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Portable heaters for microhabitat heating experiments

Christina S. Baer[1] | **Diego Dierick**[2] | **Carlos Garcia-Robledo**[1,3]

[1]Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT, USA
[2]La Selva Biological Station, Organization for Tropical Studies, San Pedro Montes de Oca, Costa Rica
[3]Laboratory of Interactions and Global Change, University of Connecticut, Storrs, CT, USA

Correspondence
Christina S. Baer
Email: christina.baer@uconn.edu

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Abstract

1. Global warming will likely cause more ecological change by altering how species interact with each other than by directly affecting individual species. Field heating experiments are essential to test how warming will change species interactions. However, such experiments pose many logistical challenges, including heater construction and accuracy and accessing necessary infrastructure.
2. To facilitate these experiments, we developed portable active heaters suitable for heating microhabitats and sites of species interactions. We validated heater performance using two different target microhabitats: rolled leaf refugia and aquatic microcosms.
3. Using plastic mesh, resistive heating wire and an Arduino UNO microcontroller system with a custom shield, we built adjustable heaters that can dynamically heat small targets to at least 5°C above ambient temperature. Leaf target systems were heated with mean absolute errors (MAE) of 0.40–1.06°C. Water target systems were heated with MAE of 0.02–0.04°C.
4. These heaters can be customized to accurately heat a wide range of target sites (leaves, flowers, nests, small pools of water, etc.), many of which cannot be easily heated with traditional heaters. They can be easily constructed and require less field site infrastructure than many active heaters. These heaters' adjustability and portability mean that they can help test the effects of global warming in many situations, particularly in remote and lightly developed areas.

KEYWORDS
climate change, experimental warming, global change ecology, global warming, microhabitats, species interactions

1 | INTRODUCTION

Global warming will affect ecosystems in many ways, but more of its effects are expected to result from complex changes in biotic and abiotic interactions rather than the direct effects of temperature alone (Berg et al., 2010; Cahill et al., 2013; Urban et al., 2016). Field heating experiments have provided many insights into the effects of warmer temperatures on other abiotic factors, species interactions or combinations of both for over 20 years (Aronson & McNulty, 2009; Ettinger et al., 2019). Experimental designs vary, but generally involve heating regularly shaped microcosms or mesocosms using passive or active heating. Passive heating does not require electricity but can cause large unplanned variations in temperature and other abiotic conditions (Aronson & McNulty, 2009). Active heating provides more controlled heating and is less likely to inadvertently affect other abiotic conditions. However, it requires electrical inputs, often from established power grids or generators. Given these constraints, few field heating experiments have been performed in remote, lightly developed and/or tropical areas (Aronson & McNulty, 2009; but see Slot et al., 2014). This is unfortunate, as many questions and decisions regarding global warming are particularly concerned with its effects on remote, lightly developed and tropical ecosystems.

During our research on how global warming will affect tropical plant–insect interactions, we realized that the complex effects of warming can be addressed by individually heating structures and microhabitats that are centres of species interactions. These interaction sites include nests, shelters and other microhabitats, leaves and flowers, or transient resource patches such as fallen fruits, dead wood and carrion. Heating these sites can efficiently test how future warming will affect many types of species interactions, including ecosystem engineering, trophic interactions, competition, pollination and decomposition.

To heat individual microhabitats and interaction sites, we have developed a portable microhabitat heater. The control system provides dynamic active heating and can be plugged into an electrical outlet or powered from batteries. The heater itself consists of wire attached to flexible mesh, allowing the heating surface to be tailored to the shape and size of the target microhabitat. The power output to each heater is regulated using a proportional-integral-derivative (PID) control algorithm which uses estimated past, present and future errors to keep a system near a target value (Åström, 2002; Åström & Murray, 2010). The dynamic behaviour of a PID control loop can be optimized for a particular system by adjusting its parameter values. This is particularly useful for microhabitat heaters, as different microhabitats will have different dimensions and specific heats and thus different thermal inertias. For instance, flowers and leaves will have low thermal inertia because they have low densities and large surface areas relative to their volume. By contrast, dense, compact targets such as water, soil or wood will have higher thermal inertia. We demonstrate the heaters' effectiveness by using them to heat both low- and high-inertia microhabitats (rolled leaf refugia and aquatic microcosms).

2 | MATERIALS AND METHODS

2.1 | Heater control system design and construction

We designed and built a heater control system that could independently regulate the power delivered to up to four heater units. The control system's weatherproof enclosure housed a 24 V DC power supply, an Arduino UNO microcontroller with a custom heater control shield, a cooling fan and a liquid crystal display (LCD). The main elements on the heater control shield were a real-time clock for timekeeping, an SD slot to allow data storage, switching components to control the heaters and connections for temperature sensors and heaters. The control system read the external temperature sensors (ambient plus four habitats), adjusted the output power to each heater and recorded the measured temperatures and output power for each heater unit on the SD card at 1-min intervals (Figures 1 and 2a).

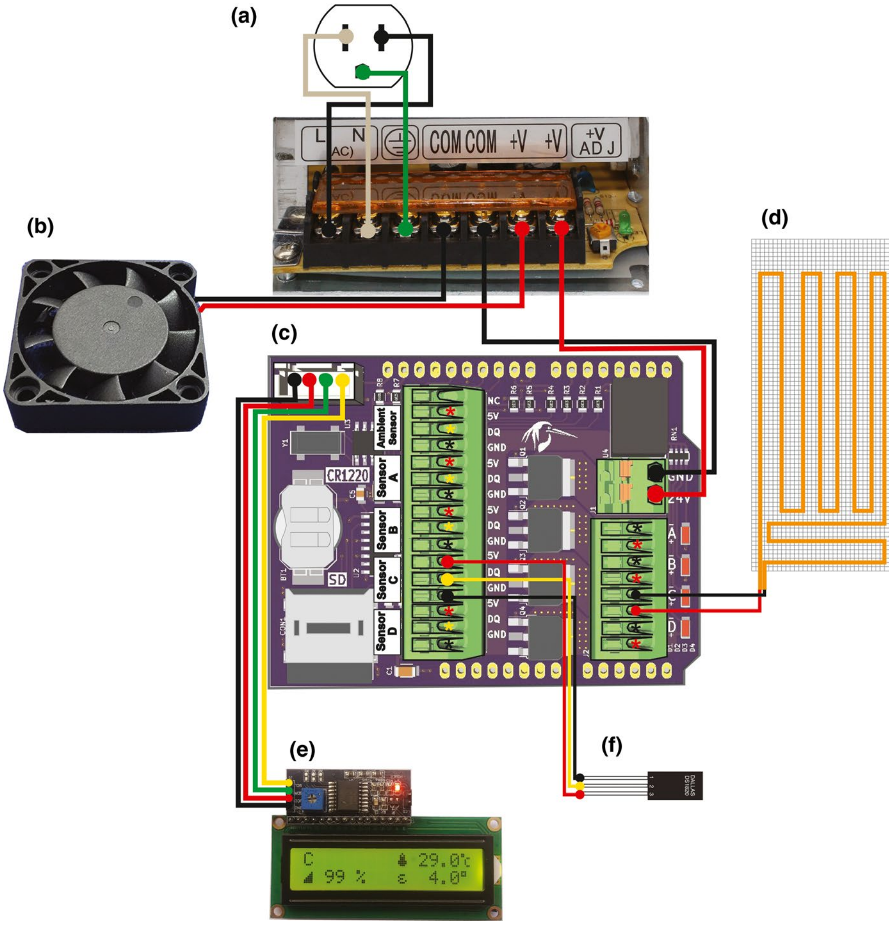

FIGURE 1 Heater control system wiring diagram. Components not shown to scale. (a) Mains powered 24 V DC (8 A) power source. (b) Cooling fan. (c) Custom heater control shield stacked on Arduino UNO (not pictured) with connections for an LCD, temperature sensors and heater units. Only one heater–sensor pair is shown (ambient temperature sensor not shown). Asterisks indicate wiring for additional units. (d) Heating unit with constantan wire (orange) mounted on plastic mesh. (e) LCD with I2C backpack. Display shows sample data for one heater unit: Measured temperature is 29°C, which is 4°C from the target temperature. The heater is receiving 99% of maximum power. (f) DS1820 temperature sensor

FIGURE 2 Heater implementation. (a) Heater control box, containing a DC power source (1), LCD (2), air outlet (3), heater control shield and Arduino UNO microcontroller board (4), air intake with fan (5). See Figure 1 for control shield wiring details. (b) Heater (powered by the blue wire) with temperature sensor (grey wire) on a rolled leaf. This image is a composite of a photo and digital drawings, as the leaf inside the heater and the temperature sensor wire are otherwise very difficult to see. (c) Heating 2-L aquatic microcosms in an ambient laboratory. Heater screens (grey) are wrapped around plastic containers and insulated with a layer of bubble wrap. The control microcosm is on the far left

Each heater unit was constructed by weaving 5.8 m of 24 AWG (American wire gauge) insulated constantan (a copper–nickel alloy) wire harvested from thermocouple extension wire onto 80 cm × 33 cm rectangles of fine plastic window screen mesh. With a supply voltage of 24 V DC, this results in a maximum power of 44 W for each heater. By adjusting the supply voltage and heater wire cross-section and length, this maximum power can be adjusted to heat targets with various sizes and thermal properties. For the rolled leaf refugia, each heater was secured around a rolled leaf in the form of a narrow, open-ended cone (Figure 2b). For the aquatic microcosms, the heater was wrapped around the microcosm and insulated with bubble wrap to minimize heat loss (Figure 2c). Detailed instructions for constructing both the heaters and control system, as well as the control program, are available in a GitHub repository (https://github.com/diegodierick/Heater-shield). A heater controller and four heaters cost approximately $180 USD, not including tools and basic supplies such as solder (see repository for an itemized list). If assembled heater control shields are used, only basic soldering skills are required. More soldering experience is necessary to assemble the shield components.

2.2 | Heater validation

Our validation trials took place at La Selva Biological Station in Costa Rica. We tested the heaters on two microhabitats with different thermal inertias due to their physical properties. For a low-inertia microhabitat, we chose the unfurling rolled leaves of Zingiberales plants (the order containing gingers and bananas). These rolled leaves form open-ended cylinders that serve as refugia for a wide variety of invertebrates (Darby & Chaboo, 2015; Staines & García-Robledo, 2014) engaged in herbivory, predation and parasitism. Specifically, we used *Pleiostachyia pruinosa* (Marantaceae) plants growing in open areas and directly exposed to sun and rain. The temperature in all four low-inertia microhabitats was raised to 5°C above the ambient temperature. For our high-inertia microhabitat trials, we used 2-L plastic containers filled with 1.7 L of water. These aquatic microcosms are similar in volume to microhabitats such as water-collecting tree cavities and tank bromeliads. Temperatures in these microhabitats were raised to 2, 3, 4 and 5°C above the ambient temperature.

In each instance, we wrapped heaters around four microhabitats and placed temperature sensors inside. Heaters around aquatic microcosms were then wrapped in bubble wrap to minimize heat loss to the surroundings. A control system with four heaters raised the temperature in each set of microhabitat for 3 days. To assess heater precision, ambient and habitat temperatures were recorded every minute (Baer, Dierick, & Garcia-Robledo, 2020). After the heaters stabilized, habitat temperatures were compared to the ambient temperature using linear models. We also calculated the MAE from the target temperature. The presented errors are based on system measurements and thus do not reflect the sensor error (up to ±0.5°C). To assess power use, the percent power used by each heater was recorded every minute.

3 | RESULTS

TABLE 1 Linear model estimates for heater performance with rolled leaves. All four heaters were programmed to heat their leaves 5°C above the ambient temperature

	Estimate	MAE (°C)	*t*	*p*
Slope	1.0746	–	386.89	$<2 \times 10^{-16}$
+5°C A *y*-intercept	4.4007	0.824	230.59	$<2 \times 10^{-16}$
+5°C B *y*-intercept	4.8682	0.402	255.09	$<2 \times 10^{-16}$
+5°C C *y*-intercept	4.2138	1.062	220.80	$<2 \times 10^{-16}$
+5°C D *y*-intercept	4.8496	0.558	254.11	$<2 \times 10^{-16}$

Abbreviation: MAE, mean absolute error.

TABLE 2 Linear model estimates for heater performance with aquatic microcosms. Each heater was programmed to heat its microcosm to a different amount (2–5°C) above the ambient temperature

	Estimate	MAE	*t*	*p*
Slope	0.9997	–	3,808.7	$<2 \times 10^{-16}$
+2°C *y*-intercept	1.9992	0.0364	1,800.7	$<2 \times 10^{-16}$
+3°C *y*-intercept	3.0000	0.0372	2,702.1	$<2 \times 10^{-16}$
+4°C *y*-intercept	4.0002	0.0276	3,602.9	$<2 \times 10^{-16}$
+5°C *y*-intercept	4.9993	0.0266	4,502.8	$<2 \times 10^{-16}$

Abbreviation: MAE, mean absolute error.

After the heating systems stabilized, both the low-inertia rolled leaves and the high-inertia aquatic microcosms followed changes in the ambient temperature (Figure 3). As expected, the rolled leaves (Figure 3a) experienced much larger and faster temperature changes than the aquatic microcosms (Figure 3b). Heating the low-inertia rolled leaves during rainfall was difficult (Figure 3a), but the heaters still followed the ambient temperature fairly closely (Figure 3c, Adjusted R^2 = 0.92, see Table 1 for all statistics). The high-inertia aquatic microcosms followed the ambient temperature even more closely (Figure 3d, Adjusted $R^2 \geq 0.99$, see Table 2 for all statistics). MAE was 0.40–1.06°C for the leaf microhabitats and 0.026–0.037°C for the aquatic microcosms.

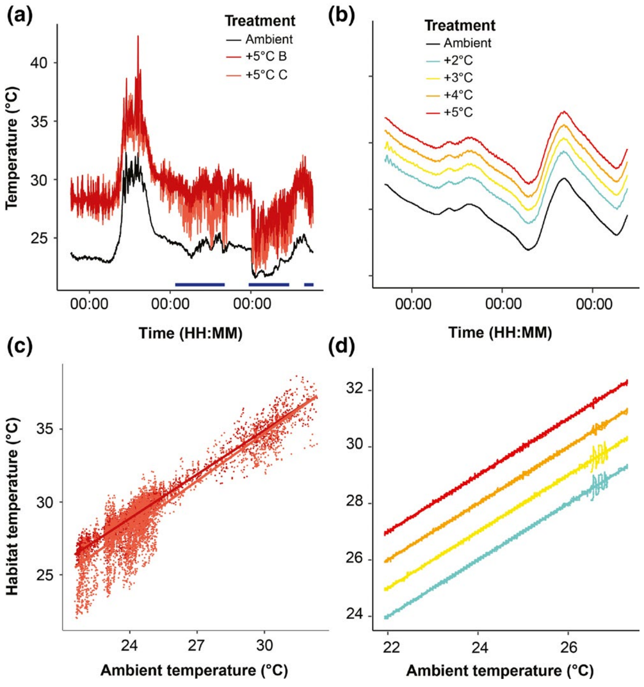

FIGURE 3 Heating performance for microhabitats with low thermal and high thermal inertia. (a) Temperatures for low-inertia rolled leaves heated to 5°C above ambient temperatures for 3 days. To prevent clutter, only the heaters with the lowest (Heater B) and highest (Heater C) mean absolute errors (MAE) are shown. Blue bars indicate rainfall. (b) Temperatures for high-inertia aquatic microcosms heated to 2, 3, 4 and 5°C above ambient temperatures for 3 days. (c) Correlations between temperatures inside heated leaves and the ambient air temperature. To prevent clutter, only the heaters with the lowest and highest MAEs are shown. Adjusted R^2 = 0.92. (d) Correlations between temperatures inside heated microcosms and the ambient water temperature. Adjusted R^2 = 0.99

Mean (±*SE*) heater power use varied by target and treatment. It ranged from 5.0 ± 0.164 W for the +2°C aquatic microcosm heater to an average of 24.4 ± 3.31 W for the +5°C leaf heaters. Running an array of forty heaters at one temperature for 28 days at La Selva Biological Station would require between 134 kWh (+2°C aquatic microcosm heating) and 654 kWh (+5°C leaf heating).

4 | DISCUSSION

These heaters are portable, accurate, easily built and ideal for experimentally heating small but ecologically important structures and processes. These can range from leaves and flowers to nests and other animal-built structures. Some densely packed plant and invertebrate targets can be studied effectively within heating plots (e.g. 5 m diameter enclosures, Diamond et al., 2016; Marchin, Dunn, & Hoffmann, 2014; Pelini et al., 2011). However, many plants and invertebrates, and nearly all vertebrates, occur at natural densities too low to be well-sampled in heating plots. In cases of less common species, transient resources and many animal-built structures, the ability to heat individual targets wherever they occur will be particularly useful. In structurally complex ecosystems such as forests, target microhabitats may also occur at heights or positions inconvenient for large plot heaters. Plot heater systems generally heat the first metre of air above ground level. While whole-tree heating systems exist (Crous et al., 2013), they require substantial infrastructure and completely enclose the tree. To study the interactions between warming and herbivores, pollinators or frugivores on plants taller than 1 m, it will be more effective to heat individual targets than to attempt to heat the entire plant.

These heaters can be customized to meet various research needs. First, the shape and size of the heaters themselves can be changed to accommodate different targets. The heaters we built can surround up to 15 L of space, although actual heating capacity will vary with the target's thermal properties. Smaller cylindrical heaters could heat flowers or leaf rolls built by caterpillars and other insects. Flat heaters could heat fully expanded leaves, insect-built structures that are primarily flat (e.g. leaf mines), nest and burrow interiors or patches of ground. Depending on target size, thermal properties and the power required for the heating treatment, the heaters' maximum power can be adjusted by changing the diameter and length of the constantan wire. When small, low power heaters are desired, users may also use commercially available heating components, such as silicone heat mats or heat tape. Regardless of heater type, experimental designs should include a control treatment of non-functional heaters and/or measure any other abiotic properties of interest. In our work, we place plastic mesh cylinders around control rolled leaves to simulate the heater mesh's effects on rainfall, air flow and insect movement. If air flow through the heater is not important, users can also insulate the outer surface of the heater, as we did for our aquatic microcosms.

Second, these types of changes will likely require users to adjust the parameters for PID algorithm that controls the heaters. Our control code uses PID parameters optimized for our microhabitats and heater configuration, and other targets or heater configurations will likely require different parameters. There are various methods for optimizing or ‘tuning’ PID parameters, but regardless of which is used, pilot tests should ensure that the heating system reaches the targeted temperature increases. For instance, our rolled leaf heating trial indicates that these heaters may not be able to maintain 5°C of heating when low-inertia microhabitats are also exposed to cooling conditions such as steady rainfall. The system should also stabilize near the target, rather than oscillating around it (Åström, 2002; Åström & Murray, 2010). Our systems took up to 3 hr to stabilize, which we consider acceptable for experiments lasting a week or more. The aquatic microcosm heating trial demonstrates that multiple heating treatments with 1°C intervals are achievable for high-inertia targets, considering the MAEs for the control system and a 0.5°C sensor error. Regardless of the heating treatments, users may prefer to analyse experimental results using the mean temperature increase for each replicate as a continuous variable rather than using categorical treatment levels (Ettinger et al., 2019).

Third, users may wish to make more substantial changes to the system. For instance, the control code could be modified to heat habitats to a fixed temperature, if that temperature will always be above the ambient temperature. Changes could also allow the control system to provide different daytime and night-time heating treatments. This could be done either by incorporating the system time into the control program or by making larger changes to incorporate data from a light sensor. In some study systems, it may be necessary to consider relative humidity, as drying is one of the most common side effects of experimental warming regardless of method (Ettinger et al., 2019). For instance, 100% relative humidity in a sealed container at 20°C will drop to 75% relative humidity at 25°C if no liquid water is available. In field conditions, this may be partly counteracted by transpiration, evaporation or a net movement of water vapour into the heated area from unheated air, so actual relative humidity may vary. The extent of drying and whether it is likely to be biologically relevant will need to be considered by users on a case by case basis. Users might wish to use combined temperature and humidity sensors in place of temperature sensors. Similarly, while we have envisioned these heaters as being powered by electrical grids or batteries, solar panels could be added for long-term operation in environments with little cover, such as deserts or grasslands.

These heaters will be a useful tool for researchers interested in the effects of global warming on localized interactions including herbivory, pollination, fruit development and dispersal. They will also be useful for studying community processes in small microhabitats such as plant structures, shelters built by animals or resource patches like logs or carrion. Additionally, they provide accurate active heating while requiring less time, money and infrastructure than traditional active heating plots. They will allow researchers to perform a wider range of heating experiments to understand how global warming will alter species interactions in ecosystems world-wide.

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AUTHORS' CONTRIBUTIONS

C.G.-R., D.D. and C.S.B. conceived the idea; C.G.-R. and C.S.B. secured funding; C.S.B. and D.D. designed the methodology and collected the data; C.S.B. led the writing of the manuscript and D.D. assembled the GitHub repository materials. All authors contributed to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The validation test data and analysis code are archived in the Dryad Digital Repository: https://doi.org/10.5061/dryad.c2fqz614d (Baer et al., 2020). Control code for the heaters and detailed instructions for constructing them are archived at https://doi.org/10.5281/zenodo.3660783 (Dierick, 2020).

ORCID

Christina S. Baer https://orcid.org/0000-0001-6294-6780
Diego Dierick https://orcid.org/0000-0002-4854-3819
Carlos Garcia-Robledo https://orcid.org/0000-0002-5112-4332

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