realistic canopy temperatures are achieved while allowing input of target air temperatures. The latter is another advantage compared to conventional infrared heating, which relies on canopy temperature inputs, while these are not generally explicit in climate projections. A variation on this method, but with the same general advantages, was proposed by Kimball (2015).

One of the major benefits of using IR heaters is that it does not require enclosing the plants, therefore avoiding most artifacts associated with enclosures (reduced light and wind, absence of pollinators, etc.). This also means IR warming can be combined with the well-established free-air CO_2 enrichment technique (LeCain et al., 2015). In principle, the surface area of plots is unlimited as new hexagons (the normal shape of infrared heater arrays) can be added (Kimball et al., 2012). The fact that warming is direct because infrared lamps heat the surface without having to overcome a boundary layer resistance makes the technique very responsive (Nijs et al., 1996; Kimball et al., 2008). Obviously, this implies that the air is only warmed indirectly and generally to a lesser extent than the surface (a characteristic of infrared heating that is sometimes misinterpreted). Finally, large deviations from the ambient (canopy) temperatures can be achieved (+8°C and more), allowing heat wave research (e.g., Dreesen et al., 2014).

A drawback of infrared irradiation is that it works well for low-statured vegetation (e.g., tundra, grassland, heather) but that multilayered vegetation poses serious challenges. Although theoretically not impossible, warming a forest would require infrared heaters suspended throughout the canopy, resulting in substantial technological complexity (e.g., differential energy outputs in different canopy layers) and high running costs. Similarly, the fact that the technique warms surfaces also results in artifacts in less complex canopies. First, especially in dense canopies, soil warming can be lower than could be expected under air warming (Rich et al., 2015), although this problem is not universal (Nijs et al., 1996). Second, the gradient for water vapor from surface to air is increased, resulting in higher evapotranspiration. This artifact was recently quantified (De Boeck et al., 2012), with results suggesting a 12%–15% increase in transpiration for a 1°C canopy warming compared to 1°C air warming at constant relative humidity. Potential resolutions are adding supplemental irrigation water (Kimball, 2005) or making use of free-air humidification systems (Kupper et al., 2011). Importantly, the artifact is less of a concern when simulating heat waves as the higher atmospheric water demand underneath the heaters reflects naturally occurring increases of potential evapotranspiration during heat waves resulting from atmospheric feedback, that is, drier and warmer air (De Boeck et al., 2010).

Infrared heating seems most suitable for warming small statured vegetation and especially for imposing short but intense temperature increases as this turns an artifact of the heating method (exacerbating the atmospheric demand for water) into a benefit as it mimics naturally occurring feedbacks. New control methods (De Boeck and Nijs, 2011; Kimball, 2015) also incorporate other natural feedbacks, which together with the open air nature of the method further increases its realism. Like with actively climatized greenhouses, technological know-how is a necessity, however.

9.4 Conclusions

The methods we discussed here are the most commonly used techniques to warm ecosystems under sunlit conditions. Passive warming methods are generally cheaper to install and require less technology, but the main drawback is that the amount of warming is generally uncontrolled and dependent on ambient conditions, which means that not only the mean is changed but also the variability. Active warming methods generally rely on electric power to provide the temperature increase, confining their applicability in remote areas especially if power demands are high (i.e., when the use of generators would not meet demands or would prove too costly). In places that are connected to mains power, such as on campus research sites, active warming methods may be preferred because of their high degree of temperature control and the ability to create stable and large temperature increases year-round. Active methods also facilitate the creation of warming gradients, an approach that allows for better detection of general trends, thresholds, and tipping points (Kreyling et al., 2014). The recent SPRUCE experiment with climate-controlled OTCs (Krassovski et al., 2015), for example, features five levels of warming (from +0°C to +9°C). Note that such a gradient approach is also possible through monolith translocation and in geothermal hot spots, although these passive methods come with the limitations described earlier.

Some studies have combined warming methods in order to profit from the advantages each technique offers. For example, Sun et al. (2013) used OTCs supplemented with heating cables suspended in the air to provide a more continuous warming. Rich et al. (2015) combined an infrared heater array with soil heating cables to provide a more uniform warming above- and belowground. While such combined approaches can indeed reduce some artifacts (e.g., temperature variability), they also can create new issues (e.g., the need for electricity in the first example and soil disturbance in the second). Combinations with alternative, niche methods not discussed here, such as the addition of black carbon to decrease albedo (De Simon et al., 2013), installing heating cables within the tree canopy (Nakamura et al., 2010), or the soil warming side effect of belowground high-pressure natural gas ducts (De Frenne, 2015), could also be considered. In some cases, combinations of different techniques may be used to unravel the impact of asymmetric warming on ecosystem functioning (e.g., soil heating and warmed OTCs; Bronson et al., 2008), thereby reducing uncertainties associated with the method(s) in question.

Our overview of the main current warming methods indicates clearly that no method is without flaws and disadvantages. Luckily, weaknesses vary among the different methods (Table 9.1), which allows researchers to carefully consider what would work best for their research goals and their ecosystem. A clear understanding of peculiarities, advantages, and disadvantages of a

TABLE 9.1

Overview of General Characteristics of Different Warming Methods as Described in This Chapter

Method	Technological Demands	Cost	Intrusiveness	Plot Size	Potential ΔT	Control	Main Artifact
Passive types							
Open top chambers	Low	Low	Low	Small	Small	Low	Reduced wind
Thermal screens	Medium	Medium	Low	Large	Small	Low	Asymmetric warming
Translocation	Low	Medium	High	Small	High	Medium	Soil disturbance
Geothermal hot spots	Low	Low	Low	Unlimited	High	Medium	Asymmetric warming
Active types							
Soil heating cables	Medium	Medium	High	Large	Medium	High	Asymmetric warming
Climate-controlled chambers	High	High	Medium	Medium	High	High	Reduced light
Infrared heating	Medium/high	Medium	Low	Medium/large	High	High	Increased ET

technique could avoid unwanted consequences (e.g., erroneous extrapolation, fatal flaws) of mismatches between the warming method and the envisaged study.

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