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RESEARCH ARTICLE

Influence of nest box design on internal microclimate: Comparisons of plastic prototypes

Michael N. Callan[1,2] | Alexander Johnson[3] | David M. Watson[1,4]

[1]School of Agriculture, Environmental and Veterinary Sciences, Charles Sturt University, Albury, New South Wales, Australia
[2]Habitat Innovation & Management, Wollongong, New South Wales, Australia
[3]School of Engineering, Charles Sturt University, Albury, New South Wales, Australia
[4]Gulbali Institute, Charles Sturt University, Albury, New South Wales, Australia

Correspondence
David M. Watson, School of Agriculture, Environmental and Veterinary Sciences, Charles Sturt University, Albury, NSW, Australia.
Email: dwatson@csu.edu.au

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Abstract
Hollow-dependent fauna are declining worldwide, due primarily to the widespread clearing of hollow-bearing trees. Artificial cavities such as timber and plywood boxes are commonly used to increase hollow availability, yet there is increasing evidence that they are poor facsimiles of natural cavities, characterized by lower insulative properties and a shorter field life. We evaluated whether plastic materials could create a nest box with a stable thermal profile that more closely resembles the complex shapes and textures of natural tree hollows while containing fewer mechanical joins that represent potential failure points when installed. We developed three sets of prototype nest boxes comprising various combinations of plastic density (10%, 25% and 50%), insulation (single vs. double wall with or without sawdust between them), nesting chamber (with or without timber inserts) and bedding (with or without decomposed heartwood) and compared their thermal performance in a temperature-controlled laboratory to compare internal temperature and relative humidity. We found double-walled plastic nest box with an internal timber-lined chamber was best able to buffer ambient temperature fluctuations, consistently recording internal temperatures of 6+°C below maximum ambient temperature, maintaining high levels of relative humidity (76%–92%) when furnished with decomposed timber heartwood. This design also performed better during a simulated hot day; internal temperatures exhibiting twice the lag time of single-walled designs, noting that plastic density had little influence on internal conditions. While the recruitment and protection of hollow-bearing trees must be a priority, this work shows significant potential in improving the design and functionality of artificial hollows that are critical to the conservation of hollow-dependent species.

KEYWORDS
3D-printing, cavity, climatic extremes, heat wave, thermal ecology

INTRODUCTION

One functional group that is consistently reported to be declining in numbers is tree hollow-dependent species, comprising a wide range of vertebrate and invertebrate fauna (Peterson & Grubb, 1983; Stojanovic et al., 2012). Extensive land clearing drove dramatic decreases in tree hollows in forest and woodland communities worldwide (Lindenmayer et al., 2016; Rayner et al., 2014) and traditional silvicultural practices either prevent the development of hollows or encourage the removal, of large trees, and in particular dead trees which are more likely to contain them (Eyre, 2005; Webb & Shine, 1997). Where revegetation for wildlife habitat is occurring, trees are typically planted at high stem densities in lower productivity landforms, resulting in slower growth rates, fewer and smaller radial branches (Vesk et al., 2008). So, although both numbers of trees and proportion of native vegetation cover are increasing in many regions, delayed development means that hollow availability will continue decreasing for many decades before increasing once planted trees become sufficiently mature (Horner et al., 2010; Taylor et al., 2014).

Although nest boxes are widely considered the best available interim solution to the reduction in tree hollows globally, their effectiveness as even a short-term solution to tree hollow availability at larger scales is questionable due to three aspects of their construction: short lifespan relative to the time it takes for natural tree hollows to form, high microclimate variation and a mismatch between nest box dimensions and species preferences (Goldingay, 2009; Goldingay et al., 2020; Rueegger et al., 2019). A key concern is the temperature and humidity extremes and variability within nest boxes which do not replicate the thermal properties of natural hollows (Larson et al., 2018). Current nest box designs may be of limited value to wildlife during heat events due to extreme temperatures, with peaks of up to 52°C being recorded in timber roost boxes for arboreal mammals (Rowland et al., 2017). Although it has been demonstrated that there was no mortality or decline in abundance of brush-tailed phascogales (*Phascogale tapoatafa*) or sugar gliders (*Petaurus breviceps*) using nest boxes during a prolonged extreme heat event (Goldingay & Thomas, 2021), commonly used bat box designs have been recorded exceeding 44°C, the lethal limit for bats (Nagorsen, 2009). Birds using nest boxes may be impacted by reduced reproductive success or disrupted offspring development when exposed to extreme heat (Ardia et al., 2006; Fukui et al., 2010; Larson et al., 2015). Humidity is also a determining factor in nest/roost selection and reproductive success for various birds and bats (Bartonicka & Rehák, 2007; Bobek et al., 2018; Butler et al., 2009; Sedgeley, 2001), but the bedding which increases humidity can accelerate decomposition of the structure itself (Hebda et al., 2017). A range of novel artificial hollow solutions have been tested, largely unsuccessfully, including the use of masonry pipes (Campbell et al., 2012) and polystyrene trees (Peterson & Grubb, 1983) as well as the inoculation of trees with decay fungi using firearms to accelerate hollow development (Filip et al., 2004). New technology is allowing the use of computational modelling, 3D-scanning and augmented reality assembly of digitally fabricated materials to create artificial refuges, with use by target species yet to be determined (Parker et al., 2022). Recent work in creating artificial hollows in standing trees with chainsaws appears to provide the potential for a successful medium-term solution, with similar thermal properties to natural hollows, and the ability to create hollow specifications in a suitable range for target species (Best et al., 2022; Rueegger, 2017).

We evaluated whether known shortcomings of conventional nest boxes could be overcome using additive manufacturing like 3D printing to refine prototypes for mass production of nest boxes made of long-lasting materials. The use of plastic in the construction of nest boxes may influence the humidity within the nesting/roosting chamber, and the impervious plastic nest boxes are predicted to maintain high levels of humidity in comparison with ambient conditions, and more consistent with natural tree hollows. In a coordinated series of studies, we designed and manufactured prototype nest boxes and used laboratory trials to compare thermal performance under three simulated temperature regimes. Prototype nest boxes displayed various combinations of plastic density (10%, 25% and 50%), insulation (single vs. double wall with or without sawdust between them), nesting chamber (with or without timber inserts) and bedding (with or without decomposed heartwood). Subsequent work deployed the best-performing designs to compare how the prototypes perform under field conditions and evaluate use by both target and non-target species, but this contribution focuses on determining which design component(s) has the greatest influence on internal microclimate.

METHODS

Three sets of prototype nest boxes (nine in total) were made to test the thermal properties of different materials, all conforming to the same overall size and shape. These boxes were designed for small hollow-dependent species including Striated pardalote (*Pardalotus striatus*) and Feathertail glider (*Acrobates pygmaeus*); dimensions of nest/den sites acquired from published measurements (Milledge, 1978; Shanahan et al., 2008). Internal dimensions of the cylindrical nest boxes were 150 mm height and 100 mm diameter with an entrance hole located 100 mm above the base of the box. Unless otherwise noted, all boxes were furnished to a depth of 50 mm with decomposed heartwood timber sourced from natural tree hollows by an arborist several months earlier (stored in the interim in unsealed containers outside, so deployed with field-ambient water content). All boxes were painted with two coats of exterior grade paint (Dulux Weathershield; 'Buffalo Bill' colour) prior to testing, noting that nest boxes painted with darker colours have been found to become significantly hotter in field conditions (Ellis & Rhind, 2021; Rueegger, 2019). In addition to five 3D-printed double-walled nest boxes (Type 1) of various plastic densities and bedding material, we tested three 3D-printed double-walled nest boxes with timber inserts (Type 2) of various plastic densities and one single-walled box made from PVC pipe lined with timber. These nine prototypes revealed the influence of construction type (single vs. double wall), plastic density (10%, 25% and 50%) and bedding (decomposed heartwood, or nothing) on internal conditions (temperature and humidity).

3D-printed nest boxes

Type 1 nest boxes featured a double-wall construction with the walls 6 mm thick, with an 8-mm cavity in between. External walls had a textured surface designed to imitate bark, which added up to 2 mm in additional thickness (Figure 1a). A separate double-wall lid was designed and printed using the same materials and measuring 18 mm thick. Eight 4 mm drainage holes were spaced around the base of the box and a separate concave drainage base with an 8-mm central drainage hole was fitted inside the base of the box and supported by an incorporated ledge to raise this component 10 mm above the convex base. Five 3D-printed nest boxes of Type 1 were produced for this trial using Mamorubot brand wood filament, which incorporates timber residue in a polylactic acid (PLA)-based plastic filament. One box was printed at 10% density, three boxes at 25% density and one box at 50% density, where density relates to the volume of plastic used to infill the gaps; that is, 100% density would have no air gaps within the printed product. Of the three boxes produced with 25% density, one had the wall cavity filled with sawdust as additional insulation, one acted as a control and one excluded the use of decomposed timber heartwood.

FIGURE 1 Different designs of plastic nest boxes compared in climatic trials. (a) Nest box Type 1: 3D-printed nest box, with no timber inserts. Note the textured bark exterior. (b) Nest box Type 2: Double-height, 3D-printed nest box with timber inserts (unpainted). The air space between the double walls has been enclosed in the design and is not visible; decomposed heartwood timber furnishes the base. (c) Double-height, 3D-printed nest box showing entrance, and blank that closes off the lower entrance hole; bayonet-style fittings allow for multiple body sections to be connected. (d) Nest box Type 3, with octagonal timber insert fitted inside a 150-mm diameter PVC pipe housing, showing marine plywood base with central drainage hole, drilled entrance hole and horizontal cuts in timber inserts to facilitate fauna egress. (e) A range of PVC/timber habitat hollows showing the octagonal hardwood timber insert, 3D-printed entrances, and bracket systems for fitting to trees, power poles and other convex structures

3D-printed nest boxes with timber inserts

Nest box Type 2 also featured double plastic walls, creating an air pocket enclosed at the top and bottom. Additionally, timber panels slid into incorporated cavity slots to create a wooden nesting/denning chamber. The boxes were designed to have comparable internal dimensions to the Type 1 boxes. Six 19 mm thick hardwood panels were inserted into the custom slots to create a hexagonal nesting chamber (Figure 1b,c). The double plastic walls were 8 mm thick, with an 8-mm wide air pocket between them. An entrance tunnel 35 mm in diameter extended 30 mm from the main body of the nest box. The base of the nesting chamber was constructed separately and fitted to the nest box via an incorporated bayonet locking mechanism. Ten 4-mm drainage holes were located around the outer perimeter of the concave base designed to facilitate drainage. A nesting cup of a convex shape was inserted into the base of the box, featuring an 8-mm central drainage hole. A separate lid fitted into the top of the nest box via a bayonet fitting, 18 mm in thickness comprising two 4-mm thick walls enclosing a 10-mm thick air void. The design of this nest box is modular, allowing multiple nest chambers to be connected to increase internal height of the nest box. Where multiple chambers are connected, a blank was produced to block additional entrance holes (Figure 1c). One nest box of this design was printed at 25% density, one at 50% density and a double-height box, comprising two connected body modules, printed at 25% density.

Polyvinyl chloride/timber nest box

Nest box Type 3 was constructed from 150-mm diameter polyvinyl chloride (PVC) pipe fitted with end caps for the base and lid. The bottom end cap was drilled to include four 5-mm drainage holes, then glued and riveted to the PVC pipe to provide a secure base. The end cap for the lid was a push-on fitting to permit inspection when installed in the field. Discs of 19-mm marine plywood were attached to the inside of both lid and base using polyurethane adhesive to provide a full timber internal nest/roost cavity, with a 6-mm hole drilled in the centre of the base for drainage. An octagonal internal chamber was constructed of 18-mm hardwood providing an internal useable diameter of approximately 110 mm (Figure 1d). Three of the eight timber panels used to construct each octagon had a series of horizontal saw cuts creating a textured climbing / roosting surface (Figure 1e). Sections of ‘artificial bark’ (designed in cooperation with a consultant design engineer) were manufactured using 3D printing in the form of fused deposition modelling (FDM) using Mamorubot brand wood filament. ‘Artificial bark’ was attached to the outside of the PVC pipe to provide a more natural appearance and to help fauna to grip. An entrance hole was cut through both the PVC pipe and timber insert, and a 3D-printed entrance, designed and manufactured as above, was glued and screwed to the exterior of the PVC pipe to create a branch stub hollow appearance.

Temperature regimes

Thermal testing was conducted in a temperature-controlled laboratory at Charles Sturt University's Bathurst campus, in New South Wales, Australia. Climate within the laboratory is controlled by an Innotech control system, which was used to adjust temperature. Humidity settings were not altered throughout the trials, so any variation in ambient humidity was stochastic rather than experimentally adjusted. Nest boxes were positioned on a plastic trestle table; relative positions determined using a random number generator. Testing commenced on 23 September 2019 at 7:00 AM and concluded on 25 September 2019 at 4:30 PM. Due to manufacturing delays, the double-height Type 2 box (double-walled 3D-printed box with timber inserts) was not included in the testing until 25 September 2019. The boxes were all stored and transported together, placed into the laboratory at the same time and not removed until the end of the last trial. Variation within the temperature and humidity within the boxes at the start of the trials were minimal, subsequent changes entirely due to the thermal properties of each box type. Temperature and humidity data loggers (Thermochron iButton DS1923) were used to monitor thermal properties within habitat boxes, as well as ambient conditions. All thermochrons were factory calibrated, variance from reference temperature to recorded temperatures equal to ±0.15°C, with humidity variance equal to ±2.5%. All thermochrons were attached to plastic thermochron fobs screwed to the inside wall of each nest box on the opposite side to the nest box entrance, positioned 25 mm above the level of furnished decomposed heartwood timber. Thermochrons were programmed to record temperature and humidity at 5-min intervals for the duration of the study. Three additional thermochrons recorded ambient temperature and humidity and placed in the centre and at either end of the trestle table.

Three temperature regimes were selected to test how different nest box designs performed under different real-world conditions. For regime 1, a hot day was replicated by gradually adjusting the Innotech thermostat at 30-min intervals from 21°C at 7:30 AM to the maximum temperature setting at 12:00 PM for 4 h. The second regime replicated the decreasing temperatures of a cool change, temperature settings adjusted every half hour for 4 h, beginning at 36°C and reducing to 26°C, then dropped for 6 h to reach the minimum available temperature within the thermally controlled environment. The third regime comprised a rapid temperature change to quantify any delay in temperature within the nest boxes. From a setting of 1°C overnight, the thermostat was increased to 20°C at 7:00 AM; 30°C at 8:30 AM; and 34.6°C (a higher temperature could not be reliably achieved) at 10:00 AM. Settings were then reduced to 30°C at 11:30 AM; 20°C at 1:00 PM; and minimum available temperature at 2:30 PM. The trial concluded at 4:30 PM.

To evaluate determinants of variation thermal conditions inside the different nest boxes, temperature and relative humidity in each nest box were compared with contemporaneous ambient conditions using Wilcoxon matched pairs (critical value of 0.05). Although replicated trials were conducted to compare performance of different nest box designs under natural conditions (quantifying effects of aspect, habitat structure and animal usage on microclimate, reported in a follow-up publication), the purpose of these trials was to evaluate the effect of individual design parameters (plastic density, insulation, timber lining and bedding) of prototypes under controlled conditions. Mean values of temperature and humidity, maximum and minimum temperatures within each nest box were deemed the most biologically significant variables. All analyses were performed using RStudio version 1.1.453.

RESULTS

Temperatures within each of the nest boxes demonstrated a lag period of 2 to 3 h compared with ambient in the first trial (Figure 2) replicating a hot day. All boxes were significantly cooler than ambient (Wilcoxon matched pairs test, $p < 0.0001$ for each test), means ranging from 19.8 to 26.0 °C (SD range 7.5–8.7), compared with ambient mean of 27.9°C (SD = 7.0). The Type 1 box (3D-printed, no timber inserts) without bedding material warmed faster than all other boxes, with a mean of 26.0°C (SD = 8.0). Mean temperatures in other Type 1 boxes varied little (means 23.9–24.8°C, SD range 7.6–8.1°C), the box with sawdust-filled wall cavities warming the slowest (peak temperature of 31.0°C). Percentage density explained little variation in internal temperatures, the 50% density box reaching a maximum of 32.7°C, compared with 32.6°C for the 25% box and 32.9°C for the 10% box (Figure 2). Type 2 boxes (3D-printed with timber inserts) warmed more slowly than all other boxes trialled. Maximum temperatures reached in these boxes were 30.7°C (25% density) and 30.9°C (50% density) compared with

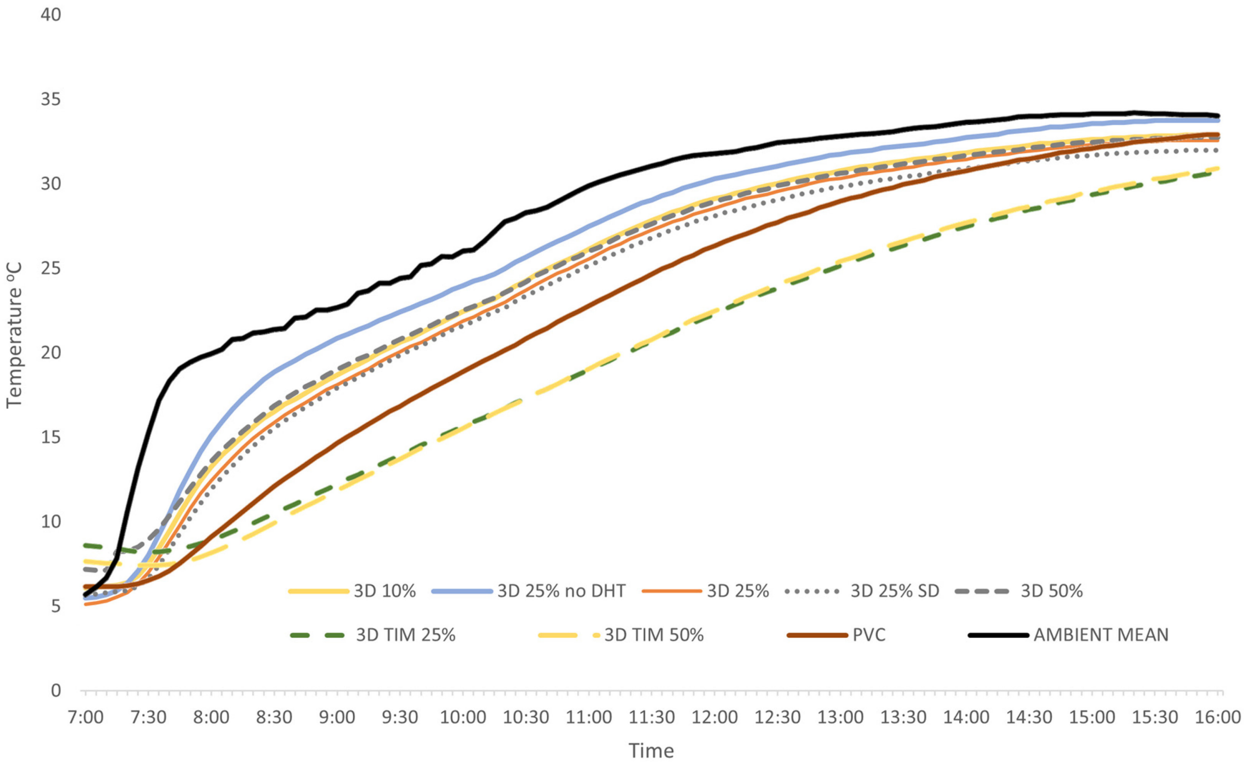

FIGURE 2 Temperature variation in thermal trial no. 1 inside eight plastic nest boxes compared with ambient. Type 1 3D-printed boxes contained decomposed heartwood printed at 10% density (3D 10%), 25% density (3D 25%) and 50% density box (3D 50%) compared with 25% density boxes with sawdust insulation (3D 25% SD) and without decomposed heartwood (3D 25% no DHT); compared with Type 2 3D-printed nest boxes with timber inserts printed at 25% density (3D TIM 25%) and 50% density (3D TIM 50%) and Type 3 PVC pipe with timber inserts (PVC).

maximum ambient temperature of 34.2°C. The Type 3 box (PVC pipe with timber inserts) recorded a maximum temperature of 32.9°C.

For the second trial, replicating the cooling down period following a hot day, all boxes recorded significantly warmer mean temperatures than ambient (Wilcoxon matched pairs test, $p<0.05$ for all tests), with mean values of 19.3–21.1°C (SD range 5.1–9.7°C) compared with the ambient mean of 19.1°C (SD = 10.8°C). Type 1 boxes exhibited shorter lag times; the box without bedding recorded the highest and lowest temperatures (32.6°C and 7.1°C, compared with 27.3–30.3°C and 7.1–11.4°C, approaching ambient temperatures of 34.6°C and 6.3°C; Figure 3). Type 2 boxes exhibited more moderate internal temperatures, maxima of 27.3 and 27.4°C and minima of 11.3 and 11.4°C for 25% and 50% densities, respectively. The Type 3 box recorded maximum and minimum temperatures of 28.8 and 9.1°C.

In the third thermal trial (extreme fluctuation), Type 2 nest boxes exhibited the greatest internal stability, taking longer to warm up when ambient temperatures climbed (lag time of 3 to 4 h) and staying warmer for longer when ambient temperatures fell (Figure 4). The only box that showed no significant difference from ambient temperature was the Type 1 box without bedding (mean of 21.1°C; SD = 6.3; ambient mean 21.5°C; SD = 6.2, Wilcoxon matched pairs test, p = 0.074). All other nest box variants differed significantly from ambient (Wilcoxon matched pairs test, $p<0.001$ for each test). The double-height Type 2 box exhibited the longest lag times and least fluctuation (mean of 17.0°C, SD = 5.8; ambient mean of 21.5°C, SD = 6.2; Figure 3).

Humidity was assessed during trial three, comparing all nine box types (Figure 5). The only nest box that did not differ from ambient was the Type 1

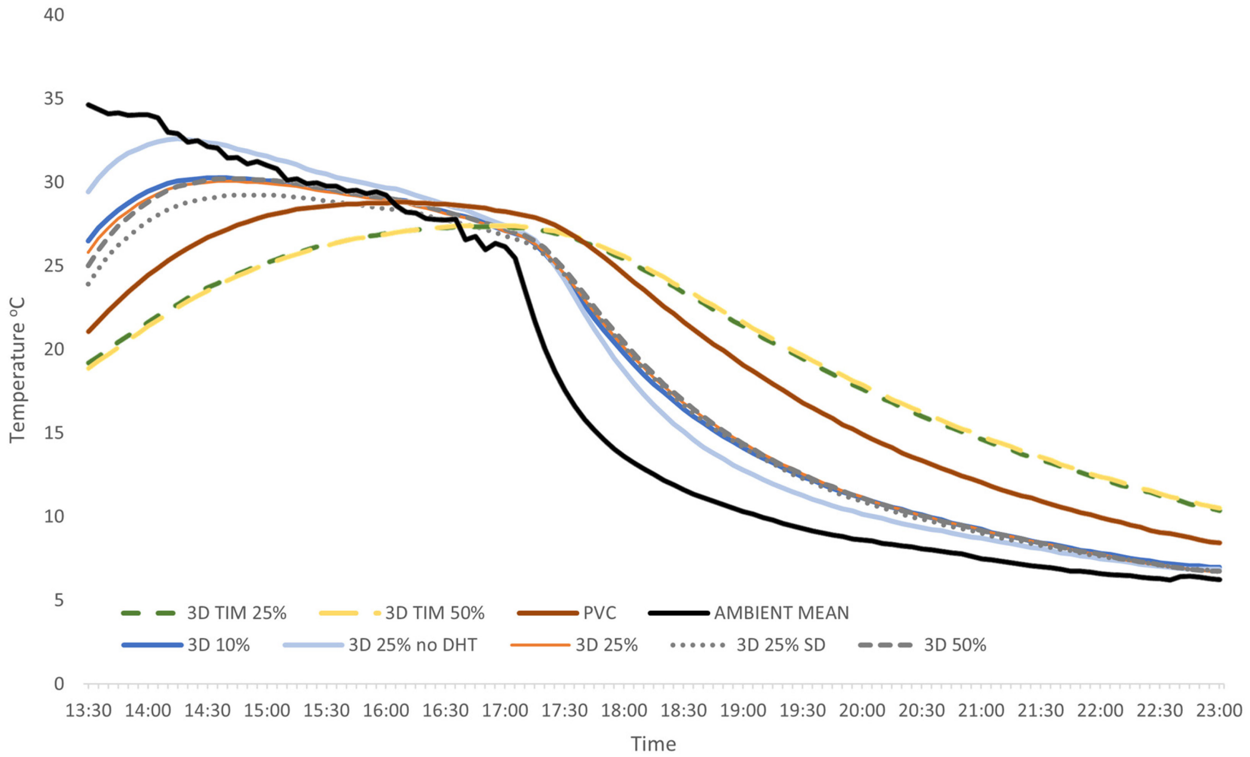

FIGURE 3 Temperature variation in thermal trial no. 2 inside eight plastic nest boxes compared with ambient. Type 1 3D-printed boxes containing decomposed heartwood printed at 10% density (3D 10%), 25% density (3D 25%) and 50% density box (3D 50%) compared with 25% density boxes with sawdust insulation (3D 25% SD) and without decomposed heartwood (3D 25% no DHT), Type 2 3D-printed nest boxes with timber inserts printed at 25% density (3D TIM 25%) and 50% density (3D TIM 50%), and Type 3 PVC pipe with timber inserts (PVC).

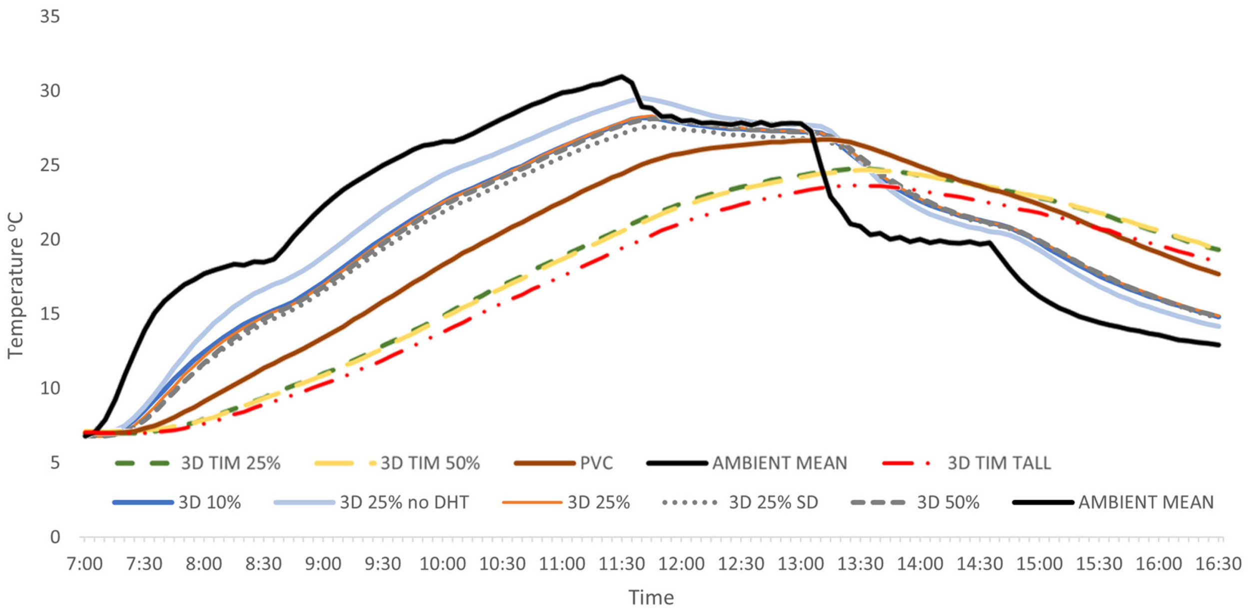

FIGURE 4 Temperature variation in thermal trial no. 3 inside nine plastic nest boxes compared with ambient. Type 1 3D-printed boxes containing decomposed heartwood printed at 10% density (3D 10%), 25% density (3D 25%) and 50% density box (3D 50%) compared with 25% density boxes with sawdust insulation (3D 25% SD) and without decomposed heartwood (3D 25% no DHT), Type 2 3D-printed nest boxes with timber inserts printed at 25% density (3D TIM 25% for regular height, 3D TIM TALL for double height), and 50% density (3D TIM 50%) and Type 3 PVC pipe with timber inserts (PVC).

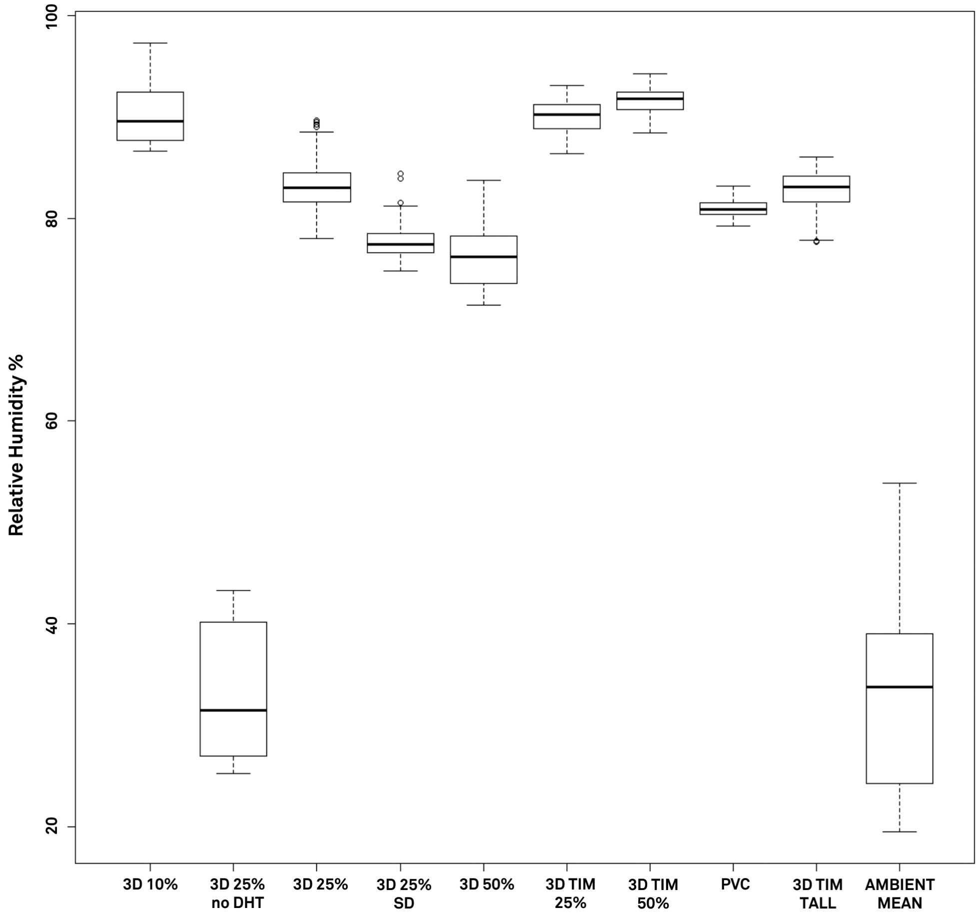

FIGURE 5 Mean, minimum and maximum humidity of nine nest box types, in comparison with ambient humidity, from trial no. 3. 3D-printed boxes containing decomposed heartwood timber printed at three densities: 10% density (3D 10%), 25% density (3D 25%) and 50% density box (3D 50%) compared with 25% density boxes with sawdust insulation (3D 25% SD) and without decomposed timber (3D 25% no DHT) compared with 3D-printed nest boxes with timber inserts printed at 25% density at regular and double-height (3D TIM 25% and 3D TIM TALL, respectively) and 50% density (3D TIM 50%) compared with PVC pipe with timber inserts (PVC).

box without bedding (Wilcoxon matched pairs test, p = 0.29). All other box types showed significantly higher humidity than ambient (76.1%–91.7%; SD = 0.9%–2.9% compared with 32.4%, SD = 8.1%, Wilcoxon matched pairs tests; p = 2.2 E-16; Figure 5.).

DISCUSSION

Our trials demonstrated that a double-walled plastic nest box with timber inserts provides a stable internal microclimate under testing in a temperature-controlled laboratory. Across three separate thermal trials, the 3D-printed nest boxes with timber inserts (Type 2 design) demonstrated significantly more stable thermal profiles than the other two plastic nest box designs tested. The best performing nest box in Trial 3 (simulating rapidly fluctuating temperatures during an energetic storm) was a double-height version of the 3D-printed, double-walled box with timber inserts (Type 2 design), recording a maximum temperature that was 7.3°C below the peak ambient temperature. This demonstrates the effect of the insulative casing as this maximum temperature was recorded 4 h after the equivalent ambient temperature recording, in a period when ambient temperature continued to increase. During the same trial, the single-height 3D boxes with timber inserts, recorded 6°C below ambient maximum temperature. The first and second trials simulated a gradual increase and decrease in temperature (respectively), with the double-walled plastic boxes with timber inserts (Type 2 design) consistently recording the lowest maxima as ambient temperatures increased, and the highest minima as ambient temperatures decreased. Regardless of plastic density, this same design took the longest to heat up and cool down, with lag times of ~4 h required to attain maximum temperatures. Incorporating decomposed heartwood timber as bedding had a significant impact on both temperature and humidity. In each of the three tests conducted, the 3D-printed box (Type 1 design) lacking bedding material exhibited the greatest temperature fluctuations, with no significant variation from ambient temperature in Trial 3.

Although plastic nest boxes have been previously developed (Elston et al., 2007; Rueegger et al., 2013; Saunders et al., 2020), this is the first comparative study of various designs. The consistently greater stability of internal temperatures within double-walled plastic boxes aligns with previous comparisons of timber nest boxes (Ellis & Rhind, 2021), approaching the thermal profile of natural hollows. In addition to buffering fluctuating ambient temperatures, all double-walled box types we tested displayed prolonged lag periods in attaining comparable ambient temperatures. This is in marked contrast to timber nest boxes, numerous studies noting high internal temperatures (Isaac et al., 2008; Maziarz et al., 2017) and prolonged periods exceeding critical thermal maxima for inhabitants (Nagorsen, 2009; Rowland et al., 2017; but see Goldingay & Thomas, 2021). By providing a significantly more stable microclimate than ambient conditions, and consistently lower maxima, our findings have demonstrated that nest boxes can be designed and built to more closely resemble the microclimate of natural tree hollows.

When evaluating the microclimate of a nest/roost cavity, humidity is an important consideration (Clement & Castleberry, 2013). Timber nest boxes are generally unable to replicate the relatively high humidity (mean ~ 90%) found in tree hollows (Maziarz et al., 2017; Rueegger, 2019). Our study has demonstrated mean relative humidity values ranging from 76.1% to 91.7% across all boxes furnished with decomposed heartwood timber. A study on the Brown long-eared bat (*Plecotus auritus*) and Daubenton's bat (*Myotis daubentonii*) demonstrated that evaporative water loss from these species could be in excess of 30% of body mass in a single day, when exposed to low levels of relative humidity (Webb et al., 1995). The New Zealand long-tailed bat (*Chalinolobus tuberculatus*) actively selects roosts with high levels of humidity, that maintain a consistent humidity range, in comparison with other available roosts (Sedgeley, 2001). Nest humidity is also an important factor in the loss of water vapour, and associated mass, from birds and their eggs (Deeming, 2011; Vleck et al., 1983). However, high humidity can also encourage fungal growth, with Aspergillosis, an infectious fungal disease impacting on the avian respiratory tract, known to particularly impact on captive birds exposed to high humidity levels, but is less common in wild avifauna (Beernaert et al., 2010). We selected decomposed heartwood timber for use in these boxes as it is the natural substrate found in tree hollows. Many nest box studies fail to identify whether a bedding material is included in their nest boxes, or if so, the type of bedding material included (Brazill-Boast et al., 2013; Butler et al., 2009; Charter et al., 2010; Rowland et al., 2017). However, for timber nest boxes, the utilization of decomposed heartwood timber would likely contribute to rapid failure of the box, as it would lead to the accelerated decomposition of the nest box timber (Hebda et al., 2017), more than half the nest boxes deployed in wet forest for Leadbeater's Possum (*Gymnobelideus leadbeateri*) failing within less than 10 years (Lindenmayer et al., 2009). Indeed, a report into the use of artificial hollows by Carnaby's black cockatoos (*Calyptorhynchus latirostris*) specifies that bedding materials that retain moisture are not suitable, and that any material used should be free draining (Groom, 2010). More recent work with Carnaby's black cockatoos using PVC artificial hollows furnished with wood chips demonstrated high uptake and breeding success by the target species (Saunders et al., 2020).

Nest boxes are not a substitute for the loss of hollow-bearing trees (Le Roux et al., 2016; Lindenmayer et al., 2017), and must be seen as an interim measure to support wildlife, while the natural recruitment, and protection, of hollow-bearing trees occurs (Beyer & Goldingay, 2006; Lindenmayer et al., 2009). As tree hollows take many decades, and even centuries, to form in the absence of primary hollow users (Salmona et al., 2018; Wormington & Lamb, 1999), it is critical that artificial habitat provided to sustain hollow obligate species through this period is functional, long-lasting, able to buffer ambient temperature extremes, and as closely as possible replicates the natural hollows of which the target species utilizes. Hollow creation and augmentation are useful for many hollow-dependent species (Best et al., 2022) but difficult to scale up and inappropriate for many settings, especially in urban environments where built structures and street trees predominate. Fitted correctly, nest boxes can be added to buildings and other infrastructure and have no effect on the risk (perceived or actual) of premature branch shedding. Ongoing efforts to commercialize and upscale nest box production should align closely with best-practice steps developed by Cowan et al. (2021) for artificial refuge science and implementation, ongoing monitoring of usage and determinants of success informing improved design and performance.

AUTHOR CONTRIBUTIONS

David M Watson: Conceptualization (equal); funding acquisition (equal); investigation (supporting); methodology (equal); project administration (equal); supervision (lead); writing – original draft (equal); writing – review and editing (equal). **Michael Callan:** Conceptualization (equal); data curation (equal); formal analysis (equal); funding acquisition (supporting); investigation (lead); methodology (lead). **Alexander Johnson:** Formal analysis (supporting); investigation (supporting); methodology (supporting).

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DATA AVAILABILITY STATEMENT

All data associated with this manuscript are available via the corresponding authors website, www.ecosystemunraveller.com.

ORCID

Michael N. Callan https://orcid.org/0000-0002-3528-3050
Alexander Johnson https://orcid.org/0000-0003-0153-7734
David M. Watson https://orcid.org/0000-0003-1821-4632

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