Project Title:

Assessing Susceptibility of Birds to Heatwaves at a Priority National Estuarine Research Reserve through Conservation Physiology and Hypothesis-Driven Citizen Science

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Abstract

Predictive studies expect that rising temperatures and heatwaves will increase the risk of heat stress and heat-related mortality in birds. It is known that birds acclimatize to heat through a suite of behavioral and physiological adjustments, yet little is known about how acclimatization develops over the course of seasonal change. Using field-based thermography and behavioral analyses, we are investigating the process of acclimatization to heat in wild birds at Bird Island Reserve, a National Estuarine Research Reserve in southeastern North Carolina. We are investigating two mechanisms of acclimatization: behavioral thermoregulation and heat exchange through the body surface. We are investigating changes in heat exchange by measuring the surface temperatures of thermal windows, such as the bill and legs, which are known sites of heat exchange. We are studying changes in behavioral thermoregulation by instantaneously sampling behaviors. We model these responses in surface temperature and behavior as a function of time, represented as the Julian day, and thermal conditions, represented as the wet-bulb globe temperature, which includes air temperature, humidity, solar radiation, and wind speed. Of the thermoregulatory behaviors investigated, wing spreading and panting were the most common, and wing spreading occurred significantly more frequently, and at lower temperatures, when compared to panting behavior. That birds used postural adjustments, such as wing spreading, before panting provides further evidence that birds prioritize the use of behaviors that do not carry resource or opportunity costs. That the date was only included in a competitive model of panting, and not any of the other behaviors, may provide further evidence that costly behaviors are adjusted through acclimatization. Data extraction from thermal images is ongoing, but current results indicate that both bill and leg temperatures increased as temperatures increased, and that birds elevated their surface temperature, and therefore heat dissipation, more as the season went on.

Introduction

Multiple recent studies predict that rising temperatures and heatwaves will increasingly cause mortality in birds in the next century (Albright et al., 2017; Conradie et al., 2019; Conradie et al., 2020; McKechnie and Wolf, 2010). These rapid changes threaten to outpace birds' evolutionary adaptability by occurring over short-term ecological timescales, especially when coupled with past (Perkins-Kirkpatrick and Lewis, 2020) and projected (Perkins-Kirkpatrick and Gibson, 2017) increases in the intensity and frequency of heatwaves. Out of four climate related threats expected to affect bird populations in North Carolina, spring heatwaves are projected to impact the greatest geographic area and number of species (Wilsey et al., 2019). Conservation physiologists are making progress in assessing the susceptibility of birds to heat in general, but susceptibility to heatwaves specifically is not well understood. Studying thermoregulatory adaptations, and how these adaptations are optimized through seasonal acclimatization, is a promising avenue of research that is yielding novel insights regarding susceptibility to heatwaves (e.g., Cooper et al., 2020; Pessato et al., 2023; Zuluaga and Danner, 2023b).

Thermoregulatory adaptations

When temperatures rise, birds use thermoregulatory behaviors to dissipate heat from the body via evaporative and non-evaporative (i.e., dry) pathways. Behavioral mechanisms of evaporative cooling in birds include respiratory evaporation (e.g., panting, tongue wagging, gular flutter), urohidrosis, and wetting of the bill with saliva (Cabello-Vergel et al., 2021; Dawson, 1982; Janse van Vuuren et al., 2020; Kemp and Kemp, 1980; Zuluaga and Danner, 2023b). Behavioral mechanisms of non-evaporative cooling in birds include simple postural changes such as wing spreading, standing tall, flattening feathers, seeking shade, and avoiding activity (Cunningham et al., 2021; van de Ven et al., 2019; Zuluaga and Danner, 2023b). Evaporative cooling mechanisms rely on the expenditure of water to dissipate heat, whereas the postural changes that characterize dry heat loss focus on enhancing cooling through convective and radiative means. The use of this diverse suite of behaviors varies among taxonomic groups. For example, Passeriformes pant as the primary means of evaporative cooling, whereas Columbiformes rely more on cutaneous evaporation to maintain their body temperature (McKechnie et al., 2016). Similarly, postural changes that mediate dry heat loss have been found to vary with variation in morphology between taxonomic groups, particularly with variation in the size of thermal windows (Ryeland et al., 2017; Ryeland et al., 2019).

Thermal windows are areas of the body characterized by low insulation paired with high vascularization, which together make them efficient sites of heat exchange; an archetypal example of a thermal window is the bill of the toucan, which can momentarily dissipate up to 100% of the heat produced through resting metabolism (Tattersall et al., 2009). The rate of heat exchange across a thermal window is determined by the difference between ambient temperature and the surface temperature of the thermal window, which in turn is regulated by vasomotor changes that control blood flow to the region (reviewed in Tattersall et al., 2017). Since the finding that thermal windows can represent a substantial pathway for heat exchange (i.e., potentially equal in magnitude to metabolic heat production; Tattersall et al., 2009), researchers have continued to accumulate evidence that thermal windows are important adaptations for thermoregulation. Ecogeographical trends in appendage morphology indicate that selective pressure drives the evolution of enlarged thermal windows in warm and humid environments (Gardner et al., 2016; Symonds and Tattersall, 2010), and there is evidence that the size of thermal windows across diverse taxonomic groups is increasing in response to warming temperatures caused by climate change (Ryding et al., 2021).

Seasonal acclimatization

In summer, birds undergo seasonal changes resulting in lower metabolic heat generation, increased evaporative cooling, and increased heat tolerance (Noakes and McKechnie, 2020; Noakes et al., 2016; Tieleman et al., 2002). Recent research has found that when presented with the same high temperature, birds in winter rely more heavily on thermoregulatory behaviors to stay cool relative to birds in summer (Zuluaga and Danner, 2023b). Although thermoregulatory behaviors can be used to stave off heat stress and heat related mortality, these behaviors carry resource costs (McKechnie, 2022) and opportunity costs, such as suboptimal foraging in shaded habitats or the inability to forage while panting (Cunningham et al., 2021). Thus, reducing reliance on costly behaviors through acclimatization may be a mechanism to avoid both resource and opportunity costs. It has been suggested that behavioral indices of heat dissipation can be used to quantify vulnerability to high temperatures (McKechnie, 2019; Pattinson et al., 2020; Smit et al., 2016; Zuluaga and Danner, 2023b).

In addition to behavioral and metabolic changes, acclimatization may take place in the form of seasonal changes in heat dissipation. Birds can cool off by dissipating heat through uninsulated surfaces called thermal windows. By increasing blood flow to raise the surface temperature of the bill and legs, birds can use these surfaces to dissipate heat to the surrounding air (Tattersall et al., 2017). Because heat dissipation through thermal windows does not rely on evaporation, it may serve as an alternative to costly evaporative cooling mechanisms like panting, and thermal windows may therefore reduce birds' reliance on costly thermoregulatory behaviors. Support for this hypothesis has been found in ecogeographical trends of morphology as well as empirical measurements of heat dissipation. Greenberg et al. (2013) found that the bills of song sparrows (*Melospiza melodia*) were larger in summer than in winter to aid in heat dissipation. Interestingly, some species have been found to dissipate more heat through thermal windows when acclimatized to heat (Szafrańska et al., 2020; preliminary analyses in Zuluaga and Danner, 2023a), whereas the opposite pattern has been observed in other species (Zuluaga and Danner, 2023b). The inter-species variation in this thermoregulatory trait creates an opportunity to assess susceptibility to heat because it suggests that not all birds have the capacity to increase heat dissipation in summer.

Here, we measured seasonal change in thermoregulatory behaviors and surface temperatures in wildlife at Bird Island Reserve from May 1st to August 1st, 2024. Using these data, we will test the hypotheses that 1) acclimatization to heat happens gradually, and that that 2) some species have the capacity to adjust heat dissipation seasonally. By monitoring the change in thermoregulatory behaviors and surface temperatures (i.e., heat dissipation) over the course of a summer, we aim to reveal the time periods when birds are most susceptible to heatwaves. Testing hypothesis (1) will reveal the timing of acclimatization and therefore the time period when birds are the most susceptible to heat, and testing hypothesis (2) will describe the biological mechanisms that species have (or lack) for acclimatization to heat. Additionally, this research is designed to investigate how physiological constraints can determine habitat use (Cooke et al., 2013), which has directly informed methods for maintaining habitats for species of conservation concern (e.g., Kearney et al., 2016).

Methods

Study site and sampling approach

Bird Island Reserve is a 1,481-acre National Estuarine Research Reserve located on a barrier island in southeastern North Carolina. The reserve is composed of salt marshes, beaches, and sand dunes, all of which are challenging thermal habitats because of the high exposure to solar radiation and the lack of freshwater in these habitats. Bird Island Reserve is an ideal site for research investigating the susceptibility of different species to heat because of the diversity of species present in the reserve, the challenging thermal characteristics of the reserve, and the multiple distinct habitats that are accessible within the reserve.

In the first weeks of sampling, we developed an understanding of the most active parts of the reserve and the best routes to take in relation to tides. Based on these early explorations, we divided the reserve into 4 regions, and we sampled the reserve three times weekly between 10:00AM and 3:30PM from 1 May to 1 August 2024. In total, we sampled BIR on 33 separate days, where we collected 9.21±0.85 (mean±s.e.m.) observations per day. We modeled the number of observations made as a function of date, and we found that the null model received more support than the model with Julian day, confirming that sampling effort remained consistent throughout the field season (Figure S1). We visited each of the four regions of the reserve at least once per week, ensuring regular coverage of the diverse habitats and the species therein.

During our sampling transects through the reserve, we recorded data using *ThermAves* an ArcGIS-Online survey that we built specifically for this research. Upon encountering wildlife, we used *Thermaves* to instantaneously collect data on the encountered organism's behavior, its surrounding habitat characteristics (structure, shade, precipitation, and cloud cover), and the current thermal conditions (temperature, wind speed, relative humidity, and solar energy); we also used the survey to record the numeric identifier of the thermal images associated with each entry. We measured ambient temperature (T_{air}; °C), relative humidity (RH; %), and wind speed (m/s), using an anemometer (Kestrel 5000), and we measured solar radiation (W/m^2) using a solar power meter (DBTU1300). Lastly, we measured the distance (m) between the camera and the bird after each survey entry using a laser range finder; we always waited for the bird to leave the area before using the range finder.

Behavioral observations and thermal imaging

Upon encountering a bird, we collected binary data on the following behaviors: panting, tongue wagging, gular flutter, wing spreading, and standing in water (Pattinson et al., 2020; Smit et al., 2016; Snowden, 2018; Zuluaga and Danner, 2023b). After noting these behaviors, we collected thermal images using a FLIR T840 thermal camera (resolution of 464×348 pixels) with a long range 6° lens. We collected as many images as possible before the bird moved. From each series of images, we chose the clearest image where the bird's bill was most visible (i.e., angled perpendicular to the camera), and images where the bird was still (i.e., no motion blur present in the frame) to extract surface temperature data for each survey entry. We then extracted the mean, maximum and minimum surface temperatures (T_s) by drawing separate region of interest (ROI) polygons around the bird's bill, eye region, and one of the legs using FLIR Thermal Studio Pro. When extracting surface temperature data, we specified object parameters using the air temperature, relative humidity, and distance data that we collected during each survey entry.

Analyses

We modeled the thermal environment using wet-bulb globe temperature (WBGT; °C), a metric that incorporates all four measurements of the thermal environment. We calculated WBGT in R package heatmetrics (Spangler et al., 2022) using air temperature, relative humidity, wind speed, and solar energy values recorded during each survey entry. For this report, we analyzed the effects of WBGT and date on the response variables (behavior and surface temperatures) using package 'lme4' (Bates et al., 2015) in R (R Core Team, 2024). Specifically, we analyzed the behavioral data using generalized linear mixed effects models with a binomial probability distribution and a logit-link function, and we analyzed surface temperature data using linear mixed effects models. We tested hypotheses 1 and 2 by building a global model that includes the fixed effects of date (represented as Julian day), WBGT, and taxonomic family. We then ranked these models using AICc in package MuMIn (Bartoń, 2022), and we report all the top-ranked models and competitive (ΔAICc < 2) models for each response variable. We visualized data using package ggplot2 (Wickham, 2016) following methods from Zuluaga & Danner (2023) and Zuluaga and Danner (2023b). Pending the complete extraction of data from the remaining thermal images, we plan to more deeply investigate how the response variables are influenced by the thermal habitat, the passage of time (i.e., gradual acclimatization), and taxonomy. In the next round of analyses, we will use phylogenetic generalized linear models (Pattinson et al., 2020).

Results

Sample size

We sampled 68 bird species representing 18 families. We collected 299 behavioral observations and 1,066 thermal images in total. Representative images are presented in Figure 1, and all images will be available publicly (see *Data management plan progress*). Currently, we are in the process of extracting data from the thermal images, and we have collected data for 140 of the 299 survey entries; note that the 140 surface temperature measurements available primarily come from the earlier parts of the field season, therefore our estimates of the effect of time on the response variables is likely conservative.

Figure 1. A subset of the 1,066 collected thermal images representing 9 of the 18 sampled families. In order from left to right, top to bottom: green heron (*Butorides virescens*; Ardeidae), white ibis (*Eudocimus albus*; Threskiornithidae), boat tailed grackle (*Quiscalus major*; Icteridae), mourning dove (*Zenaida macroura*; Columbidae), bank swallows (*Riparia riparia*; Hirundinidae), great black-backed gull (*Larus marinus*;

Laridae), painted bunting (*Passerina ciris*; Cardinalidae), northern mockingbird (*Mimus polyglottos*; Mimidae), willet (*Tringa semipalmata*; Scolopacidae).

Thermal environment

Raw data of T_{air}, RH, solar energy, and wind speed are presented in Figure 2, and are included in the public dataset. Using these data, we calculated WBGT, which increased at a rate of 0.070°C/day over the course of this research. The model-average WBGT increased from 28.27 to 34.69°C from May 1st to August 1st (Figure 3). This research was conducted during the hottest summer on record globally (Younger, 2024).

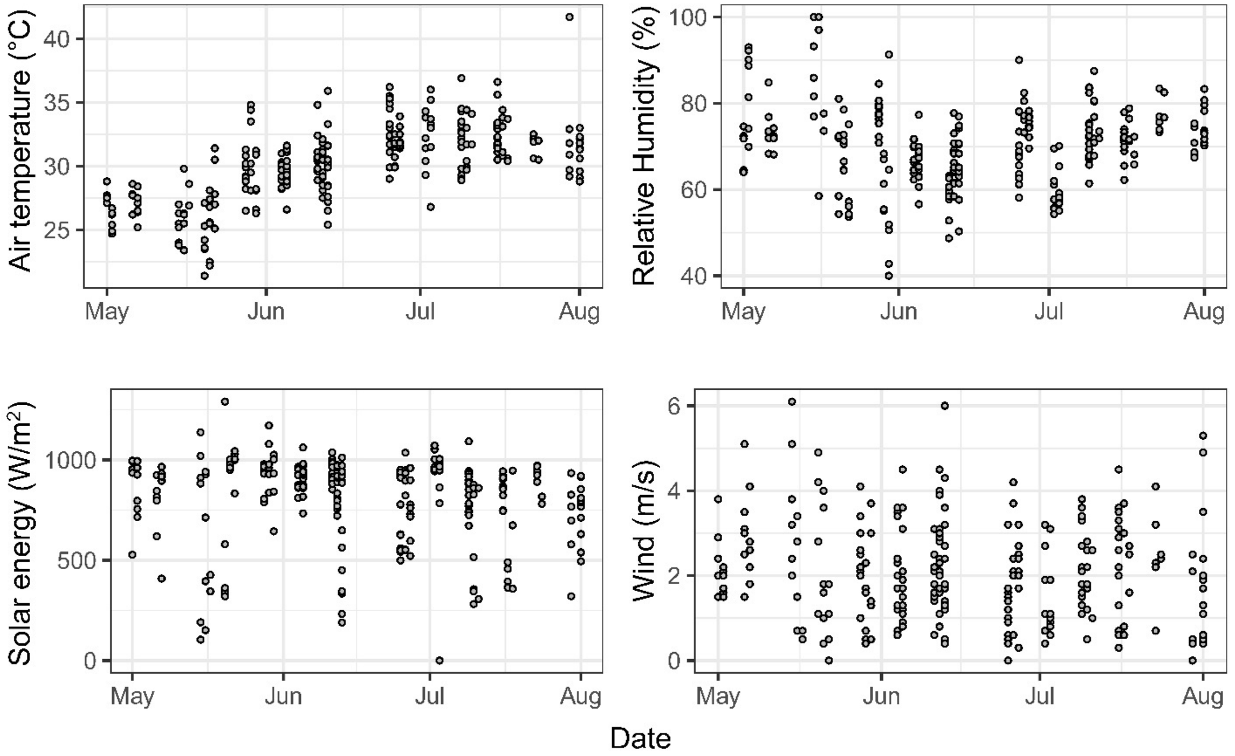

Figure 2. Measurements of air temperature, relative humidity, solar energy, and wind speed collected during each survey entry at Bird Island Reserve, NC, over the course of summer 2024.

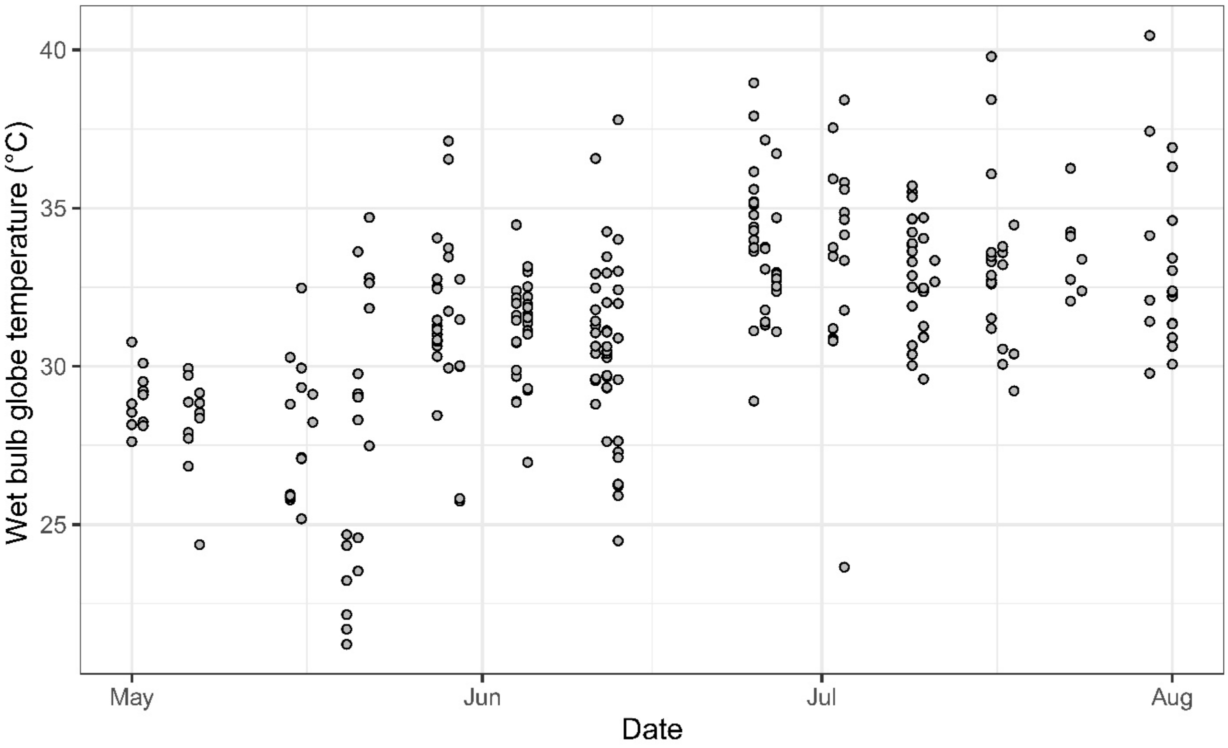

Figure 3. Thermal conditions at Bird Island Reserve, NC, over the course of summer 2024 represented as the wet-bulb globe temperature, which incorporates values of air temperature, relative humidity, solar energy, and wind speed.

Thermoregulatory behaviors

Of the 5 thermoregulatory behaviors investigated, wing spreading and panting were the most common. As WBGT increased, birds increasingly exhibited wing spreading and panting behaviors. Wing spreading occurred significantly more frequently, and at lower temperatures, when compared to panting behavior. The top ranked model for wing spreading contained family and WBGT, and there were no competitive models (Figure 4; Table 1). The top ranked model for panting behavior included WBGT as the only fixed effect, and the only competitive model included both WBGT and Julian day (Figure 5; Table 1).

Tongue flutter was only observed in two laughing gulls (*Leucophaeus atricilla*) in July (Figure 6; Table 1), and gular flutter was not observed (Figure 7). Although standing in water can provide a thermoregulatory benefit, the use of this behavior was not clearly associated with thermal conditions in the overall dataset (Figure 8; Table 1). However, a preliminary investigation has found that groups that frequently stand in water for foraging, such as Ardeidae (herons and egrets), exhibit panting behavior less frequently than groups that do not stand in water (see *Appendix 1*).

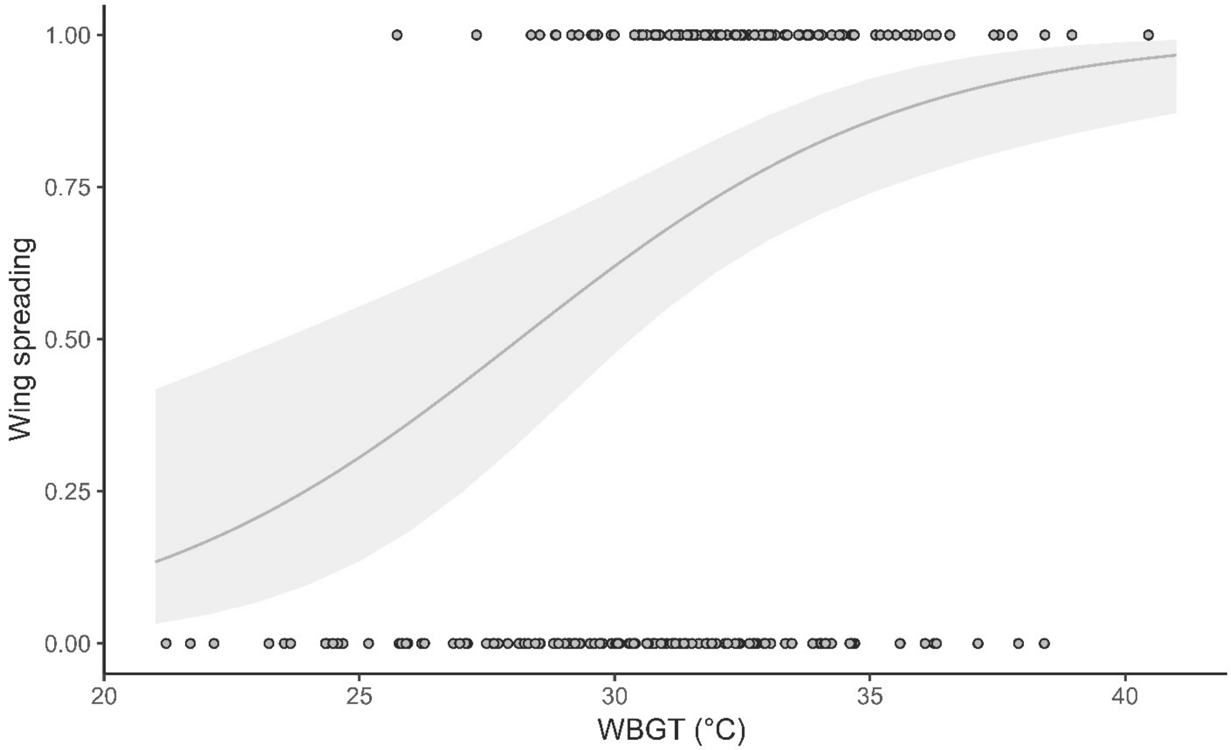

Figure 4. The use of wing spreading behavior in relation to wet-bulb globe temperature. The line represents the prediction (±95% CI) from the top ranked model.

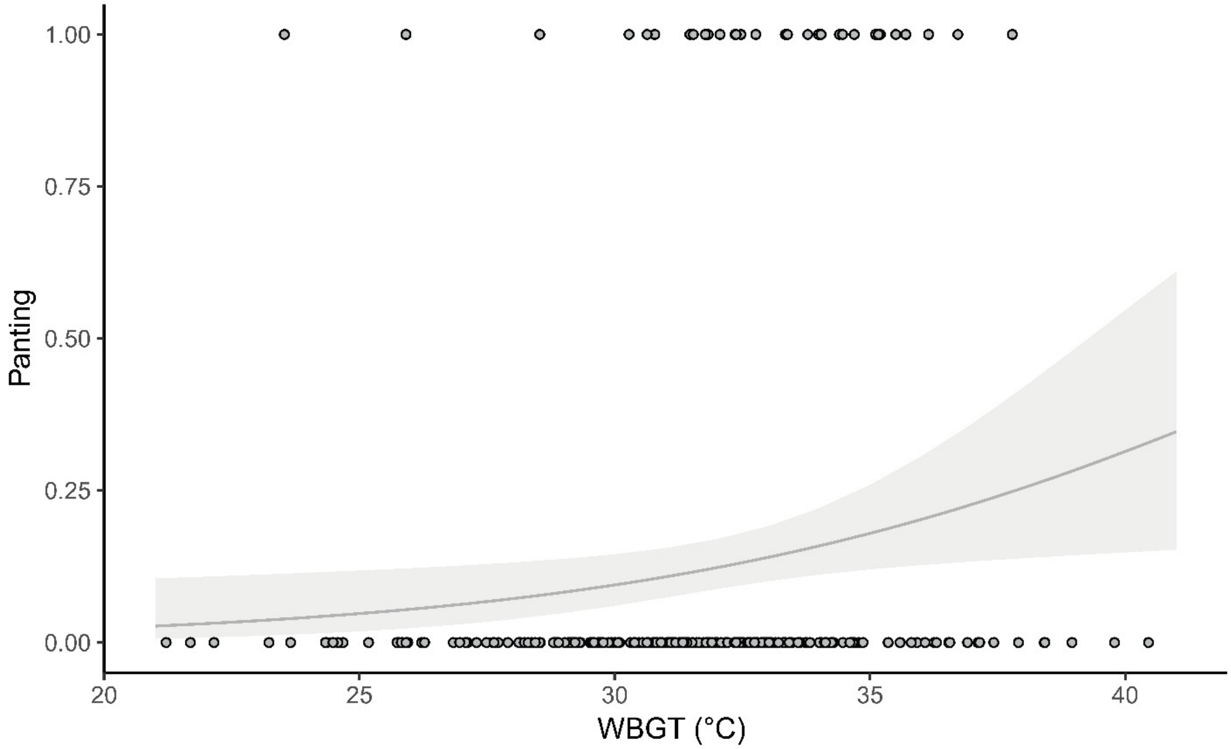

Figure 5. The use of panting behavior in relation to wet-bulb globe temperature. The line represents the prediction (±95% CI) from the top ranked model.

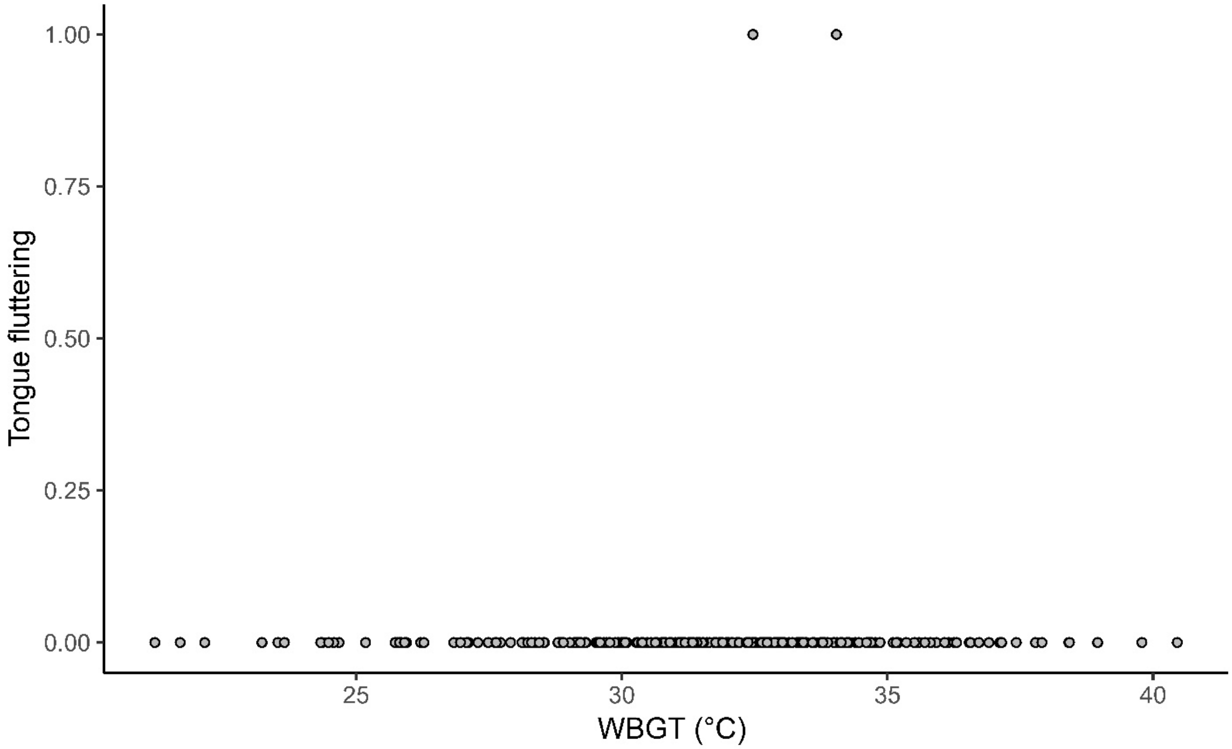

Figure 6. The use of tongue fluttering behavior in relation to wet-bulb globe temperature.

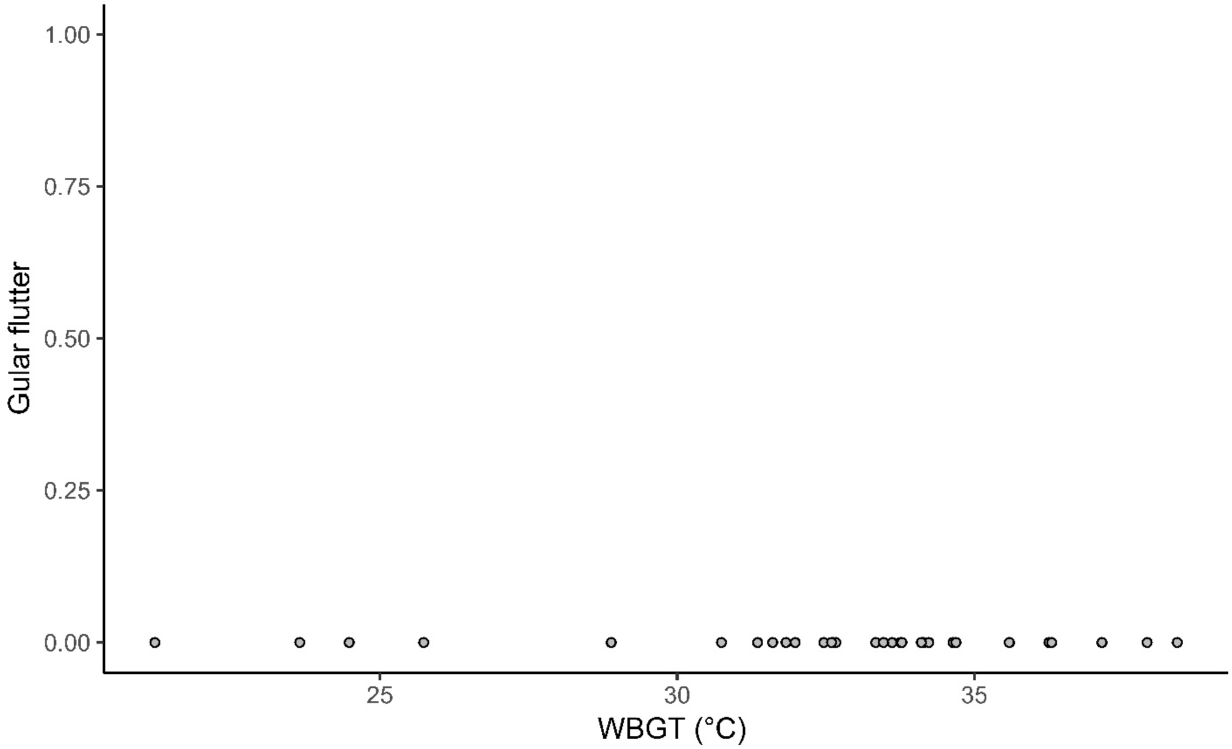

Figure 7. The use of gular fluttering behavior in Ardeidae in relation to wet-bulb globe temperature.

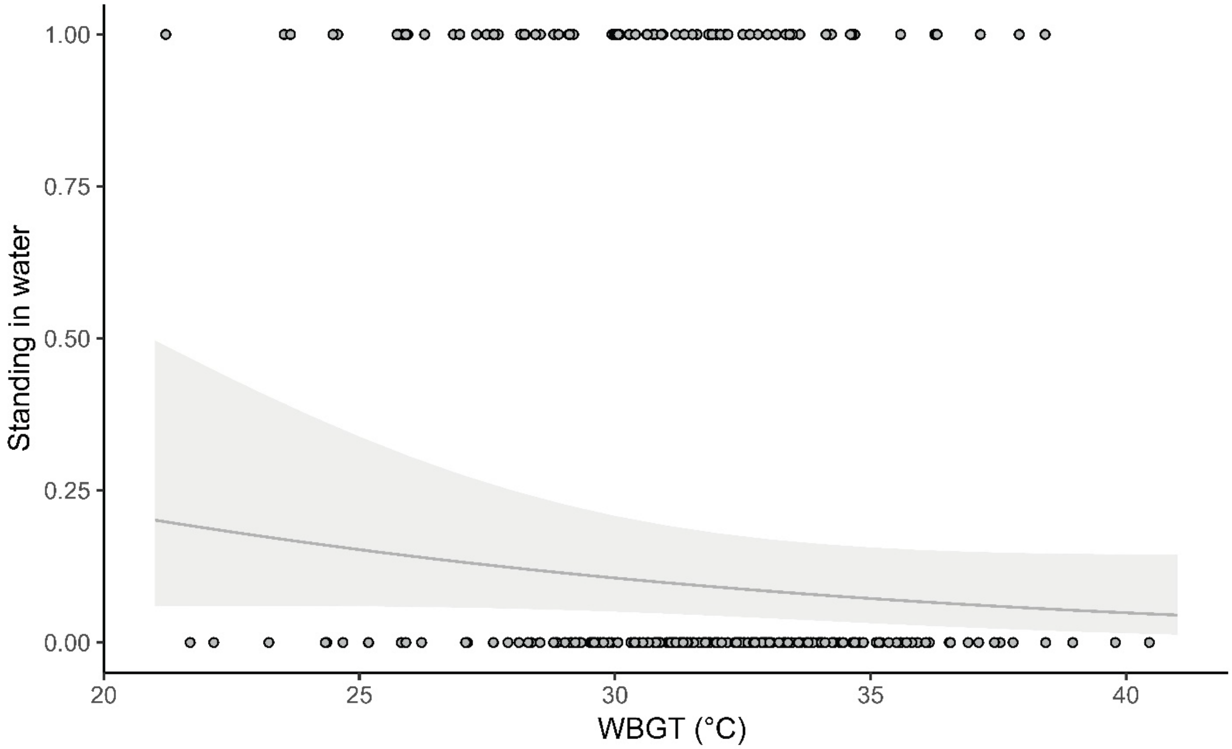

Figure 8. The frequency with which birds were observed standing in water in relation to wet-bulb globe temperature. The line represents the prediction (±95% CI) from the top ranked model.

Table 1. Top ranked and competitive (ΔAICc > 2) generalized linear models describing the use of heat dissipating behaviors.

Behavior	Model	d.f.	AICc	ΔAICc	AICc weight
Wing spreading	WBGT + family	17	233.9	0	0.751
Panting	WBGT	2	197.3	0	0.626
	Julian Day + WBGT	3	199.3	1.99	0.232
Standing in water	WBGT + family	18	277.5	0	0.387
	Family	17	277.7	0.18	0.354

Surface temperatures

The surface temperatures of the bill and legs increased as WBGT increased (Figures 9 and 10, respectively). The top-ranked model for the surface temperature of the bill included WBGT as the only fixed effect, and there were no competitive models (Table 2). The top-ranked model for the surface temperature of the legs included WBGT as the only fixed effect, and the only competitive model included both WBGT and Julian day (Table 2).

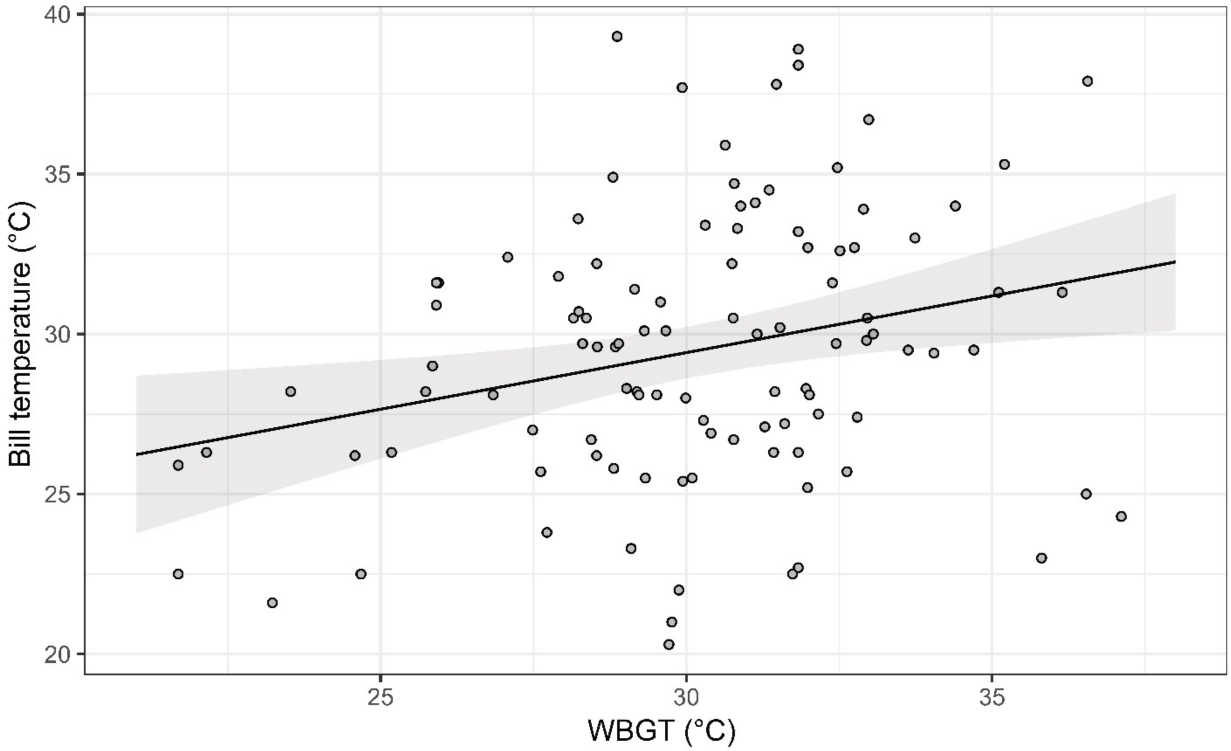

Figure 9. The surface temperature of the bill in relation to wet-bulb globe temperature. The line represents the prediction (±95% CI) from the top ranked model.

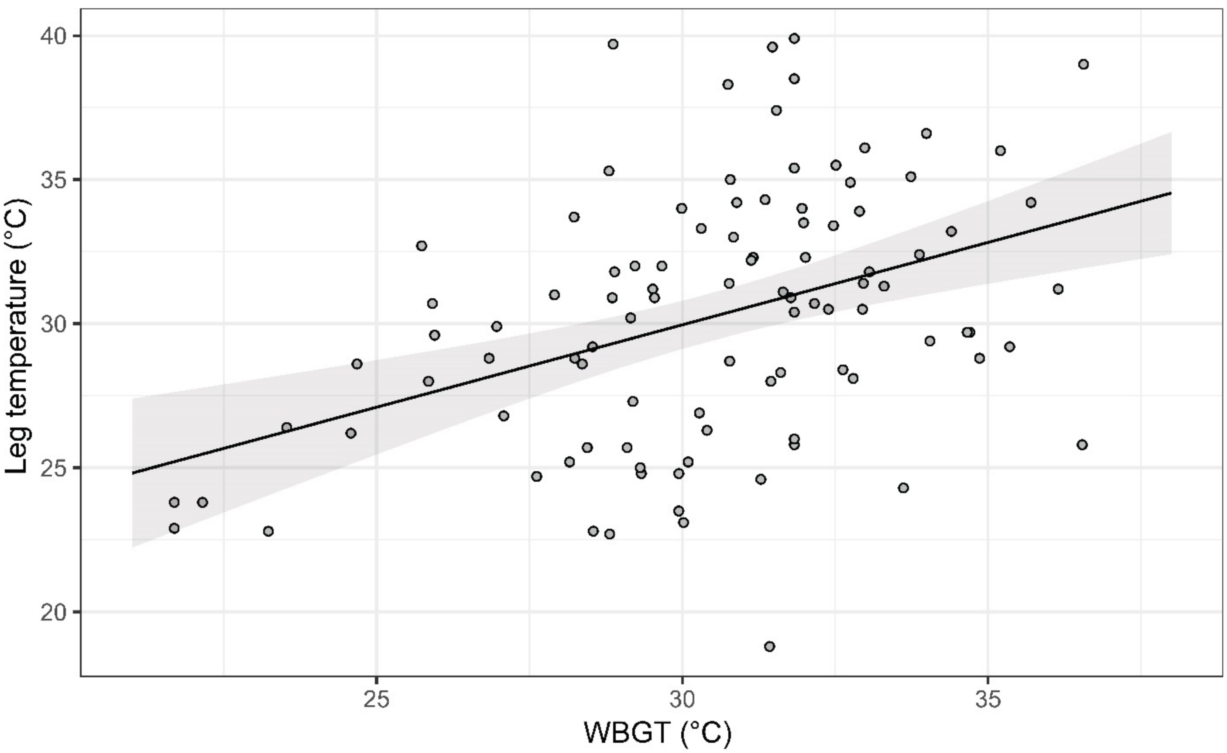

Figure 10. The surface temperature of the legs in relation to wet-bulb globe temperature. The line represents the prediction (±95% CI) from the top ranked model.

Table 2. Top ranked and competitive (ΔAICc > 2) generalized linear models describing the surface temperature of the bill and legs of birds.

Body surface	Model	d.f.	AICc	ΔAICc	AICc weight
Bill temperature	WBGT	3	593.0	0	0.628
Leg temperature	WBGT	3	565.0	0	0.545
	WBGT + Julian Day	4	566.7	1.69	0.234

Discussion

While predictive models are powerful tools, they require costly, time-consuming, and invasive methods that involve capturing birds for physiology experiments; these methods are therefore not realistic for widespread use in traditional conservation frameworks. Reflecting the difficulty of building these powerful but costly models, less than 30 out of the ~10,000 bird species have been modeled in this context, despite compelling examples of success when such methods are applied specifically for conservation (e.g., Kearney et al. 2016). As climate change advances, there is a growing need for a similar physiology-based approach that is designed for application in broader conservation frameworks. Here, we discuss the results of a study designed to apply conservation physiology concepts and methods in a field setting with the overarching goal of assessing susceptibility to heat.

Modeling the thermal environment

Studies of avian thermoregulation rarely focus on groups inhabiting areas with high humidity (McKechnie, 2019), even though humidity has influenced the evolution of avian thermoregulation (Freeman et al., 2024). This bias is reflected in the analyses of most studies of avian thermoregulation, which primarily use air temperature as the sole predictor of thermoregulatory responses. Humidity reduces the efficacy of evaporative cooling, an important thermoregulatory mechanism (Gerson et al., 2014; Powers, 1992; van Dyk et al., 2019), therefore studies of species that have evolved in hot and humid habitats will need to incorporate humidity in analyses to ensure the ecological relevance of their measurements. Studies conducted in field settings will also need to consider additional environmental metrics, such as solar radiation and wind speed, which are both important components of the thermal habitat (Cestari and de Melo, 2022; Wolf and Walsberg, 1996). On hot and sunny days, birds are known to seek shade (Cunningham et al., 2021 and references therein), and wind speed directly influences both evaporative and dry heat loss pathways (Gates, 2003). To account for all of these components, we used wet bulb globe temperature, a metric that incorporates a thermal metric that uses values of air temperature, relative humidity, solar energy, and wind speed (Spangler et al., 2022), and is already used to predict outdoor heat stress by US federal organizations such as the National Weather Service (https://www.weather.gov/tsa/wbgt) and the Occupational Safety and Health Administration (https://www.osha.gov/otm/section-3-health-hazards/chapter-4#).

Thermoregulatory behaviors

As expected, we found that thermal conditions strongly influenced the use of thermoregulatory behaviors, as evidenced by the presence of wet-bulb globe temperature as a fixed effect in three of the top-ranked models describing the use of thermoregulatory behaviors. Although we sampled five thermoregulatory behaviors, two of them (tongue flutter and gular flutter) did not have enough variation to accurately model; in other words, these behaviors were too rare to accurately model. The sparce use of these behaviors suggests that birds avoid relying on these behaviors, likely due to the resource and opportunity costs associated with panting and its derivative behaviors (Cunningham et al., 2021; McKechnie, 2022; van de Ven et al., 2019; Zuluaga and Danner, 2023b).

That birds used postural adjustments, such as wing spreading, before panting provides further evidence that birds prioritize the use of behaviors that do not carry resource or opportunity costs. Zuluaga and Danner (2023b) found that birds reduce their reliance on costly behaviors, such as panting, through acclimatization. That Julian day was only included in a competitive model of panting, and not any of the other behaviors, may provide further evidence that costly behaviors are adjusted through acclimatization. Although we expected tongue wagging and gular fluttering behaviors to have patterns similar to panting, we did not observe these behaviors enough to accurately model them. The lack of gular flutter and tongue wagging behavior may be because as temperatures rise, birds may opt to seek shade instead of engaging in these costly behaviors; this may also explain why panting appeared to have a decrease in use at the highest temperatures.

Surface temperatures

In keeping with other studies of thermal windows, the surface temperature of the bill and legs increased as temperature increased. It should be noted that the analyses of surface temperatures are preliminary because we are currently extracting surface temperature data from thermal images. Currently, we have extracted data for 140 of the 299 observations in our dataset. That being said, it is interesting and encouraging that Julian day was included in the competitive models for surface temperatures, given that the majority of the data comes from early in the season. In the model of leg temperature, the parameter estimate for Julian day was positive, and it was included alongside the fixed effect of wet-bulb globe temperature; this indicates that birds elevated their surface temperatures more as the season went on, and that they did so regardless of ambient conditions. As more data is collected, we expect the pattern of Julian day to become clearer.

In addition to finalizing the extraction of surface temperatures from the thermal images, further study is planned regarding the effects of phylogenetic relatedness in our dataset. Specifically, we will refine our current analyses with more control of phylogenetic relationships, which may help clarify the observed trends in both surface temperatures and behaviors. Additionally, we will conduct focused analyses on taxonomic groups to investigate behaviors specific to certain families (e.g., wading in Charadriidae, Scolopacidae, and Ardeidae). Thus far, we have prepared two preliminary investigations focusing on wading birds (see *Focused investigations on taxonomic groups* and *Appendix 1*).

Focused investigations on taxonomic groups

The willet was a species that we commonly found in BIR, particularly during the month of March, which is the peak of the breeding season for willets (Lowther et al., 2020). During the breeding season, male willets defend nesting and feeding territories, and the species exhibits biparental care, where both the male and female incubate eggs and raise chicks (Lowther et al., 2020). With rising global temperatures causing changes in the climate of breeding habitats, there could be concern for how breeding willets will be affected. During heatwaves, there could be changes in willet behaviors if they need to spend more energy regulating their body temperature instead of allocating that energy for growth, survival, and reproduction. These trade-offs could lead to a rise in nest abandonment or decreased adult survival, as has been observed in other seabirds (e.g., Cook et al., 2020). Other possible trade-offs could include exploiting cooler environments while sacrificing foraging efficiency, territorial defense, and parental care (Cook et al., 2020; Cunningham et al., 2021). The lack of costly behaviors such as tongue fluttering and gular fluttering suggests that willets primarily rely on non-evaporative cooling mechanisms such as wing spreading, even during the hottest periods of the summer. It is unknown if willets, or other species, are shifting their use of behaviors to include more evaporative cooling. Thus, further observation of thermoregulatory behavior during the breeding season may provide valuable insights into how rising temperatures affect the reproductive performance of birds in the long term.

We also conducted a preliminary assessment of the family Ardeidae (*Appendix 1*), which includes species such as herons and egrets. The preliminary investigation shows that no birds in the family Ardeidae were observed panting during the duration of the study. This is noteworthy because Ardeidae is the only family in our study that was not observed panting. Interestingly, members of the family Ardeidae were found standing in water during 69% of observations, likely due to their foraging strategy (Winkler et al., 2020). In comparison, other groups that inhabit similar habitats and have access to nearby water, such as the family Icteridae, were only found standing in water 10% of the time. This difference in the use of wet or inundated habitat is a potential reason why the family Ardeidae was not observed panting during the study. By standing in water, herons and egrets likely dissipate heat efficiently through their legs, thus allowing them to save energy and water by avoiding other thermoregulatory behaviors. Another potential reason could be that herons and egrets inhabit some of the most humid microclimates found in Bird Island Reserve. Higher humidity makes evaporative cooling less efficient (Gerson et al., 2014; Powers, 1992; van Dyk et al., 2019), which could cause birds who are found in or near water to avoid relying on evaporative cooling because it would require unnecessary expenditure of energy in a highly competitive environment. This is further supported by members of the Ardeidae family exhibiting other thermoregulatory behaviors like wing spreading while being in the water, which indicates that simply standing in the water is not enough to meet all of their thermoregulatory demands. Although it is known that humidity influences evaporative cooling (Gerson et al., 2014; Powers, 1992; van Dyk et al., 2019), relatively little is known about how humidity influences behaviors, thus further research may reveal the effects of humidity on thermoregulatory behaviors.

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Outreach

During this research, we brought n = 3 volunteers to help collect data in the field. Additionally, n = 3 community members that were involved with logistics (parking and housing) received regular updates throughout the season. JDZ (pictured below) joined the Bird Island Stewards for three of the Wednesday morning birding tours through the reserve, where he presented the research to n = ~25 members of the community per tour (n = ~75 total).

JDZ (right) presenting the research conducted through the NC Seagrant Coastal Research Fellowship to members of the community at Bird Island Reserve.

Students supported

While a thesis or dissertation chapter involves research, analyses, and writing, these tasks are fundamentally the graduate student's responsibility. Even in labs that promote collaboration between graduate and undergraduate students, it is difficult for undergraduate students to engage with research on a deep level that involves all of these unique forms of experience. Thus, research fellowships such as the NC Seagrant Coastal Research Fellowship create unique opportunities for graduate students to develop research that impacts their professional development alongside the professional development of collaborating undergraduate students. To this end, JDZ designed and led this research with an emphasis on the impact it would have on undergraduate students. This NC Seagrant Coastal Research Fellowship supported one PhD candidate (JDZ), three undergraduate students (RBD, BFF, and TWV), and one middle school student (AW). Here we will briefly describe the impact of this research on these students.

This research allowed two undergraduate students (RBD and BFF, pictured below) to participate in field-based ecophysiology research. Working in the field provides a unique opportunity for students to engage in active learning, which raises the impact of the experience they gain through research. Students that have conducted field work often express a deeper connection to science after working in the field, where they develop unique skills, gain logistical experience, and experience the subjects of their coursework in the real world. Students also benefit from experiencing field work because it provides important context for the entire process of science, thus developing their understanding and appreciation for the work that happens both in and out of the field.

This research has created opportunities for students to remain involved in the research after field work, which is typically the phase that undergraduate students have access to. After the conclusion of the field work, n = 3 undergraduate students and n = 1 middle school student (RBD, BFF, TWV, and AW) continued to collaborate on the research through data extraction, analyses, and writing. In addition to the students' authorship on this report, BFF has prepared a poster for presentation in Spring 2025, and AW is preparing a research paper on how environmental conditions influence changes in the surface temperatures of birds at Bird Island Reserve, which will be submitted to Polygence, an online mentoring platform, by 11 October 2024.

In addition to the direct engagement of students with the research, this project has created opportunities for students to gain experience with grantspersonship. This year, RBD and BFF were awarded an Undergraduate Travel Award from the Biology and Marine Biology Department at UNCW totaling $1248.00 to fund their travel associated with the research at Bird Island Reserve; It should be noted that RBD and BFF co-authored the application for the Undergraduate Travel Award with TWV and three additional undergraduate students, all of whom JDZ mentored and guided through the process of applying for funding (5 of these 6 students are pictured below learning to use field equipment). BFF also applied for, and was awarded, the Louis Stokes Alliance for Minority Participation Research Stipend, totaling $5,000.00. JDZ applied for, and was awarded, the Society for Integrative, Comparative, and Marine Biology Fellowship of Graduate Student Travel, totaling $2,000. Outside of the $10,000.00 in funding provided through the NC Seagrant Coastal Research Fellowship, this research has generated an additional $8,248.00 in funding for students to engage in active learning through research; importantly, students were the primary authors and applicants of all funding applications.

Importantly, many of the students that have been involved with this research were recruited from Futuros En STEM, an organization that aims to provide mentorship and networking opportunities for members of underrepresented communities in science. Thus, the impacts of the NC Seagrant Coastal Research Fellowship have been amplified because they simultaneously create novel research opportunities while supporting Diversity, Equity, and Inclusion (DEI). We enthusiastically voice support for research funds that enable graduate students to conduct research outside of their planned theses and dissertations because it creates valuable opportunities for undergraduate students to engage in research alongside early career professionals.

RBD (left) and BFF (right) collecting thermal images of wildlife at Bird Island Reserve.

TWV (right) teaching fellow lab members how to use an anemometer and a solar power meter to measure environmental conditions. Note that these are 5 out of 6 students that co-authored the application for travel funding; the remaining student had graduated by the time preparations began for research at Bird Island.

News/Media coverage of this project

One completed interview (JDZ), one planned interview (JDZ), one completed poster (BFF), one in-progress research paper (AW).

Data management plan progress

Data extraction from thermal images is in progress, and the finalized dataset and associated thermal images will be uploaded to a public Dropbox folder by the end of Fall 2024. The public dataset and thermal images can be accessed via the following link:

https://www.dropbox.com/scl/fo/10pit0sxbqjklzp07xnxh/AKPVIhRkdVFKs7MDnjXfuf4?rlkey=rls383vve57ajy9m45ael1ir8&st=qjv9qcvb&dl=0

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Supplementary Information

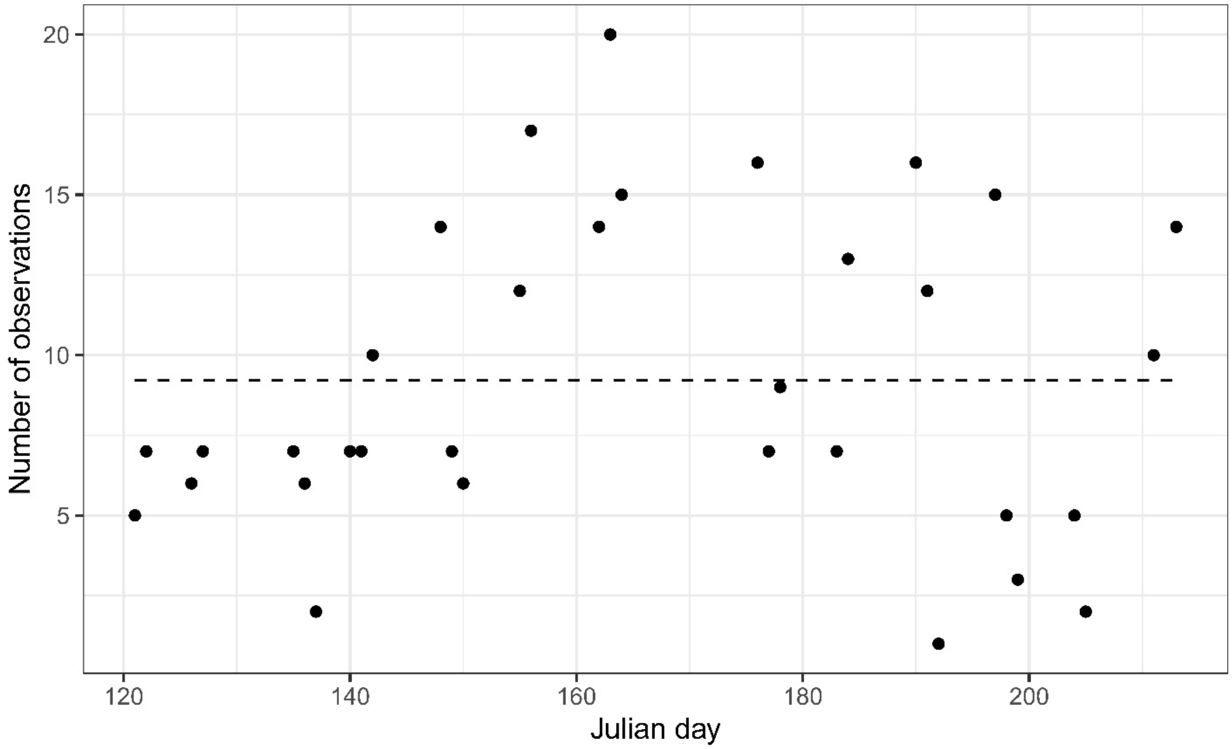

Figure S1. Number of observations over the course of the field season from Julian day 121 (1 May 2024) to Julian day 213 (1 August 2024).