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An improved open-top chamber warming system for global change research

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Abstract

This study is an assessment of an improved temperature warming system developed to enhance global warming research-based forest ecosystem and soil ecophysiological experiments. The architecture couples a standard open-top chamber (OTC) with a heating cable. A 16 m wire cable with an 18 W m^{-1} and 288 W h^{-1} power rating was coiled around a polyvinyl chloride (PVC) pipe 2.5 m in length and 3.5 cm in diameter. The pipe was reshaped into a circle and fixed inside the OTC at a height of 15 cm. PVC pipe distance to plants was 10 to 15 cm while distance to OTC inner walls was 15 cm. The cable was constructed from a heating source with an alloy resistance wire, an aluminum foil and copper wire shielded layer, a crosslinking polyethylene inner insulator, a PVC coating, and a tinned copper grounding wire. After the cable is powered up, air and soil inside the OTC-cable system is heated by conductivity. Temperature is manipulated according to the voltage and resistance of the cable. The OTC-cable system was developed to examine plant reaction to an increase in air and soil temperatures by 2.84 °C and 1.83 °C, respectively. Temperature values are adjustable by changing cable and PVC pipe length. It offers a new, affordable, low energy consumption and low running cost method by which to study climate change effects on forest ecosystems. This method is especially useful for application in forest ecosystems of many developing countries or in many remote areas of developed countries where the feasibility in supplying sufficient power from local power grids is questionable.

Keywords OTC-cable system; open-top chamber; climate change; temperature; forest ecosystem
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1 Introduction

There are two main approaches in global warming research: field observations obtained over time and/or space and small-scale experiments (Wolkovich et al. 2012). Wolkovich et al. (2012) suggested that the field observation approach is better at measuring biotic responses to climate change when compared to experimental warming approaches; however, this approach requires a long time span to achieve results. Occasionally, field observations have resulted in misleading inferences (Fukami and Wardle 2005) as unknown variation (aside from site history focal variables) can affect long-term community dynamics. In addition, researchers may not have a good understanding of biotic responses and, consequently, how to replicate them experimentally. Artificial warming experiments remain one of the chief methodologies used in global climate change research (Shen and Harte 2000). Nevertheless, results of such experiments may be highly uncertain and greatly underestimate ecosystem response to global warming (Wolkovich et al. 2012). Therefore, coupling two approaches (field observations and small-scale experiments) may be a better choice in predicting plant response to climate change.

A great number of researchers are using devices to manipulate increases in temperature for various habitats when studying potential impacts of climate warming on terrestrial ecosystems (Hollister and Webber 2000; Wan et al. 2002). Accordingly, many techniques have been adopted to simulate increases in temperature for different terrestrial biomes. These techniques can be classified into four types (Wan et al. 2002; Niu et al. 2007): 1) greenhouse and open-top chambers (OTC) (Chapin and Shaver 1985; Robinson et al. 1998; Kudernatsch et al. 2008; Jassey et al. 2012; Xu et al. 2012), 2) soil heating pipes and cables (Peterjohn et al. 1993; Schindlbacher et al. 2009), 3) infrared reflectors (Zeiher et al. 1994; Beier et al. 2004), and 4) infrared radiators (Harte et al. 1995; Kimball et al. 2008; Morin et al. 2010). Among these techniques, the most generally applicable and truly accurate in predicting climate change is the infrared radiator while the least expensive is OTC (Aronson and McNulty 2009).

However, all four types have limitations. For example, although soil heating pipes and cables buried underground can be successfully deployed in forest biomes, accommodating them disturbs the natural state of soil, roots, and existing understory. In addition, soil heating pipes and cables only increase soil temperature and are therefore incapable in simulating future global warming conditions (i.e., simultaneous increases in both air and soil temperature).

Infrared reflectors primarily enhance nighttime air temperature but have little daytime affect (Zeiher et al. 1994). As a result, it can overstate ecosystem carbon budgets due to nighttime increases in plant respiration (Wan et al. 2005). The utility of this method may also be limiting in forest ecosystems due to canopy height and reduced sunshine (Aronson and McNulty 2009).

Infrared radiators, although deemed as the most accurate method in predicting climate change (Aronson and McNulty 2009), primarily warm plants and soil surfaces. Their ability to enhance air temperature (dependent on wind speed) is still under debate (Harte et al. 1995; Kimball 2005; Niu et al. 2007). Vapor pressure gradients caused by infrared radiators are not the same as those caused by global warming (Kimball 2005). Moreover, the energy consumption and cost of infrared radiators are high due to their exorbitant electrical requirements. For example, the actual power of one IR lamp (Kalglo Electronics Inc., Bethlehem, PA, USA) ranges between 800 and 2000 W h^{-1}, depending on the size of the lamp. This may limit its adoption in developing countries and in some remote areas of developed countries where the feasibility of supplying sufficient power from power grids would be tested, consequently hindering climate change impact assessments on ecosystem processes in these regions of the world (Aronson and McNulty 2009).

Being the least expensive of the four types, OTCs perform well in grassland and tundra biomes with high solar radiation. Amthor et al. (2010) even considered that OTC as an active warming approach (compared to passive warming approaches such as soil cables, infrared radiators, and infrared reflectors), allowing a wider range of scientific questions to be answered with appropriate quantitative control of temperature treatments. However, temperature increases in forest ecosystems are insufficient due to the limited available photosynthetically active radiation (PAR). OTC systems elevate daytime mean air temperatures but the effect is minimal at night. In addition, daily increases in air temperature are more prevalent in summer than in winter (Marion et al. 1997; Wan et al. 2002). Moreover, A few studies have also reported that warming chambers can sometimes result in the cooling of plots (Molau 1997). The one year investigation carried out by this study in a coniferous forest under reduced light conditions showed a slight decrease in OTC air temperature when compared to ambient air temperature.

The aim of this study was to introduce a new heating system that can simulate global warming. The design was an improvement on the standard OTC and is applicable for use in forest biomes that typically experience low PAR. Compared to other warming systems, this new heating system can simultaneously increase air and soil temperatures, thereby simulating true conditions of global warming. More importantly, this method is energy efficient and has a low running cost, and is especially useful in forest ecosystems in many developing countries or in many remote areas of developed countries the feasibility in supplying sufficient power from power grids is questionable.

2 Materials and methods

2.1 Experimental site

The experimental site was located on Mount Gongga at an altitude of 3060 m (lat 29°34.424′N, long 101°0.271′E), Sichuan Province, China. Mount Gongga is the tallest peak in the Henduan mountain range with an elevation of 7556 m above mean sea level. The experiment was carried out in a dark conifer forest (3000 m a.s.l.) dominated by *Abies fabri* (Mast.) Craib trees along with sparsely distributed shrubs and dense understory bryophytes. The annual mean temperature of the experimental site is 3.8 °C (–4.3 °C in January and 11.9 °C in July). The annual mean precipitation is 1940.0 mm, 60.6% of which occurs from June to September. The average annual transpiration is 1578.6 mm, and the annual average relative humidity (RH) is 90.2%. The soil is typical mountain dark brown soil with high sand content and strong permeability. For this study, the warming experiment, which employed a standard OTC between June 2009 and May 2010, demonstrated that an OTC in itself is incapable of warming air and soil temperatures (Fig. 1) in the dark coniferous forest site selected for this investigation. This is primarily attributable to low light conditions.

2.2 Design

For the investigation, three plots were warmed using the new OTC-cable system while three other open area plots without OTCs were maintained as ambient control plots. The OTC-cable system with a 288 W power rating consisted of a standard International Tundra Experiment (ITEX) six-sided OTC (Bokhorst et al. 2008), a heating cable, and a polyvinyl chloride (PVC) pipe (Fig. 2). It was constructed from poly methyl methacrylate (PMMA UV-transparent) plates of the following dimensions: 4 mm thickness with a 100 cm base, 70 cm top, and 52 cm sides cut at an angle of 60°. These plates feature high light transmittance (86%) and low infrared transmittance (< 5%). A 16 m wire cable with an 18 W m^{-1} and 288 W power rating was coiled around a PVC pipe 2.5 m in length and 3.5 cm in diameter, after which the pipe was reshaped into a circle and fixed inside the OTC (using timber stakes) at a height of 15 cm. PVC pipe distance to plants was 10 to 15 cm

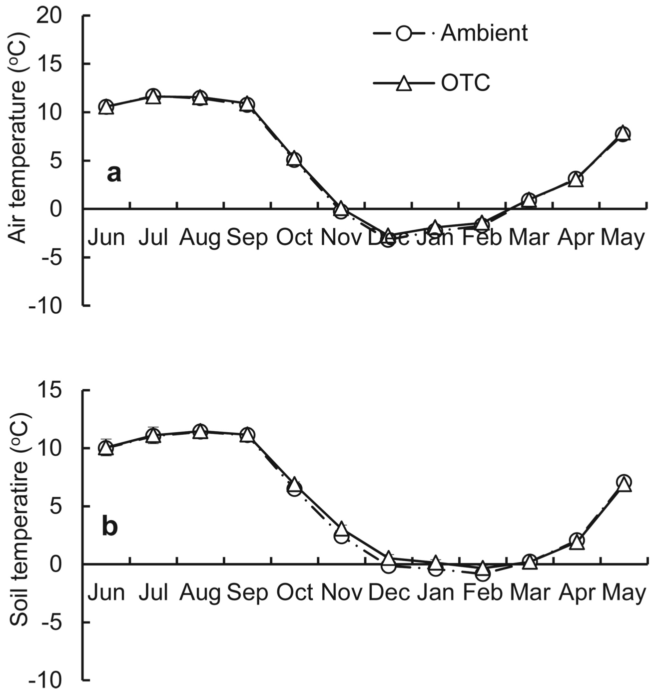

Fig. 1. Annual temperature variations in ambient and standard OTC warmed plots in a conifer forest understory; (a) air temperature and (b) soil temperature. OTC, open-top chamber.

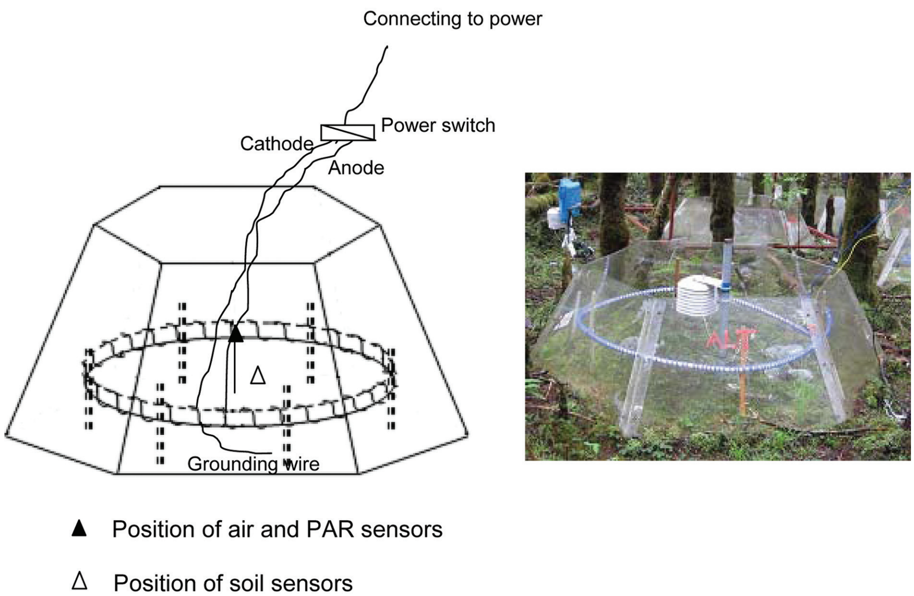

Fig. 2. Design of OTC-cable system. OTC, Open-top chamber; PAR, photosynthetically active radiation.

while distance to OTC inner walls was 15 cm. This was to prevent compromising the OTC or risk burning the plants. The cable used for this system was constructed from a heating source with an alloy resistance wire, an aluminum foil and copper wire shielded layer, a crosslinking polyethylene inner insulator, an aging-resistant blue PVC coating, and a tinned copper grounding wire. After the cable was powered up, air and soil inside the OTC was heated by conductivity. The resistance wire generated heat through the transfer of electric energy into heat energy, the quantity of which was based on the voltage and resistance of the cable itself.

2.3 Testing

Air and soil temperatures, RH, and soil moisture inside and outside the OTC-cable system were instantaneously recorded using Hobo Pro data loggers (Onset Computer Corporation, Pocasset, MA, the United States of America) at intervals of 15 minutes from May 2010 to May 2011. Positioned in the center of the chamber at a height of 30 cm above the soil surface were one air sensor used to detect both air temperature and RH (THB sensors, Onset Computer Corporation) and one PAR sensor (LIA sensors, Onset Computer Corporation). The sensors were protected by white PVC elbows open at both ends to allow for the free flow of air across the sensors and angled in such a way as to avoid sensor contact with direct or back radiation. Soil sensors to detect temperature (TMB sensor, Onset Computer Corporation) and moisture (SMC sensor, Onset Computer Corporation) were positioned 5 cm from the center of the chamber at 5 cm below the soil surface. All sensors featured reliable zero calibration, and, according to Tang et al. (2006), their stability and absolute accuracy had been tested in an ice water bath.

2.4 Statistics

Data were presented as the monthly average, monthly daytime average, and monthly nighttime average air and soil temperatures, RH, and soil moisture. Statistical significance of warming was evaluated using analysis of variance (ANOVA).

3 Results

For the experimental plots, air temperature was consistently maintained at an average of 2.84 °C above ambient conditions where mean daytime and nighttime temperatures increased by 2.78 °C and 2.89 °C, respectively (Fig. 3). Compared to the control plots, a lower but consistent increase in soil temperature of 1.83 °C was measured in the experimental plots where mean daytime and nighttime soil temperatures increased by 1.78 °C and 1.88 °C, respectively (Fig. 4).

Insignificant differences were found in PAR between the OTC-cable system and the ambient control plots (Fig. 5a). However, the RH inside the OTC-cable system decreased by 6.11 %-units relative to the control plots (Fig. 5b). A 0.062 kPa increase in the water vapor pressure deficit (VPD) was found in the experimental plots (Fig.5c). In addition, monthly averaged soil moisture decreased by 1.55 %-units in the experimental plots compared to the control plots (Fig. 5d); however, the influence of the OTC-cable system on soil moisture varied seasonally (Fig. 5d). On average, a 4.14 %-units decrease in soil moisture was found throughout the growing season (from April to September) as a result of warmer air temperatures, whereas a 1.03 %-units increase was observed throughout winter (from October to March) as a result of conditions of slower freezing and faster snow melt.

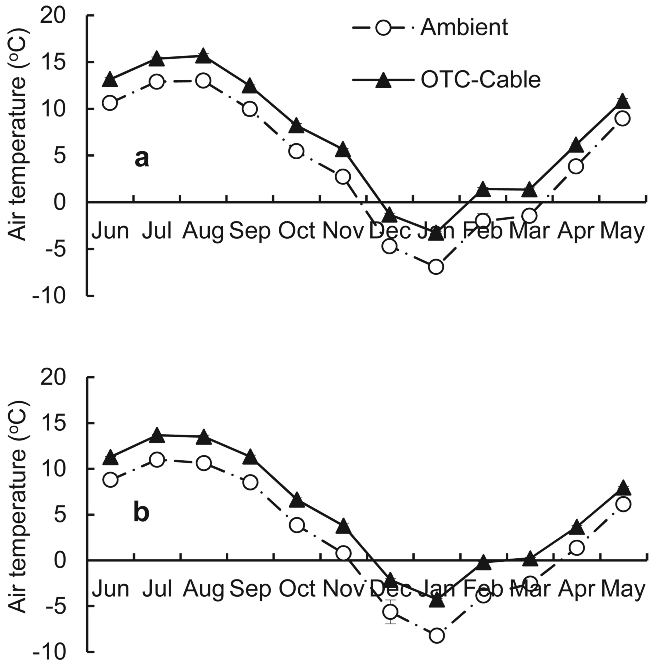

Fig. 3. Annual air temperature variations in ambient and OTC-cable system warmed plots in a conifer forest understory; (a) monthly daytime averages; and (b) monthly nighttime averages. OTC, open-top chamber.

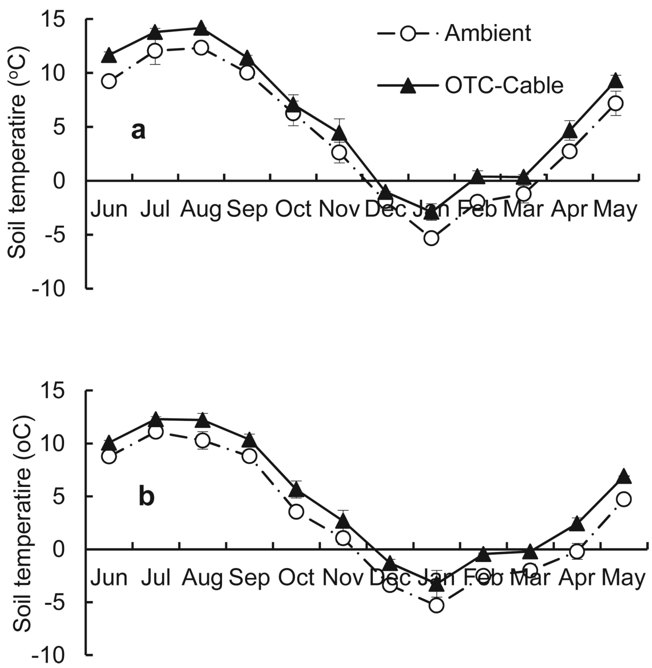

Fig. 4. Annual soil temperature variations in ambient and OTC-cable system warmed plots in a conifer forest understory; (a) monthly daytime averages; and (b) monthly nighttime averages. OTC, open-top chamber.

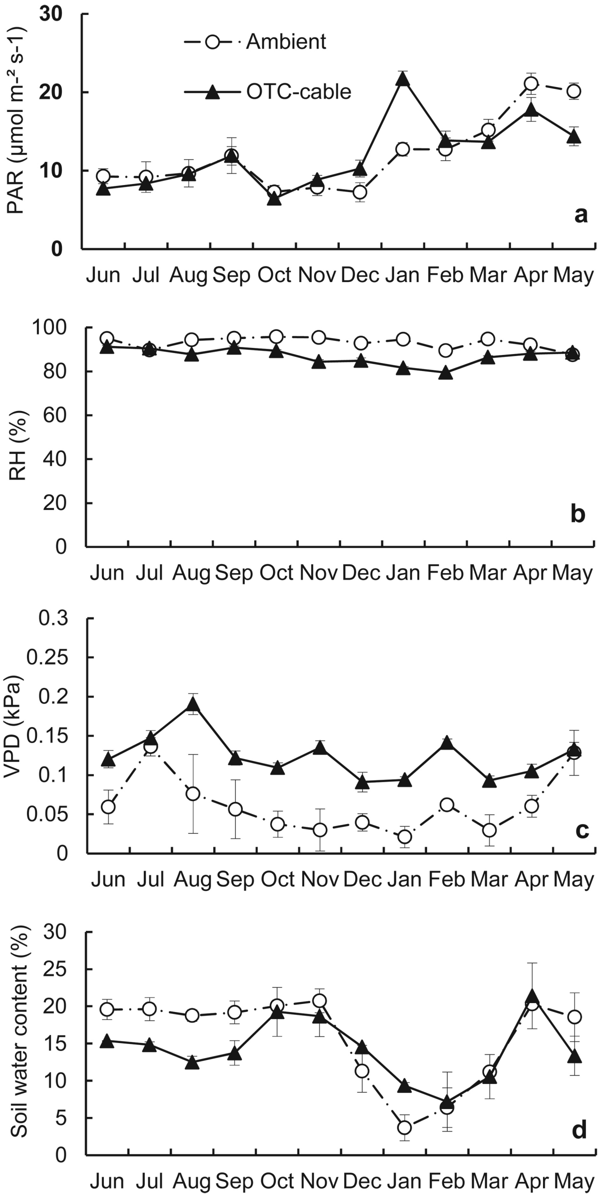

Fig. 5. Annual variations in (a) PAR, (b) RH, (c) VPD, and (d) soil moisture in ambient plots and OTC-cable system warmed plots in a conifer forest understory; PAR, photosynthetically active radiation; RH, relative humidity; VPD, water vapor pressure deficit; OTC, open-top chamber.

4 Discussion

Relative to the ambient control plots, a consistent increase of 2.84 °C and 1.83 °C was respectively measured in air and soil temperature in the experimental plots. Nighttime warming changes in air and soil temperatures in the experimental plots were comparable to daytime changes (Fig. 3 and Fig. 4). These findings suggest that the OTC-cable system is effective in increasing air and soil temperatures while not magnifying or abridging daytime and nighttime temperature differences. According to the fourth assessment report published by the Intergovernmental Panel on Climate Change (IPCC 2007), global average air temperature is estimated to increase between 1.1 °C and

6.4 °C by 2099. In view of this, the temperature enhancement provided by this study's OTC-cable system was reasonable. By using a range of cable lengths and PVC pipes, increased values in temperature can be adjusted according to research aim and ecosystem type for a diverse assortment of experiments.

The OTC-cable system was constructed from poly methyl methacrylate (PMMA UV-transparent) plates with high light transmittance (86%) and low infrared transmittance (< 5%), providing an environment proven to not significantly influence PAR. Observation data (Fig. 5a) from this study also demonstrated that no significant difference was apparent in PAR between the OTC-cable plots and the ambient control plots. This indicates that the OTC-cable system itself does not cause light attenuation. However, since the PAR sensor was located above the pipe, OTC-cable plot effects relating to the structural components of the pipes and the support system on PAR was unclear. Same with traditional OTCs, the open-top area of the OTC-cable system was the effective area of investigation. As the pipes and support system were out of range of the open-top area and therefore could not be determined as influencing factors, it was assumed these components and structural elements did not significantly influence PAR measured in the open-top area.

A 6.11 %-units decrease in RH was measured in the OTC-cable system relative to the ambient control plots (Fig. 5b). This was assumed to result from by an increase in air temperature. For the OTC-cable plots, a 1.55 %-units decrease in soil moisture was measured relative to the ambient control plots, which was lower or comparable to data from other studies. For example, a study carried out in a subalpine meadowland ecosystem found that the use of an infrared heater decreased summer soil water content by 25 %-units (Loik and Harte 1997). In a warming experiment carried out in the eastern region of the Tibetan Plateau, a standard OTC caused a decrease in soil moisture by 2.8 %-units to 3.8 %-units (Xu et al. 2012). Another warming experiment jointly carried out using a standard OTC in the Falkland Islands and the Antarctic Islands measured a decrease in soil moisture between 2.8 %-units and 20.2 %-units (Bokhorst et al. 2008). Compared to these results, the decrease in soil moisture measured in this study's OTC-cable system was low and acceptable.

Unlike soil cables, infrared reflectors, infrared radiators, and standard OTCs, the OTC-cable system allows for the controlled manipulation of temperature, preserving characteristics of daily cycles. More importantly, it is practical for use in understory vegetation in densely wooded forests. Compared to soil cables, which cannot increase air temperature (Wan et al. 2002), the OTC-cable system does not impair soil structure, affect soil hydrology regimes, or disturb understory vegetation. This new system also simultaneously increases both daytime and nighttime air and soil temperatures for only a small financial investment compared to infrared reflectors or infrared radiators. Compared to the high electrical requirements of infrared radiators, such as an IR lamp's 800–2000 W power rating (Kalglo Electronics Inc., Bethlehem, PA, the United States of America), the power rating of the OTC-cable system using a 16 m length wire cable is only 288 W. This energy efficient system can be supplied by solar energy. For example, a set of 2500 W h^{-1} solar panels (by assuming an average of 4 hours sunshine per day) can supply enough energy to operate the OTC-cable system on its own.

The OTC-cable system also overcomes shortcomings of standard OTCs in increasing daytime and decreasing nighttime air temperatures (Werkman et al. 1996; Hollister and Webber 2000; Musil et al. 2005), resulting in an broader range of the diurnal temperatures (Wan et al. 2002) and the disparity between daily summer and winter air temperatures (Marion et al. 1997). Furthermore, standard OTCs are not appropriate for use in forest ecosystems due to the inherent light limitation of such environments. Although Hartely et al. (1999) attempted to simulate climate warming by coupling a buried soil heating wire and an OTC, the method has not been widely adopted. Moreover, this particular method could also potentially impair soil structure, soil hydrological regimes, and understory vegetation. Recently, another improvement in traditional OTCs was proposed by

Godfree et al. (2011), making use of the buffering capacity of water to control temperature extremes. Because plots using this method were also heated by solar radiation, the method is not applicable for forest ecosystems under low light condition. Compared to these upgrades, the OTC-cable system does not impair soil structure, soil hydrological regimes, and understory vegetation, and is applicable for use in forest ecosystems.

Similar to standard OTCs, the OTC-cable system is not fixed to the ground and therefore allows for the free exchange of air. As a result, it undergoes the same chamber effects as standard OTCs, such as abnormal movements in air currents, insects, animals, pollination, seed dispersal, and reduced light intensity (Marion et al. 1997; Gedan and Bertness 2009). However, the OTC-cable system improved on traditional OTCs by increasing both summer and winter nighttime and daytime temperatures and making it applicable for use in forest ecosystems under low light intensity conditions. Generally, the OTC-cable system offers a new, affordable, and practical approach that can be used in dense forests to determine those influences that global warming has over ecosystems. It is important the appropriate warming methods should be chosen according to ecosystem type, objective, practicality, and the funding levels of relevant studies.

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