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Bat Box Design Affects Microclimate And Suitability As Habitat

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BAT BOX DESIGN AFFECTS MICROCLIMATE AND SUITABILITY AS HABITAT

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by

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ABSTRACT

Bats that roost in cavities and crevices are vulnerable to deforestation and habitat loss. Bat boxes can serve as alternate roosts for tree-dependent bat species, but we know little about how box design affects internal microclimate. If a box gets too hot (> 45°C), it can become an ecological trap. We assessed microclimate in 20 different box designs, using data loggers to measure internal temperatures in each box installed at a 20 ha site in Vigo County, Indiana (20 May–15 September 2018). We evaluated maximum (T_{max}), minimum (T_{min}), stability, and instantaneous temperature ranges and proportion of suitable space. The average temperature across all boxes was 25.9°C (range 25.1–26.8°C). Maximum and minimum temperatures recorded by data loggers were 54°C and 11°C, respectively. Changes to box height, which also increased volume, produced the greatest differences in T_{max}, T_{min}, and instantaneous temperature ranges. The short box was cooler and more stable than longer boxes, but longer boxes offered the greatest instantaneous range of temperatures. Slight modifications, like removing vents and adding a chimney dramatically altered box temperatures. Major alterations, like adding internal or external water chambers, stabilized temperatures, but further testing of these designs in more extreme weather conditions is required. Also, studies should examine metabolic heat production of bats, which may be retained more in some designs than others. Based on this study, we recommend careful consideration of bat box designs, as the top-most layer of many designs can reach lethal temperatures. Thus, usable space within a box may be restricted by high temperatures.

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CHAPTER 1

BAT BOX DESIGN AFFECTS MICROCLIMATE AND SUITABILITY AS BAT HABITAT

LIST OF TERMS

Availability	Mean hourly temperature (max – min) range in a box on a given day as recorded by temperature data loggers (9–12/roost)
Chamber	The cavity space where bats roost within a bat box
Hourly availability	The range of temperatures (max-min) in a box on any given hour as recorded by temperature data loggers (9–12/roost)
Observation	An hourly value recorded by an iButton temperature data logger
Rocket box	Two-chambered, four-sided, two-vent rocket box
Suitable temperature	Temperature between 15–40°C
T_{lethal}	Temperature ≥ 45°C
T_{max}	Maximum box temperature
T_{min}	Minimum box temperature
Δ T	Box temperature – air temperature
Unsuitable temperature	Temperature < 15°C or > 40°C
Variability	The maximum range of temperatures (max – min) in a box on a given day as recorded by temperature data loggers (9–12/roost)

Introduction

Cavities and crevices serve as potential roost or nest sites for many fauna, but the availability of such roosts is limited by habitat loss and a paucity of old growth forest. Some bat species (order Chiroptera) are especially reliant on cavities and crevices for roosts. Kunz and Lumsden (2003) estimated that > 50% of the ~ 1,300 bat species worldwide use plants, either exclusively or situationally, as roosts. Cavity and crevice dwelling bats in particular rely heavily on trees as natural roosts. More specifically, bats often use large dead trees in which cavity formation is more common when compared to younger live trees (Bennett et al. 1994; Kunz and Lumsden 2003). Some bat species depend on large, solar-exposed trees that are more frequently found in old forests (Britzke et al. 2003; Johnson et al. 2009; Vonhof and Barclay 1996). However, forest loss (Kunz and Lumsden 2003) and lack of mature forests restricts natural roost recruitment (Cline et al. 1980). Where natural roosts are limited, artificial roosts (bat boxes) may serve as surrogates to promote bat conservation.

Bat boxes are potential alternative roosts for bat species that rely heavily on natural cavity roosts, though bat box use has seen mixed results depending on species' preferences. In northeast England, for example, bat boxes are readily used by *Plecotus*, *Myotis*, and *Pipistrellus* bat species in areas of marginal habitat (Meddings et al. 2011). Zeale et al. (2016) used bat boxes paired with ultrasound speakers and artificial lighting to effectively relocate Natterer's bats (*M. nattereri*) from churches in Norfolk, England. Importantly, bat boxes are used as alternative roosting structures by maternity colonies of various bat species in different parts of the world (Hoeh et al. 2018; Kerth et al. 2006; Park et al. 1998; Siemers et al. 1999). For example, in Pennsylvania, Brittingham and Williams (2000) documented a little brown bat (*M. lucifugus*) maternity colony and a big brown bat (*Eptesicus fuscus*) maternity colony transitioning into bat boxes after exclusion from buildings. However, bat boxes are not always a suitable alternative to natural roosts. Some species will not occupy artificial roosts and opt to abandon a roost site lacking suitable natural roosts rather than inhabit a bat box (Neilson and Fenton 1994).

Roost microclimate is an important consideration when designing and installing alternatives to natural roosts. Bats often use multiple roosts in a season and frequently switch between those roosts to find microclimate conditions that meet their energetic demands (Lewis 1995; Vonhof and Barclay 1996). The following factors are important for artificial roost adoption: roost mount location (Flaquer et al. 2006; White 2004), height (Neilson and Fenton 1994), aspect (Brittingham and Williams 2000; Mering and Chambers 2014), roost materials (Whitaker et al. 2006), landing area size and nature of the surrounding area (White 2004), and internal microclimate (Brittingham and Williams 2000; Hoeh et al. 2018; Lourenço and Palmeirim 2004; Neilson and Fenton 1994). Microclimate features such as temperature and humidity may be especially important for daily roost selection because these factors affect energy budgets and neonatal growth rates (Hoying and Kunz 1998; Racey and Swift 1981; Zahn 1999). Bats prefer artificial roosts with a wide range of temperatures (Brittingham and Williams 2000; Lourenço and Palmeirim 2004) and generally will not use cooler roosts (Hoeh et al. 2018; Neilson and Fenton 1994). However, it is important to note that cooler roosts may actually facilitate energy savings in lactating and post-lactating bats by enabling them to readily enter torpor while day roosting (Bergeson 2017; Dzal and Brigham 2013).

Bat boxes come in a variety of designs that presumably influence their thermal properties, but few studies have assessed the impact of box design on microclimate. Some designs like the standard flat-faced, multi-chambered roost or artificial bark mimics may get too hot or too cold (Brittingham and Williams 2000; Hoeh et al. 2018; Lourenço and Palmeirim 2004), making them less desirable as roosts. For example, bats actively avoid sections of flat-faced roosts with temperatures > 40°C (Brittingham and Williams 2000; Lourenço and Palmeirim 2004), which suggests that these temperatures are too hot. In a study where internal temperatures were measured in flat-faced bat boxes, bats preferred warm boxes (< 40°C) with high solar exposure (≥ 7 hours of sunlight; Brittingham and Williams 2000). Commonly implemented artificial roost designs do not effectively buffer cold temperatures (Hoeh et al. 2018; Rueegger 2016). Modifications such as heat mats may prevent temperatures from dropping below the optimal range (Wilcox and Willis 2016; Zeale et al. 2016), but this would require electricity and could become a fire hazard. Bats using artificial roosts are most likely to experience “too cool” temperatures in spring and “too hot” temperatures in summer, but temperatures inside an artificial roost can fluctuate by as much as 40 °C on a sunny day (Hoeh et al. 2018). Thus, bats may actually experience a wide range of conditions in one roost in a single day. To account for daily fluctuations in ambient temperature, bats may seek out roosts that provide a temperature gradient from hot to cool. For example, Hoeh et al. (2018) found that Indiana bats preferred the box type (of three provided) that offered the largest temperature gradient from top to bottom.

Current bat box designs are rarely suitable alternatives to natural roosts and require modifications (Kurta 2005; Rueegger 2016), this is why systematic comparisons of artificial roosts are important. However, systematic comparisons of multiple bat box designs are lacking. Existing work has compared only a few designs at a time (two designs, Brittingham and Williams 2000; two designs, Kerth et al. 2001; three designs, Hoeh et al. 2018) and only for short periods of time (three months, Brittingham and Williams 2000; 12 days, Kerth et al. 2001). Hoeh et al. (2018) was one of few studies to compare multiple artificial roost designs for greater than three months; Griffiths et al. (2017) also compared roosts, but did not focus exclusively on bat boxes. Existing comparisons include dramatically different designs with different internal volumes, roosting surface areas, and entrance areas (Hoeh et al. 2018; Neilson and Fenton 1994; Rueegger 2016). Griffiths et al. (2017), Lourenço and Palmeirim (2004), and Hoeh et al. (2018) are among the few studies that document roost microclimate. Lourenço and Palmeirim (2004) is also one of few published studies with baseline microclimate measurements taken in the absence of bats.

During April to September 2016, Hoeh et al. (2018) measured roost microclimate parameters (relative humidity and temperature) in three different bat roost types. Hoeh et al. (2018) found that the top layer of one roost design reach high temperatures (> 60°C) more frequently than others and that none of the roosts were able to effectively buffer cool temperatures (< 10°C). This indicates that bats would have to expend energy to remain thermally neutral during cold spells. This study showed that Indiana bats (*M. sodalis*) at a research site near Plainfield, Indiana, prefer rocket-style bat boxes and that this roost type provided the greatest range of temperatures among the types tested. However, Hoeh et al. (2018) compared roosts with dissimilar internal volume, roosting surface area, and entrance area. In addition, none of the roost types in the study were designed to buffer cool temperatures. We aimed to build upon these results by identifying structural alterations capable of buffering temperature changes while retaining a similar internal volume, roosting surface area, and entrance area.

Our goal was to determine the impact of relatively subtle and complex changes in bat box design on microclimate in the absence of bats and to develop bat box designs that could buffer against temperature fluctuations. Our first step was to design and build 20 bat boxes before deploying them at a study site in Vigo County, Indiana. Here, we characterize the temperature profile of a standard two-chambered rocket box, compare the temperature profiles of the 20 bat box designs we built, and assess the impact of air temperature (T_a), global radiation, and wind speed on microclimate in all 20 designs.

Methods

Study Area

Our study took place on a ~0.5 ha plot on private property in Vigo County, Indiana. This area is characterized by agriculture and rural housing. The study site was along a gravel road with agricultural fields to the north and south and strips of pine-hardwood forest 100 m and 70 m to the west and east, respectively (Figure 1A). This site offered high solar exposure with minimal shading and similar elevation angles to the tops of nearby trees. Mean maximum and minimum air temperatures (T_a) for this location between April and September were 27°C (range of 2–41°C) and 14°C (range of -5–27°C), respectively (2010–2018 dry bulb temperature data from NOAA weather station 10.5 km away). In addition, for April–September 2010–2018, the site received 24.9 cm of annual precipitation on average (range 15–29.9 cm), with a mean daily precipitation of 0.3 cm (range 0–7 cm).

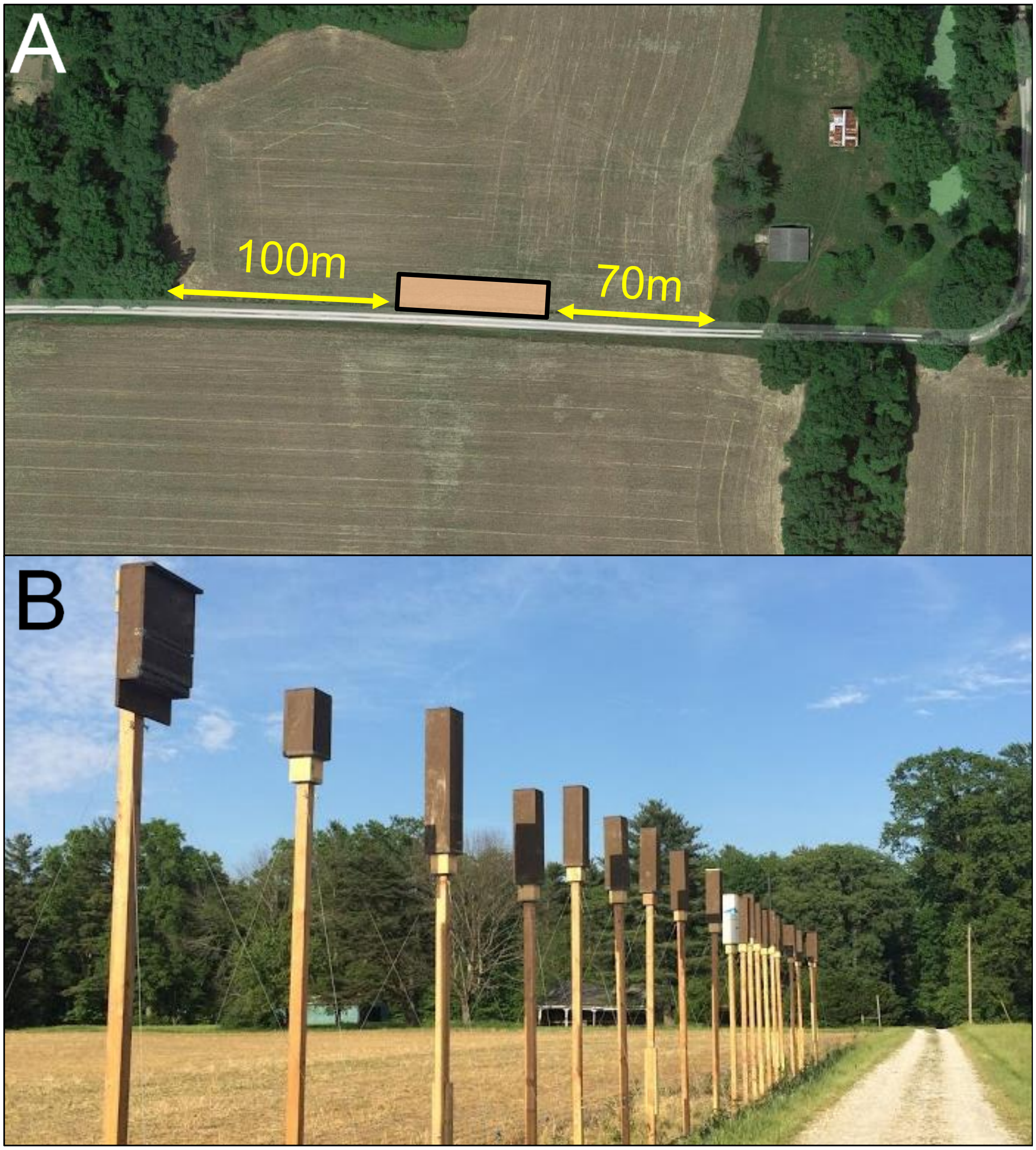

Figure 1. A) Study site where bat boxes were installed (orange rectangle) and B) twenty bat box designs arranged by box category, with the reference design near the middle in Vigo County, Indiana, May 2018–September 2018.

Artificial Roosts

Roost designs.

We built a single flat faced box design with three chambers, and 19 variations of a two-chambered rocket box design (Figure 1B) used by Hoeh et al. 2018. One of the rocket box designs was used as a reference. All other box designs were placed into one of three categories: designs that should reduce high temperatures, designs that should increase low temperatures, and designs that alter box volume (Table 1). Nine designs were meant to reduce maximum internal roost temperatures: chimney, double vent, house wrap, three internal cavity designs (empty, foam, and water), south roof shade, upper vent, and white gloss. Six designs were meant to increase minimum temperatures within a roost: composite, three external jacket designs (empty, foam, and water), opening wedge, and vent removal. Four designs altered box volume: long, short, three-chamber, and two-inch roof shade. We only built one of each design, devoting our resources to box modifications rather than replication of box designs. Each rocket-style box, except the three cavity designs, had the same internal structure and composition. In addition, we excluded bats from these boxes and installed them in an open location where there was no risk of incidental shading. Therefore, we assume differences in box microclimate are due to design modifications and not natural variation. As validation for this premise, when we compared designs with very slight modifications we noted very minor differences in microclimate.

Table 1. Box category and description of 20 bat boxes deployed in Vigo County, Indiana, May 2018–September 2018.

Box Category	Design	Acronym	Description
Control	Reference	std	A two chambered rocket box with two vents on opposite sides
Decrease T_{max}	Chimney	chim	A rocket box with a 0.9 m black pvc chimney (6.4 cm internal diameter)
	Double vent	dv	A rocket box with four vents, two on the north and south sides, respectively
	House wrap	hr	A rocket box wrapped in two layers of white, latticed house wrap
	South roof shade	srs	A rocket box with a 1.2 m x 0.6 m roof extending on the south side
	Upper vent	uv	A rocket box with vents 0.3 m from the top of the box
	White gloss	wg	A rocket box with a roof that was painted glossy white
	Empty cavity	ice	A rocket box with an empty 8.9 cm x 8.9 cm x 0.9 m chamber replacing the top 0.9 m of the post
	Foam cavity	icf	A rocket box with an 8.9 cm x 8.9 cm x 0.9 m foam filled chamber replacing the top 0.9 m of the post
	Water cavity	icw	A rocket box with an 8.9 cm x 8.9 cm x 0.9 m water filled chamber replacing the top 0.9 m of the post
Increase T_{min}	Composite	comp	A rocket box constructed out of composite decking material
	Empty jacket	eje	A rocket box surrounded by an empty wooden jacket
	Foam jacket	ejf	A rocket box surrounded by a foam filled wooden jacket
	Water jacket	ejw	A rocket box surrounded by a water filled wooden jacket
	Opening wedge	ow	A rocket box with a 1.3 cm wide chamber opening, as opposed to the usual 1.9 cm chamber opening
	Vent removal	vr	A rocket box without vents
Altered volume	Long	long	A 1.4 m tall rocket box
	Short	short	A 0.5 m tall rocket box without vents
	Three-chamber	tcb	A flat-faced, three chambered, birdhouse style roost
	Two-inch roof	two	A rocket box 1.9 cm wider on each side that also has a 5.1 cm roof overhang

Box construction.

We constructed the bat boxes out of ~2.54 cm thick untreated pinewood, with the exception of the composite material box design (made from ChoiceDek Wood-Polymer Composite Lumber Product; 45–55% wood dust, 43–47% polyethylene, 1.5–3% pigment, < 1% zinc borate, and < 1% carbon black) and three-chamber box (ACX exterior plywood). Plywood (1.9 cm thick) was used for roofs. The seams of each box were sealed with DAP paintable latex caulk with silicone (DAP Products Inc., Baltimore, MD) and we painted the outer shell of each box with two coats of flat exterior paint (medium brown).

We attached each bat box to an untreated wooden post (10.2 cm x 10.2 cm) with the top of each box at a height of ~4.9 meters. Each box/post was stabilized by 0.3 cm cable extended in three directions to 33 cm long soil anchors. Bats were excluded from roosts with 0.6 cm wire mesh that did not hinder air flow. We installed the artificial roosts in one row, oriented east–west, with two meters of separation between boxes. We placed the reference design near the middle of the box arrangement and all other designs were installed in groups, based on box category (Figure 2). We installed the boxes so that vents, if present, were oriented north to south to maximize temperature gradients.

Roost Comparison

To measure internal temperatures, we used thermochron, temperature-only iButton data loggers (DS1921G Thermochron iButton Device, Maxim Integrated, San Jose, CA) that measure 0.5°C increments, with an accuracy of ± 1°C between -30 and 70°C. We placed 12 iButtons in the outer chamber (the space habitable between each box layer) of each rocket-style box (nine iButtons in the three-chambered design) to measure temperature variability. Across each structure, we placed iButtons in three layers oriented vertically (top, middle, and bottom). Across layers, we placed iButtons facing four directions: north-, south-, east-, and west-facing. We only measured temperatures of the outer chamber due to a limited quantity of thermochrons and because other studies showed higher temperature stability in internal chambers (Brittingham and Williams 2000; Rueegger 2019), which heat more slowly and retain heat longer. To maximize storage space on iButtons, the iButtons were programmed to record temperature every two hours, with half of the iButtons recording during even hours and half of the iButtons recording during odd hours. The iButtons began recording at 0000 and 0100h, respectively, on 1 April, 2018. Recording did not overwrite, and thus we expected iButtons to stop recording with a full memory by 10 September 2018. We oriented all the iButtons the same way to record T_a in the outer chamber of each box. We assume temperatures recorded by iButtons are an accurate indicator of temperatures experienced by bats, but we recognize that the recorded temperatures may have been influenced by thermal radiation from nearby wood surfaces. We took down the boxes and retrieved all iButtons by 15 September 2018.

To measure T_a, we used shielded temperature data loggers (HOBO UA-002-64, Onset Computer Corporation, Bourne, MA), mounted on the south side of four bat box posts. These shielded loggers were placed in solar shields, 1.5 m above the ground, which did not hinder air flow. Two of these shielded loggers were installed at the east and west end roosts. Two more shielded loggers (UA-002-64) were located 6 m equidistant from the center point of the roost arrangement in the same fashion. To determine T_a of the study site, we averaged T_a values recorded by the shielded temperature data loggers.

We installed a weather station (CR10, Campbell Scientific, Logan, UT) on 23 May 2018 to measure wind speed and direction and solar radiation. Wind speed was measured via anemometers (Thornthwaite Model 901-LED sensitive cup anemometer, C. W. Thornthwaite

Associates, New Jersey) at the eastern and western ends of the artificial roost arrangement. Hourly wind speed was calculated by averaging wind speed values from the eastern and western anemometers. Due to a storm on 8 September 2018, the eastern anemometer was damaged and could no longer record wind speed. Wind speed values after 8 September 2018 are from the western anemometer only. Meanwhile, wind direction and solar radiation were measured in the center of the arrangement via one wind vane (Gill Microvane model 12302, R. M. Young Company, Traverse City, Michigan) and one Eppley (Eppley Laboratory, Inc., Newport, Rhode Island) black and white (model 8-48) pyranometer, respectively.

Microclimate Variables

To assess microclimate, we evaluated availability and variability as defined by Hoeh et al (2018). We measured daily (24-hour period) availability by calculating the daily mean instantaneous temperature range from hourly temperature readings. This range denotes the available hourly temperatures a bat could choose to occupy within a roost. We determined the variability of temperature within each roost by calculating the difference between daily maximum and minimum temperature measurements. We also determined suitable space, which represents the proportion of a box that remained within an upper (40°C) and lower (15°C) suitable temperature range. Bats must expend energy to remain torpid at temperatures < 10°C (Davis and Reite 1967; Neuweiler 2000; Wojciechowski et al. 2006), while temperatures ≥ 45°C prove deadly within an hour (O’Farrell and Studier 1970; Neuweiler 2000). Suitable space represents the torpor and lethal temperature thresholds of many bat species found in Indiana, with a 5°C buffer. However, we recognize that some bat species have a higher thermal preference (35–42°C; Bronrier et al. 1999). Suitable space was computed using measurements from the 9–12 iButtons in each box. Due to a limited amount of cool weather data, we characterized suitable space on cool days in the reference design only. For all other designs, we evaluated suitable space hot days only.

Data Analysis

We conducted all statistical analyses using R version 3.5.1 (R Core Team 2018). We utilized parametric statistics after assessing normality and homogeneity of variances. We evaluated significance at $p < 0.05$ and present means ± SE unless otherwise noted. Although mean values might conceal subtle differences in temperature, mean values may be important when assessing roost optimality (Huey 1991).

We used analysis of covariance (ANCOVA) to determine the response of daily temperature availability and variability values to the following predictor variables: box type, daily mean outside air temperature, range of daily outside air temperature, daily mean global radiation, and daily mean wind speed. We selected these predictor variables after removing highly correlated variables (Pearson's $r > 0.70$). We also tested for correlation between daily box temperature variability and daily T_a variability in the reference design (Pearson's $r > 0.70$). To characterize differences among box types, we simplified the initial models, with all main effects and their interactions to remove non-significant parameters (based on F values) and interactions not including box design (Hoeh et al. 2018). We present plots for significant interactions between predictor variables and box design, with regression lines for each box category and 95% confidence intervals.

Results

Weather

Throughout our study period (24 May–14 September 2018), air temperature (T_a) at the study site ranged from 11.6–35.4°C (mean of 23.8°C). Maximum daily (24-hour period) T_a was

> 32.2°C (equivalent of 90°F) on 29 different days. We did not observe freezing T_a at any point in our study. Daily precipitation averaged 0.04 cm and the maximum daily precipitation was 3.7 cm (precipitation data from a NOAA weather station 10.5 km away). Wind speeds, recorded by the on-site anemometers, ranged from 0–36.8 m/s (mean of 7.2 m/s) and only exceeded 30 m/s on one day (10 June 2018). Global radiation, recorded by the on-site pyranometer, ranged from 0–1126.3 W/m^2 (mean of 241.5 W/m^2). Maximum daily global radiation was > 1000 W/m^2 on 12 days and < 100 W/m^2 on one day.

Section 1: Reference design microclimate characterization

Temperature.

Temperatures inside the reference design ranged from 12–52°C (mean 26.2 ± 6.2°C) throughout the study period. The entire box never reached unsuitably hot temperatures ($T_{min} > 40°C$; Table 2), but we did see the entire box reach unsuitably cool temperatures on 5 of 113 days ($T_{max} < 15°C$; Table 3), and lethally hot temperatures (T_{lethal}; ≥ 45°C) on 20 days). The minimum temperature (T_{min}) averaged 18.9 ± 3.1°C (Table 2) and most frequently occurred near sunrise (mode was 0700 on 59 days), while the maximum daily temperature (T_{max}) averaged 39.6 ± 6.0°C (Table 3), frequently occurring in the early evening (mode was 1800 on 36 days).

Table 2. Daily (24-hour period) minimum mean ± SD (range) temperatures recorded in 20 bat box designs, where bats were excluded, in Vigo County, Indiana, 24 May 2018–14 September 2018.

Box Category	Design	Daily T_{min} (°C)	Days when daily box T_{min} > 40°C
Control	Reference	18.9 ± 3.1 (12.0–24.0)	0
Decrease T_{max}	White gloss	19.0 ± 3.2 (11.5–24.5)	0
	Upper vent	19.0 ± 3.1 (12.0–24.5)	0
	Chimney	19.0 ± 3.1 (12.0–24.0)	0
	Double vent	19.0 ± 3.1 (11.5–24.5)	0
	Water cavity	19.0 ± 3.1 (11.5–24.5)	0
	House wrap	18.9 ± 3.2 (11.5–24.0)	0
	South roof shade	18.9 ± 3.1 (11.5–24.0)	0
	Foam cavity	18.9 ± 3.1 (11.5–24.0)	0
	Empty cavity	18.7 ± 3.1 (11.0–24.0)	0
Increase T_{min}	Empty jacket	19.3 ± 3.0 (12.5–24.5)	0
	Opening wedge	19.2 ± 3.2 (12.0–24.5)	0
	Foam jacket	19.2 ± 2.9 (12.5–24.0)	0
	Water jacket	19.2 ± 2.9 (12.5–24.0)	0
	Vent removal	19.0 ± 3.1 (12.0–24.0)	0
	Composite	18.7 ± 3.1 (11.5–24.0)	0
Altered volume	Short	19.1 ± 3.1 (12.0–24.5)	0
	Long	19.0 ± 3.2 (11.5–24.5)	0
	Three chamber	19.0 ± 3.1 (12.0–24.0)	0
	Two inch roof	19.0 ± 3.0 (12.0–24.0)	0

Table 3. Daily (24-hour period) maximum mean ± SD (range) temperatures recorded in 20 bat box designs, where bats were excluded, in Vigo County, Indiana, 24 May 2018–14 September 2018.

Box Category	Design	Daily T_{max} (°C)	Days when daily box T_{max} < 15°C
Control	Reference	39.6 ± 6.0 (17.5–52.0)	5
Decrease T_{max}	Water cavity	39.7 ± 6.3 (16.5–52.5)	3
	Empty cavity	39.5 ± 6.2 (17.0–52.0)	8
	Foam cavity	39.2 ± 6.1 (17.0–51.5)	8
	Upper vent	37.2 ± 6.0 (16.5–52.0)	7
	White gloss	36.9 ± 5.6 (16.5–49.0)	7
	Double vent	36.0 ± 5.8 (16.5–50.5)	7
	South roof shade	35.6 ± 5.0 (17.0–45.0)	2
	Chimney	35.3 ± 4.9 (17.0–46.0)	7
	House wrap	34.1 ± 4.5 (17.0–43.0)	5
Increase T_{min}	Vent removal	42.1 ± 6.3 (17.5–53.5)	6
	Composite	40.8 ± 6.9 (16.5–54.0)	6
	Opening wedge	39.6 ± 6.3 (16.5–53.0)	4
	Empty jacket	37.1 ± 5.4 (17.5–48.0)	1
	Water jacket	36.2 ± 5.0 (17.5–47.0)	0
	Foam jacket	35.9 ± 5.1 (17.0–47.0)	0
Altered volume	Long	41.5 ± 6.2 (17.5–53.0)	3
	Two inch roof	36.4 ± 5.5 (16.5–50.5)	5
	Three chamber	35.7 ± 5.2 (16.5–44.5)	5
	Short	34.4 ± 5.0 (16.5–48.0)	8

For the reference design, mean ΔT (hourly box T_{max} – T_a) was generally low, averaging 2.5 ± 3.1°C; however, ΔT was sometimes negative or positive, ranging from -3.8–21.7°C and was related to height and aspect of the iButton. We observed 65% of negative ΔT values, when iButton temperature was lower than T_a, in the morning (0600–0900) and midday (1000–1300). Most (67%) of the negative ΔT values occurred in bottom layer iButtons and 27% occurred in middle layer iButtons. Of negative ΔT values recorded in bottom layer iButtons, only 11% were on the east side. A similar pattern was observed in middle layer iButtons (16% of observations on east side). In top layer iButtons, 66% of negative ΔT values were observed in the morning (0600–0900) and occurred most frequently (46%) on the west side.

Positive ΔT values, when iButton temperature exceeded T_a, occurred mainly in the evening (1800–2100) and early in the night (2200–0200), and generally in the top and middle layers (Figure 2). Top layer temperatures were hotter than T_a by an average of 4.5 ± 3.6°C; middle layer temperatures were also warmer, but only by an average of 2.2 ± 2.3°C. Bottom layer temperatures, near box openings, were closest to T_a, averaging 0.8 ± 2.0°C ΔT. The south-facing iButton in the top layer recorded the highest mean ΔT (4.9 ±3.6°C, range -1.1–18.1°C) and the west-facing iButton in the bottom layer recorded the lowest mean ΔT (0.1 ± 1.6°C, range -3.8–6.0°C; Figure 2). We observed the highest ΔT in the top layer west-facing iButton on a hot, calm evening (1800–2100) when T_a ranged from 26.4–33.0°C and wind speed ranged from 0.1–2.4 m/s.

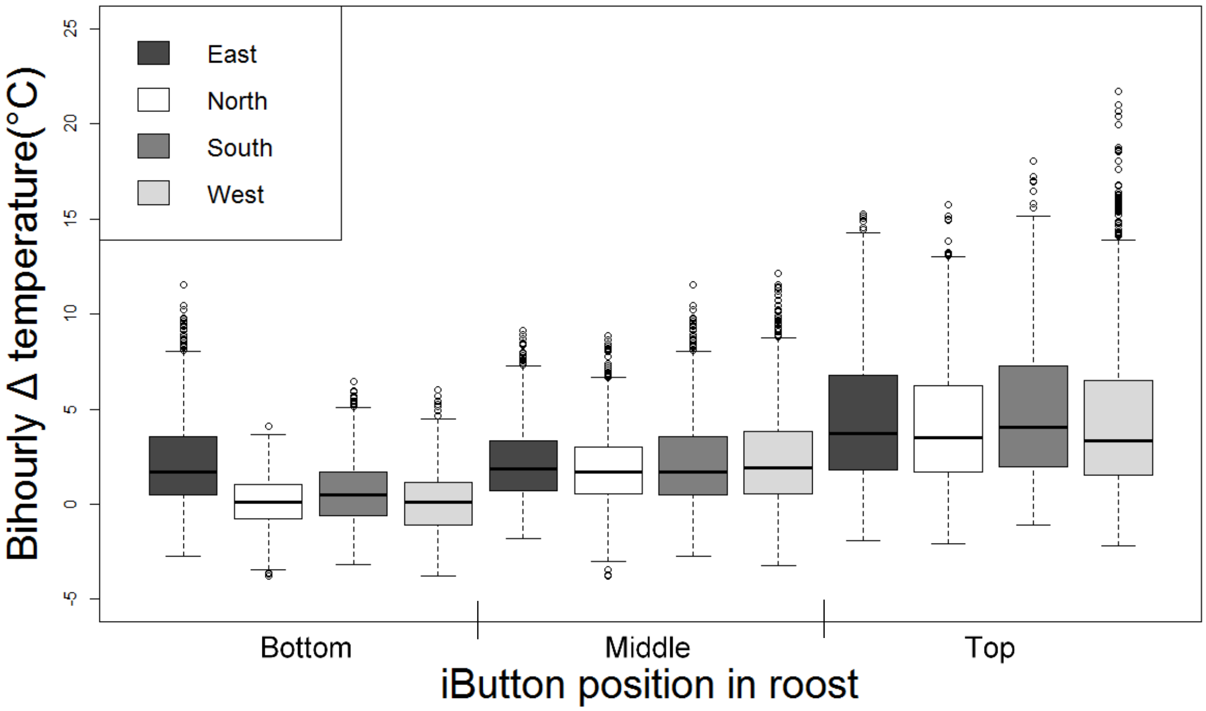

Figure 2. Boxplots of the bihourly Δ temperature ($T_{max} – T_a$) recorded at each iButton position of the reference design, where bats were excluded, in Vigo County, Indiana, May 2018–September 2018. Boxes represent inter–quartile range. Upper whiskers represent the largest observation less than or equal to a box's upper hinge + 1.5 * IQR (inter-quartile range). Lower whiskers represent the smallest observation greater than or equal to a box's lower hinge – 1.5 * IQR. The solid horizontal lines in each box indicate the median.

The reference design typically offered moderate mean daily temperature availability, which was the daily mean instantaneous temperature range from hourly observations. Mean daily temperature availability was 5.3 ± 1.8°C, meaning that bats could choose among positions in the same box that differed by 5.3°C, on average. Hourly temperature availability was highest during the day (midday–evening; Figure 3), with the highest value (17.5°C) observed on three different sunny, calm days (always at 1000 or 1900). We recorded low hourly availability at night (Figure 3), with the lowest value (0.5°C) observed on 14 different days, typically between 0200–0800.

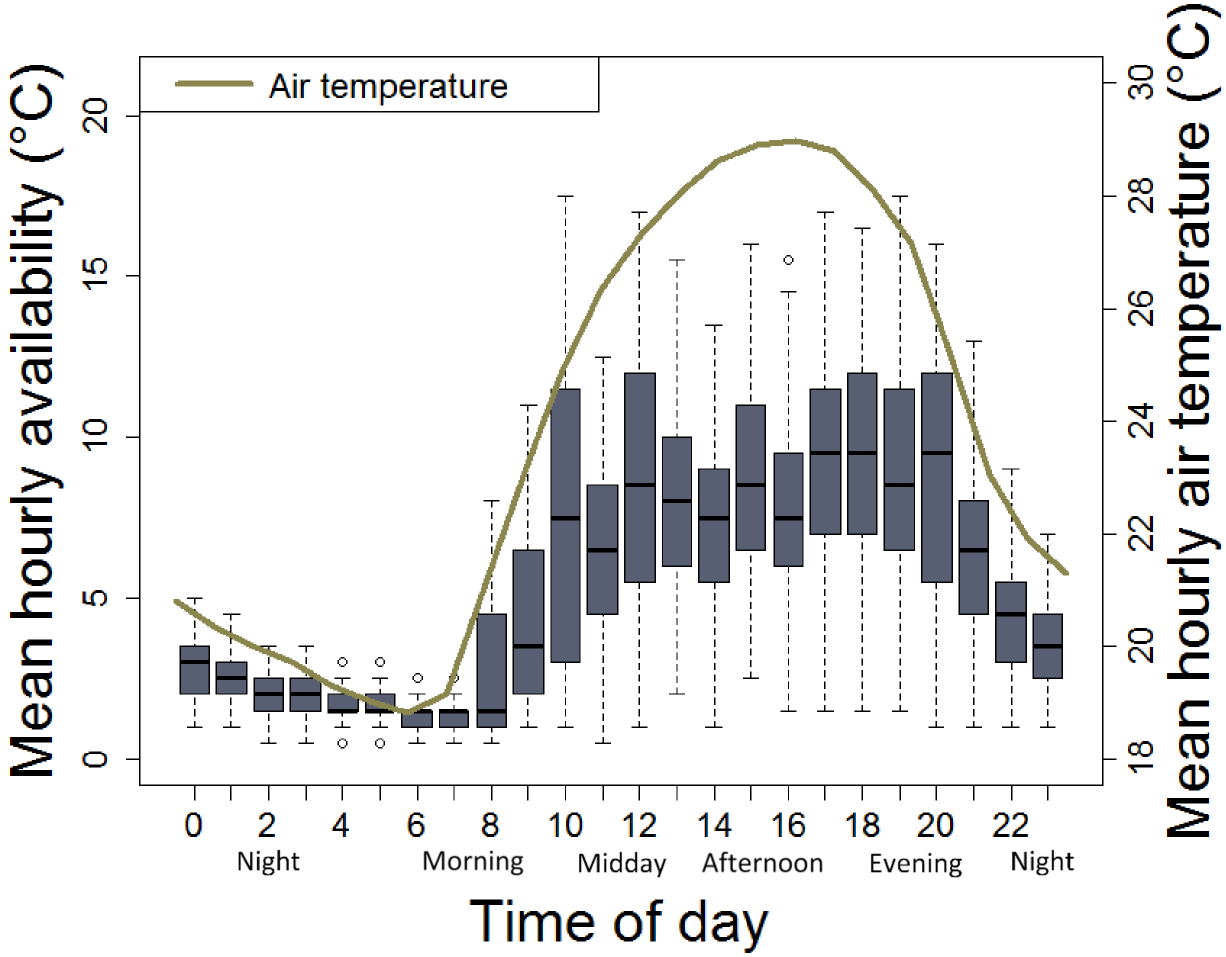

Figure 3. Boxplot of average hourly temperature availability (°C) in the reference design, overlaid by average hourly air temperature (°C; tan line). Numbers on x-axis correspond to hours in military time. Data recorded in a reference rocket-style box, where bats were excluded, in Vigo County, Indiana, May 2018–September 2018.

In the reference design, daily temperature extremes (i.e., T_{min} and T_{max}) varied widely. Mean temperature variability, the difference between maximum and minimum daily temperatures within the box, was 20.7 ± 6.6°C. There was a strong, direct correlation between box temperature variability and the variability in outside air temperature ($p < 0.001$; Figure 4). Box temperatures varied the most (top 10% of box variability values 29.5–34.5°C) on sunny, calm days (n=11 days). Six of these high variability days were also days with the greatest range of outside air temperatures (15.5–18.7°C).

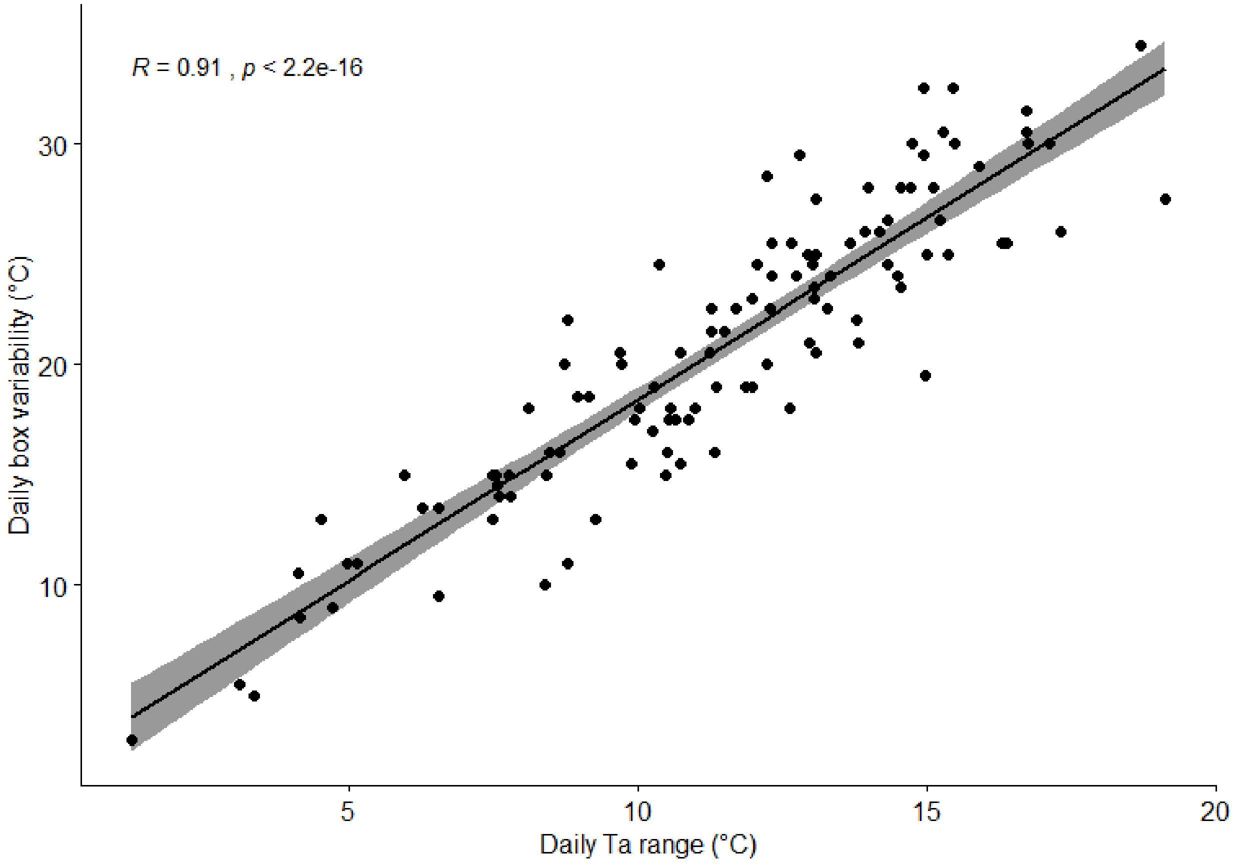

Figure 4. Correlation plot for daily (24-hour period) box temperature variability (°C; daily T_{max} – daily T_{min}) for a reference design and daily range of outside air temperatures (°C; T_a). A Pearson test showed daily box variability and daily range of air temperatures were strongly correlated (results in figure).

Suitable space.

Generally, the bottom and middle portions of the reference design offered suitable temperatures for bats (15–40°C). Most (97%) of the 319 observations of unsuitably hot temperatures within the box occurred in top layer data loggers (on 57 days) and all 44 observations of T_{lethal} occurred in top layer data loggers (20 days; Figure 5). Most observations of lethal temperatures (93%) were recorded in the afternoon and evening (1400–2000) and on days when wind speed was < 10 m/s and T_a was 24–35°C (M = 31.6°C). Many (48%) of these T_{lethal}

observations were for the top layer west-facing data logger, likely due to its longer exposure to afternoon sun. Unsuitably hot temperatures in the middle layer, although rare (comprising 2% of unsuitably hot observation), were observed in south- (n=1) and west-facing (n=6) data loggers. On the five days they occurred, T_a was ≥ 30°C and wind speeds were < 5.3 m/s. On the evening (1800–2100) of 4 July (one of the five previously noted days), we recorded a single observation of unsuitably hot temperature (40.5°C) in an east-facing bottom layer data logger. Temperature observations by this data logger steadily increased throughout the day, from 25.0°C at 0800 to 40.5°C at 2000. On the same evening (1800–2100 on 4 July 2018), four other data loggers recorded unsuitably hot temperatures (north top, south top, south middle, and west middle). Throughout much of the same day (1200–2100), seven different data loggers recorded unsuitably hot temperatures (all top layer loggers, south middle, west middle, and east bottom). On 4 July, mean T_a was 28.4°C (range = 22.8–35.0°C) and mean wind speed was 4.2 m/s (range = 0.8–12.5 m/s).

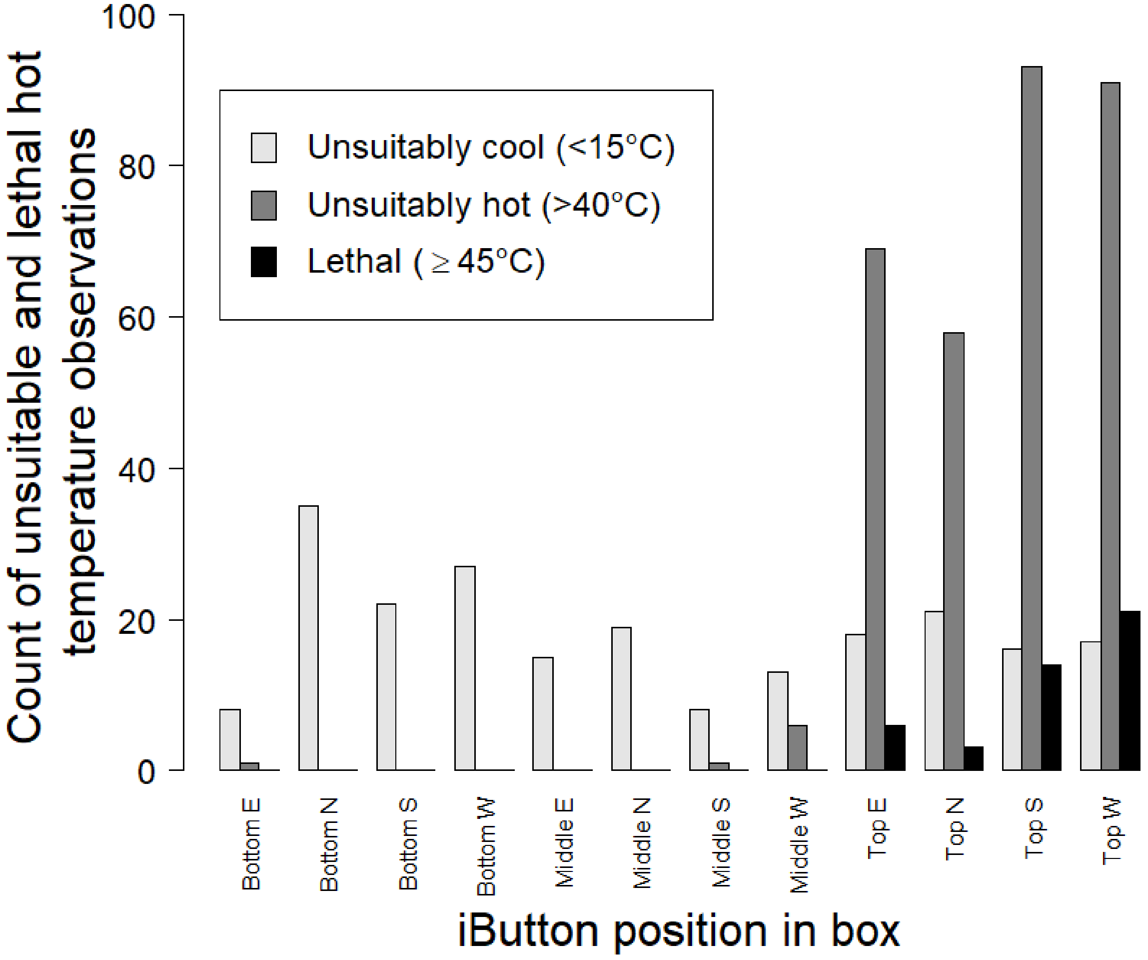

Figure 5. Observations of unsuitably cool (< 15°C; light grey), unsuitably hot (> 45°C; dark grey), and lethal (≥ 45°C; black; T_{lethal}) temperatures recorded by iButtons in the reference design, where bats were excluded, in Vigo County, Indiana, May 2018–September 2018.

Every aspect and layer of the reference design reached unsuitably low temperatures (Figure 5; n=219 total observations). Most observations (71%) of < 15°C occurred in the morning (0600–0900) and on cool days ($T_a < 17.7$°C) when wind speed was < 8.8 m/s. The north bottom data logger recorded unsuitably low temperatures most often (n=35 of 219 observations), while the east bottom and south middle recorded the fewest unsuitably low temperatures (n=8 observations each). On the five days we observed unsuitably cool temperatures in the east bottom and south middle data loggers, the entire box was unsuitably cool. This always occurred on cool, still mornings (0600–0900) when T_a was < 14.5°C and wind speed was < 1.8 m/s. On average, 81% of the reference design remained within a suitable temperature range and provided usable space for bats.

Section 2: Microclimate comparison across designs

Temperature.

Across designs, daily box temperatures ranged from 11.0–54.0°C (mean 25.9 ± 5.9°C) throughout the study period, with the lowest observed temperatures occurring in the empty cavity design (mean 26.0 ± 6.4°C, range 11–52°C) and the highest observed temperatures in the composite material design (26.3 ± 6.6°C, range 11.5–54.0°C). Furthermore, we observed contrasting temperature profiles in the jacket and cavity designs.

The availability, variability, and ΔT profiles of the external jacket designs (empty, foam, and water), which were designed to increase T_{min}, closely resembled the temperature profiles of the double vent, upper vent, and white gloss designs (see Figures 7–9 for comparison). The relatively low ΔT, temperature availability, and temperature variability of the external jacket designs are likely due to increased mass and insulation provided by the external jackets. The opposite occurred in the cavity designs, meant to decrease T_{max}, as availability, variability, and ΔT profiles of these designs more closely resembled the reference, composite material, opening wedge, and vent removal designs (see Figures 7–9 for comparisons). Cavity designs had relatively high ΔT, temperature availability, and temperature variability compared to other designs meant to decrease T_{max}. We expect that the cavity designs were fairly similar to the reference design because the cavity was relatively small (only 6,231 cm^3). Such a small cavity could only contain ~1.0 liter of water, foam, or empty space, thereby limiting its effectiveness for heat absorption.

Across designs, the minimum daily temperature (daily T_{min}) averaged 19.0 ± 3.1°C (Table 2) and the maximum daily temperature (daily T_{max}) averaged 37.7 ± 6.1°C (Table 3). Like the reference design, daily T_{min} observations in the other designs most frequently occurred in the morning (mode = 0700 on 92 days), just after mean sunrise (0645), and daily T_{max} observations most frequently occurred in the evening (mode = 1800 on 75 days), ~180 min before mean sunset (2058). Minimum box temperatures were frequently lower than T_a; 44% of all daily T_{min} values coincided with negative ΔT values.

Minimum daily temperatures across designs ranged from 11.0–24.5°C (Table 2), whereas in the reference design T_{min} ranged from 12.0–24.0°C (Table 2). We expected to observe the lowest mean T_{min} in designs meant to decrease T_{max}, but this was not the case. Mean T_{min} was the lowest in two designs meant to increase T_{min}, the composite material and empty cavity designs (Table 2), suggesting these two designs did not retain heat through the night as well as other designs. We also observed unsuitably cool temperatures (< 15°C) on the most days (17 days each) in the house wrap, empty cavity, composite material, and long designs.

Of designs meant to increase T_{min}, five were effective: the three jacket designs, and the opening wedge and vent removal designs. The three jacket designs and opening wedge design were most effective, rarely (10–12%) recording unsuitably cool temperatures (Figure 6). Elevated T_{min} values in the opening wedge design are probably due to its reduced entrance area, which was 34% smaller than in the reference design. Decreasing box volume also decreased the frequency of unsuitably cool temperature observations. We also observed high mean T_{min} values in the short design (19.1°C; Table 2), which also rarely (11% of study days) reached unsuitably cool temperatures, while also having the fifth greatest mean T_{min} (Figure 6; Table 2).

Maximum daily temperature across all boxes ranged from 16.5–54.0°C (Table 3), whereas in the reference design T_{max} ranged from 17.5–52.0°C (Table 3). As expected, designs meant to decrease T_{max} had some of the lowest mean T_{max} values (Table 3). The house wrap design, essentially a white box, had the lowest mean T_{max} (34.1 ± 4.5°C) and never reached T_{lethal} (≥ 45°C; Figure 6). We also observed relatively low mean T_{max} (≤ 37.1°C) in the three jacket designs and three designs with altered volume (short, two-inch roof, and three-chamber designs). The three-chamber box was also the only other design that remained below T_{lethal} during the entire study (Figure 6). In contrast, the vent removal and composite material designs, along with the long design, had mean T_{max} > 40.8°C—i.e., greater than the suitable temperature range (15–40°C). Collectively, at least one of these three designs recorded the highest daily T_{max} of all designs on 110 days. Across designs, T_{max} throughout the entire box dropped below 15°C on 0–8 days; however, this never occurred in the water or foam jacket designs.

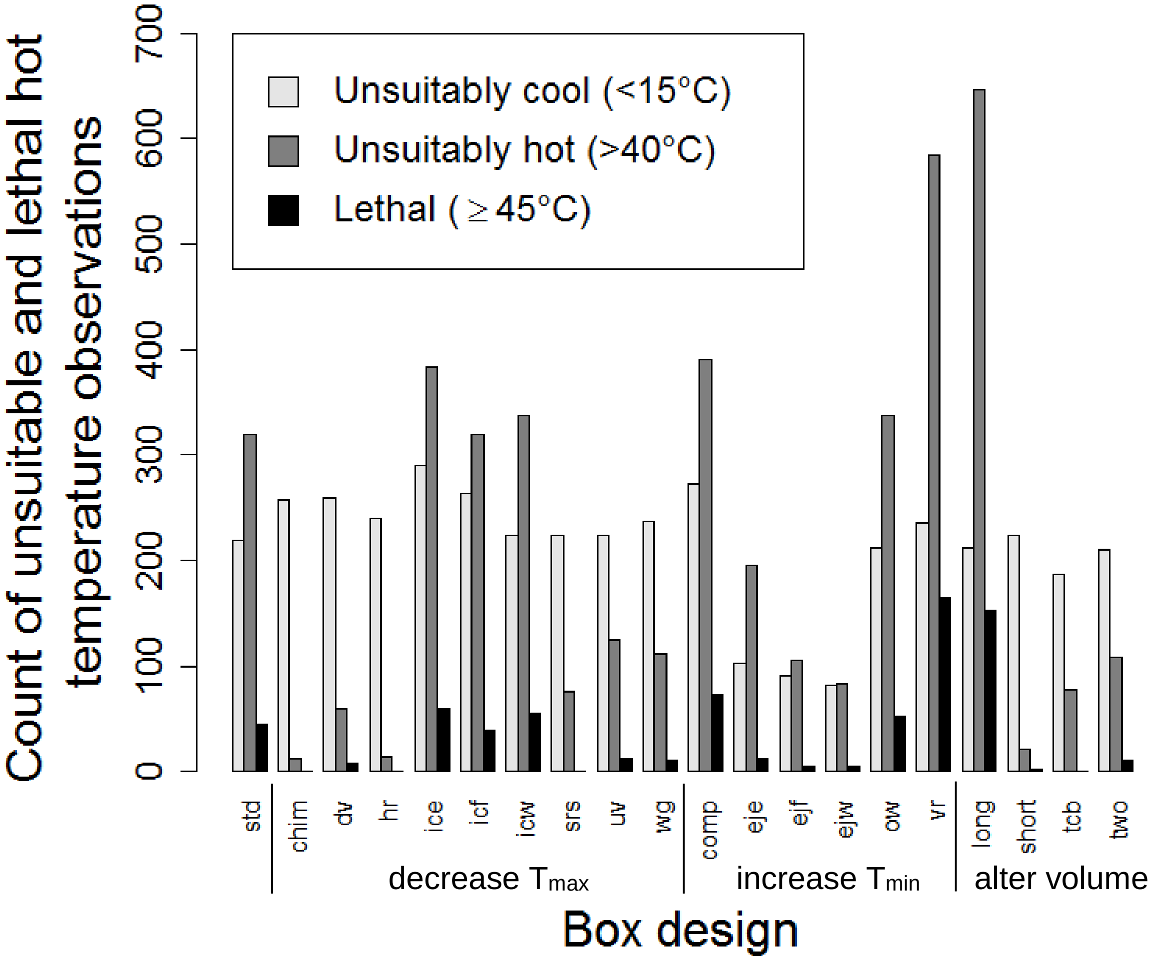

Figure 6. Observations of unsuitably cool (< 15°C; light grey), unsuitably hot (> 40°C and < 45°C; dark grey), and lethal (≥ 45°C; black; T_{lethal}) temperatures recorded (n=9272) by iButtons in 20 bat boxes of three box categories (Table 1), where bats were excluded, in Vigo County, Indiana, May 2018–September 2018.

We noted observations of unsuitable or lethal temperatures in 10–12 iButton positions in every design; only the south and east middle iButtons in the water jacket design never recorded an unsuitable or lethal observation. Across designs, most (68%) observations of unsuitable/lethal temperatures were in top layer iButtons, while middle and bottom layer iButtons represented 12% and 20% of unsuitable/lethal observations, respectively. Across top layer iButtons, only 11% of observations of unsuitable/lethal temperatures were lethal. Considering aspect, east-facing iButtons recorded the fewest observations of unsuitable temperatures (22%) and south-facing iButtons recorded the most (27%). Most (99%) of T_{lethal} observations occurred in top layer iButtons, while only 1% occurred in middle layer iButtons. Across top layer iButtons, only 8% of T_{lethal} observations occurred in north-facing iButtons, while 45% were observed in west-facing iButtons. The east-facing and south-facing top layer iButtons recorded 18% and 29% of T_{lethal} observations, respectively.

Across designs, mean ΔT (hourly box $T_{max} – T_a$) was 2.1 ± 3.0°C (range of all values -6.3–23.2°C). Most designs (n=17) had high ΔT values (maximum ΔT > 15°C), but four designs (chimney, house wrap, south roof shade, and three-chamber) had low ΔT values (maximum ΔT ≤ 16°C). Although the chimney, house wrap, and south roof shade designs had relatively low mean ΔT (1.3–1.7°C), they occasionally reached temperatures much warmer than T_a (maximum ΔT range 12.2–16.0°C; Figure 7). In the other 17 designs, maximum ΔT ranged from 14.5–23.2°C. Designs that deviated the most from T_a (mean ΔT ranging from 1.4–3.1°C) were the reference, three cavity designs, the upper vent, composite material, opening wedge, vent removal, and long designs. The long design had the highest mean ΔT (3.1 ± 3.7°C, range -4.3–22.2°C). Designs meant to decrease T_{max} had the most negative ΔT values (47%), many of which occurred in the chimney, double vent, house wrap, and south roof shade designs. We observed 32% of negative ΔT values in designs meant to increase T_{min}. Across designs meant to increase T_{min}, the vent removal had the fewest negative ΔT values and the water jacket design had the most. We observed 17% of all negative ΔT values in the long, short, three-chamber, and two-inch roof boxes, all altered volume designs.

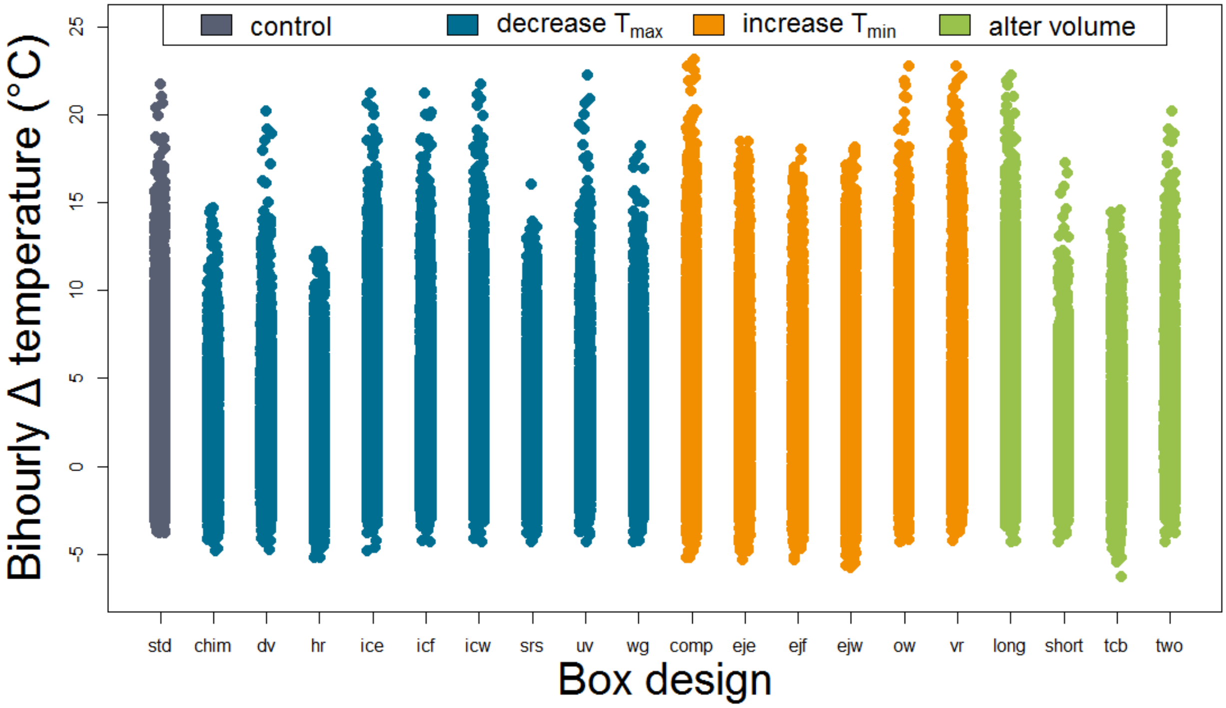

Figure 7. Stripchart of bihourly Δ temperature (hourly box $T_{max} - T_a$; °C) across box designs organized by category: reference (gray), designs meant to decrease T_{max} (blue), designs meant to increase T_{min} (orange), and designs that alter box volume (green). A "jitter" function was used to better visualize overlapping data points. Data recorded in 20 bat boxes of three box categories (Table 1), where bats were excluded, in Vigo County, Indiana, 24 May 2018–14 September 2018.

Across all designs, availability or the daily mean instantaneous temperature range from hourly observations ranged from 0.58–10.0°C. We recorded the lowest mean availability in the short design (2.7 ± 1.0, range 0.6–5.3°C) and the highest in the long design (6.2 ± 2.1, range 1.2–10.0°C; Figure 8). The house wrap and three-chambered box designs offered significantly less availability than the reference design ($p < 0.05$; Table A.2; Figure 8). Across designs, we define three levels of temperature availability: low (availability range 0.6–5.8°C), medium (0.6–7.9°C), and high (0.6–10.0°C; Figure 8). Designs meant to increase T_{min} tended to have high availability, while designs meant to decrease T_{max} typically had low availability (with the exception of the cavity designs; Figure 8). Of designs that altered box volume, the long design had high temperature availability and the other designs had low–medium availability. Temperature availability appears to be highly variable and attempts to create a cooler box often diminished availability. In contrast, attempts to create a warmer box appeared to improve availability.

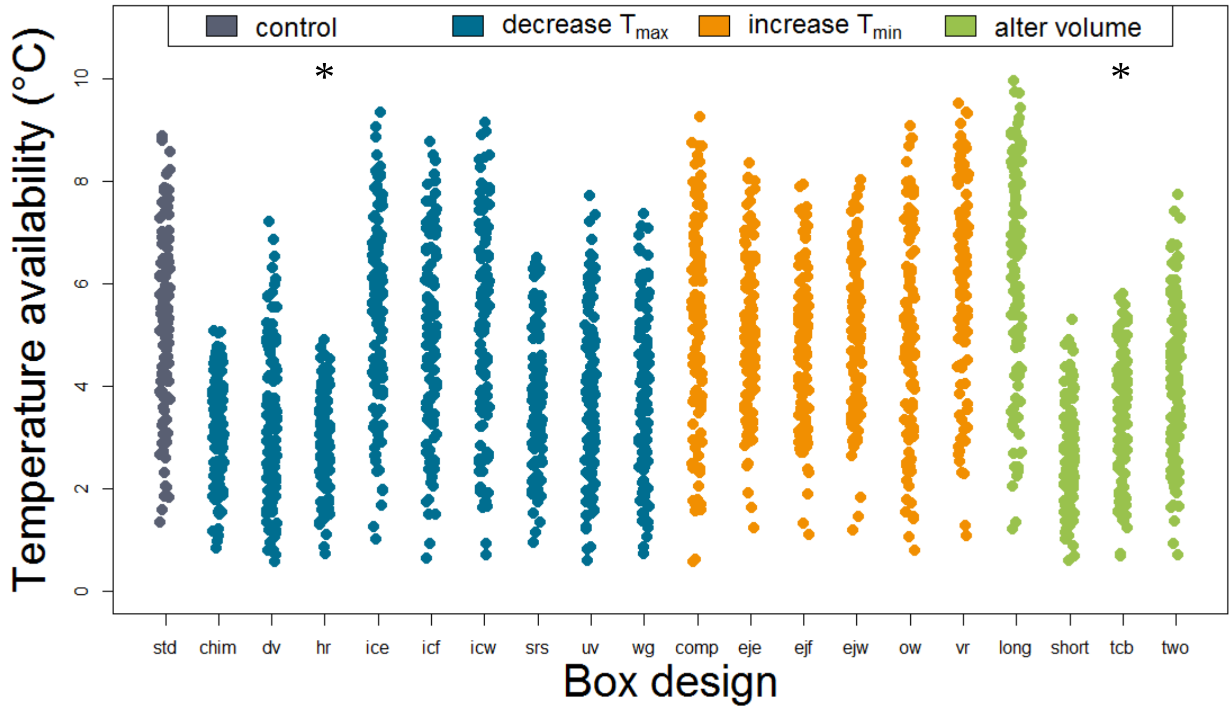

Figure 8. Stripchart of temperature availability (°C), the daily (24-hour period) mean instantaneous temperature range from hourly observations, across box designs organized by box category: reference (gray), designs meant to decrease T_{max} (blue), designs meant to increase T_{min} (orange), and designs that alter box volume (green). Asterisks (*) denote designs that were significantly different than the reference design in our model (Table A.2). A "jitter" function was used to better visualize overlapping data points. Data recorded in 20 bat boxes of three box categories (Table 1), where bats were excluded, in Vigo County, Indiana, 24 May 2018–14 September 2018.

Across designs, variability (daily T_{max} minus daily T_{min}) ranged from 2.0–36.5°C. We observed the lowest mean variability (i.e., highest stability) in the house wrap design (15.2 ± 4.9°C), closely followed by the short design (15.3 ± 5.5°C; Figure 9). In contrast, we saw the highest mean variability (i.e., least stability) in the vent removal design (23.1 ± 6.7°C; Figure 9). Across designs, we define two levels of variability; low (2.0–29.5°C) and high (2.0–36.5°C; Figure 9). Eight designs had low variability: house wrap, short, chimney, south roof shade, three chamber, and all three jacket designs. Low variability designs were characterized by lighter color, more air flow and shading, or smaller internal volume. All other designs had high variability and were characterized by lower air flow, lack of shading, or greater internal volume. Five low variability designs (chimney, house wrap, short, south roof shade, and three-chamber; mean variability = 16.1°C, range 2.0–29.5°C) and one high variability design (white gloss; mean variability = 17.9°C, range 2.0–31.5°C) were more stable than the reference design (mean variability = 20.7°C, range 3.0–34.5°C; $p < 0.05$; Table A.3; Figure 9).

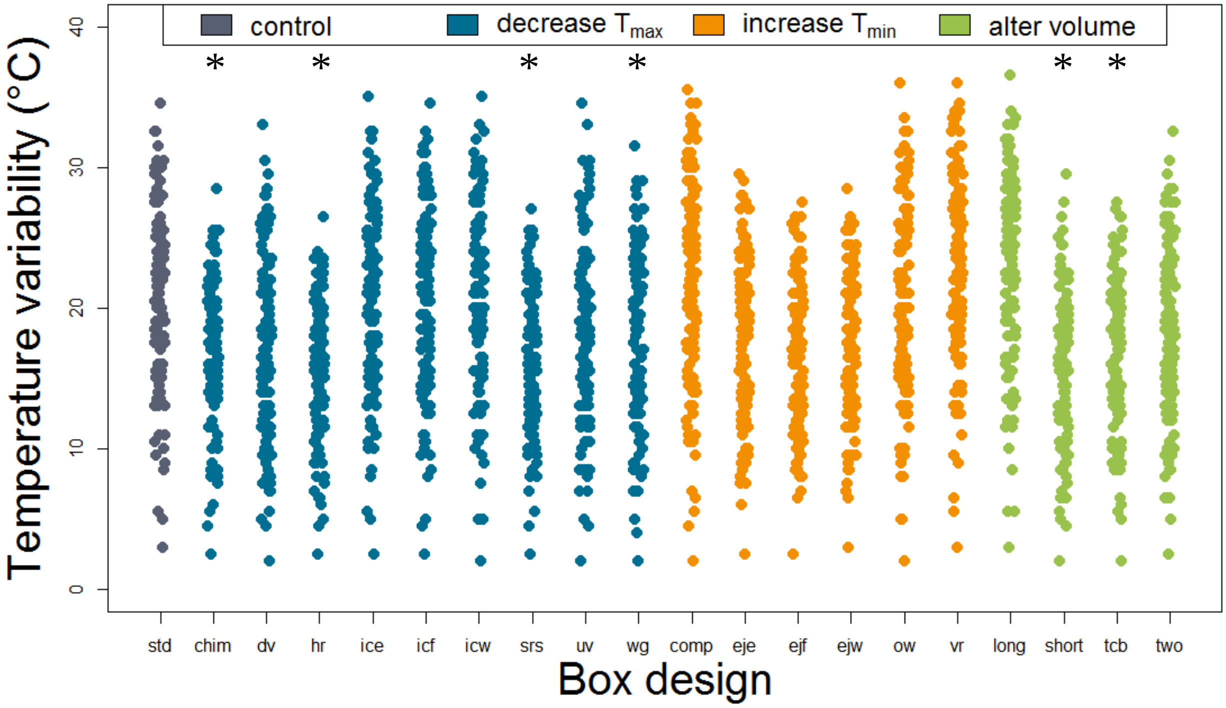

Figure 9. Stripchart of daily (24-hour period) temperature variability (°C; daily T_{max} – daily T_{min}) across box designs organized by box category: reference (gray), designs meant to decrease T_{max} (blue), designs meant to increase T_{min} (orange), and designs that alter box volume (green). Asterisks (*) denote designs that were significantly different than the reference design in our model (Table A.3). A “jitter” function was used to better visualize overlapping data points. Data recorded in 20 bat boxes of three box categories (Table 1), where bats were excluded, in Vigo County, Indiana, 24 May 2018–14 September 2018.

Suitable space.

Due to a limited amount of cool weather data (n = 17 days), we chose to characterize suitable and unsuitable space on hot days only (n = 79 days). On hot days (mean T_a = 29.9°C), mean suitable space across designs ranged from 80–99%, with the lowest proportion of suitable space in the long design and the greatest proportion in the house wrap, chimney, and short designs (Table 4). Even on the hottest days, all designs retained some portion of suitable space. While the cavity designs were on average 88–89% suitable, the remaining boxes designed to decrease T_{max} were 94–99% suitable, on average. Designs meant to increase T_{min} were 81–96%

suitable, on average, whereas the jacket designs were 93–96% suitable. A potential explanation for these results is that the jacket designs have more mass than the other designs meant to increase T_{min}, but provide the same volume. Thus, the jacket designs, specifically the one filled with water, have greater heat capacity and require more heat energy to reach the same temperature as other designs.

Table 4. Total box volume (cm^3), daily (24-hour period) mean volume of suitable space (volume of box between 15–40°C), and proportion of roost that remained within suitable temperature range (≤ 40°C; mean ± SD) on hot days (mean T_a = 24.4°C, n = 96 days) recorded in 20 bat box designs (variable volumes noted), where bats were excluded, in Vigo County, Indiana, May 2018–September 2018.

Box Category	Design	Total box volume (cm^3)	Mean volume of suitable space (cm^3)	Mean proportion suitable on hot days
Control	Reference	24,538	21,839	0.89 ± 0.14 (0.50–1.00)
Decrease T_{max}	House wrap	24,538	24,293	0.99 ± 0.05 (0.50–1.00)
	Chimney	24,538	24,293	0.99 ± 0.03 (0.92–1.00)
	Double vent	24,538	23,802	0.97 ± 0.06 (0.58–1.00)
	South roof shade	24,538	23,556	0.96 ± 0.10 (0.58–1.00)
	White gloss	24,538	23,311	0.95 ± 0.09 (0.58–1.00)
	Upper vent	24,538	23,066	0.94 ± 0.10 (0.58–1.00)
	Foam cavity	24,538	21,839	0.89 ± 0.14 (0.58–1.00)
	Water cavity	24,538	21,593	0.88 ± 0.15 (0.50–1.00)
	Empty cavity	24,538	21,593	0.88 ± 0.15 (0.58–1.00)
Increase T_{min}	Water jacket	24,538	23,556	0.96 ± 0.09 (0.58–1.00)
	Foam jacket	24,538	23,311	0.95 ± 0.10 (0.67–1.00)
	Empty jacket	24,538	22,820	0.93 ± 0.12 (0.67–1.00)
	Opening wedge	24,243	21,334	0.88 ± 0.14 (0.50–1.00)
	Composite material	24,538	21,103	0.86 ± 0.16 (0.50–1.00)
	Vent removal	24,538	19,876	0.81 ± 0.16 (0.42–1.00)
Altered volume	Short	12,296	12,173	0.99 ± 0.06 (0.58–1.00)
	Three-chamber	20,549	19,727	0.96 ± 0.09 (0.66–1.00)
	Two-inch roof	27,414	26,043	0.95 ± 0.09 (0.58–1.00)
	Long	36,779	29,423	0.80 ± 0.17 (0.33–1.00)

The long design had the lowest mean proportion of suitable space of all designs (range 0.33–1.00; Table 4). However, when considering volume, the long design offered similar suitable space compared to other designs. For example, on a sunny, clear day when mean daily T_a was 28.4°C (4 July 2018), only 33% of the long design (12,137 cm^3; Table 4) was suitable. On the same day, only 58% of the short design (7,132 cm^3) and 50% (12,269 cm^3) of the reference design were suitable. Although 66% of the three-chamber design was suitable, the volume it provided (13,562 cm^3) was similar to that of 12 other designs (50–58% of box volume; 12,121–14,232 cm^3). Like the short design, the vent removal design provided little suitable space (42% of box volume; 10,306 cm^3). Under these conditions, the long design provided nearly double the suitable space of the short design and similar suitable space to the other designs. Meanwhile, on the same day, the chimney design provided the greatest amount of suitable space (92% suitable; 22,575 cm^3), followed by the empty jacket and foam jacket (67% of box volume; 16,440 cm^3) designs.

Section 3: How weather affects box design microclimate

Air temperature was an important predictor of bat box temperature availability and variability, while wind speed (Table A.2) and global radiation (Table A.3) acted as modifiers for differences in temperature across box designs.

Availability.

After model simplification, the accepted ANCOVA model to predict temperature availability within boxes included the following as main effects: design type, mean daily T_a, T_a daily range, mean daily global radiation, mean daily wind speed, and the 2-way interactions between design type and each of these four weather variables (multiple $R^2 = 0.88$, residual SE = 0.67, $F_{99,\,2160} = 168.8$, $p < 0.001$; Table A.2). Across all designs, availability increased with increasing mean daily T_a, T_a daily range, and mean daily global radiation, while decreasing with increasing mean daily wind speed.

Wind speed significantly interacted with design to affect temperature availability in six designs: three designs meant to decrease T_{max} (chimney, house wrap, and south roof shade; $p < 0.01$), one design meant to increase T_{min} (water jacket; $p < 0.05$), and two altered volume designs (short and three-chambered box; $p < 0.01$; Table A.2). At low wind speeds (< 4 m/s), the reference design and water jacket design provided approximately 3°C greater temperature availability than the three designs that decreased T_{max} or two altered volume designs (Figure 10A). At high wind speeds (> 15 m/s), all of the designs were more similar in terms of availability, differing by only 1.5°C. At low wind speeds, the reference design provided approximately 0.5°C greater temperature availability than the water jacket design, but at high wind speeds the water jacket design provided approximately 0.5°C greater temperature availability than the reference (Figure 10A).

Global radiation significantly interacted with design to affect temperature availability in 10 designs: three designs meant to decrease T_{max} (chimney, double vent, and house wrap; $p < 0.05$), three designs meant to increase T_{min} (all jacket designs; $p < 0.01$), and all four of the altered volume designs (long, short, three-chambered box, and two-inch shade; $p < 0.05$; Table A.2; Figure 10B). On cloudy days with little sunlight (mean global radiation < 100 W/m^2), the difference in temperature availability across box categories was between 0–1.3°C, with the three jacket designs providing the greatest temperature availability, which was slightly higher (< 0.5°C) than availability in the reference design (Figure 10B). The decrease T_{max} designs provided the lowest temperature availability (~1°C). On sunny days (mean global radiation > 300 W/m^2), the reference design got warmer at the top (Figures 2 and 5) and provided 0.4°C more temperature availability than the three jacket designs, 2°C more availability than the four altered volume designs, and ~3.5°C more availability than the three decrease T_{max} designs.

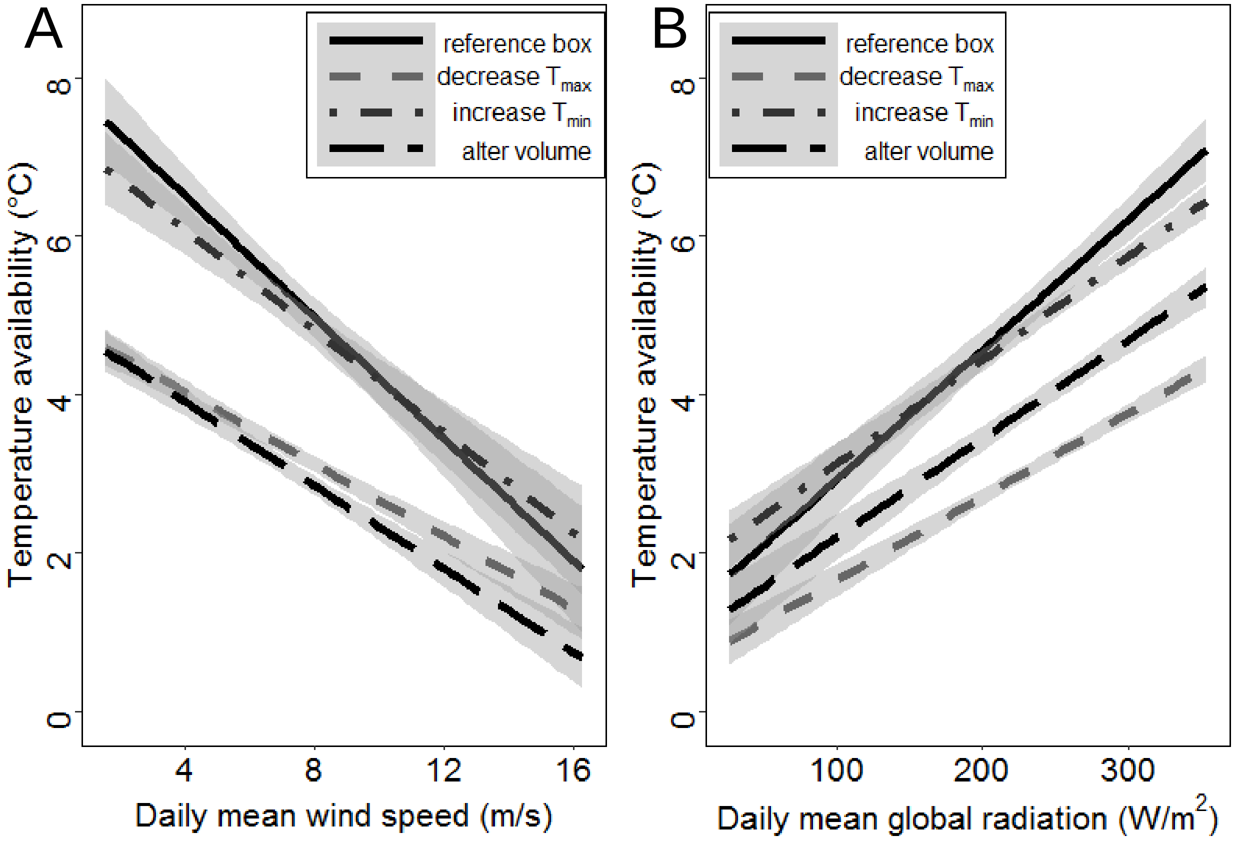

Figure 10. Interaction plots for predictor variables that significantly interacted with box design and availability, with regression lines and 95% confidence intervals for those interactions. A) By category, box designs that significantly interacted with daily mean wind speed included chimney, double vent, house wrap (decrease T_{max}), water jacket (increase T_{min}), and short, and three-chamber (alter volume) designs. B) By category, box designs that significantly interacted with daily mean global radiation included chimney, double vent, house wrap (decrease T_{max}), all jacket designs (increase T_{min}), and short, long, three-chamber, and two-inch roof (alter volume) designs.

Variability.

After model simplification, the accepted ANCOVA model to predict temperature variability included the following as main effects: box design, mean daily T_a, T_a daily range, mean daily global radiation, mean daily wind speed, and the 2-way interactions between box design and T_a daily range, mean daily global radiation, and mean daily wind speed (multiple $R^2 = 0.92$, residual SE = 1.93, $F_{80,\ 2179} = 303.8$, $p < 0.001$; Table A.3). Across all box designs, variability increased with increasing mean T_a, T_a range, and mean global radiation, while decreasing with increasing mean wind speed.

Increasing wind speed significantly affected temperature variability in five designs: three designs meant to decrease T_{max} (chimney, house wrap, and south roof shade; $p < 0.01$), one design meant to increase T_{min} (water jacket; $p < 0.05$), and one altered volume design (short; $p < 0.01$; Table A.3). At low wind speeds (< 4 m/s), temperatures in the reference design were 5°C more variable than the three decrease T_{max} designs, and 7°C more variable than the water jacket and short designs (Figure 11A). At higher wind speeds (> 15 m/s), boxes became more stable, presumably due to an increase in air flow within the box. During the windiest conditions, the short design was the least variable (~3°C less than the reference), but confidence intervals overlapped for all design categories (Figure 11A).

Global radiation significantly increased temperature variability in only the composite material design when compared to the reference design ($p < 0.01$; Table A.3). On cloudy days with little sunlight (mean global radiation < 100 W/m^2), temperature variability in the reference design was 0.5–3°C higher than in the composite material design. On sunny days (mean global radiation > 300 W/m^2), the composite material design was 0–5.5°C more variable (i.e., less stable) than the reference design.

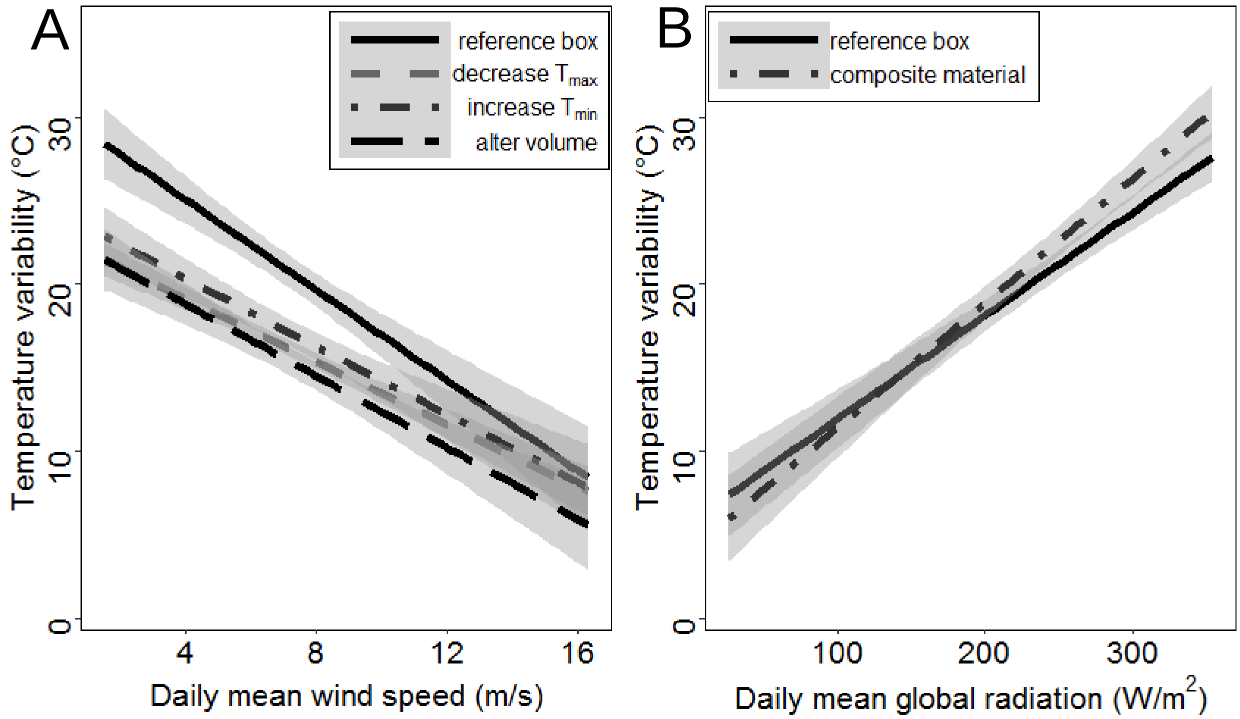

Figure 11. Interaction plots for predictor variables that significantly interacted with box design and variability, with regression lines and 95% confidence intervals for those interactions. A) By category, box designs that significantly interacted with daily mean wind speed included (decrease T_{max}) chimney, house wrap, south roof shade, (increase T_{min}) water jacket, and (alter volume) short designs. B) Only the composite material design significantly interacted with daily mean global radiation.

Discussion

Many different bat box designs are being used for conservation purposes (Brittingham and Williams 2000; Flaquer et al. 2006; Griffiths et al. 2017; Hoeh et al. 2018; Lourenço and Palmeirim 2004; Rueegger 2016; Rueegger 2019), but we lack an understanding of the complex microclimate mechanisms that could contribute to bat boxes being potential ecological traps. Bat boxes often reach temperatures known to cause physiological stress to bats (> 40°C; Brittingham and Williams 2000; Licht and Leitner 1967; Hoeh et al. 2018; Lourenço and Palmeirim 2004). In this study, we found that novel modifications to a bat box design significantly decreased high temperatures and created generous thermal gradients for potential bat box occupants. Simple modifications to box height, air flow, and color improved survivability of boxes. Easily modifiable bat box designs will improve roost suitability for the many species using artificial roosts across the globe (Kerth et al. 2006; Meddings et al. 2011; Zeale et al. 2016).

In the reference design we tested, a two-chambered rocket-style box, microclimate conditions were mainly suitable, but sometimes a subset of positions were unsuitable as a function of height and aspect in the box. We recorded temperatures as high as 52°C, well above the 45°C critical thermal maximum of Myotid bats (Neuweiler 2000; O'Farrell and Studier 1970). We also recorded temperatures as low as 12°C, near the torpor temperature threshold of some bat species found in Indiana (Davis and Reite 1967). Hot temperatures, above 40°C, have been documented in various box designs. Hoeh et al. (2018) recorded T_{max} of 51°C in a rocket-style box, while Lourenço and Palmeirim (2004) observed temperatures up to 53°C in a flat-faced Bat Conservation International design (BCI; Tuttle and Hensley 1993). Another flat-faced design, tested by Brittingham and Williams (2000), had temperatures > 40°C. Bideguren et al. (2018) tested 15 variations of five box styles—laminar (flat-faced), pillbox, cubical, rhomboid, and bat house—and 10 of these designs recorded temperatures > 40°C. In the same study, Bideguren et al. (2018) tested 11 variations of two box styles—laminar and cubical—10 of these designs recorded temperatures > 40°C.

Bat box height and aspect are important factors affecting box temperature (Bideguren et al. 2018; Brittingham and Williams 2000; Lourenço and Palmeirim 2004; Hoeh et al. 2018; Rueegger 2019). The vertical arrangement of a box design is important for determining high and low temperature areas within. Tall boxes have higher maximum temperatures than shorter boxes (Brittingham and Williams 2000; Hoeh et al. 2018). We observed a thermal gradient in our reference design where the highest temperatures occurred in the top layer and the coolest temperatures in the bottom layer, similar to findings from earlier work (Brittingham and Williams 2000; Hoeh et al. 2018; Lourenço and Palmeirim 2004; Rueegger 2019). As expected, the long design (137 cm tall) we tested provided the greatest thermal gradient. However, we were surprised to find a relatively narrow (0.6–5.8°C) thermal gradient in both the three-chamber box (61 cm tall) and short designs (45.7 cm tall). Like the short design, no position in the three-chamber box design reached T_{lethal}, suggesting short boxes may be more appropriate for warmer climates. In contrast, the top layer and west-facing middle data loggers in the long design periodically reached T_{lethal}. Critically, the top layer of our reference design reached T_{lethal}, but the bottom and middle layers never reached T_{lethal}. Despite reaching lethal temperatures, the long and reference designs provided a greater thermal gradient than the short and three-chamber designs. Therefore, the long and reference designs may be better suited for temperate climates where weather is highly variable and it is important for bats to be able to select preferred temperatures in a variety of weather conditions. We recommend long designs be tested in cold climates in spring, as warmer boxes may benefit bats recovering from white-nose syndrome (WNS; Wilcox and Willis 2016).

Artificial roost temperatures can also vary with directional aspect, where east- and west-facing surfaces reach higher temperatures than south- or north-facing surfaces (Mering and Chambers 2012). We observed this pattern in our reference design, where east-facing iButtons recorded the highest morning and afternoon temperatures and west-facing iButtons recorded the highest evening temperatures. When flat-faced box (Brittingham and Williams 2000) and rocket-style designs (Hoeh et al. 2018) were tested, peak temperatures in southeast and southwest box faces occurred in the afternoon and evening, respectively. These findings are best explained by periods of solar exposure: east-facing cavities receive morning sunlight, south-facing cavities receive midday sunlight, and west-facing cavities receive evening sunlight (Bondo et al. 2017). Therefore, southeast box faces receive early morning sun and should reach peak temperatures around noon, while southwest box faces receive afternoon sun and should reach peak temperatures in the evening. We recommend installing east-facing boxes in warm climates, though bats in desert environs tolerate higher temperatures (Bondarenco et al. 2014), and west-facing boxes in temperate climates when four-faced boxes (i.e., rocket-style) are not an option.

Novel box modifications, such as chimneys, jackets, and cavities are rarely used, but we demonstrated that such modifications can alter microclimates in bat boxes. Instead, typical bat box designs often resemble BCI's flat-faced box design. Developed by Tuttle and Hensley (1993), the design is simple to build, capable of housing many bats (> 100), and easy to install; our three-chamber design was a variation of the BCI design. The rocket-style design is less commonly used, probably due to its difficult construction and installation, but offers ~360° of living space. As suggested by Bideguren et al. (2018), complex box designs may exhibit complex temperature profiles, some of which we did not expect.

We expected to see less variable temperatures in our cavity designs, especially the water cavity design, as water has a high specific heat capacity; however, this was not what we observed. Maximum temperatures in the cavity designs were actually high (51.5–52.5°C), exceeding lethal temperatures on several days. Also, minimum temperatures were low. Regardless of cavity fill (water, foam, or empty), mean temperatures in the water (26.2 ± 6.3°C), foam (25.9 ± 6.2°C), and empty (26.0 ± 6.4°C) cavity designs were similar to that of the reference design (26.2 ± 6.2°C). These similarities in temperature between the cavity designs and reference design are probably due to internal cavity size. The internal cavities we constructed could only hold 0.75L of water, which was constrained by the 10.2 x 10.2 cm posts used as box support. To construct larger internal cavities, the post used to erect each box would need to be wider or the innermost chamber of the design would have to be closed off and used as a cavity.

We also did not expect the jacket designs, meant to increase T_{min}, to be effective at buffering both cold and hot temperatures. As predicted, the jacket designs buffered cool temperatures, with T_{min} values often 0.5°C higher than the reference design; unfortunately, we lack data for days when temperatures dropped to freezing. We suggest further testing of the jacket designs under cool conditions, as the heat of solidification of water in a jacket should halt temperatures from dropping below 0°C for the length of time it takes all of the water in the jacket to freeze. Interestingly, the jacket designs also had 2.5–3.7°C lower mean T_{max} values when compared to the reference design and other designs meant to increase T_{min}. The success of the jacket designs is most likely a result of two factors: 1) mass and 2) insulation. An object's heat capacity, the amount of heat energy required to raise the temperature in one gram of substance by one Kelvin, depends on the size and mass of the object; thus, as an object's mass increases so too does the amount of thermal energy needed to reach a specific temperature (Blundell and Blundell 2010). The jacket surrounding each jacket design provided additional thermal mass, or heat storage ability, that then required additional energy input (i.e., global radiation or T_a) to reach the same temperature as the other designs. As for insulation, adding a jacket to each of these designs inhibited heat flow, increasing the time it took each jacket design to reach the same temperature as other designs. We witnessed this principle in the empty jacket design, which had the highest mean T_{max} of the jacket designs. Because the jacket was empty, it provided the least amount of insulation and reached higher temperatures than the water and foam jacket designs. Furthermore, the empty jacket was the least stable, varying by 0.8–1.1°C more than the water and foam jacket designs. We recommend filling jacket space with water, especially when installing boxes in locations with variable temperatures.

Four designs were top performers based on T_{max}, T_{min}, availability, variability, and suitable space. Under hot conditions, the chimney design provided suitable roost temperatures (15–40°C), never reaching T_{lethal} ($\geq$ 45°C). Even on hot days (mean T_a = 24.4°C, n=96 days), 92% of the chimney design always remained within the suitable temperature range. Although we had limited cold weather data, the chimney design had a high number of unsuitably cool (< 15°C) temperature observations; thus, additional testing of chimney designs in cold climates is required. The chimney structure and color provided a natural outlet for rising heat, effectively drawing heat out from the box by creating a thermal gradient. Hot air rises to the top of the chimney, where it is expelled, while cooler air falls and remains within the box. Inner diameter and length of the chimney are important in establishing a thermal gradient, as short or narrow chimneys will provide small thermal gradients and long or wide chimneys will provide large thermal gradients. We found no other studies that have tested the effects of adding chimneys to bat boxes.

The house wrap design performed well under hot conditions, which was expected as the design was essentially a white box. White-painted boxes are cooler and more stable compared to black-painted boxes (Bideguren et al. 2018; Griffiths et al. 2017; Lourenço and Palmeirim 2004; Rueegger 2019). We initially created this design to assess the effects of wind on box temperature, but were unable to acquire house wrap of the desired color. We note that temperature availability and variability in the house wrap design were significantly less affected by wind speed compared to the reference design.

The water jacket design was the seventh most stable design tested (mean temperature variability = 17.0°C, range across all designs was 15.2–23.1°C) and provided suitable temperatures (15–40°C) throughout much of the study period. In addition, the water jacket design provided relatively high mean temperature availability (5.0 ± 1.5°C) and some of the highest T_{min} values recorded (M = 19.2 ± 2.9, across box range 18.7–19.3°C). Mean T_{min} in the water jacket design was comparable to mean T_{min} of interior snag roosts (19.04°C) used by Indiana bats in Missouri (Callahan et al. 1997). We predict that, of designs we tested, the water jacket design will best mimic natural roost temperatures, which are more stable (i.e., less variable; Humphrey et al. 1977; Rueegger 2018). To our knowledge, this study marks the first time a water jacket design has been tested for suitability as an artificial roost.

Another top performer was the long design, which provided the greatest thermal gradient. Although the top layer often reached T_{lethal} and only 33% of the box remained suitable under the hottest conditions, the long design provided an equal or greater amount of living space compared to all other designs but the chimney design. Additionally, the large thermal gradient found in the long design is likely to offer temperatures suitable for survival (15–40°C; Davis and Reite 1967; O’Farrell and Studier 1970) under a wide range of weather conditions, particularly important in temperate climates and for recovery from WNS (Wilcox and Willis 2016). Brittingham and Williams (2000) and Hoeh et al. (2018) also found that tall boxes provide greater thermal gradients than shorter designs.

We also designated some designs “bottom performers” if they became excessively hot or provided narrow thermal gradients. Due to the composite material design’s high T_{max} (54.0°C) and the frequency with which it reached T_{lethal} (n = 35 days), we considered it to be a poor design. In addition to reaching high temperatures, the composite design had the lowest mean T_{min}

(Table 2). While other studies have evaluated the microclimate of boxes composed of wood and rice cement, a sawdust/rice and concrete mixture (e.g., Bideguren et al. 2018; Rueegger 2019), and polyester resin (e.g., Mering and Chambers 2012), no studies have tested microclimate of boxes made from composite deck material. However, boxes made from composite material and recycled plastic are commercially available from multiple vendors. Composite deck material could be beneficial to the longevity of an artificial roost due to its increased durability and because boxes constructed out of wood are susceptible to warping. Like the composite material, boxes constructed from wood cement, rice cement, and polyester resin are durable and potentially more cost effective than the composite material design (> 150 USD), which was more expensive to build than the reference (~80 USD).

The short design was also a poor performer in our study site. Temperatures in the short design were stable (mean temperature variability = 15.3 ± 5.5°C, across box range 15.2–23.1°C), but the thermal gradient was narrow (mean temperature availability = 2.7 ± 1.0°C, whereas other designs ranged from 2.9–6.2°C). This narrow range of available temperatures is less likely to meet the biological requirements of bats in an ever changing weather environment for any substantial length of time. Box designs with wide thermal gradients are important for bats and preferred over designs with narrow thermal gradients (Brittingham and Williams 2000; Hoeh et al. 2018). Unfortunately, many commercially available designs are short (< 61 cm).

Weather significantly affected roost availability and variability. Higher mean T_a, T_a range, and mean daily global radiation resulted in greater availability and variability, while higher mean daily wind speed resulted in less availability and variability. Air temperature and T_a range have direct effects on box temperatures. Increasing T_a results in increasing box temperatures, which peak 1–2 hours after peak T_a (Bideguren et al. 2018; Brittingham and Williams 2000; Hoeh et al.

2018; Griffiths et al. 2017; Rueegger 2019). Additionally, increasing T_a range leads to greater temperature availability and variability in three artificial roost designs (Hoeh et al. 2018). Global radiation has a similar effect on temperature availability and variability. Some studies did not directly measure global radiation, but found that east- and west-facing sections of a roost, which get the most morning and afternoon sunlight, respectively, provided the greatest range of temperatures (Brittingham and Williams 2000; Rueegger 2019). Percent cloud cover (i.e., solar radiation) had a direct and significant effect on roost temperature availability and variability in bat boxes deployed in central Indiana (Hoeh et al. 2018).

To our knowledge, there are no other bat box studies that considered wind speed as a factor in roost temperature. However, Little Penguin (*Eudyptula minor*) nest box temperatures on Penguin Island, Rockingham, Western Austrailia decrease with increasing wind speed (Ropert-Coudert et al. 2004); however, these designs were rectangular and deployed at ground level. In contrast, wind speed does not affect nest box temperatures of Mountain Chickadees (*Parus gambeli*), though the nest boxes in this study had limited air flow due to a small (25 mm) entrance area (Wachob 1996). Work by Cooper (1999) showed that wind speed reduction inside occupied cavity roosts of Mountain Chickadees (*P. gambeli*) and Juniper Titmice (*Baeolophus griseus*) increases standard operative temperatures by 2.5–5.9°C, compared to outside of roosts. These nest boxes had 32 mm entrance holes; therefore, it is likely that wind speed has a more pronounced effect on artificial roosts with greater entrance area, such as that of the rocket style bat box (252 cm^2). This is important because bats within a box are likely increasing box temperatures via metabolic heat production, therefore convective heat loss caused by high wind speeds could prevent overheating events. We recommend additional testing of how wind speed affects temperatures within bat boxes occupied by bats.

It is important to understand how modifications to bat box design affect roost temperatures, as bat boxes are becoming increasingly popular (De La Cruz et al. 2018; Griffiths et al. 2017; Hoeh et al. 2018). Artificial roosts are being used with increasing frequency in conservation and exclusion projects, without complete understanding of the microclimate they provide (Chambers et al. 2002; Flaquer et al. 2006; Meddings et al. 2011; White 2004). While artificial roosts have the potential to mitigate for the loss of natural roosts, which are often ephemeral, careful consideration must be taken to provide appropriate roost designs. Therefore, we recommend installation of multiple bat box designs in clusters of two or more at any one location. We recommend installing a design to buffer cool temperatures (increase T_{min}) and a design to buffer hot temperatures (decrease T_{max}), as female bats have changing physiological requirements throughout the summer (Dzal and Brigham 2013). Additionally, bats tend to switch among multiple roosts in search of microclimate conditions that meet their energetic demands (Bergeson 2017; Lewis 1995; Vonhof and Barclay 1996).

We also recommend that further work be done to characterize bat box design temperatures under different environmental conditions. For example, an ongoing study by Crawford (M.S. student, Eastern Kentucky University, Richmond, Kentucky) is comparing box temperatures of multiple designs in four different solar regimes: open, east-facing sun, west-facing sun, and open sun. Given that modifications can effectively buffer hot or cold temperatures, we recommend testing our top performing designs, or other novel designs, in warmer and cooler climates. We recommend testing modifications to other bat box types, such as the flat-faced box, because modifications will likely affect them differently. Additionally, future work should compare temperatures in artificial and locally available natural roosts, while assessing variation in roost preferences of bats (Boyles 2007).

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APPENDIX A: TABLES OF MEAN BOX TEMPERATURE, TEMPERATURE AVAILABILITY, AND TEMPERATURE VARIABILITY

Table A.1. Table of means and ranges for box temperature (T_{box}; °C), temperature availability (the daily mean instantaneous temperature range from hourly observations; °C), and temperature variability (maximum daily T_{box} – minimum daily T_{box}).

Box Category	Design	Mean T_{box} (°C)	Mean availability (°C)	Mean variability (°C)
Control	Reference	26.2 ± 6.2 (12.0–52.0)	5.3 ± 1.8 (1.4–8.9)	20.7 ± 6.5 (3.0–34.5)
Decrease Tmax	Water cavity	26.2 ± 6.3 (11.5–52.5)	5.2 ± 2.0 (0.7–9.1)	20.7 ± 6.8 (2.0–35.0)
	Empty cavity	26.0 ± 6.4 (11.0–52.0)	5.5 ± 1.9 (1.0–9.3)	20.8 ± 6.6 (2.5–35.0)
	Foam cavity	25.9 ± 6.2 (11.5–51.5)	4.9 ± 1.8 (0.6–8.8)	20.3 ± 6.7 (2.5–34.5)
	White gloss	25.6 ± 5.7 (11.5–49.0)	3.9 ± 1.6 (0.7–7.4)	17.9 ± 6.1 (2.0–31.5)
	Upper vent	25.5 ± 5.5 (12.0–52.0)	3.8 ± 1.6 (0.6–7.7)	18.1 ± 6.6 (2.0–34.5)
	South roof shade	25.5 ± 5.5 (11.5–45.0)	3.8 ± 1.3 (1.0–6.5)	16.7 ± 5.2 (2.5–27.0)
	House wrap	25.2 ± 5.3 (11.5–43.0)	2.9 ± 1.0 (0.7–4.9)	15.2 ± 4.9 (2.5–26.5)
	Double vent	25.1 ± 5.4 (11.5–50.5)	3.3 ± 1.5 (0.6–7.2)	17.0 ± 6.4 (2.0–33.0)
	Chimney	25.1 ± 5.2 (12.0–46.0)	3.2 ± 1.0 (0.8–5.1)	16.4 ± 5.2 (2.5–28.5)
Increase Tmin	Vent removal	26.6 ± 6.8 (12.0–53.5)	6.1 ± 1.9 (1.1–9.5)	23.1 ± 6.7 (3.0–36.0)
	Composite	26.3 ± 6.6 (11.5–54.0)	5.2 ± 2.0 (0.6–9.3)	22.1 ± 7.6 (2.0–35.5)
	Opening wedge	26.2 ± 6.2 (12.0–53.0)	5.0 ± 2.0 (0.8–9.1)	20.4 ± 6.9 (2.0–36.0)
	Empty jacket	26.1 ± 5.5 (12.5–48.0)	5.0 ± 1.6 (1.2–8.4)	17.8 ± 5.8 (2.5–29.5)
	Water jacket	26.1 ± 5.2 (12.5–47.0)	5.0 ± 1.5 (1.2–8.0)	17.0 ± 5.3 (3.0–28.5)
	Foam jacket	25.9 ± 5.2 (12.5–47.0)	4.9 ± 1.5 (1.1–7.9)	16.7 ± 5.4 (2.5–27.5)
Altered volume	Long	26.8 ± 6.8 (11.5–53.0)	6.2 ± 2.1 (1.2–10.0)	22.4 ± 6.7 (3.0–36.5)
	Three chamber	25.7 ± 5.8 (12.0–44.5)	3.4 ± 1.2 (0.7–5.8)	16.7 ± 5.7 (2.0–27.5)
	Two inch roof	25.7 ± 5.6 (12.0–50.5)	4.2 ± 1.5 (0.7–7.7)	18.1 ± 6.1 (2.5–32.5)
	Short	25.2 ± 5.2 (12.0–48.0)	2.7 ± 1.0 (0.6–5.3)	15.3 ± 5.5 (2.0–29.5)

Table A.2. Model results (parameter estimate, SE, t value, and p value) of the most parsimonious analysis of covariance describing the effects of box type and weather parameters on temperature availability, or the mean hourly range of temperatures in a design. The reference design represents the intercept, which is significantly different than zero. Daily (24-hour period) mean wind speed and daily mean global radiation significantly interacted with box design. Data collected from 20 box designs in Vigo County, Indiana, May 2018–September 2018 where bats were excluded.

Parameter	Estimate	SE	t	p
Reference design	3.02	0.61	4.94	< 0.001
Chimney design	-1.61	0.86	-1.87	0.06
Double vent design	-0.43	0.86	-0.50	0.62
House wrap design	-2.04	0.86	-2.37	< 0.05
Empty cavity design	-1.53	0.86	-1.77	0.08
Foam cavity design	-1.16	0.86	-1.35	0.18
Water cavity design	-0.75	0.86	-0.87	0.38
South roof shade design	-0.83	0.86	-0.96	0.34
Upper vent design	-0.66	0.86	-0.76	0.45
White gloss design	-1.39	0.86	-1.61	0.11
Composite material design	-0.77	0.86	-0.90	0.37
Jacket: empty design	-0.95	0.86	-1.10	0.27
Jacket: foam design	-0.80	0.86	-0.93	0.35
Jacket: water design	-1.08	0.86	-1.25	0.21
Opening wedge design	0.15	0.86	0.17	0.87
Vent removal design	-1.60	0.86	-1.86	0.06
Long design	-1.28	0.86	-1.49	0.14
Short design	-1.42	0.86	-1.65	0.10
Three-chambered design	-2.03	0.86	-2.35	< 0.05
Two-inch roof design	-0.98	0.86	-1.13	0.26
TaDailyMean	0.04	0.03	1.55	0.12
TaDailyRange	0.08	0.03	2.63	< 0.01
GlblRadDailyMean	0.01	0.00	7.75	< 0.001
WindSpdDailyMean	-0.33	0.02	-13.23	< 0.001
Chimney design:TaDailyMean	0.00	0.04	-0.10	0.92
Double vent design:TaDailyMean	-0.04	0.04	-1.03	0.30
House wrap design:TaDailyMean	-0.01	0.04	-0.28	0.78
Empty cavity design:TaDailyMean	0.05	0.04	1.18	0.24
Foam cavity design:TaDailyMean	0.02	0.04	0.54	0.59
Water cavity design:TaDailyMean	0.00	0.04	0.00	1.00
South roof shade design:TaDailyMean	-0.02	0.04	-0.39	0.69
Upper vent design:TaDailyMean	-0.03	0.04	-0.83	0.41
White gloss design:TaDailyMean	0.00	0.04	-0.10	0.92
Composite material design:TaDailyMean	-0.01	0.04	-0.37	0.71
Jacket empty design:TaDailyMean	0.04	0.04	1.00	0.32
Jacket foam design:TaDailyMean	0.05	0.04	1.16	0.24
Jacket water design:TaDailyMean	0.05	0.04	1.25	0.21

Parameter	Estimate	SE	t	p
Opening wedge design:TaDailyMean	-0.04	0.04	-0.98	0.33
Vent removal design:TaDailyMean	0.04	0.04	1.01	0.32
Long design:TaDailyMean	0.01	0.04	0.26	0.80
Short design:TaDailyMean	-0.02	0.04	-0.45	0.65
Three-chambered design:TaDailyMean	0.02	0.04	0.52	0.60
Two-inch roof design:TaDailyMean	0.01	0.04	0.31	0.76
Chimney design:TaDailyRange	-0.02	0.04	-0.47	0.64
Double vent design:TaDailyRange	0.01	0.04	0.29	0.77
House wrap design:TaDailyRange	-0.01	0.04	-0.20	0.84
Empty cavity design:TaDailyRange	0.04	0.04	0.92	0.36
Foam cavity design:TaDailyRange	0.02	0.04	0.47	0.64
Water cavity design:TaDailyRange	0.03	0.04	0.68	0.50
South roof shade design:TaDailyRange	-0.04	0.04	-0.97	0.33
Upper vent design:TaDailyRange	0.03	0.04	0.72	0.47
White gloss design:TaDailyRange	0.03	0.04	0.70	0.48
Composite material design:TaDailyRange	0.03	0.04	0.73	0.47
Jacket empty design:TaDailyRange	0.05	0.04	1.23	0.22
Jacket foam design:TaDailyRange	0.03	0.04	0.74	0.46
Jacket water design:TaDailyRange	0.05	0.04	1.15	0.25
Opening wedge design:TaDailyRange	0.02	0.04	0.54	0.59
Vent removal design:TaDailyRange	0.04	0.04	0.81	0.42
Long design:TaDailyRange	0.05	0.04	1.03	0.30
Short design:TaDailyRange	-0.02	0.04	-0.36	0.72
Three-chambered design:TaDailyRange	0.02	0.04	0.53	0.60
Two-inch roof design:TaDailyRange	0.04	0.04	0.95	0.34
Chimney design:GlblRadDailyMean	-0.01	0.00	-2.74	< 0.01
Double vent design:GlblRadDailyMean	0.00	0.00	-2.10	< 0.05
House wrap design:GlblRadDailyMean	-0.01	0.00	-2.62	< 0.01
Empty cavity design:GlblRadDailyMean	0.00	0.00	-0.18	0.86
Foam cavity design:GlblRadDailyMean	0.00	0.00	-0.08	0.94
Water cavity design:GlblRadDailyMean	0.00	0.00	0.59	0.55
South roof shade design:GlblRadDailyMean	0.00	0.00	-1.28	0.20
Upper vent design:GlblRadDailyMean	0.00	0.00	-1.46	0.14
White gloss design:GlblRadDailyMean	0.00	0.00	-1.37	0.17
Composite material design:GlblRadDailyMean	0.00	0.00	1.26	0.21
Jacket empty design:GlblRadDailyMean	-0.01	0.00	-2.67	< 0.01
Jacket foam design:GlblRadDailyMean	-0.01	0.00	-2.80	< 0.01
Jacket water design:GlblRadDailyMean	-0.01	0.00	-3.00	< 0.01
Opening wedge design:GlblRadDailyMean	0.00	0.00	0.64	0.52
Vent removal design:GlblRadDailyMean	0.00	0.00	1.16	0.25
Long design:GlblRadDailyMean	0.00	0.00	1.98	< 0.05
Short design:GlblRadDailyMean	-0.01	0.00	-3.11	< 0.01
Three-chambered design:GlblRadDailyMean	-0.01	0.00	-2.87	< 0.01

Parameter	Estimate	SE	t	p
Two-inch roof design:GlblRadDailyMean	0.00	0.00	-2.40	< 0.05
Chimney design:WindSpdDailyMean	0.16	0.04	4.60	< 0.001
Double vent design:WindSpdDailyMean	0.04	0.04	1.03	0.30
House wrap design:WindSpdDailyMean	0.18	0.04	5.22	< 0.001
Empty cavity design:WindSpdDailyMean	0.03	0.04	0.76	0.45
Foam cavity design:WindSpdDailyMean	0.01	0.04	0.26	0.80
Water cavity design:WindSpdDailyMean	-0.01	0.04	-0.15	0.88
South roof shade design:WindSpdDailyMean	0.11	0.04	3.02	< 0.01
Upper vent design:WindSpdDailyMean	0.04	0.04	1.12	0.26
White gloss design:WindSpdDailyMean	0.06	0.04	1.65	0.10
Composite material design:WindSpdDailyMean	0.00	0.04	-0.01	0.99
Jacket empty design:WindSpdDailyMean	0.06	0.04	1.71	0.09
Jacket foam design:WindSpdDailyMean	0.04	0.04	1.06	0.29
Jacket water design:WindSpdDailyMean	0.08	0.04	2.19	< 0.05
Opening wedge design:WindSpdDailyMean	-0.02	0.04	-0.55	0.59
Vent removal design:WindSpdDailyMean	0.07	0.04	1.90	0.06
Long design:WindSpdDailyMean	0.06	0.04	1.72	0.09
Short design:WindSpdDailyMean	0.13	0.04	3.78	< 0.001
Three-chambered design:WindSpdDailyMean	0.11	0.04	3.06	< 0.01
Two-inch roof design:WindSpdDailyMean	0.04	0.04	1.01	0.31

Table A.3. Model results (parameter estimate, SE, t value, and p value) of the most parsimonious analysis of covariance describing the effects of box type and weather parameters on temperature variability (maximum daily box temperature – minimum daily box temperature). The reference design represents the intercept, which is significantly different than zero. Daily (24-hour period) mean wind speed and daily mean global radiation significantly interacted with box design. Data collected from 20 box designs in Vigo County, Indiana, May 2018–September 2018 where bats were excluded.

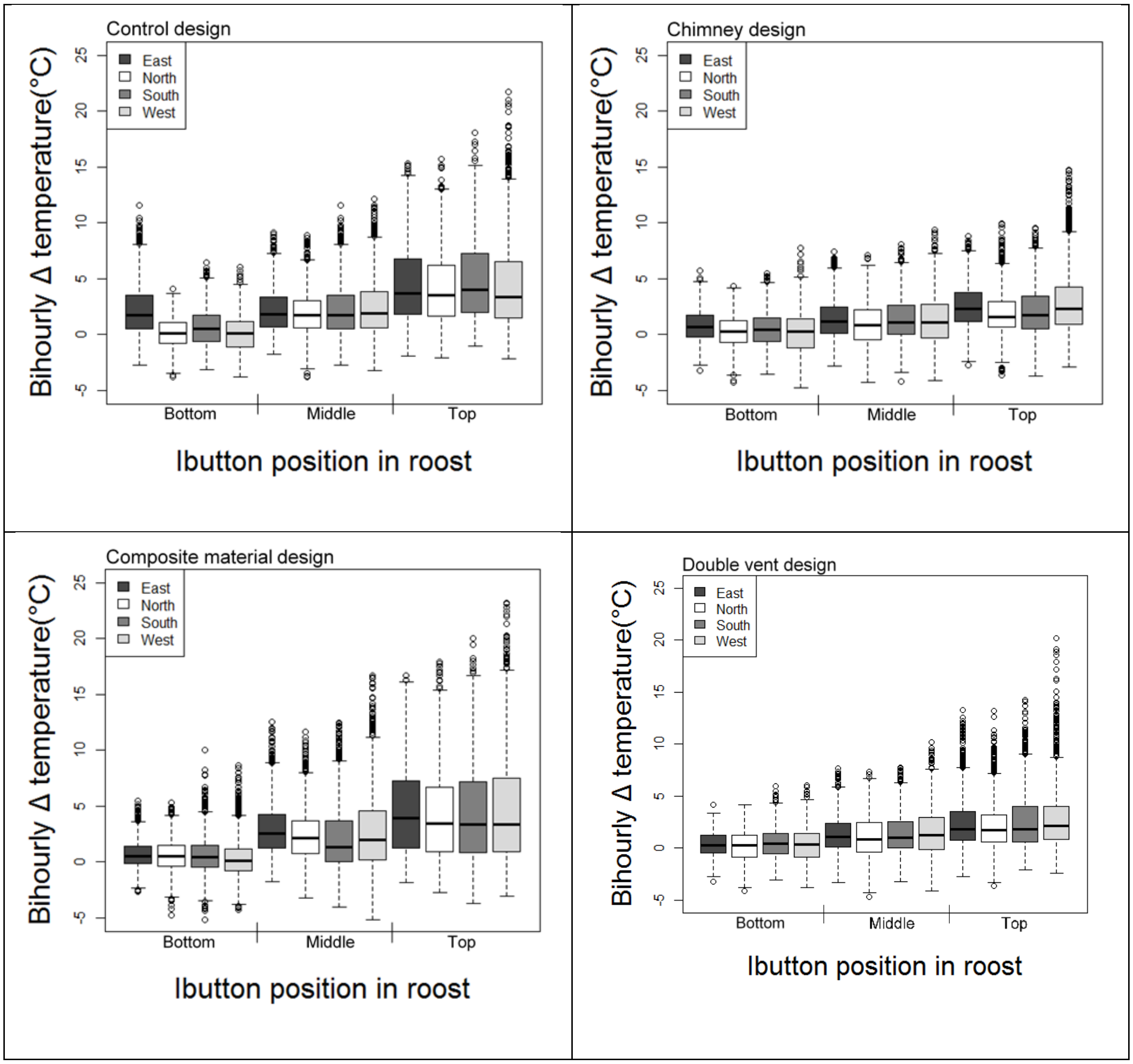
Parameter	Estimate	SE	t	p
Reference design	8.39	1.01	8.34	< 0.001
Chimney design	-4.50	1.34	-3.35	< 0.001
Double vent design	-2.45	1.34	-1.82	0.07
House wrap design	-5.24	1.34	-3.90	< 0.001
Cavity: empty design	-1.33	1.34	-0.99	0.32
Cavity: foam design	-0.90	1.34	-0.67	0.50
Cavity: water design	-1.24	1.34	-0.92	0.36
South roof shade design	-3.14	1.34	-2.34	< 0.05
Upper vent design	-2.17	1.34	-1.61	0.11
White gloss design	-2.83	1.34	-2.10	< 0.05
Composite material design	-1.45	1.34	-1.08	0.28
Jacket: empty design	-2.01	1.34	-1.50	0.13
Jacket: foam design	-1.86	1.34	-1.39	0.17
Jacket: water design	-2.59	1.34	-1.93	0.05
Opening wedge design	-0.75	1.34	-0.56	0.58
Vent removal design	-0.20	1.34	-0.15	0.88
Long design	-1.20	1.34	-0.90	0.37
Short design	-4.26	1.34	-3.17	< 0.01
Three-chambered design	-2.94	1.34	-2.19	< 0.05
Two-inch roof design	-1.88	1.34	-1.40	0.16
TaDailyMean	0.04	0.02	2.26	< 0.05
TaDailyRange	1.15	0.09	12.86	< 0.001
GlblRadDailyMean	0.01	0.00	3.85	< 0.001
WindSpdDailyMean	-0.74	0.07	-10.64	< 0.001
Chimney design:TaDailyRange	-0.08	0.13	-0.66	0.51
Double vent design:TaDailyRange	0.00	0.13	0.00	1.00
House wrap design:TaDailyRange	-0.09	0.13	-0.74	0.46
Empty cavity design:TaDailyRange	0.06	0.13	0.49	0.63
Foam cavity design:TaDailyRange	0.03	0.13	0.21	0.83
Water cavity design:TaDailyRange	0.00	0.13	0.01	0.99
South roof shade design:TaDailyRange	-0.21	0.13	-1.64	0.10
Upper vent design:TaDailyRange	0.03	0.13	0.26	0.80
White gloss design:TaDailyRange	0.04	0.13	0.30	0.76
Composite material design:TaDailyRange	-0.05	0.13	-0.41	0.68
Empty jacket design:TaDailyRange	-0.06	0.13	-0.49	0.63
Foam jacket design:TaDailyRange	-0.17	0.13	-1.34	0.18
Water jacket design:TaDailyRange	-0.16	0.13	-1.31	0.19

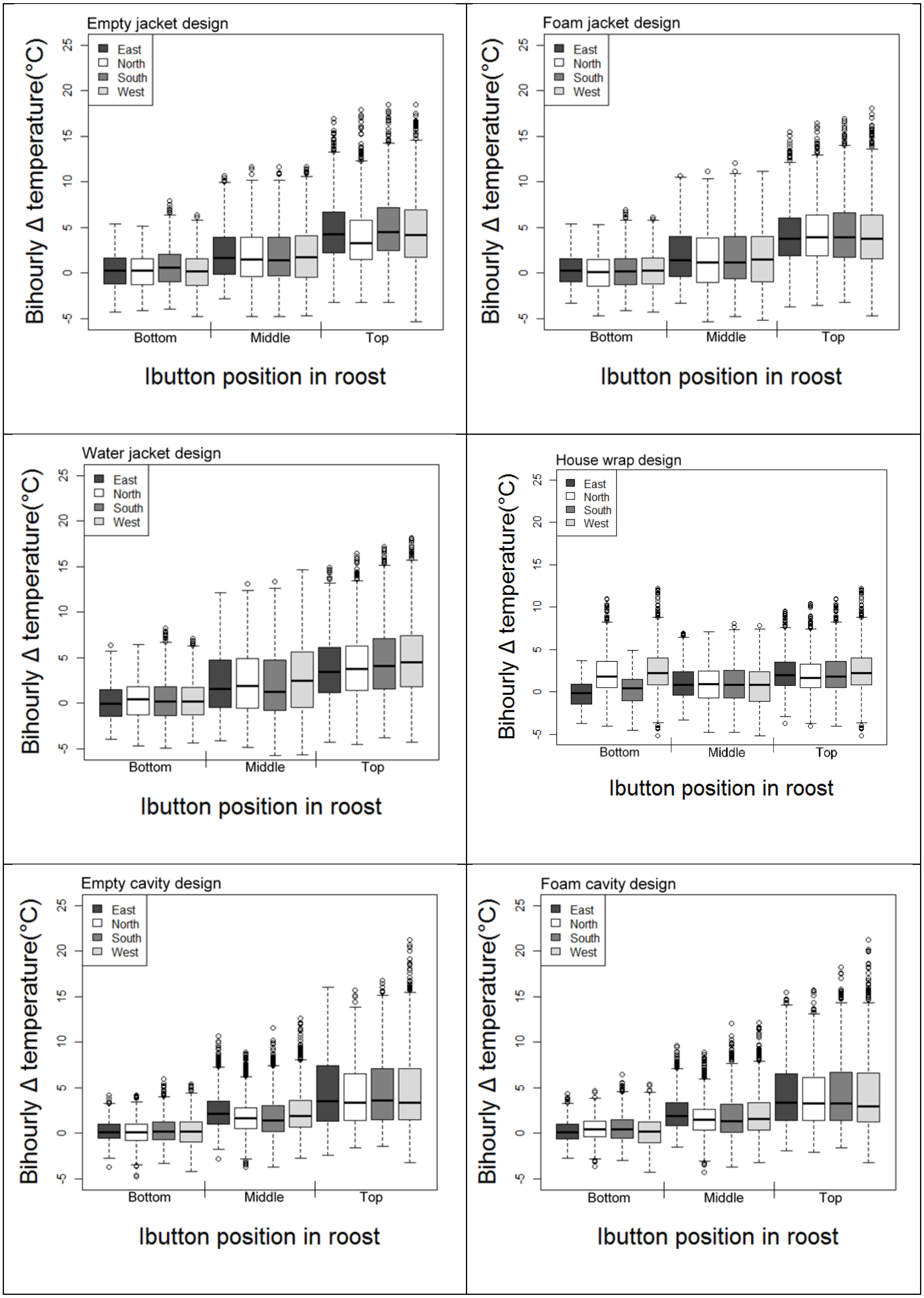
Parameter	Estimate	SE	t	p
Opening wedge design:TaDailyRange	-0.01	0.13	-0.08	0.93
Vent removal design:TaDailyRange	0.05	0.13	0.37	0.71
Long design:TaDailyRange	0.03	0.13	0.22	0.83
Short design:TaDailyRange	-0.05	0.13	-0.40	0.69
Three-chamber design:TaDailyRange	-0.07	0.13	-0.58	0.56
Two-inch roof design:TaDailyRange	-0.01	0.13	-0.11	0.91
Chimney design:GlblRadDailyMean	-0.01	0.01	-1.04	0.30
Double vent design:GlblRadDailyMean	-0.01	0.01	-0.96	0.34
House wrap design:GlblRadDailyMean	-0.01	0.01	-1.41	0.16
Empty cavity design:GlblRadDailyMean	0.00	0.01	0.11	0.91
Foam cavity design:GlblRadDailyMean	0.00	0.01	0.23	0.82
Water cavity design:GlblRadDailyMean	0.00	0.01	0.81	0.42
South roof shade design:GlblRadDailyMean	0.00	0.01	-0.31	0.76
Upper vent design:GlblRadDailyMean	0.00	0.01	-0.57	0.57
White gloss design:GlblRadDailyMean	-0.01	0.01	-1.01	0.31
Composite material design:GlblRadDailyMean	0.02	0.01	2.92	< 0.01
Empty jacket design:GlblRadDailyMean	0.00	0.01	-0.86	0.39
Foam jacket design:GlblRadDailyMean	0.00	0.01	-0.91	0.36
Water jacket design:GlblRadDailyMean	0.00	0.01	-0.69	0.49
Opening wedge design:GlblRadDailyMean	0.00	0.01	0.80	0.42
Vent removal design:GlblRadDailyMean	0.00	0.01	0.83	0.41
Long design:GlblRadDailyMean	0.01	0.01	1.13	0.26
Short design:GlblRadDailyMean	-0.01	0.01	-1.60	0.11
Three-chamber design:GlblRadDailyMean	-0.01	0.01	-0.94	0.35
Two-inch roof design:GlblRadDailyMean	0.00	0.01	-0.85	0.39
Chimney design:WindSpdDailyMean	0.35	0.10	3.53	< 0.001
Double vent design:WindSpdDailyMean	0.00	0.10	0.00	1.00
House wrap design:WindSpdDailyMean	0.37	0.10	3.82	< 0.001
Empty cavity design:WindSpdDailyMean	0.08	0.10	0.84	0.40
Foam cavity design:WindSpdDailyMean	-0.01	0.10	-0.09	0.93
Water cavity design:WindSpdDailyMean	0.02	0.10	0.19	0.85
South roof shade design:WindSpdDailyMean	0.27	0.10	2.77	< 0.01
Upper vent design:WindSpdDailyMean	0.00	0.10	-0.01	0.99
White gloss design:WindSpdDailyMean	0.12	0.10	1.27	0.20
Composite material design:WindSpdDailyMean	-0.06	0.10	-0.56	0.57
Empty jacket design:WindSpdDailyMean	0.13	0.10	1.34	0.18
Foam jacket design:WindSpdDailyMean	0.14	0.10	1.43	0.15
Water jacket design:WindSpdDailyMean	0.24	0.10	2.45	< 0.05
Opening wedge design:WindSpdDailyMean	-0.06	0.10	-0.63	0.53
Vent removal design:WindSpdDailyMean	0.13	0.10	1.36	0.18
Long design:WindSpdDailyMean	0.16	0.10	1.58	0.11
Short design:WindSpdDailyMean	0.22	0.10	2.24	< 0.05

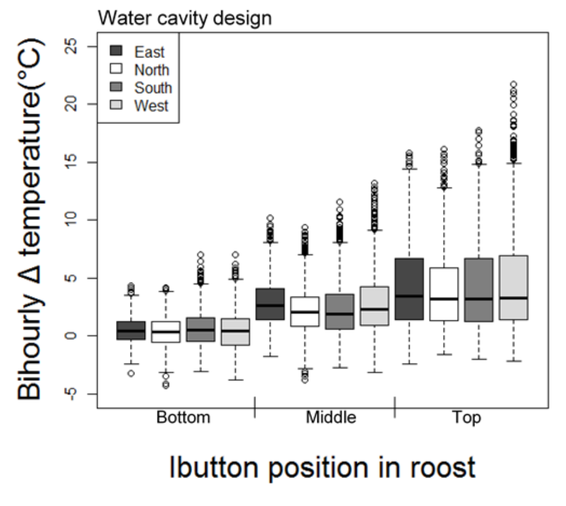
Parameter	Estimate	SE	t	p
Three-chamber design:WindSpdDailyMean	0.15	0.10	1.50	0.13
Two-inch roof design:WindSpdDailyMean	0.08	0.10	0.81	0.42

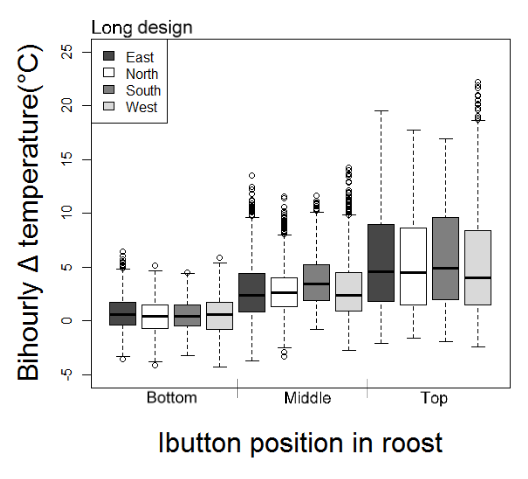
APPENDIX B: BIHOURLY Δ TEMPERATURE BY IBUTTON POSITION

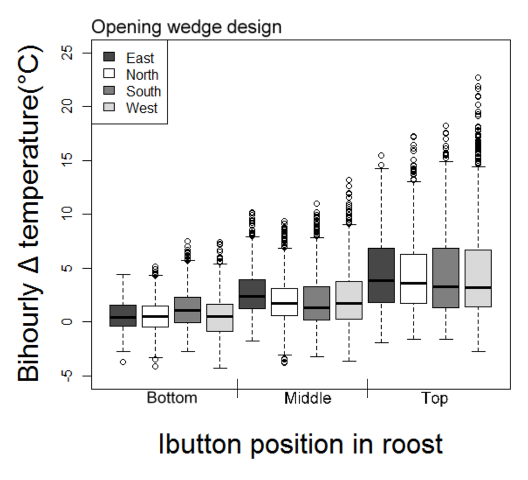
Boxplots of the bihourly Δ temperature ($T_{max} – T_a$) recorded at each iButton position of each box design in Vigo County, Indiana, May 2018–September 2018 where bats were excluded. Boxes represent inter–quartile range. Upper whiskers represent the largest observation less than or equal to a box's upper hinge + 1.5 * IQR (inter-quartile range). Lower whiskers represent the smallest observation greater than or equal to a box's lower hinge – 1.5 * IQR. The solid horizontal lines in each box indicate the median.

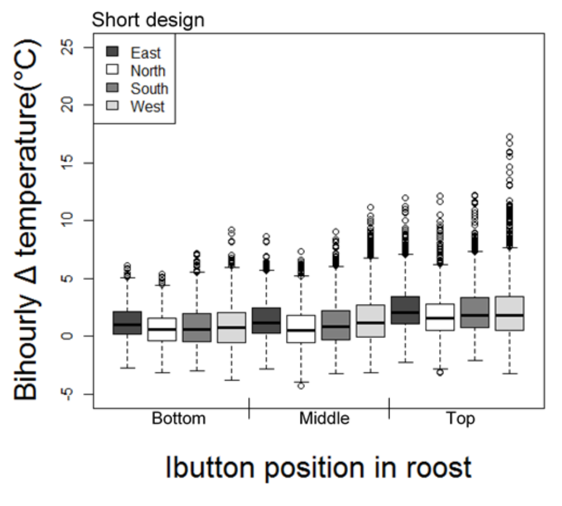


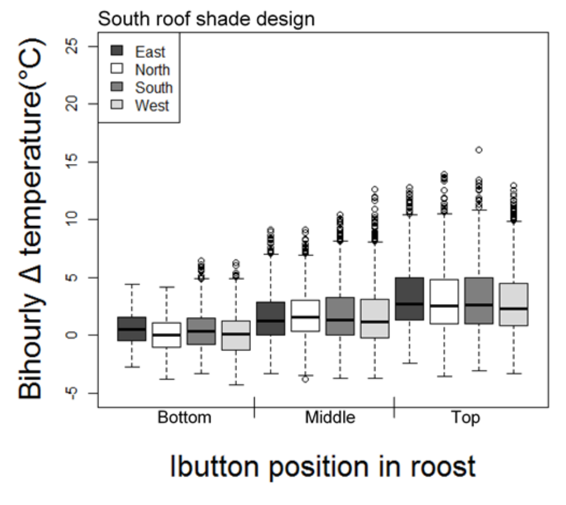

Empty jacket design
Foam jacket design
Water jacket design
House wrap design
Empty cavity design
Foam cavity design
■ East
□ North
■ South
□ West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost

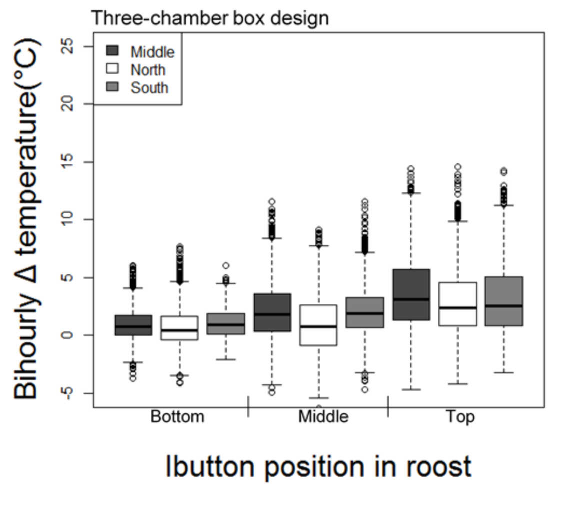

Water cavity design
East
North
South
West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost


Long design
East
North
South
West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost


Opening wedge design
East
North
South
West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost


Short design
East
North
South
West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost


South roof shade design
East
North
South
West
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost


Three-chamber box design
Middle
North
South
Bihourly Δ temperature(°C)
-5
0
5
10
15
20
25
Bottom
Middle
Top
Ibutton position in roost