Received: 3 May 2023 | Revised: 16 October 2023 | Accepted: 18 October 2023

DOI: 10.1002/wsb.1501

RESEARCH ARTICLE

WILDLIFE SOCIETY BULLETIN Open Access

Effectiveness of novel artificial seabird nest modules for reducing ambient temperature transfer in a warming climate

Michael E. Johns[1] | Russell W. Bradley[2] | Pete Warzybok[1] | Michelle M. Hester[3] | Nathan Lynch[4] | Jaime Jahncke[1]

[1]Point Blue Conservation Science, 3820 Cypress Drive, Suite 11, Petaluma, CA 94954, USA

[2]Santa Rosa Island Research Station, CSU Channel Islands, 1 University Drive, Camarillo, CA 93012, USA

[3]Oikonos Ecosystem Knowledge, P.O. Box 1918, Kailua, HI 96734, USA

[4]California College of the Arts, 1111 Eighth Street, San Francisco, CA 94107, USA

Correspondence

Michael E. Johns, 3820 Cypress Drive, Suite 11, Petaluma, CA 94954, USA.
Email: mjohns@pointblue.org

Funding information

Frank A. Campini Foundation; Giles W., and Elise G. Mead Foundation; Farallon Islands Foundation; Richard Grand Foundation; Wildlife Society Climate Adaptation Fund; Elinor Patterson Baker Trust; RHE Charitable Foundation; Marisla Foundation; Volgenau Foundation; Cosco Busan Restoration Council; Kimball Foundation

Abstract

Artificial habitat for cavity nesting birds can provide excellent opportunities for research and conservation efforts but may expose species to the negative impacts of warming ambient temperatures with climate change. Artificial nest boxes have been successfully used to monitor the breeding activity of the Cassin's auklet (*Ptychoramphus aleuticus*), a small burrow-nesting seabird, on Southeast Farallon Island (SEFI) since 1971. Mean monthly ambient air temperatures on SEFI during the summer months have increased at an annual rate of roughly 0.03°C from 1971 to 2022, along with an increase in the number of extreme heat days and average maximum temperature, confirming a warming trend at this seabird colony. Given a projected increase in global temperature, we assessed the effectiveness of traditional wooden nest boxes vs. newer ceramic modules at buffering external ambient air temperatures in normal and extreme heat days across a gradient of microclimates on SEFI. Results from fitting linear mixed effects models indicated that, on average, internal temperatures of wooden and ceramic nests (of comparable size and shape) exhibited similar rates of deviation from ambient air temperature of approximately 0.15°C, even during extreme heat events. Ceramic modules did keep nest chambers cooler by approximately 1.2°C than wooden boxes during extreme events at the warmer, drier southern location of the island. Our results can help guide future efforts to design artificial nests that can effectively provide habitat for seabirds as ambient temperatures increase.

KEYWORDS

burrow nesting, Cassin's auklet, climate change, conservation, extreme heat, nest box, *Ptychoramphus aleuticus*

Half of the avian orders rely on natural cavities for nesting or roosting (Gill 2007), with cavity nesters making up as many as 30% of bird species in some locations (Newton 1994). Constructing artificial nest boxes is a common strategy in seabird, waterfowl, passerine, parrot, and raptor studies to provide easy access for monitoring objectives and to establish new breeding habitat for conservation or management efforts (Bolton et al. 2004, Corrigan et al. 2011). Nest boxes have been demonstrated to increase nesting density, productivity, and recruitment (Libois et al. 2012, Sutherland et al. 2014); however, they can be ineffective and potentially hazardous if they are utilized in ways unfavorable to the target species or incompatible with the local environment (Zingg et al. 2010, Lei et al. 2014).

Artificial nest boxes have been made using various materials such as wood (Ainley and Boekelheide 1990, Priddel and Carlile 1995), concrete (Wingate 1975), plastic (Ackerman et al. 2004), clay (Carle et al. 2019), and mixed materials (Mejías et al. 2017), and the thermal behavior of these materials depends on interacting factors (e.g., density, thickness, composition, color). Assessment of the materials and designs used in the construction of artificial nests is particularly important given ongoing and projected increases in global temperatures and a greater frequency of extreme heat events associated with climate change (Hansen et al. 2006, IPPC 2021). Warmer weather patterns may result in elevated temperatures in natural and artificial nesting sites, which can lead to potentially lethal cases of hyperthermia for adult birds and chicks (Ropert-Coudert et al. 2004, Lei et al. 2014, Kelsey et al. 2016). Therefore, the adoption of climate-smart artificial nesting habitat that buffers against the impacts of increasing temperatures will be critical for creating safe breeding conditions for cavity-nesting birds in a warming world (Stein et al. 2014).

The Cassin's auklet (*Ptychoramphus aleuticus*; hereafter auklet) is a small diving seabird found throughout the northeast Pacific (Manuwal 1974, Ainley and Boekelheide 1990) that lays a single egg in an excavated burrow or rock crevice. Egg laying date ranges from March to May depending on environmental conditions (Lee et al. 2007), with some individuals initiating a second breeding attempt in mid-summer when conditions are favorable (Johns et al. 2017). Researchers from Point Blue Conservation Science have used wooden nest boxes to study auklet breeding biology on Southeast Farallon Island (SEFI) since 1971 (Ainley and Boekelheide 1990, Lee et al. 2007). Nest boxes were originally constructed out of plywood with an above ground nesting chamber and were installed throughout the breeding habitat of auklets on SEFI (Figure 1).

Long-term environmental monitoring data from SEFI suggest an increasing trend in maximum ambient air temperature on the island since the early 1970's, along with periodic spikes in the number of days when the midday air temperature was greater than or equal to 20°C, referred to here as extreme heat events. Extreme heat events at or greater than 20°C in previous years have resulted in heat stress and even death of adult auklets (Warzybok and Bradley 2008), leading researchers at Point Blue to experiment with different nest materials and designs that would be more resistant to extreme heating. As a first step, wooden shade structures were installed over the original plywood nests to reduce temperature extremes. The shades helped moderate temperature inside the nest boxes relative to unshaded boxes (Kelsey et al. 2016), but a more durable and effective solution was required. In response, we began a multi-year effort to design and test new heat-tolerant auklet nest modules. We explored an array of nontraditional materials including ceramic, cement, insulated cement, and plastic. Also, we designed features to both insulate and cool the nest chamber by adding solar reflection (white glazed sun shields) and air flow (warm air

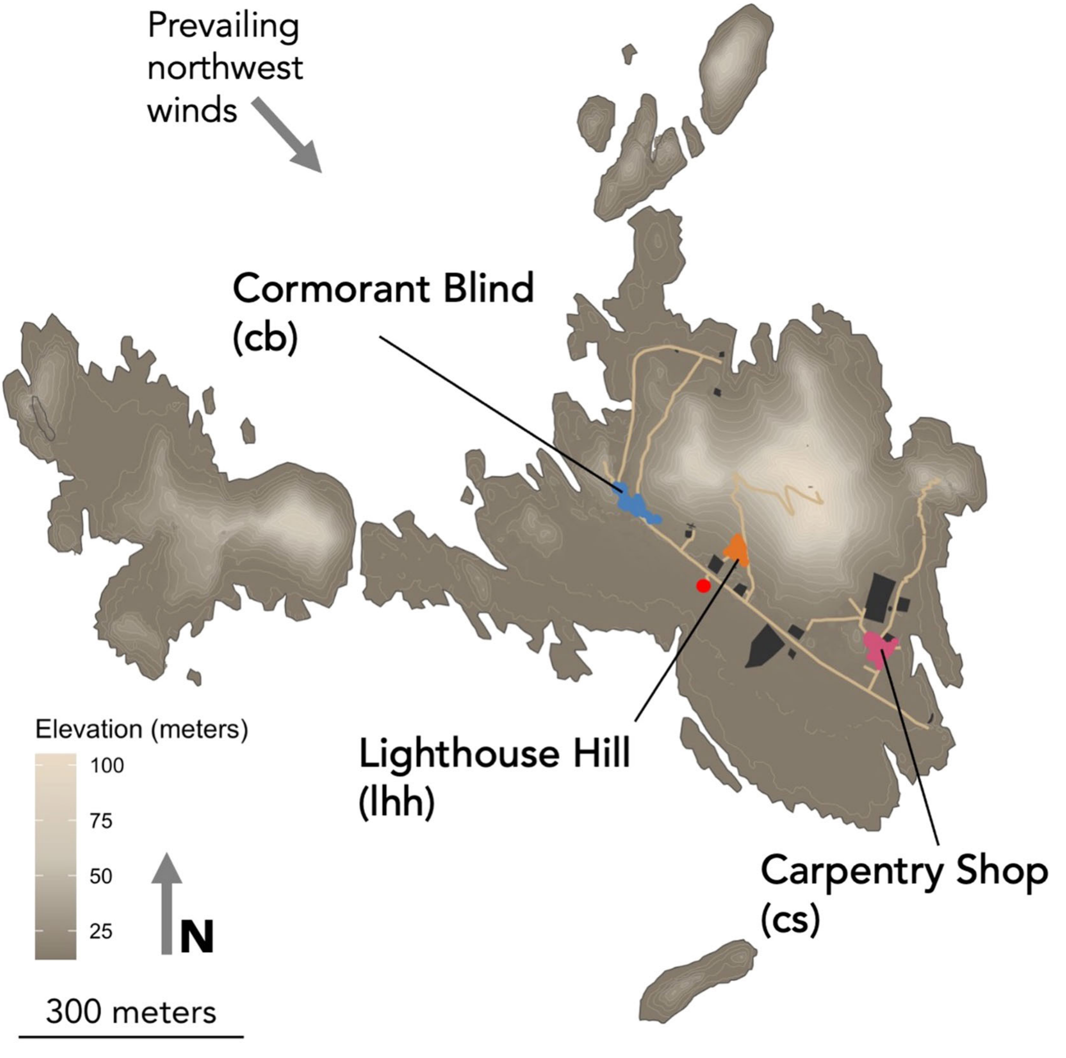

FIGURE 1 Map of Southeast Farallon Island, USA showing clusters of Cassin's auklet nest boxes (colored points), with labels denoting the three areas used in this study. Red dot shows the location of the weather station used to measure daily ambient air temperatures. The arrow in the upper left depicts direction of the prevailing northwest winds in the spring, and color ramp with contour lines show the topographic relief of the island and Lighthouse Hill. Tan lines show the trail system and black polygons show building footprints.

escapes through roof ventilation). After initial testing, we chose to focus on ceramic solutions over concrete and other materials because clay displayed promising thermal properties, can mimic the shapes of natural burrows, and when fired is durable and long-lasting.

The purpose of our study was to test whether the ceramic module design provided better protection from extreme ambient air temperatures compared to the shaded wooden nest box design. First, we further examined trends in ambient air temperature during the core breeding season of auklets (May through September) to quantify the degree of warming on SEFI over the past 50 years. Second, we examined whether there were significant differences in temperatures observed between the ceramic and wooden designs, while factoring in location on the island and the occurrence of extreme heat events. We hypothesized that ceramic modules would regulate burrow temperatures better than wooden boxes and provide more protection from extreme temperature days.

STUDY AREA

Southeast Farallon Island (37.6969°N, 123.0019°W) is part of the Farallon Islands National Wildlife Refuge, located 48 km west of San Francisco, California, USA. The island has an area of 0.39 km^2 with a dominant peak named Lighthouse Hill, which is centrally located and reaches 109 m in elevation (Figure 1). Lighthouse Hill blocks the southeast portion of the island from prevailing northwest winds, creating a cooler, wetter climate on the northwest side of the hill and a warmer, drier climate on the southeast side.

METHODS

Trends in long-term island air temperature

Ambient air temperature data were collected at a standard, shielded weather station containing a mercury thermometer on the low-lying marine terrace (~2 m elevation) 3 times each day (0600, 1200, 1500 hours local time) since 1971. The 3 daily measurements of ambient air temperature were summarized as mean monthly ambient air temperature, monthly maximum ambient air temperature, and monthly total number of extreme heat days observed to negatively impact auklet health (defined as a day when the maximum temperature exceeded 20°C) for each year (Warzybok and Bradley 2008).

The nonparametric Mann-Kendall Trend Test (showing the measure of monotony of the slope with rank correlation coefficient T, which varies between −1 and 1) was implemented using R version 4.0.2 (R Core Team 2020) with the package Kendall (McLeod 2022) to determine whether any of the months of the core auklet breeding season between May and September showed an increasing trend in mean monthly ambient air temperature, whether the annual mean of the monthly maximum ambient air temperature across all months of the core breeding season (May through September) showed a trend, and whether there was a trend in total number of annual extreme heat days from 1971 through 2022. The Mann-Kendall Trend Test is the preferred method for analyzing meteorological time-series data because it tests for a consistently increasing or decreasing pattern over time and is less sensitive to outliers compared to simple linear regression (Mann 1945, Kendall 1975, National Center for Atmospheric Research Staff 2014). The null hypotheses were no trend in mean monthly ambient air temperature, annual mean of the maximum ambient air temperature for the auklet breeding season, or annual number of extreme heat days, with an alpha of 0.05. If a significant trend was detected, the Sen's Slope function in the R package trend (Pohlert 2020) was used to calculate the linear rate of change.

Nest Chamber Temperature Recordings

We examined the effectiveness of 2 artificial nest designs for moderating ambient temperature: shaded wooden boxes and shaded ceramic modules. The designs were similar in size, shape, and placement above ground. The dimensions of wooden nests were 20 × 20 × 40 cm with a 10-cm diameter polyvinyl chloride (PVC) pipe as an entrance tunnel (Figure SA, see Supporting Information). The ceramic design had a nest chamber with rounded sides and overall dimension of approximately 20 × 20 × 33 cm with a separate 10-cm diameter ceramic tube as an entrance tunnel (Figure SB, see Supporting Information). The topsoil is very shallow on Southeast Farallon Island and mixed with large, weathered granite rocks, making excavation difficult. Thus, both artificial nest designs were installed on the surface, and the nest chambers lined with a thin layer of dirt.

The nest treatments differed in the building materials and some design features of the nest chambers and shade structures. The wooden nests were constructed with 1.3-cm thick CDX plywood and painted to prolong the useful life of the nest box. For the ceramic nests, stoneware type clay was shaped by hand, molds, and extruders for production, and fired at 1,180°C (cone 5). After firing, the ceramic walls were 1.3–1.5 cm thick, with 2 cm diameter holes in the ceiling to allow warm air to escape. The shade structure on top of the wooden nests was a flat sheet of plywood (61 × 1.3 × 30 cm) painted white and raised 5 cm creating an air gap between the shade and the wooden box (Figure SA). The ceramic nest chamber was protected by a sunshield 1.5-cm thick that curves down the sides and back of the nest and sits on top of ridges built to create an air insulation gap. The sun-facing side of the sunshield was fired with a glossy white glaze to maximize solar reflection (Figure SB).

Ambient temperature within the nest chambers of each wooden box or ceramic module was monitored using LogTag TRIX-8 Temperature Data Recorders (microdaq.com, LTD, Contoocook, NH, USA) affixed to the ceiling of the nest chamber. The temperature loggers recorded the temperature of the nest environment every 30 minutes for the months of March through August 2017–2022. Due to restrictions associated with Covid-19 we did not collect data in 2020. Each year, a balanced sample of temperature loggers were placed in wooden boxes and clay modules in 3 different areas along a northwest to southeast gradient across the island: Cormorant Blind (cb), Lighthouse Hill (lhh), and Carpentry Shop (cs; Figure 1). These 3 areas were approximately 250 m apart. In some instances, tags became dislodged and fell onto the burrow floor, were under birds during incubation, or were kicked out of the nesting chamber, resulting in erroneous temperature readings. Tags that collected erroneous temperate readings were noted and data from these tags excluded from the analysis. Data were also visually checked for obvious signs of failed attachment (sharp spikes in temperature and unrealistic temperature readings). For a final quality control check we assigned a z-score to each 30-minute recording and removed all outlying recordings greater than 3 standard deviations from the mean recording across all wooden boxes and ceramic modules for all years. Final sample sizes after excluding failed loggers for clay modules and wooden boxes across all years were 63 and 75 loggers, respectively (treatment cb: 15 ceramic, 22 wood; lhh: 24, 26; cs: 24, 27).

We constructed a candidate set of linear mixed effects models with categorical predictors treatment type (wooden vs. ceramic), area (cb, lhh, and cs), and extreme heat event (True if daily ambient max temperature was above 20°C, otherwise False), with the difference between daily mean nest temperature and the daily mean ambient temperature of the island (Δ temp) as the response variable. Daily Δ temperatures approximated a normal distribution, and no transformations were required. A unique identifier for nest number and year was created and used as a random intercept in all models to account for repeated measures of ambient temperatures and possible biases associated with the specific conditions of each nest. The combination of year and nest ID was included given it was assumed conditions of nests used in more than 1 year likely changed over time (changes in surrounding vegetation, nest orientation, conditions of the material, etc.). Different models consisting of all possible combinations of predictors (including main effects and interactions) in the full model (3-way interaction between treatment type, area, and extreme heat event), and a null intercept only model, were fit using the R package lme4 (Bates et al. 2015) computed with maximum likelihood (ML). We ranked all candidate models with computed Akaike Information Criterion (AIC_c; Burnham and Anderson 2002) values, where models with lowest AIC_c scores with ΔAIC_c values less than 2 were assumed to be competitive at explaining the pattern in ambient temperatures in artificial nests. Model averaging was used to compute weighted average parameter estimates for explanatory variables retained in the best supported or set of models with competitive ΔAIC_c values (Burnham and Anderson 2002), and the coefficients used to infer the direction and magnitude of the effect of the retained predictors on the response.

RESULTS

Mean monthly daytime ambient temperatures for SEFI showed a significant positive trend from 1971 through 2022 for the months of May through August (May T = 0.329, $P < 0.001$; June T = 0.351, $P < 0.001$; July T = 0.213, $P = 0.026$; August T = 0.281, $P = 0.003$), and no significant trend for the month of September (T = 0.183, $P = 0.057$). May had the greatest unit increase in temperature (0.03°C) per year, equating to an approximate 1.53°C increase in mean temperature for that month over a 51-year period (Figure 2). June and August were similar (0.027°C and 0.028°C respectively), whereas July showed the smallest significant increase of 0.018°C per year. There was a significant positive trend in the annual total number of extreme heat days throughout the timeseries (T = 0.298, $P = 0.002$), with a unit increase of 0.105 days per year (Figure 3A). Extreme heat events tended to occur during the auklet nesting season between the months of May and September (Figure 3B). Further demonstrating the pattern of increasing temperatures on the island, there was also a significant positive increase in the annual mean of the maximum temperature for the auklet breeding season (T = 0.296, $P = 0.002$), with a unit increase of 0.031°C per year (Figure 3C).

Three models were considered competitive for explaining variation in deviation from ambient temperatures between wooden boxes and ceramic modules ($\Delta AIC_c < 2$; Table 1). All 3 models contained the interaction of area and extreme heat, with model 2 containing a 3-way interaction between treatment, extreme heat event, and area, and model 3 the addition of the main effects for treatment (Table 1). Given no single model received overwhelming support, inferences were made from model averaged coefficients and standard errors for parameters retained in the 3 competitive models (Table 2). On average, both wooden boxes and ceramic modules at the Carpentry Shop area showed a greater positive deviation from ambient air temperature compared to nests at the Cormorant Blind and Lighthouse Hill areas, regardless of whether it was an extreme heat day (Figure 4). The estimated mean differences between wooden boxes and ceramic modules were similar across all 3 areas during non-extreme heat days, and at the Cormorant Blind and Lighthouse Hill areas during extreme heat days. Ceramic modules showed a markedly smaller difference from ambient air temperature compared to wooden nest boxes during extreme heat days at the Carpentry Shop area, explaining the importance of the 3-way interaction between predictors.

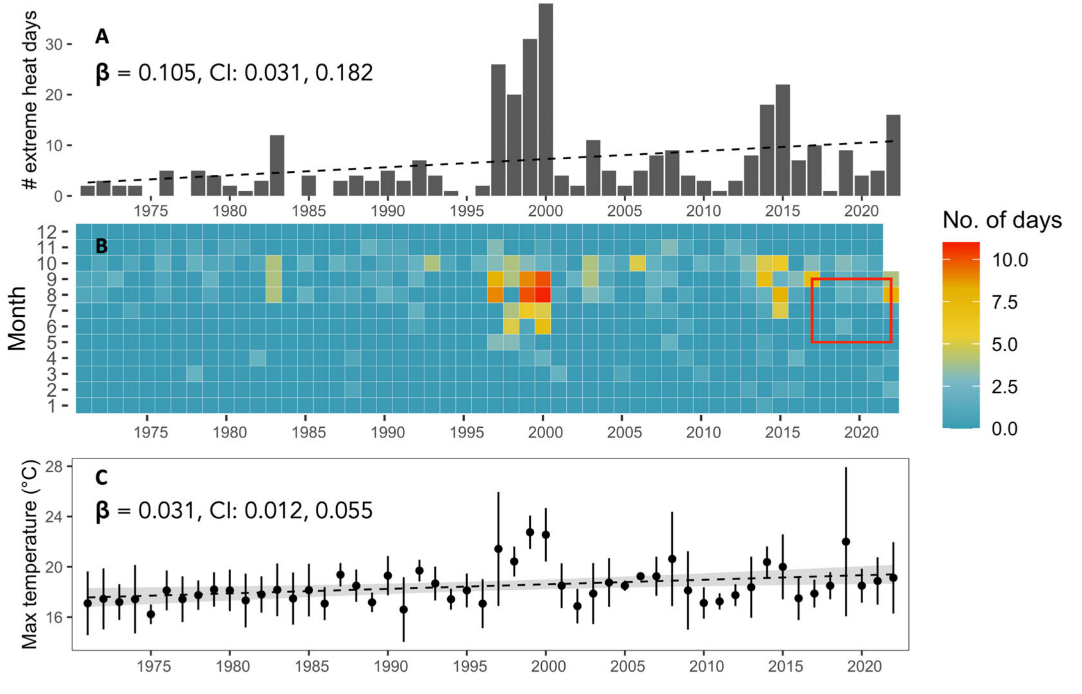

FIGURE 2 Trends in mean monthly ambient air temperature on Southeast Farallon Island, USA for the core Cassin's auklet nesting season from May through September across years 1971 to 2022. September showed no significant trend.

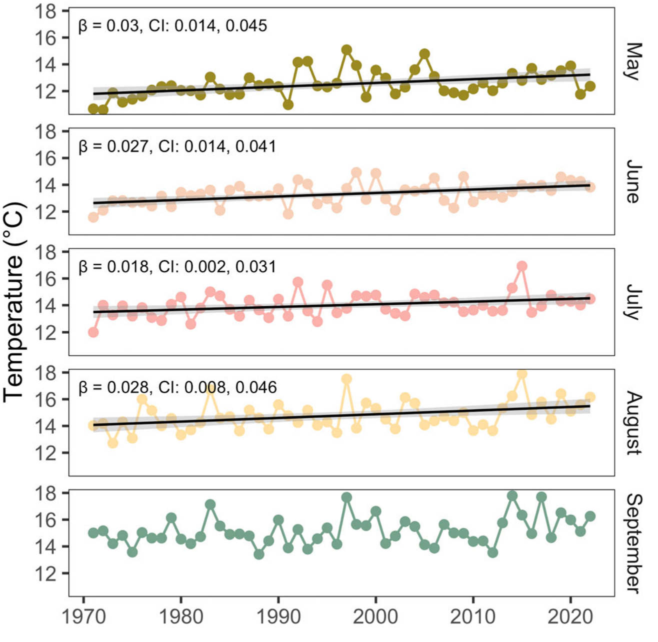

FIGURE 3 Trends in warming of ambient air temperature on Southeast Farallon Island, USA from 1971 to 2022. Panel A depicts total number of extreme heat days (max temperature ≥20°C) for each year, with a positive significant slope of 0.105 (dashed line). Panel B illustrates when these extreme heat days occurred by month for each year (warmer colors = more days, cooler colors = fewer days), with a red box that define the spatial extent of this study. Panel C depicts the annual mean of monthly maximum temperatures for the auklet breeding season (±standard deviation line range), with a significant positive slope of 0.031 (dashed line).

TABLE 1 Models representing a cumulative AIC_c weight (Wt) of 1 from the candidate set, ranked from lowest ΔAIC_c to highest. Predictors include treatment (wooden nest box or ceramic module), area (cb, lhh, cs), and whether the day represented an extreme heat event (extreme; TRUE or FALSE), for Cassin's auklet nest boxes on Southeast Farallon Island, USA for the months of March through August from 2017 to 2022. Number of parameters (K) and log-likelihood (LL) of each model are shown for completeness. Response was daily deviation of mean nest box temperatures from mean ambient air temperatures, and all models contained a random intercept for nest ID. See Table S1 in supporting information for the full candidate set.

Model ID	Predictors	K	ΔAIC_c	AIC_c Wt	LL
1	area*extreme	8	0	0.49	−19037.16
2	area*treatment*extreme	14	0.95	0.30	−19031.63
3	area*extreme + treatment	9	1.91	0.19	−19037.11
4	area + extreme	6	7.58	0.01	−19042.95
5	area*treatment + extreme	9	8.13	0.01	−19040.23
6	area + treatment + extreme	7	9.47	0	−19042.9

DISCUSSION

Our work confirms an increasing trend in ambient air temperatures and number of extreme heat days at this seabird colony off the California Coast, highlighting the importance for managers to develop strategies to help mitigate the impacts of climate change. Of particular concern is the increasing trend in the number of days where ambient air

TABLE 2 Model averaged coefficient estimates (with associated standard errors and confidence intervals) used to infer how variation in deviation from ambient temperature in artificial Cassin's auklet nest boxes on Southeast Farallon Island, USA was influenced by nest type (treatment wooden box or ceramic module), area on the island (cs: Carp Shop, lhh: Lighthouse Hill, cb: Cormorant Blind), and occurrence of extreme heat events (TRUE or FALSE). Data span the months of March through August from 2017 to 2022. Reference levels were area (cb, treatment), wooden box, and extreme heat (FALSE). Variance (Standard Deviations) for random intercept term box ID was 1.165 (1.079).

Variable	Estimate	SE	95%CI
(Intercept)	3.12	0.13	2.86, 3.37
cs	1.18	0.18	0.83, 1.53
lhh	−0.49	0.15	−0.80, −0.19
ceramic	−0.17	0.21	−0.58, 0.25
extreme TRUE	0.15	0.15	−0.14, 0.45
cs:ceramic	0.47	0.26	−0.03, 0.97
lhh:ceramic	−0.01	0.27	−0.55, 0.53
cs:extreme TRUE	−0.27	0.39	−1.02, 0.49
lhh:extreme TRUE	0.34	0.20	−0.06, 0.73
ceramic:extreme TRUE	0.11	0.26	−0.40, 0.62
cs:ceramic:extreme TRUE	−1.03	0.50	−2.00, −0.05
lhh:ceramic:extreme TRUE	0.09	0.35	−0.60, 0.78

temperatures exceed 20°C, given even a few days of extreme heat can result in heat exhaustion and death in birds occupying artificial nesting habitat, as observed in 2008 on the Farallones (Warzybok and Bradley 2008).

Both shaded ceramic modules and shaded wooden boxes exhibited similar deviation from ambient air temperature, with ceramic modules performing slightly better at the Carpentry Shop area during extreme heat days. A lack of evidence for a major difference in the performance between the 2 materials tested does not completely rule out the hypothesis that the use of ceramic as a building material reduces thermal conductivity compared to wood. The value of ceramic modules became apparent when the combination of area on the island and whether the ambient air temperatures constituted an extreme heat event was factored into the analysis. Increased thermal buffering by clay modules compared to wooden boxes at the Carpentry Shop during extreme heat events suggests that localized temperature microclimates may be important for determining suitability of artificial habitat. The wooden boxes performed similarly to ceramic modules in locations that received cool, damp wind off the ocean, in hot dry sites during non-extreme heat days, or locations in a sheltered northern aspect. Including a shade structure to the wooden boxes beginning in 2008 had a major impact on keeping wooden boxes relatively cool compared to unshaded ones (Kelsey et al. 2016), demonstrating a simple affordable solution to help regulate internal temperatures at a similar rate to shaded ceramic modules under historically normal environmental conditions, but not during extreme heat events at warmer microclimates on the island.

Both wooden boxes and clay models showed a greater deviation from the control ambient air temperature at the Carpentry Shop area compared to other locations on the island. Given the construction and installation of boxes and modules were the same across all areas, this trend implies the Carpentry Shop is a warmer microclimate on the island. The performance of shaded wooden boxes declined at the Carpentry Shop area during extreme heat events, a location that is more arid in nature with a southern aspect that receives higher solar input throughout the day than other portions of the island. Double-layered ceramic nesting modules deployed at a colony of African penguins

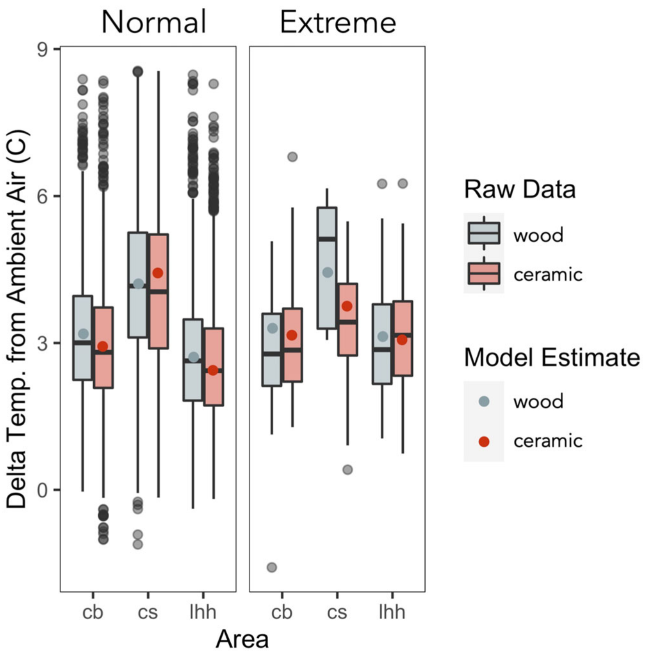

FIGURE 4 Difference in mean daily temperature of wooden boxes (grey) vs. ceramic modules (red) from mean daily ambient air temperature for artificial nest boxes used by Cassin's auklets on Southeast Farallon Island, USA for the months of March through August from 2017 to 2022. Data are presented for Cormorant Blind (cb), Carpentry Shop (cs), and Lighthouse Hill (lhh), separated by panels for normal conditions (extreme heat day = FALSE) and extreme heat events (TRUE). Boxplots show the interquartile range bounded by the 25th and 75th percentile, horizontal line in the middle of each box shows the median, whiskers the maximum and minimum values, and diamonds the extreme outliers. Predictions from model averaged coefficients for each scenario presented as black dots, with error bars showing 95% confidence intervals.

(*Spheniscus demersus*) in South Africa maintained higher levels of relative humidity compared to other habitat types (Welman and Pichegru 2022). Although not measured in our study, ceramic modules may have retained higher humidity levels compared to wooden boxes as well, explaining the ability to buffer against extreme heat even at the relatively drier sites on the island. Holes installed on the ceiling of the ceramic modules likely provided a way to vent heat from the nesting chamber compared to the more sealed-off wooden boxes, contributing to the cooling effect of ceramic modules during extreme heat at the hottest location on the island. Burying the nest boxes would likely further the thermal buffering properties of either material, but given the rocky substrate of the Farallon Islands this was not an option.

Artificial nests are commonly used to facilitate monitoring, restore habitat, translocate and maintain colonies, increase breeding success, and increase adult survival of burrow-nesting seabird species (Wilson 1986, Libois et al. 2012, Carle et al. 2019). While there are challenges in the use of artificial nests in bird studies, including potential increased rates of predation (Moore and Robinson 2004), durability and longevity of materials used, and potential sampling biases (Lambrechts et al. 2010), auklets on the Farallon Islands provide an example of a species with extremely high rates of occupancy, breeding success, and quality data obtained from artificial nest boxes (Johns et al. 2022). We demonstrated how consideration of design and materials used in artificial nesting habitat, combined with knowledge of microclimate differences in breeding habitat, can alleviate the potential negative impacts of artificial breeding habitat for burrow nesting species. The results on heat transfer and retention presented here can be used to guide future efforts in developing durable artificial ceramic habitat modules. An important practical advantage ceramic has over wood is that the material will last for hundreds of years.

This durability benefits programs with limited personnel time and infrequent colony visits required to make repairs/replacement that prevent wooden boxes from becoming hazardous to nesting adults and chicks. On Año Nuevo Island, for example, ceramic artificial nests have been observed by researchers in the field to be durable enough to withstand trampling by California sea lions (*Zalophus californianus*), brown pelicans (*Pelecanus occidentalis*), and Brandt's cormorants (*Urile penicillatus*), thus providing safe and stable breeding habitat on this colony with dense wildlife eroding the soil and competing for space. We suggest that ceramic modules with protective design features such as glazed shade coverings and ventilation holes are the preferred solution for artificial nesting habitat for burrow nesting species over more traditional wooden boxes, particularly as ambient air temperatures continue to rise or if locations are periodically exposed to harsh dry conditions.

ACKNOWLEDGMENTS

We thank the Point Blue Farallon staff and volunteers who assisted with collecting data for this project. We thank the U.S. Fish and Wildlife Service for funding, logistical support, and interest in this project. Transport to SEFI was provided by the Farallon Patrol. Additional funding for nest module design and testing was provided by the Cosco Busan Restoration Council and the Wildlife Conservation Society's Climate Adaptation Fund. Additional funders for Point Blue's Farallon Research Program include the Elinor Patterson Baker Trust, Frank A. Campini Foundation, Farallon Islands Foundation, Richard Grand Foundation, Kimball Foundation, Marisla Foundation, Giles W., and Elise G. Mead Foundation, RHE Charitable Foundation, Volgenau Foundation, and individual donors. This is Point Blue Conservation Science contribution number 2114. All authors conceived the idea and design of this study. Authors MJ RB, MH, and PW conducted the research and developed methods, NL and MH developed the ceramic nest design and production. Authors MJ performed the analysis, MJ and RB wrote the paper, with substantial edits from JJ, MH, and PW.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

ETHICS STATEMENT

All appropriate permissions for conducting research on the Farallon Islands National Wildlife Refuge were obtained from the U.S. Fish and Wildlife Service. No animals were handled in this study.

DATA AVAILABILITY STATEMENT

Data are available online upon request by contacting marinedirector@pointblue.org.

ORCID

Michael E. Johns http://orcid.org/0000-0002-0295-5121
Pete Warzybok http://orcid.org/0000-0003-1076-8745

REFERENCES

Ackerman, J. T., J. Adams, J. Y. Takekawa, H. R. Carter, D. L. Whitworth, S. H. Newman, R. T. Golightly, and D. L. Orthmeyer. 2004. Effects of radiotransmitters on the reproductive performance of Cassin's auklets. Wildlife Society Bulletin 32: 1229–1241.

Ainley, D. G., and R. J. Boekelheide. 1990. Seabirds of the Farallon Islands. Ecology, dynamics, and structure of an upwelling-system community. Stanford University Press, Stanford, California, USA.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software 67:1–48.

Bolton, M., R. Medeiros, B. Hothersall, and A. Campos. 2004. The use of artificial breeding chambers as a conservation measure for cavity-nesting procellariiform seabirds: a case study of the Madeiran storm petrel (*Oceanodroma castro*). Biological Conservation 116:73–80.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer, New York, New York, USA.

Carle, R. D., M. M. Hester, E. Coletta, and J. N. Beck. 2019. Cassin's Auklet (*Ptychoramphus aleuticus*) Population Size, Reproduction, and Habitat Management on a Recently Colonized Island in California, USA. Waterbirds 42:366–379.

Corrigan, R., G. Scrimgeour, and C. Paszkowski. 2011. Nest boxes facilitate local-scale conservation of common goldeneye (*Bucephala clangula*) and bufflehead (*Bucephala albeola*) in Alberta, Canada. Avian Conservation and Ecology 6(1):1.

Gill, F. B. 2007. Ornithology. Third edition. W.H. Freeman. London, UK.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade. 2006. Global temperature change. Proceedings of the National Academy of Sciences of the United States of America 103:14288–14293.

IPPC. 2021. Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; technical summary. Cambridge University Press.

Johns, M. E., P. Warzybok, R. W. Bradley, J. Jahncke, M. Lindberg, and G. A. Breed. 2017. Age, timing, and a variable environment affect double brooding of a long-lived seabird. Marine Ecology Progress Series 564:187–197.

Johns, M. E., P. Warzybok, J. Jahncke, P. Doak, M. Lindberg, and G. A. Breed. 2022. Episodes of high recruitment buffer against climate-driven mass mortality events in a North Pacific seabird population. Journal of Animal Ecology 91: 345–355.

Kelsey, E. C., R. W. Bradley, P. Warzybok, J. Jahncke, and S. A. Shaffer. 2016. Environmental temperatures, artificial nests, and incubation of Cassin's auklet. The Journal of Wildlife Management 80:292–299.

Kendall, M. G. 1975. Rank Correlation Methods. C. Giffin, editor. 4th edition. London, UK.

Lambrechts, M. M., F. Adriaensen, D. R. Ardia, A. V Artemyev, F. Atiénzar, J. Bańbura, E. Barba, J.-C. Bouvier, J. Camprodon, C. B. Cooper, et al. 2010. The design of artificial nestboxes for the study of secondary hole-nesting birds: a review of methodological inconsistencies and potential biases. Acta Ornithologica 45:1–26.

Lee, D. E., N. Nur, and W. J. Sydeman. 2007. Climate and demography of the planktivorous Cassin's auklet (*Ptychoramphus aleuticus*) off northern California: implications for population change. Journal of Animal Ecology 76:337–347.

Lei, B. R., J. A. Green, and L. Pichegru. 2014. Extreme microclimate conditions in artificial nests for endangered African Penguins. Bird Conservation International 24:201–213.

Libois, E., O. Gimenez, D. Oro, E. Mínguez, R. Pradel, and A. Sanz-Aguilar. 2012. Nest boxes: a successful management tool for the conservation of an endangered seabird. Biological Conservation 155:39–43.

Mann, H. B. 1945. Non-parametric test against trend. Econometrica 13:245–259.

Manuwal, D. A. 1974. The natural history of Cassin's auklet (*Ptychoramphus aleuticus*). The Condor 76:421–431.

McLeod, A. 2022. Kendall: Kendall rank correlation and Mann-Kendall trend test. R package version 2.2.1.

Mejías, M. A., D. B. Wingate, J. L. Madeiros, Y. F. Wiersma, and G. J. Robertson. 2017. Nest-cavity selection and nesting success of Bermudian white-tailed Tropicbirds (*Phaethon lepturus catesbyi*). The Wilson Journal of Ornithology 129: 586–599.

Moore, R. P., and W. D. Robinson. 2004. Artificial bird nests, external validity, and bias in ecological field studies. Ecology 85:1562–1567.

National Center for Atmospheric Research Staff. 2014. The climate data guide: Trend analysis. <https://climatedataguide.ucar.edu/climate-data-tools-and-analysis/trend-analysis>. Accessed 10 Aug 2023.

Newton, I. 1994. The role of nest sites in limiting the numbers of hole-nesting birds: a review. Biological Conservation 70: 265–276.

Pohlert, T. 2020. trend: non-parametric trend tests and change-point detection. R package version 1.1.4.

Priddel, D., and N. Carlile. 1995. An artificial nest box for burrow-nesting seabirds. Emu-Austral Ornithology 95:290–294.

R Core Team. 2020. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Australia.

Ropert-Coudert, Y., B. Cannell, and A. Kato. 2004. Temperature inside nest boxes of little penguins. Wildlife Society Bulletin 32:177–182.

Stein, B. A., P. Glick, N. Edelson, and A. Staudt. 2014. Climate-smart conservation: putting adaption principles into practice. National Wildlife Federation, Washington D.C.

Sutherland, D. R., P. M. Dann, and R. Jessop. 2014. Evaluation of artificial nest sites for long-term conservation of a burrow-nesting seabird. The Journal of Wildlife Management 78:1415–1424.

Warzybok, P. M., and R. W. Bradley. 2008. Population size and reproductive performance of seabirds on Southeast Farallon Island, 2008. Unpublished report to the U.S. Fish and Wildlife Service. Point Blue Conservation Science, Petaluma, California. Point Blue Conservation Science Contribution Number 1656.

Welman, S., and L. Pichegru. 2022. Nest microclimate and heat stress in African Penguins Spheniscus demersis breeding on Bird Island, South Africa. Bird Conservation International 33:1–9.

Wilson, U. W. 1986. Artificial rhinoceros auklet burrows: a useful tool for management and research. Journal of field Ornithology 57:295–299.

Wingate, D. B. 1975. The common crow in Bermuda. Department of Agriculture and Fisheries Monthly Bulletin 45:2–6.
Zingg, S., R. Arlettaz, and M. Schaub. 2010. Nestbox design influences territory occupancy and reproduction in a declining, secondary cavity-breeding bird. Ardea 98:67–75.

Associate Editor: Adam Behney.

SUPPORTING INFORMATION

Additional supporting material may be found in the online version of this article at the publisher's website.

How to cite this article: Johns, M. E., R. W. Bradley, P. Warzybok, M. M. Hester, N. Lynch, and J. Jahncke. 2023. Effectiveness of novel artificial seabird nest modules for reducing ambient temperature transfer in a warming climate. Wildlife Society Bulletin 47:e1501. https://doi.org/10.1002/wsb.1501