**RESEARCH ARTICLE**

**Design and performance of an ecosystem-scale forest soil warming experiment with infrared heater arrays**

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**Abstract**

1. How forest ecosystems respond to climate warming will determine forest trajectories over the next 100 years. However, the potential effects of elevated temperature on forests remain unclear, primarily because of the absence of long-term and large-size field warming experiments in forests, especially in Asia.

2. Here, we present the design and performance of an ecosystem-scale warming experiment using infrared (IR) heater arrays in a 60-year-old temperate mixed forest at Qingyuan Forest CERN in northeastern China.

3. In paired 108 m\(^2\) plots (\(n = 3\)), the surface soils were constantly elevated 2°C above control plots with a feedback control system over 4 years (2018–2021). Subsoils down to 60 cm depth were warmed 1.2–2°C. Soil warming did not significantly affect soil moisture either in surface soils or in subsoils. Turn-off time due to weather extremes (heavy rains, snow) and power outages only accounted for 2.5% of the total warming period.

4. In conclusion, we provide a proof-of-principle setup that allows long-term analysis of forest response to warming temperatures in large-size field plots. Importantly, our warming experiment demonstrated the feasibility of IR heater arrays for soil warming in tall-statured forest ecosystems.

**KEYWORDS**

feedback control, infrared heater array, open-field warming experiment, soil warming, temperate forest
Global soil organic carbon (SOC) storage is estimated at 3,000 Pg, whereas carbon storages in vegetation and the atmosphere are 750 Pg and 1,000 Pg, respectively (Köchy et al., 2015). Soil respiration is 98 Pg per year, 10 times that of anthropogenic CO₂ emissions (Bond-Lamberty & Thomson, 2010). Climate warming increases soil CO₂ efflux by increasing belowground carbon flux and enhancing SOC decomposition. Additional trophogenic CO₂ efflux by increasing belowground carbon flux and enhancing SOC decomposition.

Additional soil CO₂ release from warming-induced decomposition further enhances global climate change, presumably offsetting efforts to reduce anthropogenic CO₂ emissions. Forests harbour about 45% of the total terrestrial carbon (plant and soil), representing important feedback on future climate (Bonan, 2008; Jackson et al., 2017). In the last four decades, warming experiment has been the central focus of global change research and has deepened our understanding of how various ecosystem processes (soil microbial activity, carbon and nitrogen cycling) may respond to temperature increase (e.g. Melillo et al., 2017; Song et al., 2019; Woodward, 1992). However, our understanding of the mechanistic processes and consequential ecosystem-level impacts of warming on forests are still insufficient, likely due to the challenges and difficulties in conducting warming experiments in forests.

Multiple methods have been developed to acquire a more detailed understanding of ecosystem responses to climate warming. In general, these warming methods can be categorized as passive or active. Passive warming operates without external heat sources but uses enclosures of various kinds to slow down the relative heat loss (Marion et al., 1997), such as nighttime warming with curtains (Mikkelsen et al., 2007) and open-top chambers (OTCs; Li et al., 2021; Welshofer et al., 2018). Other passive warming methods include elevational gradients (Bragazza et al., 2016; Lie et al., 2021; Tarnocai et al., 2009) as well as geothermal gradients (O’Gorman et al., 2014; Sigurdsson et al., 2016). While field studies in remote areas may require passive methods, chamber-based methods create uneven temperature gradients, affect airflow and alter animal behaviours (Aronson & McNulty, 2009; Marion et al., 1997).

Alternatively, active warming methods promptly regulate the temperature difference between warmed and reference plots. Widely used active warming techniques include heating cables/rods, forced-air blowers and infrared lamps (IR heaters). These active warming methods have been applied to a range of ecosystems with diverse research focuses and restricted warming capacities (Aronson & McNulty, 2009; Ettinger et al., 2019; Rustad et al., 2001). Heating cables are commonly buried at shallow depths for belowground soil warming (Melillo et al., 2002; Peterjohn et al., 1993; Zhang et al., 2018). Recent whole soil warming experiments used heating rods to warm soils down to 100–120 cm depth (Hicks Pries et al., 2017; Nottingham et al., 2020). Although this heating cables/rods method maintain constant warming treatment, heavy ecosystem disturbances occur during installation. The burying of cables cuts off plant roots as well as affects below-ground biota, which may take several years to recover (Aronson & McNulty, 2009). Other experimental artefacts associated with soil cables include uneven warming between cable rows and altered water flow and percolation (Ettinger et al., 2019). Forced-air warming approaches were developed for use within open-top chambers (Norby et al., 1997; Pelini et al., 2011). An earlier study applied the forced-air warming for field application to tree seedlings in 7 m² old-field plots and achieved air warming of 3°C; however, only with a limited soil warming effect (1.2°C; Norby et al., 1997). Large enclosures (116 m²) were used in a peatland experiment in which forced-air warming was combined with buried cable/rod to maintain a wide range of above-ground and below-ground warming (+2.25 to +9°C; Hanson et al., 2011, 2017). Though notable warming treatments were achieved with forced-air warming, certain artefacts associated with the confined environment of enclosures, such as altered micrometeorology, limited free-air exchange and high cost, should be weighed (Aronson & McNulty, 2009; Kimball, 2011).

Warming with IR heaters is increasingly popular for climate experiments in open-field ecosystems (Aronson & McNulty, 2009; Dunne et al., 2003; Kimball, 2011; Kimball et al., 2018). IR heating simulates the natural warming by enhancing the downward infrared radiation, which then warms the vegetation and soils (Kimball, 2005; Wan et al., 2002). This approach disturbs the ecosystem only negligibly compared with other warming methods (Aronson & McNulty, 2009). IR heaters are often equipped with constant wattage mode, but can also be adjusted to achieve constant temperature offsets using a feedback control system. Harte et al. (1995) applied IR heaters with constant wattage across a montane meadow and achieved surface soil warming up to 3°C but inconsistent soil warming between daytime and nighttime was also observed. Nijs et al. (1996) introduced an IR system regulated with constant temperature mode and achieved moderate warming effects with less temperature variation. Subsequently, this system was further developed and applied to a tundra field with enhanced precision and reproducibility (Nijs et al., 2000). In several interesting studies, IR heaters with feedback control systems were developed and used by Kimball (2005, 2015), Kimball et al. (2008). Notably, they proposed an arrayed IR heater design for large-size plots with a potential up to 0.78 ha (Kimball et al., 2011). Recent field application of IR heater arrays (plot size ~10 m²) in a tropical forest showed promising results of maintaining a constant soil warming effect (Kimball et al., 2018).

The development and operation of active warming experiments require considerable investment and scientific resources. Although IR heaters require relatively high energy flow and operational costs, it is probably the most suitable method for conducting free-air warming experiments in open-field ecosystems. IR heating has already been applied in forest ecosystems (Jarvi & Burton, 2013; Teramoto et al., 2017). However, plot areas were relatively small (mostly <12 m²) except for one temperate forest soil warming experiment in the United States, with a plot size of 100 m² but without feedback control system (Figure 1; Table S3). Forest ecosystems are notoriously complicated, including heterogeneous understory and varying slopes, rendering large-scale warming necessary to overcome these challenges. Moreover, larger plots can eliminate edge effects.
(McHale et al., 1998), maintain warming better than smaller plots, as well as reduce energy losses from lateral transport (Hicks Pries et al., 2017). The immediate warming responses of ecosystems may differ from long-term (decades) responses, emphasizing the need for conducting longer term climate experiments (Elmendorf et al., 2012; Melillo et al., 2017; Menke et al., 2014; Reich et al., 2018). In addition, conducting larger and longer climate change manipulation experiments could overcome the challenge of scaling up the experimental findings in space and time (Ettinger et al., 2019). However, it remains a great challenge to conduct large-size and ecosystem-scale warming experiments, especially in tall-statured forest ecosystems (Templer et al., 2017).

Here, we present the design and performance of a temperature free-air controlled enhancement (T-FACE) system deployed over relatively large-size plots (108 m²) within a closed canopy and tall-statured forest. We employed IR heater arrays with a feedback control system to achieve a 2°C targeted warming in the top mineral soils. The experimental design addresses the potential for projected climate warming to alter the direction and magnitude of ecosystem carbon sink and ecosystem processes. To our knowledge, only two experiments of sufficient size have been attempted previously but both warmed by cables, with one in the Harvard Forest (Melillo et al., 2017) in North America and the other in Flakaliden Forest (Lim et al., 2018) in northern Sweden (also see Table S3). Our studied forest is situated in northeastern China, eastern part of Eurasian continent. This vast temperate forest plays a crucial role in the regional carbon budgets and global climatic system. Our study region is a climate-sensitive area that experienced rapid warming, with a 1.66°C increase in air temperature over the last six decades (Figure S1). There is an urgent need to explore the ecosystem responses to climate warming. However, no such field experiment has been conducted in East Asia so far (Figure 1). The primary goal of the warming experiment is to examine how and through what mechanisms tree growth and soil carbon cycling respond to warming. The objectives of this paper are to present the design and performance metrics and to assess the feasibility of IR heater arrays for warming large size plots in tall-statured forest ecosystems.

2 | MATERIALS AND METHODS

2.1 | Study site

The research site is located in the Qingyuan Forest CERN (Chinese Ecosystem Research Network), Liaoning Province, Northeastern China (41°51′N, 124°54′E). The site is characterized by a continental monsoon climate. Mean annual precipitation is 811 mm, with >80% of the precipitation distributed between May and September. Snowfall accounts for <6% of the annual precipitation. The mean annual temperature is 4.5°C. Daily mean extreme temperatures are −37.6°C to 36.5°C, with an annual frost-free period of approximately 130 days (Zhu et al., 2007). In the last six decades, this site has undergone an average increase in air temperature of 0.26°C per decade (Figure S1) and over thrice than the global surface average of 0.08°C (NOAA Annual 2020 Global Climate Report). The growing season spans from April to late September and snow cover lasts from late November to late March.

The forest site is located at 620 m above sea level with relatively gentle slopes ranging from 10 to 16°. Soils of this area were classified as Udalfs with clay loamy texture (sand: 17.2%, silt: 52.8%, clay:
30%). The site was occupied by primary broadleaves and Korean pines Pinus koraiensis before the 1930s, followed by decades of unregulated timber logging. In the early 1950s, controlled burns were practiced when clearing the remaining stands. Thereafter, the site was naturally regenerated to form the current closed canopy and mixed broadleaved and coniferous forest. The dominant tree species, Juglans mandshurica, Quercus mongolica and Larix kaempferi coexist in the canopy layer. The height of tree stands is 15–20 m with crown sizes ranging from 3 to 8 m. Sub-canopy layer includes Fraxinus rhynchophylla, Phellodendron amurense and Acer mono. Shrubs include Lonicera ruprechtiana, Euonymus phelloman o Loes, Rubus crataegifolius Bge, Corylus mandshurica Maxim and Euonymus alatus, and herbs include Potentilla afragarioides, Urtica laetevirens and Urtica laevivirens spp. Cyanescens. We performed a pre-treatment investigation in 2017, with those results showing that there were no prior differences in tree density and soil properties between plots (Tables S1 and S2).

2.2 | Experimental design and infrastructure

Six rectangular (18 m × 6 m) plots in a northwest-facing slope were designated in 2017, with a buffer zone of about 5–15 m between adjacent plots to avoid interferences between plots (Figure 2). These plots were placed within a pre-selected area of 1 ha of temperate mixed forest, with the layout and orientation of each plot based on the maximal number of dominant trees and the similarity of understory plants. Plots were assigned into three pairs according to their topography, with each pair containing a warmed (+2°C) and a control plot. Within each warming plot, rod-shaped infrared heaters (8 mm diameter × 151 cm long, 2,000 W, 240 V Model, HS-2420 from Kal glo Electronics Co. Inc.) with equilateral triangle housing were installed as the warming tool mimicking the natural climate warming process (Kimball, 2005; Kimball et al., 2011). The radiation from the infrared heater initially heats vegetation and soil surfaces, then the heat energy transfers deeper into the soil (Liang et al., 2017). To ensure uniform warming treatment within each plot, the IR heaters were placed in an arrayed manner, thus achieving the desired thermal radiation across the plots (Kimball et al., 2011). In all, 18 IR heaters were evenly distributed in each warming plot, into 6 × 3 rows and suspended 2 m above the ground (Figures 2 and 3).

To support the IR heater array, 24 stainless steel posts were anchored about 50 cm into the ground (Figure 3). Crossbars were then attached to the posts at a height of 2.3 m above the slope surface. The vertical posts and crossbars formed a durable structure that protects the IR heaters from strong winds, rain and snow, as well as falling branches. IR heaters were bolted to the crossbars along the 6 m side, providing an IR heaters array that stands parallel to the slope. The reference plots were set up in an identical manner, with 18 dummy heaters installed with the same shape and size as the IR heaters. Such structural control was set up to mimic any possible infrastructure effects of the IR system.

2.3 | Feedback control system

A feedback control system was used to achieve the target warming between warmed and control plots (Figure S2). The basic design of this control system consists of thermocouples (PT100), programmable logic controller (PLC) and power control units, and computing and operating system (Current/Power Output Module, Haiwell Happy, China). In each plot, six thermocouples were evenly distributed at 5 cm depth of mineral soils. Soil temperature of control and warmed plots is measured by thermocouples and transferred by the PLC placed inside the control plots or inside the junction box near the warmed plots. These readings are then transferred to the computing and operating system located inside the instrument shed, which then sends signals to the power control unit within the junction box. This signal then adjusts the output of heaters to maintain the 2°C temperature difference. Output power adjustment is operated at a precision of per second to maintain the temperature difference between warmed and control plots. Soil temperature is recorded every 5 min by computing and operating system. System debugging and initial testing were completed in 2017 and early 2018.

2.4 | Monitoring of soil temperature and soil moisture

Thermocouples in the feedback control system were used to continuously monitor the surface soil temperature at 5-min intervals. In each plot, 10 soil moisture probes (Computer Network Information Center, Chinese Academy of Sciences, Beijing, China) for surface soil measurement were evenly installed in 2018 at the 5 cm depth of mineral soil. To measure subsoil temperature and moisture, another set of probes (Campbell CS655 with data logger CR1000, Campbell Scientific) were installed at depths of 5, 10, 20, 30 and 40 cm at the centre of each plot and logged at 15-min intervals, with one probe for each soil layer of the plot. As a supplement, we deployed another set of temperature and moisture probes at 10–60 cm depths (WITU Agricultural Technology), with a 10-cm interval. Overall, we deployed 162 sensors at six plots and sensors were periodically recalibrated as needed. Subsoil measurements were initiated in 2019. To continuously monitor pre- and post-treatment effects of IR heating, the probes were running for 12 months a year.

2.5 | Power supply

Given the considerable amount of electricity required to maintain the IR warming system, it is critical to have a safe and stable power supply. Electricity was directly supplied by the national power grid (high voltage, 10 kV) and then delivered to a transformer located at the foot slope, approximately 200 m away from the research site (Figure 2a). The transformer delivers 380 V electricity to the master control unit inside the instrument shed. Electricity is then delivered to the IR heaters via the junction box adjacent to each warmed plot.
The power lines were installed above-ground to minimize the disturbance of soils and to ensure convenient maintenance. For the three warmed plots, the total maximum theoretical power usage is 108 kW; however, actual energy consumption varied depending on weather conditions and seasons. All the dataloggers and sensors are powered by 12 V outlets from the control unit. To ensure safety in the field, power surge protectors were installed, and all system units and infrastructures were grounded.

**FIGURE 2** Schematic diagram showing the layout of plots as well as the tree species at the warming experiment in the Qingyuan Forest Research Station (a). A single plot is 18 m × 6 m. Plots are numbered 1 to 6. (b) Schematic diagram showing the layout of a typical plot design. Trees with DBH > 10 cm were shown, with the number inside the circle denoting DBH. Chambers are set for soil-atmosphere gas exchange flux observations. Monitoring of seedlings, decomposition and biodiversity was performed in the designated areas.
2.6 | Warming duration

The IR warming system was designed to operate during the snow-free period to mimic the growing season warming projected in East Asia. Although warming in cold winter could have important implications on some ecological processes (Bronson et al., 2008; Templer et al., 2017), we chose not to warm in winter because of the relatively small proportion (<6%) of snowfall to annual precipitation in our site and the potential artefacts of IR heating on snowmelt processes and freeze/thaw cycles (Rich et al., 2015). In addition, we observed that in early winter snow cover also resulted in lower effective heating and high expense (see details in results and discussion). Thus, we designed to operate the IR heaters array from late March to early December. We started the warming in September 2018, and the first warming duration lasted for 69 days. In the years 2019 and 2020, we postponed the turn-on date due to system reprogramming, probe installation and examination of the downtime difference between warmed and control plots, resulting in shorter warming lengths (177 and 175 days, respectively). In the year 2021, we started the system as previously planned, achieving 253 days of operation.

2.7 | Data processing and statistical analysis

Although the control system and sensors were maintained periodically, sensor malfunction was inevitable and found in our field study. For example, the thermocouple fell down during the soil freeze and thaw period, or due to animal disturbances. In these cases, we removed temperature and moisture data based on very high or low values by comparing with the two standard deviations from the trimmed plot mean and replaced them with those trimmed plot means. From 2018 to 2021, the malfunction data accounted for 0.3% to 1.7% of hourly logged soil temperature and soil moisture. To calculate temperature and moisture differences, variables between warmed and control plots within each pair were subtracted and averaged. Next, the temperature and moisture differences in each pair were averaged to represent the warming effect. Before analysing the system performance, we tested the normality of all data using the Kolmogorov-Smirnov test and found that all data followed a normal distribution. A significance level of $p<0.05$ was used for data analysis. Statistical analysis was performed using R, version 4.1.0 (R Core Team, 2021).

3 | RESULTS AND DISCUSSION

3.1 | Effects on surface soil temperature and moisture

Overall, the IR heater array system achieved the desired warming target across 4 years of operation (Figure 4a). This IR system maintained the target warming between warmed and control plots ($2\pm0.1^\circ C$ in the top 10 cm of mineral soil except during heavy rains, power outages or snow. We concluded that this IR system is suitable for soil warming in a tall-statured temperate forest ecosystem. The tall trees provide a relatively calm environment (average wind speed in growing seasons <$0.2$ m/s) compared with grassland and cropland, which increased the efficiency of the IR system. Furthermore, at a 5-min scale, temperature elevation was very close to the $2^\circ C$ warming target (Figure S4). Daily surface soil temperature in the control plots varied seasonally, ranging from $-8.5$ to $-5^\circ C$ in February and up to $23$–$25^\circ C$ in August. Seasonal surface soil temperature distributions in warming plots matched those of control plots from 2018 to 2021 (Figure 4a). Initial soil temperatures strongly affected the time needed to reach the warming target. Surface soil temperature in the warmed plots swiftly increased to $2^\circ C$ above the reference plots within 48 h of the start of heating (Figure 4a). Once the targeted warming was achieved, the IR system maintained that difference throughout the entire operation period. However, during the warming period of 2021, achieving a $2^\circ C$ elevation of surface soil temperature required 12 days of warming. This slow warming was largely due to the low air and soil temperature (<$0^\circ C$) when the warming began. Warming at the end or beginning of the growing season could alter the freeze and thaw cycles and have important implications, but more time and energy were required to achieve the warming target.

Diurnal and seasonal variations of the surface soil temperature difference between treatments were generally within $0.05^\circ C$ (Figures 4 and 8). Soil temperature was closer to the $2^\circ C$-warming target in the morning and below the target during midday (Figure 8), this slight cooling was probably caused by evapotranspiration from growing vegetation. This result was consistent with the warming experiments in both open- and closed-canopy forests (Rich et al., 2015). While consistent target warming can be easily achieved with high precision feedback control systems, reporting only the
The grey solid line in panel (a) denotes the temperature difference between warmed and control treatments (the warming effect), while the red dashed line denotes the 2°C warming target. Warming of 2°C was generally achieved except for a few downward spikes showing the system downtime. The grey line in panel (b) denotes the volumetric water content (VWC) difference between warmed and control treatment. All the values are the daily mean of three paired warmed and control plots. All the values are mean ± SE (n = 3).

Knowledge of the fine-scale warming variations, as shown here (Figure 8), should benefit future analysis of experimental results.

As discussed in a previous study, a rectangular array of heaters theoretically provides uniform warming effects across a zero-slope
rectangular plot (Kimball et al., 2011). FLIR (Forward Looking InfraRed) images of warmed and control plots from our study forest also showed that arrayed IR heaters produced uniform warming across the plot (Figure 6). This relatively uniform warming was partially due to the IR array being in parallel with the slopes (10–16°) at the warmed plots. Another factor contributing to the uniform warming was that the FLIR images were taken at the end of the growing season when understorey vegetation had little activity since there was few live foliage to dissipate the energy. In addition, the average height of understorey plants was 30 cm for grasses and 1.3 m for shrubs. Both vegetation canopy architecture and stomatal characteristics also influenced the radiation towards the soil surface. Although understorey vegetation varied across the forest site, the arrayed IR system consistently maintained the target temperature elevation (Figure 4a).

3.2 Effects on subsoil temperature and moisture

Soil temperature was also altered by warming in deep soils, and the warming magnitude declined with soil depth (Figure 5). We measured the soil temperature profiles (0–40 cm) using probes located at the plot centre. In 2019, the soil temperature difference between warmed and control plots stabilized close to 2°C at 10 cm, 20 cm, and 30 cm depths, after 72 days, 109 days and 137 days of warming, respectively. On average, the temperature increased by 1.9°C and 1.8°C at 10 cm and 20 cm depth, respectively. At 40 cm depth, the soil temperature difference averaged 1.5°C. In 2020, warming increased soil temperatures by 1.5°C at 10–30 cm depths, and 1.2°C at 40 cm depths. In 2021, warming raised soil temperature at 10–30 cm and 40 cm depths by 1.7°C and 1.6°C, respectively. The lower temperature increases with deeper soil depth demonstrated the attenuation of the IR heating and the strong heat holding capacity of the clay loam soils in the study site. It is noteworthy that during power outage periods, subsoils in warming plots could still maintain the elevated temperatures.

Soil moisture in the subsoils was lower and fluctuated less than those observed in the surface soils. Soil moisture in subsoils was less responsive to warming than surface soils, which agreed with other observations (Kimball et al., 2018). Deeper soils were wetter in the warmed plots than those in the control plots before the start of the heating. Nevertheless, after warming began, we observed both drying and wetting effects in deep soils in the warmed plots (Figure 5). The response of deep soil moisture to warming varied over the years; variable warming of deep soils could have caused this variability.

Subsoil warming is commonly achieved by heating rods inserted into soil profiles (Hanson et al., 2011; Nottingham et al., 2020; Rich et al., 2015). That method is efficient in warming the whole soil profile; however, that method is considerably disruptive to both
plants and soils. Here, we showed that IR heating arrays heated deep soil profiles in large size plots. To demonstrate the effectiveness of IR heaters on warming deep soils, we mapped out the temperature differences to 60 cm depth between warmed and control plots (Figure 7). Subsoils were warmed by 1.2–2 °C above the reference plots. Subsoils are expected to warm as quickly as surface soils (IPCC, 2013; Soong et al., 2020), emphasizing the importance of conducting warming experiments for both surface and subsoils. Together, our results strongly suggest that an IR array system is suitable for application in warming deep soils in large size plots.

3.3 Energy use and costs

Energy use of this IR heater array system varied both diurnally and seasonally (Figure 8). This IR array system required 1.6% more energy during daytime than nighttime. The daily energy consumption started to increase around 8–9 am and peaked at 4–6 pm, and then continue to decline during the night (Figure 8). The additional energy required during the daytime to maintain target warming was caused by higher evapotranspiration from vegetation, suggesting that energy usage in such experiments could perhaps be used to track the daily patterns of evapotranspiration. Precipitation significantly increased the energy use to maintain the temperature difference, emphasizing the influence of soil moisture on energy use (Figure S6).

The energy required to maintain this ecosystem-scale IR heater array system was relatively low. Measured power consumption in our study forest was about 83.3 W m\(^{-2}\) °C\(^{-1}\), 18% lower than an IR warming experiment in a tropical forest (Kimball et al., 2018). Moreover, IR warming experiments conducted in grasslands indicated that wind speed strongly affected power usage, with power consumption ranging from 210 to 235 W m\(^{-2}\) °C\(^{-1}\) (Kimball et al., 2008). The low power consumption in our forest warming site may be attributed to climatic conditions and to the larger size of the plots than in the above two studies. Together, our IR heater array system requires relatively small energy consumption while maintaining the warming

**FIGURE 7** Dynamics of the soil temperature response to warming along with the soil profile during 2019–2021. The red dotted lines show the start and end of warming.
effect. Thus, the IR system can be energy efficient as well as economically viable, and therefore suitable for large size and ecosystem-scale warming in temperate forests.

3.4 | Environmental challenges and limitations

Precipitation directly increases soil moisture and thus increases the energy required to achieve targeted warming levels (Ettinger et al., 2019). This influence on heating was also observed in this study. However, soil moisture varied more spatially and temporally than temperature. Although it is possible that soil moisture affects the performance of heating systems, our results showed that moderate precipitation (≤40 mm) minimally affected IR warming. Between August 11th and 17th in 2019, the site received a total of 128 mm rainfall, the system was still able to maintain the targeted temperature difference between warmed and control plots. However, prolonged rainfall led to IR system shutdowns, such as a 2-week shutdown caused by extreme rainfall between late August and early September in 2020 (Figure 4a). The system was also switched off during strong typhoons for safety. Snowfall also affected the warming performance of the IR system. The study site usually received the first snow in late November. Snow cover reflects IR radiation and dramatically affected warming effects, and measured temperature difference ranged from 0.1 to 2.6°C (Figure 4a). This variable warming effect suggested that linking soil processes directly to treatment-imposed warming will be more challenging in snowy seasons.

The main challenge for operating an active warming experiment under field conditions was a reliable power supply. To ensure a stable power supply, we installed a transformer near the site that directly supplied electricity from the power grid. As a result, the power-related downtime of our IR system was negligible. While surface soil temperature in the warmed plots immediately dropped when power was shut off, deep soils maintained warmer temperatures for several days. Once power was restored, the system rapidly regained the targeted heating in surface soils in a manner of hours (Figure 4a).

At the end of the growing season, litter may accumulate on the IR heaters and should be removed. In addition, the IR heater itself may require maintenance. For example, two of the IR heaters were replaced due to malfunction in 2020 and 2021. Overall, during the 4 years of operation, this robust IR array system performed well and enabled the collection of data that could be closely tied to the experimental temperature increases.

The major infrastructure effect of structural control for IR heaters is the shading of solar radiation. In our experiment, the calculated solar shading of IR heaters is only about 3.8% of the plot area. Because our site is in a close-canopy forest, the actual shading effect of IR heaters would be much lower relative to the calculated value. Moreover, this minimal infrastructure effect maybe not affect the interpretation of the warming effects (Kimball et al., 2018; Wall et al., 2011).

It is desirable to directly warm tall trees above the canopy to address the climate feedback of the entire forest ecosystem. However, due to logistical issues, we have chosen to place the heaters beneath the tree canopy to warm understorey plants and soils. Admittedly, deploying IR heaters under the canopy could miss some above-ground warming effects, such as direct effects on leaf

![Figure 8](image-url)
photosynthesis and respiration, and tree phenology. However, the solution and experience we reported herein can provide valuable information for designing the next generation warming experiments in tall-statured forest ecosystems.

4 | CONCLUSIONS

With the rapid progress of global warming, field-plot climate change experiments are crucial to determine how temperature increase may drive ecosystem responses to climate change. Here, we demonstrated that the IR heater array system for ecosystem-scale free-air warming experiments in a temperate forest is capable of providing consistent warming with minimal disturbance. Our ongoing, long-term warming experiment has provided and will continue to provide valuable data and opportunities to study the responses to warming of various biogeochemical processes of forest ecosystems. Moreover, our site offers opportunities for collaborations across broad research interests, including soil fauna and plant feedback on future climatic conditions. The experience from this study should facilitate and improve the setting of the warming experiments in forests worldwide, enabling a comparison between results from different studies using a similar warming method.

AUTHORS’ CONTRIBUTIONS

Y.F. and D.L. designed the study; Y.D., D.L., K.H. and W.S. designed the field study operations; Data analysis was conducted by Y.D., D.L., K.H. and Y.F.; Y.D., D.L. and Y.F. wrote the paper, and other co-authors contributed to improving it; Y.D. and D.L. have equally contributed to this work. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data relating to the current study are available in the Dryad Digital Repository https://doi.org/10.5061/dryad.z34tpggp (Duan et al., 2022).

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