ResearchOnline@JCU

JAMES COOK UNIVERSITY AUSTRALIA

This file is part of the following work:

Madeira Tavares Lopes, Camila (2025) *"Roosting on the edge: evaluating thermal risk and habitat requirements of spectacled flying-foxes using infrared thermography"*. PhD Thesis, James Cook University.

Access to this file is available from:

https://doi.org/10.25903/3vxh%2Drf70

Copyright © 2025 Camila Madeira Tavares Lopes

The author has certified to JCU that they have made a reasonable effort to gain permission and acknowledge the owners of any third party copyright material included in this document. If you believe that this is not the case, please email researchonline@jcu.edu.au

“Roosting on the Edge: Evaluating Thermal Risk and Habitat Requirements of Spectacled Flying-foxes Using Infrared Thermography”

Thesis submitted by
Camila Lopes, MSc

for the degree of Doctor of Philosophy (PhD)
March 2025



College of Science and Engineering
James Cook University
Townsville, Australia

ACKNOWLEDGEMENTS

This thesis would not have been possible without many incredible people's support, generosity, and inspiration.

I am deeply grateful to my supervisory team: Professor Susan Laurance, Professor Denise Doolan, and Dr. Cadhla Firth. Your guidance, encouragement, and critical insights helped shape this research and my growth as a scientist. I am especially thankful for your patience and support during the most challenging moments of this journey.

A sincere thank you to Daniel Keane from Predict Ecology, whose provision of LiDAR data was essential to this research. I am also truly indebted to the bat carers of Cairns, whose love and commitment to these animals were both humbling and inspiring. In particular, I would like to thank Jennefer McLean and Maree Treadwell Kerr—your dedication gave me purpose and strength when I struggled to see the value of my work.

I acknowledge the Skyrail Foundation's support for providing essential resources for my research, and I’m grateful to the Australian Institute of Tropical Health and Medicine (AITHM) for fostering such a friendly and welcoming academic environment.

To my fellow PhD friends—Ashton Kelly, Maxine Smith, and Yomani Sarathkumara—thank you for walking alongside me through this difficult path. Your friendship, solidarity, and late-night chats made the weight of this journey lighter.

Finally, I thank my family and dear friends in Brazil. Your unconditional love, encouragement, and belief in me have been my anchor. Even from afar, you were my rock.

To all of you—thank you from the bottom of my heart.

STATEMENT OF THE CONTRIBUTION OF OTHERS

This thesis was conducted under the supervision of Professor Susan Laurance (primary supervisor), Professor Denise Doolan, and Dr. Cadhla Firth, who provided critical guidance and feedback throughout the research process, including assistance with conceptual design, methodology, data interpretation, and editorial advice on drafts.

Daniel Keane from Predict Ecology provided LiDAR data used for the vegetation structure analysis presented in Chapter 3 and Chapter 4. The Skyrail Foundation supported the project through the provision of resources and access for field data collection. The Australian Institute of Tropical Health and Medicine (AITHM) provided facilities and a collaborative research environment.

Bat carers, including Jennefer McLean and Maree Treadwell Kerr, offered valuable local knowledge and field support, which contributed to the development and contextual understanding of the research. Their dedication also provided inspiration during the study.

The candidate conducted all analysis, interpretation, and writing, with guidance and feedback from the supervisory team.

ABSTRACT

Climate change is accelerating shifts in species distributions, altering ecological interactions, and increasing the frequency of extreme weather events. Among the most affected are tropical species with limited thermal tolerance, such as the spectacled flying-fox (*Pteropus conspicillatus*), an endangered megabat species endemic to northeastern Australia.

In 2018, a heatwave in Cairns resulted in the mass mortality of approximately one-third of this species' population, highlighting the urgent need to understand how roost microclimate and vegetation structure influence heat stress resilience. This thesis investigates the role of urban roost characteristics in mitigating the impact of extreme heat events on spectacled flying-foxes and explores potential conservation strategies to enhance habitat resilience.

First, I assess long-term temperature trends in Cairns and the increasing frequency of excessively hot days as a growing risk to wildlife. Using historical climate data, I analyse temperature anomalies and heatwave trends to contextualise the increasing threat of extreme weather events to flying-fox populations (Chapter 2). Next, I examine the characteristics of urban roost vegetation and its influence on microclimate and occupancy. Given that my findings in Chapter 2 suggest that microclimate alone does not drive roost selection, I explore how vegetation structure modulates roost conditions and whether specific vegetation attributes correlate with higher occupancy rates (Chapter 3). Finally, in Chapter 4, I employ thermal imaging technology to estimate the impact of vegetation and microclimate on bat surface temperature. This non-invasive approach allows me to identify roosts that provide superior thermal buffering, offering a framework for using these sites as models for reforestation and habitat enhancement strategies. As a result of this study, I critically review (Chapter 5) flying-fox management plans across Queensland, identifying gaps in how climate-related risks are addressed. Through comparative analysis, I find that most plans lack clear guidelines for reducing thermal stress or integrating scientific data into policy. I propose a revised framework for roost management that incorporates regular multidisciplinary monitoring, adaptive responses to extreme heat events, and the strategic restoration of thermally resilient habitats.

Together, these chapters provide a comprehensive assessment of how urban habitat features influence the vulnerability of spectacled flying-foxes to climate extremes. By integrating climate analysis, vegetation ecology, and physiological monitoring, this thesis offers a novel approach to understanding and managing thermal risk. The findings inform conservation strategies that not only protect critical roosts but also guide habitat enhancement efforts under ongoing climate change.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS i

STATEMENT OF THE CONTRIBUTION OF OTHERS ii

TABLE OF CONTENTS iv

LIST OF TABLES ix

LIST OF FIGURES x

CHAPTER 1 1

1.1 Climate change and its impact on wildlife 1

1.2 Flying-foxes 2

1.3 Ecological Relevance of the Spectacled Flying-Fox 3

1.4 Influence of vegetation on urban roosts of spectacled flying-foxes in Cairns: roost description and its microclimate 6

1.5 Influence of vegetation and microclimate in bat surface temperature 7

1.6 Thermal camera for wildlife temperature 10

1.7 Policies for the flying-fox urban population 14

CHAPTER 2 17

2.1 Abstract 17

2.2 Introduction 18
2.3 Methods 20
2.3.1 Long-term temperature trends 20
2.3.2 Microclimate characterisation 20
2.3.3 Data analysis 22
2.4 Results 23
2.4.1 Maximum temperatures 23
2.4.2 Excessively hot days and heatwaves 25
2.4.3 The microclimate of urban spectacled flying-fox roosts in Cairns 27
2.5 Discussion 33
CHAPTER 3 36
3.1 Abstract 36
3.2 Introduction 37
3.3 Methods 40
3.3.1 Vegetation structure 41
3.3.2 Microclimate 43
3.3.3 Statistical analysis 43
3.4 Results 44
3.4.1 Vegetation characteristics of urban roosts 44
3.4.2 Canopy cover 46
3.4.3 Ground cover 46
3.4.4 Understory structure and roost occupancy 47

3.4.5 Tree diameter 48
3.4.6 LiDAR data 49
3.4.7 Vegetation characteristics of Spectacled flying-fox urban roosts and their influence on roost microclimate 53
3.5 Discussion 54
3.5.1 Implications for Roost Suitability 57
CHAPTER 4 58
4.2 Introduction 59
4.3 Methods 62
4.3.1 Field collection 62
4.3.2 Microclimate 63
4.3.3 Thermal camera 63
4.3.4 Vegetation structure: plot-based assessment 64
4.3.5 Vegetation structure: LiDAR scan 65
4.3.6 Data analysis 66
4.4 Results 68
4.4.1 Thermal readings and risk of extreme temperatures 68
4.4.2 Environmental and vegetation influence on bat surface temperature 73
4.4.3 Microclimate 78
4.4.4 Vegetation structure 78
4.4.4.1 Tree height 78
4.4.4.2 Understory 80

4.5 Discussion 81
4.5.1 Microclimate strongly influences bat thermal stress.....81
4.5.2 Vegetation structure modifies microclimate and buffers thermal extremes 82
4.5.3 Roost microclimate and their influence on bat thermal readings 84
4.5.4 Roost vegetation and their influence on bat thermal readings.....85
CHAPTER 5.....87
5.1 Abstract 87
5.2 Introduction 88
5.3 Methods.....90
5.3.1 Study Design.....90
5.3.2 Data Collection 90
5.3.3 Data Analysis.....90
5.4 Results and discussion 92
5.4.1 Roost Risk Management Across Different Plans.....92
5.4.2 Determining Levels of Intervention.....92
5.4.3 Collaboration with Researchers 93
5.4.4 Regular Roost Monitoring.....94
5.4.5 Primary Focus: Conservation vs. Conflict Resolution.....94
5.4.6 Analysis of Heat Stress Management in Queensland Flying-Fox Management Plans.....95
5.4.7 Data-Driven Conservation: A Missing Element.....96

5.4.8 Cross-Sectoral Applications for Climate Adaptation.....101

CHAPTER 6.....102

6.1 Conclusions.....102

6.2 Study Limitations and Future Directions.....104

REFERENCES.....105

APPENDIX A.....128

APPENDIX B.....130

Recording body temperature in spectacled flying-foxes, a thermal image approach 130

Objective:.....130

Methods:.....130

Introduction.....130

Methods.....131

Thermal camera.....131

iButton.....131

Device testing.....132

Results.....132

Glasshouse results.....132

External validation.....136

Specificity.....138

Discussion.....140

APPENDIX C.....141

References 142

LIST OF TABLES

Table 2.1: Analysis of Variance used to investigate the effect of temperature and humidity in the roost occupancy……...……31

Table 2.2: Binomial models evaluating the probability of roost occupancy according to microclimate and roost size……..32

Table 4.1: Mean temperatures of bat and vegetation surfaces were compared with Wilcoxon signed-rank tests at 11 urban roost sites in Cairns, Australia……68

Table 4.2: Results of linear mixed and generalised models fitted to the difference between bat surface temperature and background ranked according to the Akaike Information Criterion (AIC)……...……...70

Table 4.3: Percentage of roost site data points in high and low bat temperature environments……..……...…..78

Table 4.4: Model selection results for the association between vegetation structure, here represented as point-cloud data above different height (fixed effects) and bat surface temperature, using LiDAR-derived point cloud data across height classes……..……81

Table 5.1 Variables assessed and key classification criteria…….93

LIST OF FIGURES

Figure 1.1: Geographic distribution of four flying-fox species in mainland Australia…….1

Figure 1.2: Global distribution of spectacled flying-fox…….3

Figure 2.1: The location of spectacled flying-foxes urban roosts (A). The triangles are the unoccupied camps, and the hexagons are the occupied. (B) illustrates large and small spectacled flying-fox
camps……..…….19

Figure 2.2: The standardized anomaly of the annual average maximum temperature in Cairns (1943-2022) - (A) annual maximum temperature, (B) summer maximum, and C) winter maximum temperature…...……...……21

Figure 2.3: The number of days ≥35°C per decade measured at the Cairns airport weather station increased overall over time (3.1 SD)……..22

Figure 2.4: Daily maximum temperature (A) and humidity (B) recorded at 3pm at the Cairns airport weather station from 2018 - 2022…….24

Figure 2.5. The y axis shows boxplots containing the maximum daily temperature (°C) recorded in spectacled flying-foxes' roosts over two summers. The campsites are on the x axis, ordered by the average maximum daily temperature (°C)……..25

Figure 2.6. The expected frequency, based on ten years of data (2013-2023) registered at the airport station (A) and the recorded frequency of days in each temperature range in urban spectacled flying-fox roosts (B)……..……..……26

Figure 2.7: Boxplot graphs displaying the difference between occupied and unoccupied camps in maximum daily temperature (A), maximum humidity (B), average temperature (C), and average relative humidity (D) per visit……...……..…27

Figure 3.1: The location of spectacled flying-fox roost sites examined in this study. The roosts encompass various vegetation types related to habitat area and urban environments…….....38

Figure 3.2: Non-metric Multidimensional Scaling (NMDS) ordination plot showing the significant factors predicting roost occupancy. Occupied (blue) and unoccupied (yellow) sites are separated based on significant environmental variables……..……42

Figure 3.3: A comparison of canopy cover estimates between occupied and unoccupied flying-fox urban roosts in Cairns, Australia……..……...…43

Figure 3.4: (a) Ground cover composition in occupied and unoccupied roosts; (b) Odds ratios of ground cover types associated with occupied roosts……...……..…44

Figure 3.5: Boxplots comparing the density of vegetation categories per plot area (m^2) between occupied and unoccupied sites. Occupied sites (blue) exhibit higher density across most vegetation categories compared to unoccupied sites (yellow)……..……45

Figure 3.6: Boxplot comparing the average tree diameter between occupied and unoccupied roost sites and showing no difference between them……..……..46

Figure 3.7: Boxplots showing the proportion of tree height across height categories (m) for occupied (Y, blue) and unoccupied (N, yellow) roosts…….……..47

Figure 4.1: The interquartile range of bat and background temperature per camp. The blue lines show the interquartile range of bat temperature, and the yellow line shows the background. The dots represent the median, and the red asterisk shows the significance……...66

Figure 4.2: Comparison of the frequency (A) and probability (B) of bat temperatures exceeding 42°C across different campsites…….…...70

Figure 4.3: Non-metric multidimensional scaling (NMDS) ordination plot showing the variation in environmental conditions across roost camps. Each point represents a roost site, colored and shaped according to its respective camp……..……..73

Figure 4.4: Constrained visualisation of roost sites based on environmental variables, with bat temperature as the primary axis……...…..75

CHAPTER 1

General Introduction

1.1 Climate change and its impact on wildlife

Anthropogenic greenhouse gas emissions have significantly contributed to global warming, increasing the frequency, severity, and duration of extreme weather events such as heatwaves (Masson-Delmotte et al. 2018). Since 1950, heatwaves have intensified both globally and regionally, and this trend is expected to worsen as the climate continues to warm (Perkins-Kirkpatrick & Lewis 2020; Domeisen et al. 2023). Heatwaves are particularly common in dry and temperate regions but are less frequent in wet tropical climates, where seasonal temperature variation is typically lower (Staff 1995; Seidel & Yang 2020; Lopes & Laurance 2024). However, as the global climate shifts, even tropical species—historically adapted to stable thermal environments—are becoming increasingly vulnerable (Stevens 1989; Ghalambor 2006; Polato et al. 2018).

Tropical forests serve as important buffers against climate extremes, with their dense vegetation influencing temperature and humidity at the microclimate level (Camargo & Kapos 1995; Murcia 1995). However, deforestation and urban expansion disrupt these natural cooling mechanisms, exposing wildlife to harsher environmental conditions (Li et al. 2020; Yu et al. 2020). Many species depend on the thermal stability provided by forests, and as habitat degradation continues, their ability to cope with extreme temperatures diminishes (De Frenne et al. 2021) .

Flying-foxes (*Pteropus spp*.) are particularly sensitive to climate fluctuations due to their large colony sizes and exposure to open canopy roosts (Ratcliffe & Ter Hofstede 2005; Timmiss et al. 2021). Heatwaves have now been linked to mass mortality events in several species, including the black (*P. alecto*), grey-headed (*P. poliocephalus*), little red (*P. scapulatus*), and spectacled (*P. conspicillatus*) flying-foxes (Welbergen et al., 2008). Mortality events have been recorded when temperatures exceed 40°C, with models predicting a 42°C threshold for widespread die-offs (Welbergen et al. 2008; Ratnayake et al. 2019; Mo et al. 2021).

A severe example of this occurred during the 2018 heatwave in Cairns, where an estimated 23,000 spectacled flying-foxes perished—nearly one-third of the population

(Jason Bittel 2019, Lopes & Laurance 2024). The rapid and severe population decline highlights the urgent need to understand how species respond to climate extremes and to implement conservation strategies that enhance habitat resilience. As climate change intensifies, species with narrow thermal tolerances, restricted distributions, or habitat dependencies are expected to be disproportionately affected, underscoring the necessity of habitat protection and climate-adaptive management to mitigate biodiversity loss (Polato et al. 2018; Camacho et al. 2024).

1.2 Flying-foxes

Flying-foxes (Pteropodidae) belong to one of the largest orders of mammals (Chiroptera) and occur in tropical and subtropical climates from West Africa to Australia. In Australia, four species are distributed over the mainland: grey-headed (*Pteropus poliocephalus*), spectacled (*P. conspicillatus*), black (*P. alecto*), and little red (*P. scapulatus*) flying-foxes (Timmiss et al. 2021;Figure 1.1). These highly social animals form roosting colonies that range in size from a few hundred to over a million individuals (Brooke et al. 2008). They primarily feed on fruits, flowers, and nectar. Due to their mobility, they act in ecosystems as pollinators and seed dispersers (Enchéry & Horvat 2017).

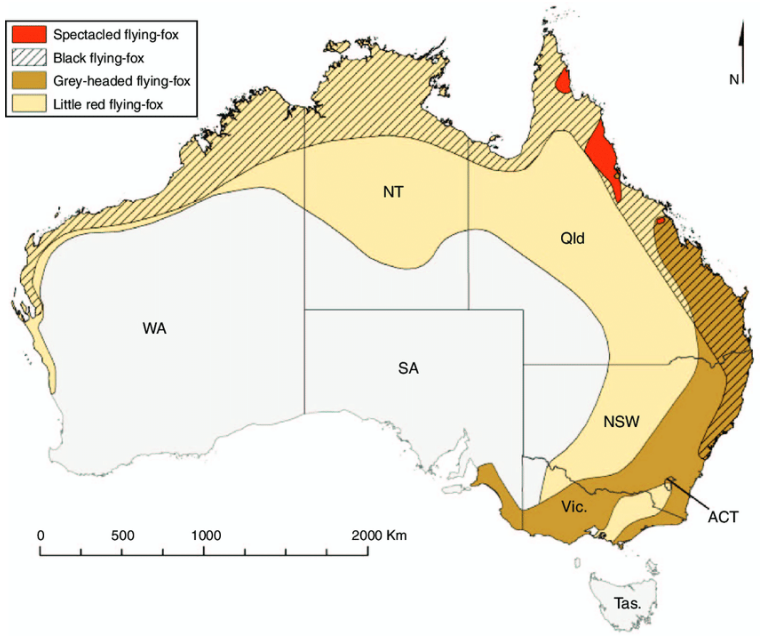


Figure 1.1 Geographic distribution of four flying-fox species in mainland Australia. The spectacled flying-fox (*Pteropus conspicillatus*) is represented in red, the black flying-fox (*P. alecto*) in hatched black, the grey-headed flying-fox (*P. poliocephalus*) in brown, and the little red flying-fox (*P. scapulatus*) in yellow. The ranges of these species overlap in some regions, particularly along the eastern and northern coasts (Timmiss et al. 2021).

1.3 Ecological Relevance of the Spectacled Flying-Fox

The seasonal availability of food resources requires high mobility in flying-foxes (Páez et al. 2018). Their movement patterns can be categorised into two types: short-distance local movements (<100 km) and long-distance migratory movements (Welbergen et al. 2020). However, in recent decades, these movement patterns have changed significantly due to habitat loss and agricultural expansion (McAlpine et al. 2009). As natural habitats decline, flying-foxes are forced to travel greater distances in search of resources, corroborating to the increase of physiological stress and colony disruption (Enchéry & Horvat 2017; Luskin 2010; Páez et al. 2018). Additionally, the proliferation of exotic plant species and the presence of year-round flowering vegetation in urban environments have altered resource availability, attracting bats to urban areas where they exploit non-native food sources outside their historical foraging periods (Gulraiz et al. 2015; Roy et al. 2020).

The spectacled flying-fox (*Pteropus conspicillatus*) is a megabat species primarily found in the tropical forests of northeastern Queensland, Australia, with populations also present in Papua New Guinea and surrounding islands (Figure 1.2). In Australia, their distribution ranges from Ingham to Cooktown and extends northward through the Cape York Peninsula (Hall & Richards 2000).

Listed as endangered since 2019 [EPBC Act 2019, 2021; Threatened species & ecological communities (TSSC, 2021)], the spectacled flying-fox faces multiple threats in addition to climate change. These include: habitat loss, declining food resources, disease, and human-wildlife conflicts. Among the diseases affecting this species, cleft palate syndrome (McMichael et al. 2023) and tick paralysis (Buettner et al. 2013) are particularly concerning, as they disproportionately impact juveniles and mothers, increasing mortality rates. In urban areas, conflicts with human residents further threaten their survival (Welbergen 2012; Tait et al. 2014; Preece 2023). These conflicts have led

to attempts to disperse urban roosts, a management practice mostly undertaken by local governments to reduce human-wildlife interactions. However, monitoring evidence suggests that roost dispersal is largely ineffective, as displaced bats tend to return or establish new roosts in equally problematic locations, exacerbating conflict rather than resolving it (Roberts et al. 2021). Community fears of disease transmission from bats, such as lyssavirus, have some justification, whereas more general concerns over coronavirus or Hendra transmission (Lu et al. 2021) are not based on evidence. Either way, concerns over disease transmission certainly have added to the complexities of its conservation in urban areas.

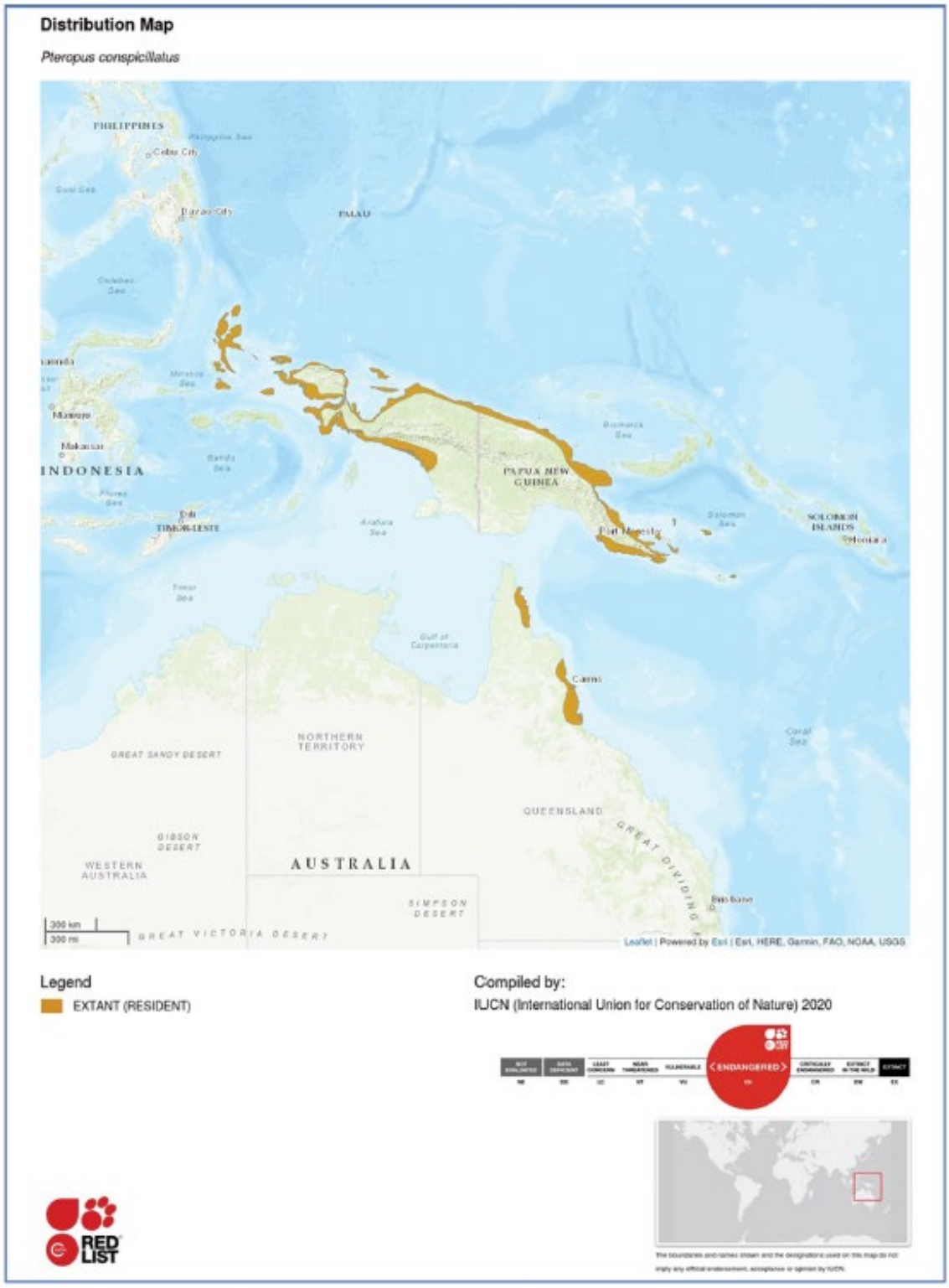


Figure 1.2. Global distribution of spectacled flying-fox (Roberts et al. 2020)

The spectacled flying-fox has a part in tropical ecosystems due to its specialised foraging habits, which include visiting inundated forests such as: mangroves, and *Melaleuca* swamps, and terrestrial rainforest and sclerophyll forests. Its diet of fruit and

flowers, combined with its ability to travel long distances in search of these resources, makes it a key pollinator and seed disperser, essential for ecosystem regeneration and maintenance (Markus & Hall 2004; Palmer et al. 2000; Parsons et al. 2006). This species is often the sole flying-fox in its habitat, with 75% of its roosts being single species (Timmiss et al. 2021).

1.4 Influence of vegetation on urban roosts of spectacled flying-foxes in Cairns: roost description and its microclimate

Microclimate describes a group of environmental factors influencing ecological patterns and processes at fine spatial scales. Defined as localised atmospheric conditions that differ from broader surrounding environments, microclimate determines species' survival (Pincebourde et al. 2016; Wolfe et al. 2025), growth (Duchicela et al. 2021; Pandey et al. 2025), reproduction rates (Huey et al. 2012; Smyser et al. 2024), occupancy (Varner & Dearing 2014; Ranius et al. 2024), and distribution (McGinn et al. 2023; Ismaeel et al. 2024). In forest ecosystems, microclimates can vary substantially due to factors such as vegetation structure, topography, soil composition, and water availability (De Frenne et al. 2021; Kemppinen et al. 2024).

The structure of the forest canopy and understory significantly affects local temperatures. Tree height, canopy density, and foliage complexity contribute to reducing temperature extremes and regulating humidity (Wang et al. 2023). Forest canopies absorb and reflect shortwave radiation, while evapotranspiration cools the environment, collectively reducing understory temperatures by up to 4°C globally (De Frenne et al. 2019) and up to 10°C in tropical forests (Ismaeel et al. 2024). The vertical stratification of vegetation also controls light penetration, heat diffusion, and air circulation, further buffering against extreme weather conditions (Scheffers et al. 2014; Atkins et al. 2018; Díaz-Calafat et al. 2023). However, drought conditions and seasonal leaf shedding can reduce cooling efficiency in closed forests during the summer, particularly in deciduous forests (de Souza et al. 2020).

Vegetation structure is also critical in determining species distribution and biodiversity patterns, including the roost selection of flying-foxes (Dos Santos et al. 2016; Majumdar et al. 2016; Lunn et al. 2021). Flying-foxes have been observed roosting in a variety of vegetation types, from tall dense forests to mangroves and even urban parks. Yet, despite the availability of large tracts of protected area in the Wet Tropics region,

only 13.9% of known spectacled flying-fox roosts are located within these reserves (MacDonald et al. 2021; Timmiss et al. 2021). Urban roosts often consist of small forest remnants and/or planted trees, which lack the structural complexity and microclimate buffering of intact forests (Majumdar et al. 2016; Morán-Ordóñez et al. 2018; González-Trujillo et al. 2023).

Despite increasing research on grey-headed and little red flying-foxes, the habitat preferences of spectacled flying-foxes remain less understood (Markus & Hall 2004; Páez et al. 2018; Boardman et al. 2021; Yabsley et al. 2021). Studies on grey-headed flying-foxes suggest that higher temperature variability correlates with increased roost occupancy (Snoyman & Brown 2010), while research on little red flying-foxes in Queensland identified taller canopy heights and greater vegetation complexity as influencing roost selection, though the association was weak (MacDonald et al. 2021).

For spectacled flying-foxes, historical data suggest a strong preference for roosting near rainforests (within 6.5 km), in dense vegetation, and with seasonal movements between traditional sites (Richards 1990). However, this information may no longer accurately represent the species' current habitat use due to land-use changes, habitat fragmentation, and climate shifts (Timmiss et al. 2021). Given that microclimate preferences have been demonstrated in grey-headed flying-foxes and vegetation preferences have been observed in little red flying-foxes, a combination of microclimatic and structural vegetation factors likely influence spectacled flying-fox roosting behavior.

The urban flying-fox’s roosts are extremely diverse, as the urban landscape and their different sizes encompass heterogeneous combinations of vegetation and degrees of disturbance. Associated with the fact that the 2018 heat waves affected some roosts and not others, I hypothesised that urban roosts are different to each other and present different microclimate and vegetation. Also, it is ecologically relevant to identify and describe the characteristics associated with occupied roosts to better understand the habitat requirements of this species, especially in the urban environment.

1.5 Influence of vegetation and microclimate on bat surface temperature

Thermal ecology is a field of study that examines how temperature influences organisms, their physiology, behaviour, and interactions within their environment. Temperature is a key ecological factor that affects metabolic rates, growth, reproduction,

and survival across all taxa (Elmore et al. 2017). Organisms have evolved physiological and behavioural mechanisms to regulate their body temperature and maintain homeostasis, but environmental changes can challenge these adaptations (Mota-Rojas et al. 2021). Bats exhibit a range of characteristics that influence their ability to cope with climate change, particularly in terms of thermal flexibility. Species with thermal flexibility can adjust their physiological responses to varying temperatures, while those without such flexibility may face greater challenges (Norin & Metcalfe, 2019; Remmers et al., 2025). Understanding these traits is crucial for assessing their vulnerability to climate change.

In a climate-changing world, extreme weather events, such as heatwaves, prolonged droughts, and erratic temperature fluctuations, are becoming more frequent and severe (Perkins et al. 2012; Han et al. 2022). These changes, coupled with the continuous rise in global average temperatures, can drive significant shifts in species distributions, alter behavioural patterns, and reshape ecological niches (Pecl et al. 2017).

Species unable to adapt physiologically or behaviourally may experience population declines, range contractions, or even local extinctions (Gibson et al. 2010; Wiens 2016; Wagner et al. 2020). Conversely, some species may expand their range into new areas, leading to novel ecological interactions, competition, and potential disruptions in community dynamics (Chen et al. 2024).

Studies often investigate thermal tolerance limits, preferred microhabitats, thermoregulatory strategies, and the impact of temperature on species interactions (Scheffers et al. 2014). Such knowledge is essential for predicting biodiversity responses to climate change and developing conservation strategies to mitigate the effects of rising temperatures on ecosystems.

Bats, as heterothermic mammals, possess a remarkable degree of thermal flexibility that is fundamental to their survival and ecological success (Rummel et al., 2019a). This physiological adaptability is particularly critical in the context of climate change, as increasing temperatures and shifting environmental conditions place considerable strain on their thermoregulatory mechanisms. Among small bat species inhabiting temperate regions, the use of torpor, a state of reduced metabolic rate and body temperature is a well-documented strategy for coping with cold stress and limited food availability. Historically, this behaviour was thought to be confined to temperate-

dwelling, small-bodied bats (typically averaging 50 g. In *Pteropus poliocephalus*, torpor has been suggested predominantly following cool, wet, and windy conditions, and was most frequently observed on days with the lowest maximum air temperatures (Turbill et al., 2024). While no previous evidence existed for torpor in tropical flying-foxes, preliminary observations in a temperate/subtropical species provide the first indications of this behaviour. Data from two individuals over five days revealed small reductions in body temperature of 3–10 °C, suggesting torpor-like bouts, though these findings remain preliminary.

Flying-foxes can be highly susceptible to temperature fluctuations due to their physiology, metabolic demands, and roosting habits (Mo & Roache 2021). Unlike many terrestrial mammals that can seek shelter underground or in insulated nests, flying-foxes roost in exposed tree canopies, making them particularly vulnerable to extreme heat events. In response to high ambient temperatures, flying-foxes display a sequence of behavioural activities to increase evaporative cooling, starting with the wing fan, passing to licking and finally panting. Water loss is one of the problems arising from heat stress, with increased respiration and cutaneous evaporation (Minnaar et al., 2014). When the ambient temperature reaches 40°C, most of the evaporation occurs cutaneously, but when temperatures exceed 40^{o}C respiration could account for 60% of water loss (Bartholomew, Leitner, & Nelson 1964).

Several factors can influence the tolerance of bats to high temperatures, including biological characteristics and roost's microclimate (Welbergen et al. 2008). Some authors have correlated dry heat with the severity of the heat stress and consequent die-offs of flying-foxes. Dry heat exacerbates heat stress in desert-dwelling bats by increasing the demand for evaporative cooling. The lack of moisture in the air limits the effectiveness of evaporative cooling mechanisms, leading to higher body temperatures. This situation forces bats to expend more energy to regulate their body temperature, which can result in physiological stress and increased mortality risk during extreme heat events (de Mel et al. 2024). Also, when bats experience dehydration, they may suppress evaporative cooling mechanisms like panting, leading to a quicker rise in body temperature. This hyperthermia poses a significant risk, especially during heatwaves, as bats struggle to maintain homeothermy without adequate water (Fuller et al. 2021). However, species respond differently to the same conditions. For example, *P. alecto* appears to be more vulnerable to heat events than *P. poliocephalus* and *P. scapulatus*. This difference is often

linked to their environmental adaptations. While *P. poliocephalus* and *P. scapulatus* thrive across a wider temperature range, *P. alecto*, a tropical flying-fox, is adapted to more stable temperatures with less variation (Ratnayake et al. 2021).

1.6 Thermal camera for wildlife temperature

Understanding wildlife body temperatures is valuable for assessing species' responses to climate change and predicting future ecological impacts. Different methods exist to measure wildlife temperature, broadly classified into contact and non-contact approaches. Non-contact devices should be calibrated against contact-based thermometers to determine the accuracy and reliability of their core body temperature estimations. This is necessary because non-contact devices measure skin surface temperature, which is inherently lower than core temperature and is influenced by ambient temperature, thermal resistance of the skin, and physiological factors such as blood flow (Beall et al., 2022).

Contact devices, such as implanted sensors or rectal thermometers, provide direct and continuous temperature readings but are invasive, stressful and often require surgeries or repeated handling (Jerem et al. 2015). Limitations include battery life, size, and the need for proximity to retrieve data, making them more suitable for long-term studies (Ibáñez et al. 2024). In contrast, non-contact devices, such as infrared thermographs and thermal cameras, allow temperature assessments without disturbing the animal (Ibáñez et al. 2024).

Thermal cameras detect infrared radiation emitted by an object, converting it into a thermogram, where each pixel represents a temperature reading. However, factors like object size, measurement distance, body region, and environmental conditions (humidity, wind, and solar radiation) can affect accuracy (Usamentiaga et al. 2014).Given these constraints, this study employs a non-invasive approach to monitor surface temperatures of spectacled flying-foxes in urban Cairns roosts without handling or disrupting the populations.

Monitoring wildlife during extreme weather is crucial for understanding climate change impacts on biodiversity. Approaches can be indirect, using climate models to predict wildlife responses (Ratnayake et al. 2019), or direct, where real-time temperature measurements track physiological responses. Homeothermic animals, including flying-

foxes, maintain a narrow thermal range, making extreme variations potentially lethal. Understanding how environmental conditions affect body temperature helps identify key determinants of heat tolerance and strategies to mitigate heat stress. Recently, Turbill et al (2024) described in a small sample of grey-headed flying-foxes, that torpor can be used as a survival strategy during low temperatures and food scarcity, demonstrating that heterothermy can be present in flying-foxes, but no other study was conducted in tropical flying-foxes.

Contact methods, such as rectal thermometers and thermocouples, are standard but invasive, often requiring chemical or mechanical restraint (Jerem et al. 2015). Consequently, infrared thermography (IRT) has emerged as a promising non-invasive alternative (Tattersall 2016; Wang et al. 2021). Initially developed for livestock management (Brcko et al. 2020), IRT is now widely used to assess infections (Bleul et al. 2021), monitor body temperature under extreme conditions (Čukić et al. 2023), and study wildlife thermoregulation, including molluscs (Seuront et al. 2018), reptiles, birds (McCafferty et al. 2011), and bats (Lancaster et al. 1997).

Modern IRT technology operates on the principle that all objects emit infrared radiation proportional to their temperature, following the Stefan-Boltzmann law (Balaras & Argiriou 2002). Thermal imaging devices, typically detecting radiation in the 8–14μm range, translate this into colour-coded temperature maps (Usamentiaga et al. 2014). This non-invasive approach has applications across scientific and industrial fields, from detecting heat loss in materials (Cai et al. 2023) to track thermal patterns in wildlife (McCafferty et al. 2015).

In mammals, thermal windows—anatomical regions with minimal hair coverage and dense vascularisation—facilitate heat exchange (Mota-Rojas et al. 2021). These structures act in thermoregulation, and their temperature readings provide insights into stress responses (Andrade 2015; Mota-Rojas et al. 2022). In a microbat *Carollia perspicillata*, temperature differences of up to 12°C have been recorded between skin and core temperatures, suggesting that the relatively small muscles controlling wing movement operate below core temperature, likely due to increased heat loss from the large, uninsulated wing surfaces, impacting their locomotor performance in varying environmental conditions (Rummel et al. 2019).This could explain bats' wing-fanning behavior when ambient temperature increases.

Survival during extreme heat events depends on behavioural adaptation and roosting conditions (Bailey et al. 2019). Roosts with dense canopy cover and complex vegetation structures provide better thermal buffering, offering shaded microclimates within the roost (Rakoto et al. 2021).

Literature has suggested that flying-fox species exhibit varying roosting preferences based on distribution and mobility. Grey-headed flying-fox seem to be more likely to occupy roosts with temperature variability, while little red flying-fox show no preference for microclimate or vegetation, aligning with their highly nomadic behaviour (Snoyman & Brown 2010; MacDonald et al. 2021). In contrast, *P. giganteus* (Indian flying-fox) are typically found in taller, large-diameter canopy trees. However, the study's habitat suitability predictions may be less reliable outside the surveyed areas, as the model was based on field data, indicating habitat selection participates in heat tolerance by favouring tall, large-diameter trees with broad canopies in extensive groves, which provide shade, reduce solar radiation, and buffer temperature extremes (Kumar & Elangovan 2019). This variability in roosting behavior suggests that different flying-fox species may have varying vulnerabilities to extreme heat events, underscoring the need for predictive models to anticipate mortality risks.

To address this, Ratnayake et al. (2019) developed the Flying-Fox Heat Stress Forecaster, a tool designed to predict mass mortality events caused by heat stress. The model operates across Australia by analysing hourly temperature forecasts from the Australian Bureau of Meteorology's ACCESS-R system. By identifying 42.0°C as the critical temperature threshold for flying-fox die-offs, the Forecaster provides an early warning system for conservation managers. The model demonstrated strong predictive accuracy, correctly forecasting 77% of die-offs with a 24-hour lead time and 73% with a 48-hour lead time, making it a valuable resource for wildlife protection efforts.

Despite its utility, the model faces challenges in accurately predicting mortality in areas beyond the original study sites. Because its predictions rely on documented roost locations, and habitat suitability estimates may not fully capture risk in unobserved regions. Additionally, potential sampling bias was acknowledged, as uneven search efforts could influence results. To improve accuracy, researchers tested the model with different spatial constraints to identify inconsistencies. Future refinements could incorporate additional environmental factors, such as humidity and microclimate

conditions, to enhance forecasting precision and provide more comprehensive risk assessments across Australia.

While predictive models enhance our understanding of heat stress impacts, they do not account for how habitat structure influences the physiological responses of flying-foxes. Despite advances in predicting heat-related mortality, research has not yet investigated the interaction between habitat characteristics and bat body temperature regulation. Two significant knowledge gaps persist: How do roost microclimate and vegetation affect the body temperature of spectacled flying-foxes? Which non-invasive methods can reliably measure bat temperature in the wild?

Addressing these gaps, this study aims to inform conservation strategies that optimise roost conditions to reduce heat stress. Establishing a noninvasive monitoring technique and assessing how vegetation structure influences thermal buffering could provide guidelines for reforesting current roosts, improving their ability to mitigate extreme heat exposure.

The limited geographic range of spectacled flying-foxes has restricted research efforts, leading to generalisations from studies on other *Pteropus* species. Additionally, the challenge of monitoring wildlife temperature in natural settings has limited methodological advancements. To overcome these barriers, this study tests thermal imaging as a non-invasive alternative, offering a potential breakthrough in tracking temperature fluctuations in tropical wild populations of spectacled flying-foxes.

In summary, the overarching aim of this thesis is to examine the influence of vegetation structure and microclimatic conditions on the thermal environment experienced by spectacled flying-foxes (*Pteropus conspicillatus*) within urban roosts in tropical Australia. In doing so, the research seeks to address critical knowledge gaps regarding species-specific responses to extreme heat, a growing conservation concern under climate change. This study evaluates the utility of infrared thermography as a non-invasive method for estimating bat surface temperature in natural settings. It is hypothesised that vegetation complexity and associated microclimatic buffering capacity are key determinants of thermal exposure in roosting bats, with simplified or degraded habitats contributing to elevated surface temperatures and increased heat stress. The findings aim to inform habitat management and restoration strategies to support the long-term persistence of this endangered species in urban landscapes.

As a consequence of this ecological investigation, the thesis also explores how scientific evidence, particularly the relationship between habitat quality and thermal stress can be integrated into flying-fox management policy. By aligning ecological research with policy development, this thesis aims to support more effective and climate-resilient management of urban flying-fox populations.

1.7 Policies for the flying-fox urban population

The *Nature Conservation Act 1992 (Queensland Goverment, 2021)* marked a foundational shift in wildlife policy in Queensland, granting formal protection to all native flying-fox species by categorising them under protected wildlife. The legislation prohibited the unauthorised taking, harming, or disturbing of flying-foxes or their roosts, ensuring that management efforts had to prioritise conservation outcomes. This legal protection reflected an ecological appreciation of flying-foxes as keystone pollinators and seed dispersers in Australian ecosystems.

The *Indooroopilly Island Conservation Park Management Plan* (1999) (Indooroopilly Island Conservation Park, 1999) represents one of the earliest documented efforts to manage flying-fox roosts in Queensland through a structured, site-specific conservation strategy.

While the plan was developed primarily to protect the ecological values of the park under the *Nature Conservation Act 1992*, it placed significant emphasis on conserving a large maternity roost of black (*Pteropus alecto*), grey-headed (*Pteropus poliocephalus*), and little red flying-foxes (*Pteropus scapulatus*). Management strategies included habitat rehabilitation, weed and fire control, long-term ecological monitoring, and the promotion of scientific research.

Although public access to the site was limited to minimise disturbance, the plan recognised the potential for environmental education and low-impact tourism. Public engagement was facilitated through initiatives such as the “Batty Boat Cruises,” which allowed observation of the dusk fly-out from the river. The plan also proposed the development of interpretive signage and brochures to enhance public understanding of the ecological importance of flying-foxes and to provide information on health-related issues, including the Australian Bat Lyssavirus (ABL).

Notably, this early management approach adopted a coexistence framework, positioning flying-foxes as both ecologically valuable and suitable for public appreciation from a safe distance, rather than as a species to be displaced or removed (Indooroopilly Island Conservation Park, 1999).

A major policy shift occurred in 2013 when the Queensland Government amended the *Nature Conservation Act*, allowing local governments to manage flying-fox roosts without requiring a permit, provided that their actions complied with the *Code of Practice for the Ecologically Sustainable Management of Flying-Fox Roosts (Department of Environment and Science, 2020)*. This change aimed to give councils the ability to respond more rapidly to community concerns regarding noise, odour, and public health. Under the new rules, councils could modify vegetation, use deterrents, or even initiate dispersals with limited ecological oversight. This decentralised model marked a departure from earlier conservation-driven approaches and led to inconsistent outcomes, including repeated and sometimes ineffective dispersals (B. J. Roberts et al., 2021).

Using existing management frameworks as a reference, this study assessed flying-fox policies in Queensland to identify common approaches and gaps in current strategies. By evaluating how scientific data informs management actions, this study aimed to propose a foundational management plan, incorporating adaptive strategies for extreme weather events and habitat conservation to support sustainable flying-fox populations in urban landscapes.

To support the development of evidence-based policy, the research also aimed to investigate the ecological drivers of thermal stress in spectacled flying-foxes (*Pteropus conspicillatus*), with a focus on the role of vegetation structure and roost microclimate. By testing the hypothesis that roosts with greater canopy complexity provide improved thermal buffering and reduce the risk of heat stress, this thesis sought to generate practical insights into habitat suitability and risk mitigation. The study also assessed the feasibility of using infrared thermography as a non-invasive monitoring tool for bat surface temperature, offering a method to evaluate habitat performance under increasing climatic pressure. Together, these findings aim to inform local authorities, land managers, and policymakers in the design and implementation of climate-resilient conservation strategies for urban flying-fox populations.

CHAPTER 2

Occupancy of urban roosts by Spectacled Flying-foxes (*Pteropus conspicillatus*) is not affected by diurnal microclimate

---

Abstract

One of the most significant changes to Earth's climate in recent decades has been an increase in the frequency, intensity, and duration of heatwaves. During heatwaves, an animal's thermal window can be exceeded, and in extreme cases, mass mortality events have been observed. In 2018, a heatwave in north-eastern Australia resulted in the death of approximately one third of the spectacled flying-fox (*Pteropus conspicillatus*) population at urban roosts in Cairns, leading to the species being listed as endangered, with future heatwaves considered the greatest threat to its survival. In this study, we investigated long-term climatic trends for Cairns, paying particular attention to the frequency of extreme heat events from 1943 to 2022. We then characterised the microclimate of urban flying-fox roosts during the Austral summers of 2021/22 and 2022/23 across Cairns to assess the long-term feasibility of urban spectacled flying-fox roosts. From the long-term climate records, we observed an overall increase in Cairns' average annual temperature of 1.3 ^{o}C from 1943 to 2022 and an increase in the number of excessively hot days per decade, from 16 in the first decade (1943-1952) to 67 in the last (2013-2022). We regularly detected maximum roost temperatures of 30-35 ^{o}C during our study, with excessively hot days (>35 ^{o}C) recorded more frequently than expected compared to Cairns's maximum temperatures from the last decade (2013-2023). We detected only one day where roost temperatures exceeded 40 ^{o}C and no period that replicated the 2018 heatwave conditions. Furthermore, we found a significant negative relationship between roost ambient temperature and humidity, where the hottest days also coincided with those with the lowest humidity. Importantly, we found no difference in microclimate between roosts that were occupied and unoccupied by flying-foxes during our study, suggesting that other environmental or behavioural factors are more influential for roost selection than the roosting microclimate. Ensuring the long-term conservation of spectacled flying-foxes under a changing climate will require the management of urban

roosts to increase their thermal resistance to heatwaves and more research is needed to identify the variables modulating this aspect.

Key Words: heatwaves, spectacled flying-fox, microclimate, roosts, bats, climate change

2.2 Introduction

The warming of Earth's atmosphere as a result of anthropogenic greenhouse gas emissions has increased the frequency and severity of extreme weather events such as heatwaves (Masson-Delmonte et al. 2018). Since 1950, heatwaves have increased in intensity, frequency, and duration both globally and regionally (Perkins-Kirkpatrick & Lewis 2020). Moreover, this trend is expected to worsen as the climate continues to warm (Perkins-Kirkpatrick & Lewis 2020; Domeisen et al. 2023). Heatwaves are often referred to as periods of excessive heat, but definitions differ between countries (Lee 2014) and can comprise qualitative and quantitative characteristics.

Qualitative definitions consider heatwave duration and associated humidity, whereas quantitative definitions focus on the duration, frequency, and magnitude of the temperature above a threshold, which varies from 2-5 days and 25-38 °C (Perkins-Kirkpatrick & Lewis 2020). The Australian Bureau of Meteorology (BOM) uses a qualitative approach, defining a heatwave as three or more consecutive days when daytime and night-time temperatures are “unusually high” relative to the local long-term climate (Coates et al. 2014). Heatwaves are especially common in dry and temperate climates (defined respectively as the area from 15 °- 30 ° N and S of the equator and 30 °- 65 °N and S of the equator) areas and are rarer in wet tropical regions (defined as the area from 10 °N to 10 °S of the equator) with highly stable climates relative to environments at higher latitudes (Staff 1995; Seidel & Yang 2020).

In intact tropical forests, the understory and canopy are each associated with microclimatic conditions that differ from those outside the forest (Camargo & Kapos 1995; Murcia 1995). Both vegetation strata experience gradients in microclimates with air temperature and vapour pressure deficits declining with distance away from the forest edge and relative humidity and soil moisture levels increasing (Camargo & Kapos 1995). In urban areas, the microclimate within patches of vegetation can be influenced by patch size, the human activities occurring in and around the patch, as well as surrounding water bodies and buildings (businesses, houses, roads, and active construction sites) (Yu et al.

2020; Li et al. 2020). Hence, a greater understanding of the factors influencing forest microclimates presents a critical opportunity to enhance the capacity of habitats to buffer the effects of a warming climate (De Frenne et al. 2021).

Canopy microclimates are extremely important for flying-foxes (*Pteropus* spp.) because they roost diurnally within forest canopies in large colonies of hundreds to thousands of individuals (Ratcliffe & Ter Hofstede 2005; Timmiss et al. 2021). Due to these high population densities, flying-foxes are highly vulnerable to changes in weather, especially heatwaves. For example, Australian heatwaves have now been associated with mass mortality events of black (*P. alecto*), grey-headed *(P. poliocephalus*), little red (*P. scapulatus*) and spectacled (*P. conspicillatus*) flying-foxes (Welbergen et al. 2008). During these events, tens of thousands of bats perished when temperatures exceeded 40 °C (Welbergen et al. 2008), with modelling (Australian Community Climate and Earth-System Simulator - Numerical Weather Prediction mode [ACCESS-R NWP- l]) suggesting a temperature threshold of 42 °C to predict the occurrence of a die-off (Welbergen et al. 2008; Ratnayake et al. 2019), as this was the cut-off for bats survival (Mo et al. 2021).

Mass mortality of Australian flying-foxes associated with heatwaves has been well-documented along the east coast of Australia (Welbergen et al. 2008). Still, the Australian tropics have seen fewer heatwaves when compared to other climates due to their stable climate. A stable climate with low variation in seasonal temperature has allowed tropical species to develop finer specialisations and narrower thermal tolerances (Janzen 1967; Stevens 1989), potentially resulting in increased vulnerability to the effects of climate warming and heatwaves (Polato et al. 2018). For example, in 2018, a heatwave (Bureau of Meteorology, 2018) killed an estimated third of the population of spectacled flying-foxes (~23000 individuals) residing in urban roosts in Cairns (Jason Bittel 2019). Both the extent and rate of population loss during this extreme event has dire implications for the future conservation of the spectacled flying-foxes and has focussed management actions on understanding the thermal resistance of urban roosts.

In this study, we assessed how climate change, and the microclimate preferences of urban spectacled flying-fox colonies may impact roost choice and the long-term success of urban colonies in Cairns. To evaluate this, we: 1) examined long-term temperature trends for Cairns, 2) investigated the temperature and humidity patterns of the 2018 heatwave, 3) described the microclimate conditions of occupied and unoccupied

spectacled flying-fox camps in Cairns during the austral summers of 2021/22 and 2022/23 and investigated the influence of camp size in roost occupancy. We hypothesised that microclimate conditions influence camp occupancy and can indicate the microclimate preferences of this species.

2.3 Methods

Cairns is a lowland tropical city in north-eastern Australia (16.92 ^{o}S, 145.78 ^{o}E) that experiences a mean annual rainfall of ~2000 mm and a pronounced dry season (<100 mm/month) from April to November. The mean monthly maximum temperature ranges from 25.8 ^{o}C (winter) to 31.5 ^{o}C (summer) (Australian Bureau of Meteorology [BOM]).

2.3.1 Long-term temperature trends

We retrieved data from BOM to examine climate trends and temperature extremes in Cairns, using the longest and most continuous data record for the region, the Cairns airport (station number 31011), covering the period of 1943 to 2023. These data comprise the maximum temperature and humidity recorded at 3pm daily and are continuously updated and available on the BOM website (Bureau of Meteorology 2023). We chose data from 1980-2010 as a baseline for the standardised anomaly due to the current anthropogenic effects and the occurrence of warm winters (Bureau of Meteorology 2007, 2009) present in this period, as the adequacy of observed baseline climate data sets can only be evaluated in the context of particular climate scenario construction methods (Carter et al. 2001).

2.3.2 Microclimate characterisation

We characterised the microclimate at 20 (nine occupied and 11 unoccupied) spectacled flying-fox roosts in the urban area of Cairns (Appendix A). The camps ranged from 0.5 to 42.2 ha and presented a diverse vegetation type with some formed by well-preserved native rainforest and other formed by a small piece of grass and tall trees along a pathway. We selected the roosts that were already assessed by the Council and bat carers in the area, due to the 2018 heatwave. We classified as occupied the camps with bats at

any point in time during the fieldwork duration and unoccupied as the camps where we could not see a bat during all the fieldwork. The roosts selected for this study were spread over a 40 km linear distance from the north to south of Cairns (16.78 ^{o}S, 145.68 ^{o}E to 17.09 ^{o}S,145.78 ^{o}E) and covered an area of ~160 km^2 (Figure 2.1 A). The roosts encompassed various vegetation communities, adjacent features, and habitat areas (0.46 – 42 ha, Appendix A). Seven roosts were located in the inner city, surrounded by houses and roads.

With respect to roost selection, we attempted to standardise between occupied and unoccupied sites: roost area, vegetation communities and location but were limited by accessibility on private lands (ie. a landholder withdrew permission to access land during the course of this study). During two austral summers, November 2021 - January 2022, and December 2022 - February 2023, microclimate data were collected at spectacled flying-fox roosts on sunny days between 11 am and 2 pm. Each roost was sampled between 4-6 times a year. At each visit, we measured air temperature (◦C) and relative humidity (%) across a 25 m transect for large camps (>0.75 ha) and as a 10 min walk throughout the roosts for small camps (<0.75 ha) using a handheld meteorological station (Kestrel 3550). This different approach was necessary due to the variability of roost configuration, as seen in figure 2.1 B.

The Kestrel 3550 measures 13 climate variables including compound ones (such as heat index). We installed data-loggers to collect temperature and humidity, but the equipment went missing after a few days. Most of the campsites are located close to neighbourhoods or paths, where they are exposed to the population's curiosity. The Kestrel collects 12 measurement points per minute, and data collection was for a 10-minute visit under the canopy to avoid direct sunlight, resulting in 120 data points per visit. The accuracy of the equipment varied by +/- 0.5 °C for air temperature and +/- 3 % for relative humidity (Kestrel Weather Meters 2020).

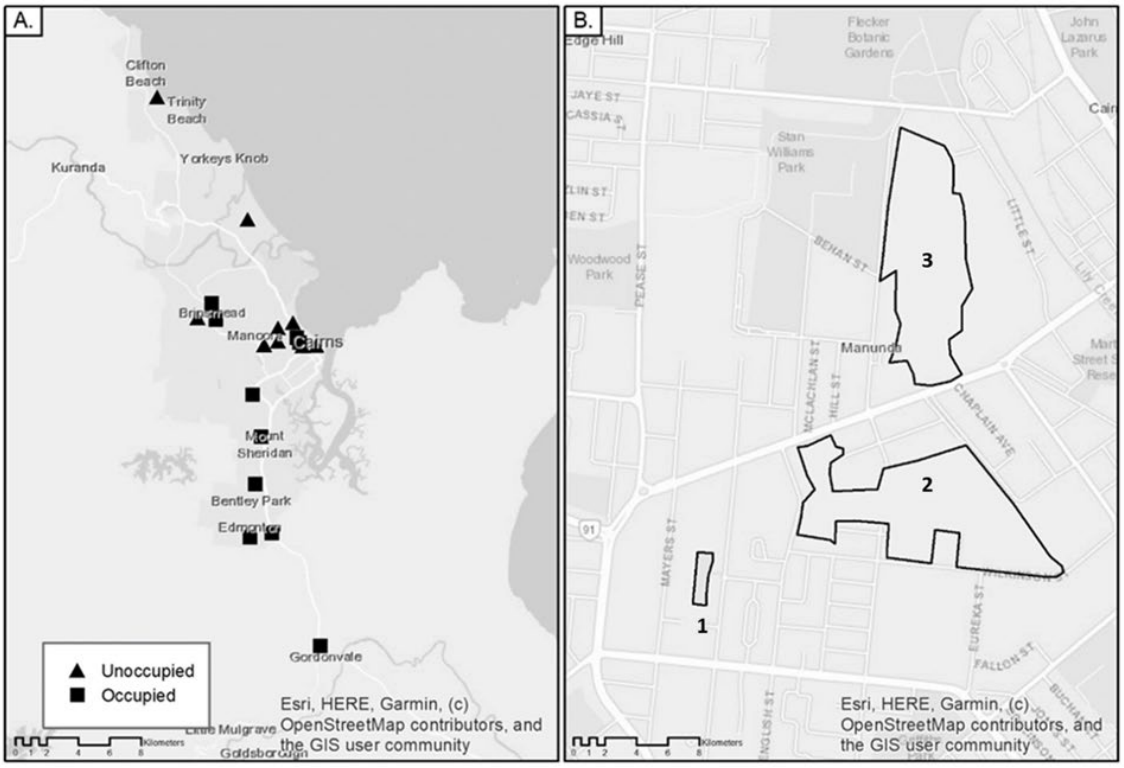


Figure 2.1. The location of spectacled flying-foxes urban roosts (A). The triangles are the unoccupied camps, and the squares are the occupied. (B) illustrates large and small spectacled flying-fox camps. The small camp (1) is Guginy Reserve with a 2.0ha area, and the large camps represented are Cairns Swamp (2) and Cairns Cemetery (3), with 37ha and 24.2ha of area.

2.3.3 Data analysis

For long-term climate trends, we calculated standardised anomalies of temperature from the 1980-2010 baseline to examine with linear regressions the: a) annual average maximum temperature; b) summertime max temp, and c) wintertime max temp. With respect to past extreme weather events, we identified excessive hot days (>35 ^{o} C) and measured changes in frequency across three ranges (<30 ^{o}C, 30-35 ^{o}C, >35 ^{o}C) with Chi-squared tests. To understand the weather conditions of the mass mortality event that occurred during the November 2018 heatwave, we described and compared the temperature and humidity measured during the heatwave with the conditions observed during subsequent years.

We examined the relationships between flying-fox occupancy, roost microclimate and roost area using binomial models (GLM and GLMM) and ANOVAs. Daily maximum

and average temperatures were compared between occupied and unoccupied roosts with ANOVAs. Further, the probability of occupancy was examined with binomial models with predictors maximum temperature, humidity and wind speed modelled individually due to their intercorrelation. We performed correlation tests to identify the variables influencing the ambient temperature. The only simple variable collected by the Kestrel influencing the ambient temperature was relative humidity. We then performed models that tested the variables independently and interacting, as temperature and humidity combined are used as a measure of heat effect in animals. The models using the camps as a random effect tested if the variability between the camps would drive the response into one of the expected outcomes (presence/absence). All statistical analyses were performed in R version 4.2.2 (R Core Team 2023) with the R package *tidyverse* (Wickham et al. 2019) and graphs produced in *ggplot 2* (Wickham 2016) and *plotly* (Plotly Technologies Inc 2015).

2.4 Results

2.4.1 Maximum temperatures

From 1943 to 2022, the annual maximum temperature in Cairns increased by 1.3 ^{o}C (from 28.9 ^{o}C to 30.2 ^{o}C), with the warmest temperatures in our dataset recorded in 2022 (annual $\bar{x}$=30.2 ^{o}C). We used the average maximum temperature per month across the observed time. For the annual tendency line, we used the average maximum temperature of all the months, while for the Summer, we used December to January and for the Winter, June to August. The fitted linear regression model (*lm(formula = data$std.anom ~ data$Year)*) indicated a significant increase in the long-term average monthly temperature (Figure 2.2 A, R^2 = 0.02, P<0.01, df = 958). This analysis was also performed for the summer (December to January) and winter (June to August) seasons separately. We observed a greater increase in annual winter temperatures (0.02 ^{o}C/y) than summer (0.009 ^{o}C) in the dataset, where the overall annual slope indicates an increase in the average temperature of 0.01 ^{o}C/y. We observed a higher slope in the winter (Figure 2.2 C, R^2= 0.06, P< 0.01, slope= 0.01, df = 238), compared to the summer (Figure 2.2 B, R^2 = 0.01, P<0.01, slope=0.0049, df = 238). To date, the summer of 2020 was the warmest on record, followed by the summers of 2016 and 2017 (Figure 2.2 B), whereas 2010 and 2009 were the warmest winters (Figure 2.2 C).

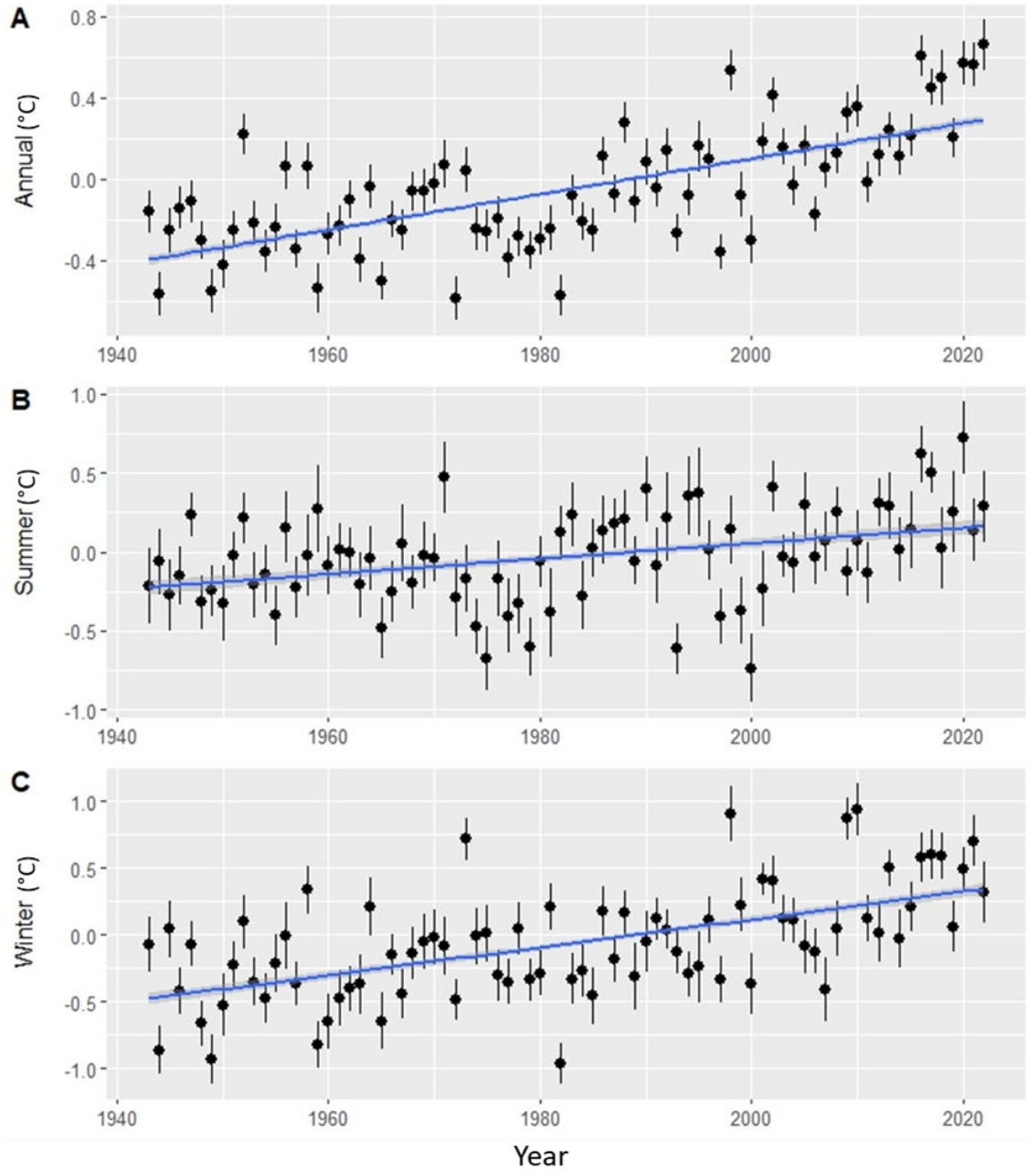


Figure 2.2. The standardized anomaly of the annual average maximum temperature in Cairns (1943-2022), calculated from a 1980-2010 baseline, showing a significant increase in temperature over time for the A) annual maximum temperature (baseline used 1980-2010, the average maximum temperature of every month), B) summer maximum temperature (baseline used 1980-2010 December, January, and February) and C) winter maximum temperature (baseline used 1980-2010 June, July, and August). The error bars present the standard deviation of the 12-month average around the overall mean (or three months for Winter and Summer) from the baseline.

2.4.2 Excessively hot days and heatwaves

From 1943 to 2022, Cairns recorded 272 days (0.9 %) considered excessively hot (>35 ^{o}C). There were 32 days with temperatures >38 ^{o}C and seven days >40 ^{o}C. Since 1943, the number of excessively hot days (here stated as days >35 ^{o}C) per decade increased from 17 in the first decade (1943-1952) to 67 in the last (2013-2022) (Figure 2.3), which represents an increase of 3.1 SD from the mean of hot days. For example, in 2022, the number of days >35 °C (N = 13) were almost equivalent to the number observed for the decade 1943-1952 (N= 17).

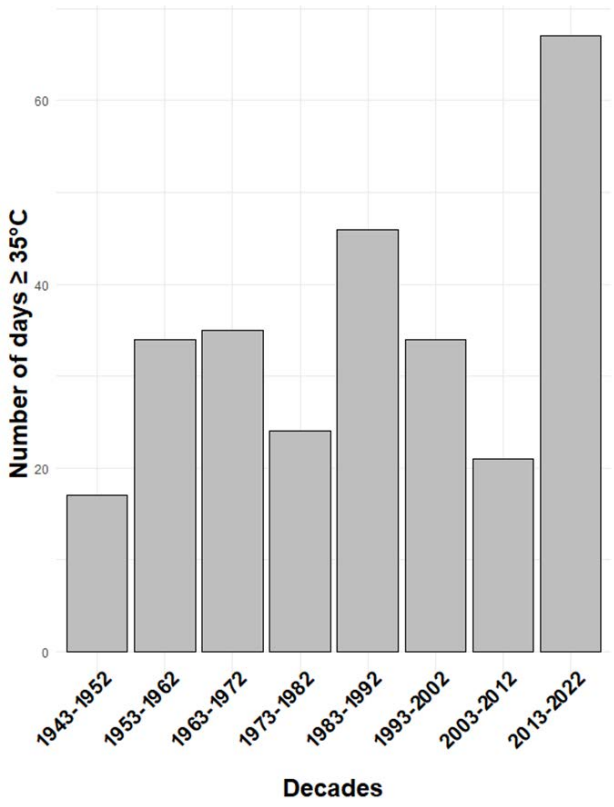


Figure 2.3. The number of days ≥35°C per decade measured at the Cairns airport weather station increased overall over time (3.1 SD).

In November 2018, Cairns had an unusual heatwave with three consecutive days recorded as the hottest on record (41.3 °C, 42.2 °C, and 41.6 °C; Figure 2.4 A) and associated with unusually low humidity (Figure 2.4 B). Heatwave temperatures each day were between 10-12 °C (10.5 °C, 11.4 °C, and 10.8 °C) above the monthly average for November, which is >6 standard deviations above the long-term average ($\bar{x}$November±SD, 30.8 °C±1.49). The minimum temperatures were also between 2-4 °C (2.6 °C, 2.3 °C and 3.9 °C) above the monthly average for November ($\bar{x}$±SD, 20.8 °C±3.1). During this same period, the humidity dropped from 54 % to 35 % on the first day of the heatwave and remained low (37 % and 47 %) over the next two days. The recorded humidity on all three days were 2-3 standard deviations below the average humidity of November (66.9 ± 9.9 %).

We compared the daily maximum temperatures and humidity in November over the past five years (2018-2022) and found no similar conditions (Figure 2.4). The temperatures observed in the following years (2019-2022) for the same period were primarily between 32 °C and 34 °C ($\bar{x}$±SD, 32.3 °C±1.09), with 5 days >34 °C and one day >36 °C. Compared to this average, 2018 had a slightly higher mean and standard deviation for November ($\bar{x}$±SD, 33.7 °C±3.3), as expected due to the extreme temperatures registered during the heatwave. These characteristics demonstrate how unusual and extreme the weather was during the extreme heatwave. There were eight days where humidity levels fell below 50 % in subsequent years, but they were not associated with excessively hot days.

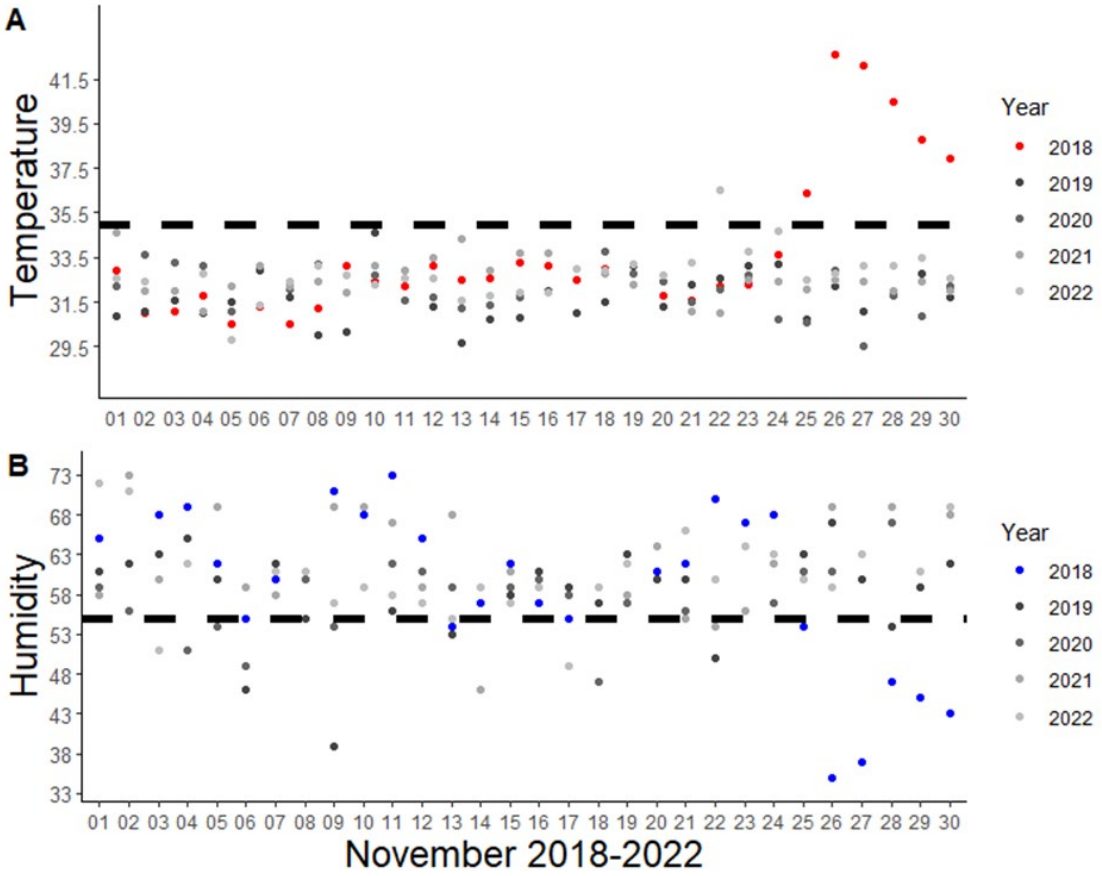


Figure 2.4. Daily maximum temperature (A) and humidity (B) recorded at 3pm at the Cairns airport weather station from 2018 - 2022. The first graph represents the unusually high temperatures recorded during the heatwave (red dots), and the temperature registered on the same days in the following years (mostly concentrated below 35°C – dashed line) (A). Panel B shows the relative humidity per day, with the majority of the data located above 55% (dashed line) of relative humidity, while the values on the heatwave dropped below 40%, resulting in an unusual hot and dry combination for 4 days.

2.4.3 The microclimate of urban spectacled flying-fox roosts in Cairns

Over the two summer periods (Nov 2021-Jan 2022 and Dec 2022 – Feb 2023), the average maximum temperature among all roosts was 32.9 ºC (SD = 2.1 ºC), and the maximum roost temperature was 40.1 ºC. We recorded higher maximum roost temperatures (40.1 ºC) in the summer of 2021-2022 compared to 2022-23 (35.6 ºC), with both summers registering daily temperatures >4 ºC warmer than the long-term average

maximum temperature for summer (31.5 ^{o}C). The roost average maximum temperatures measured on any given day were similar to those recorded from the BOM airport climate station ($\bar{x}_{maxtemp}$±SD; 32.5 °C±1.4 °C). However, the standard deviations reveal a greater variation in temperature at the urban roosts compared to the airport station (sites ranged from 3.5 °C cooler to 7.8 °C warmer than the airport). There was no significant difference in maximum temperatures recorded between roosts (Figure 2.5, ANOVA, $F_{(20,131)}$=1.152, *P*>0.05). We also investigated the coefficient of variation to understand if there was a consistent difference between the temperatures in occupied and unoccupied roosts (t-test = [-1.39], p = [0.18]), but it was not significant.

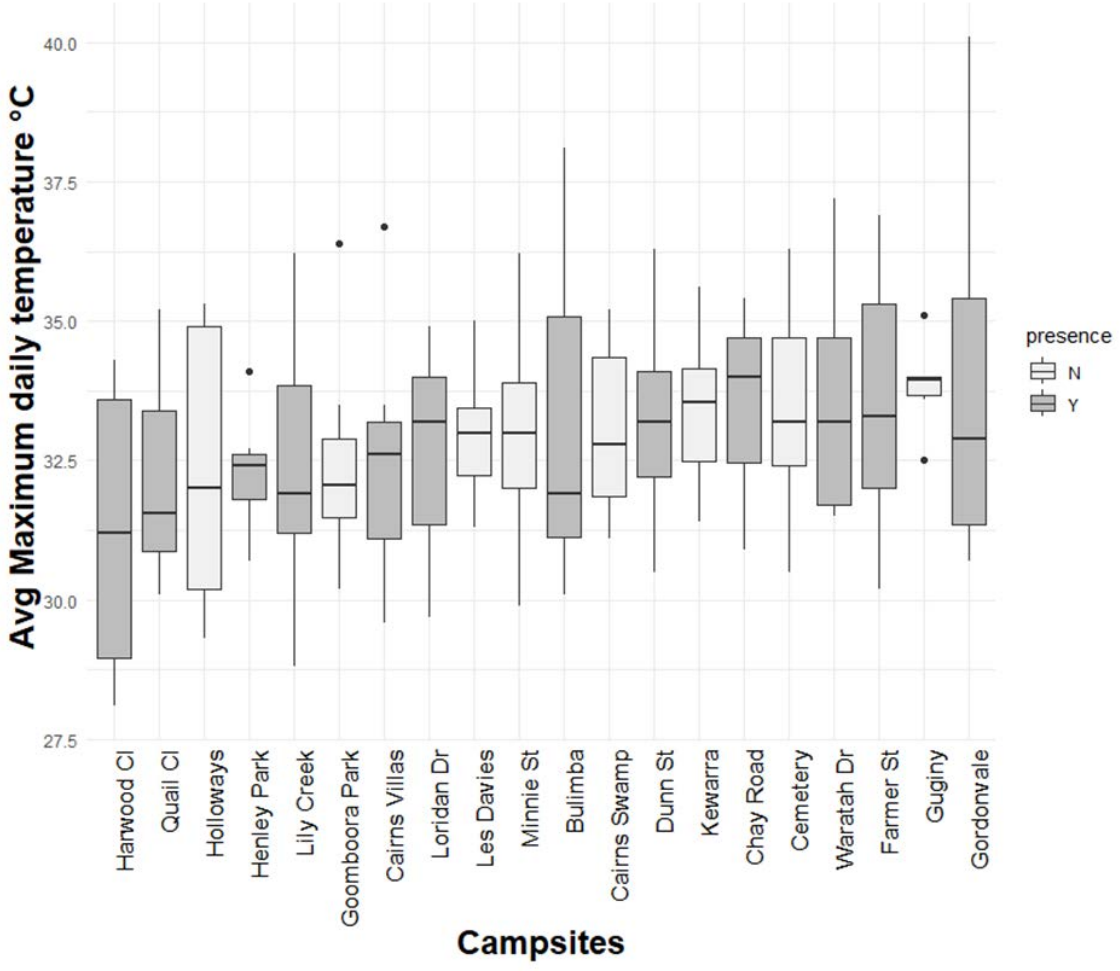


Figure 2.5. The y axis shows boxplots containing the maximum daily temperature (°C) recorded in spectacled flying-foxes' roosts over two summers. The campsites are on the x axis, ordered by the average maximum daily temperature (°C). The transversal black

lines on the boxes represent the median. The light greys are the unoccupied camps and the dark greys represent the occupied camps. The boxes are ordered according to the average maximum daily temperature of each camp (avg=average).

We compared the frequency of excessive hot summer days in spectacled flying-fox roosts from 2021 to 2023 with a recent baseline (Cairns airport max temperatures 2012-2023) and found that roosts have experienced a significantly greater frequency of excessive hot days during the last two years of the study (Figure 2.6, $\chi 2 = 86.1$, df = 7, $P<0.01$, $\alpha=0.0$) when compared to the excessive hot days registered by BOM. Bat roosts experienced max temperatures of 30 ^{o}C-35 ^{o}C for 76.7 % of the time and > 35 ^{o}C 16.9 % of the time, whereas airport decadal average was between 30 ^{o}C-35 ^{o}C 48 % of the time, and > 35 ^{o}C only 1.7 % of the observation period.

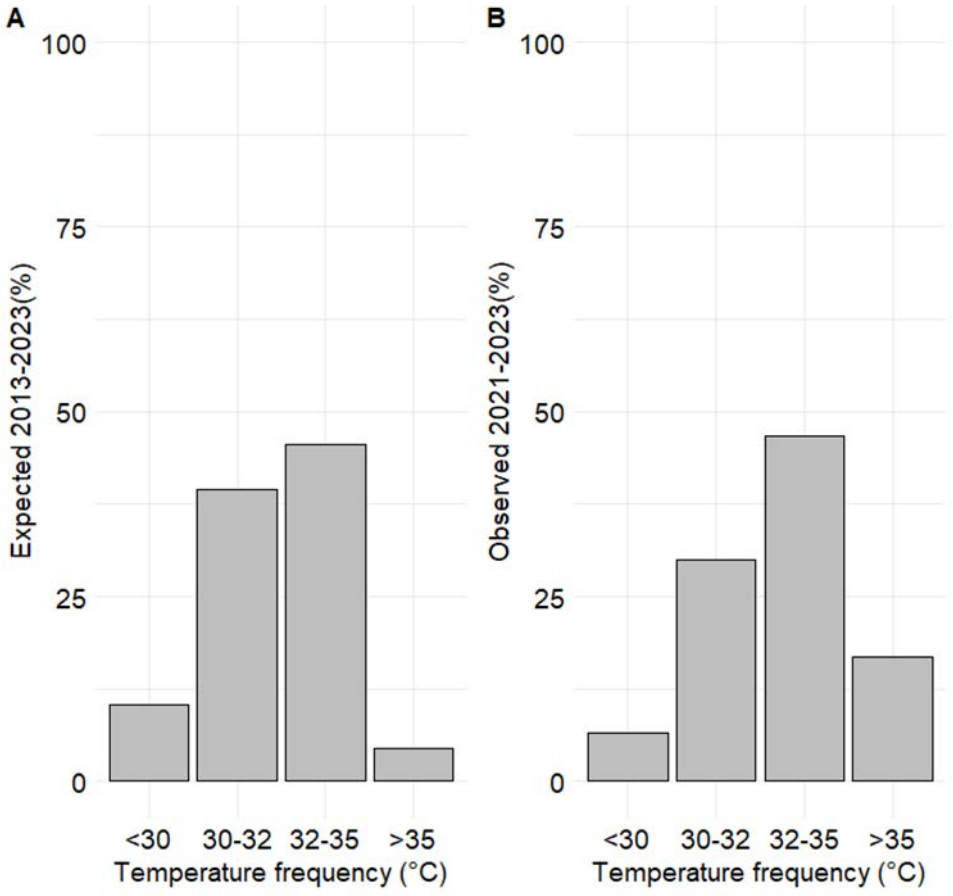


Figure 2.6. The expected frequency, based on ten years of data (2013-2023) registered at the airport station (A) and the recorded frequency of days in each temperature range in

urban spectacled flying-fox roosts (B). There was an increase in the frequency of temperatures above 32°C in the roosts compared to the long-term data.

We tested the variance (Table 2.1 and Figure 2.7) and the probability of temperature and humidity on roost occupancy and the effect of roost area on the probability of roost occupancy and found only roost area had a significant influence (Table 2.1, r^2 = 0.3915, P<0.01), where smaller camps were more frequently occupied than larger camps. Although, once roosts were >1ha in size, the chance of occupancy was reduced by 2 % for every hectare in the camp size. There was no detectable difference in max daily temperature, average temperature, max relative humidity, and average relative humidity on bat occupancy at roosts (Figure 2.7 and Table 2.2). There was a significant negative correlation between max temperature and relative humidity over the two summer periods ($\rho_{2021/2022}$ =-0.61, P<0.01; $\rho_{2022/2023}$ =-0.74, P<0.01).

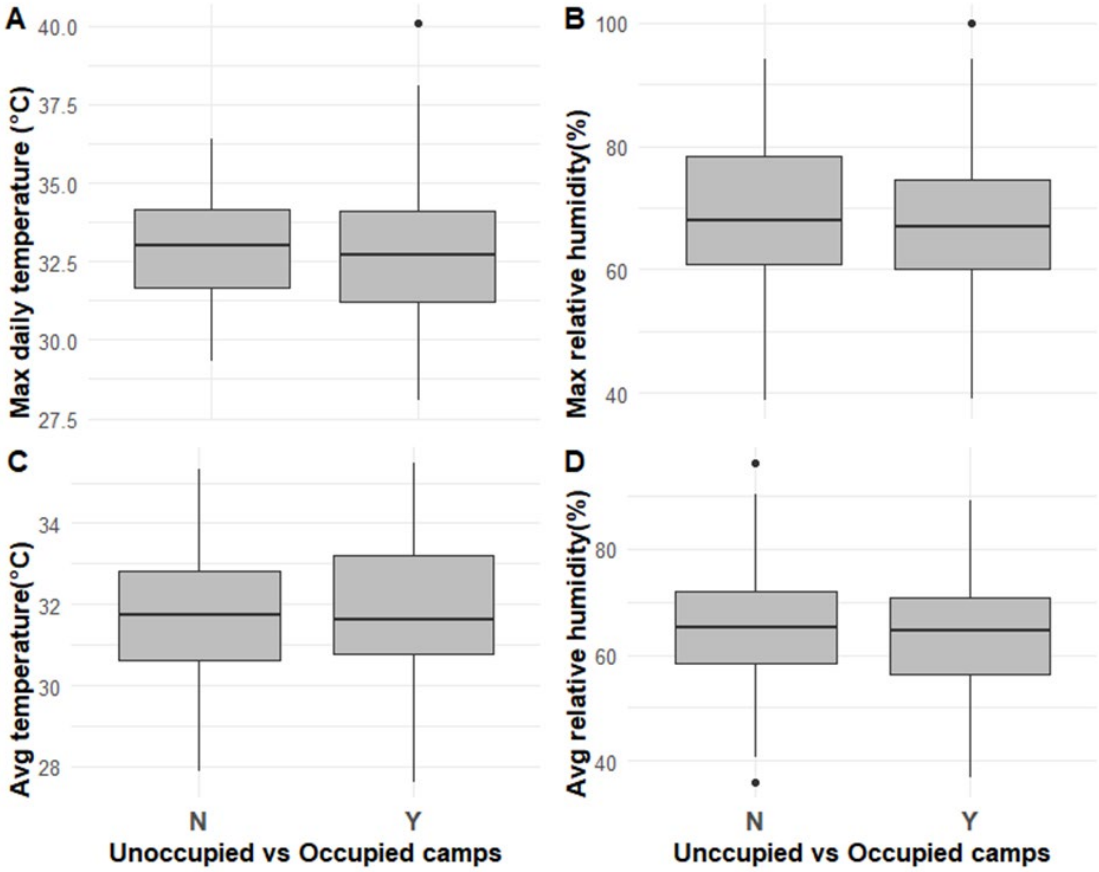


Figure 2.7. Boxplot graphs displaying the difference between occupied and unoccupied camps in maximum daily temperature (A), maximum humidity (B), average temperature (C), and average relative humidity (D) per visit. In each graph, the left box represents unoccupied camps, while the right box represents the occupied. The longitudinal lines above and below the boxes represent the temperature range, with the extremities of each line representing the lowest and the highest value of this data. The black dots represent the outliers.

Table 2.1: Analysis of Variance used to investigate the effect of temperature and humidity in the roost occupancy

Model	*df*	*F*	*P-value*
aov(max_daily ~ presence, data = data)	*1,153*	*0.238*	*P>0.05*
aov(mean_daily ~ presence, data = data)	*1,153*	*1.499*	*P>0.05*
aov(max_hum ~ presence, data = data)	*1,153*	*0.255*	*P>0.05*
aov(mean_hum ~ presence, data = data)	*1,153*	*1.633*	*P>0.05*

Table 2.2. Binomial models evaluating the probability of roost occupancy according to microclimate and roost size

Model	Characteristics	OR	95%CI	*p-value*
glm(presence ~ max_daily, data = camp_max, family = binomial)	max_daily	1.08	0.79, 1.50	0.6
glm(presence ~ max_hum, data = camp_max, family = binomial)	max_hum	0.82	0.59, 1.13	0.2
glm(presence ~ mean_daily, data = camp_mean, family = binomial)	mean_daily	1.09	0.79, 1.50	0.6
glm(presence ~ mean_hum, data = camp_mean, family = binomial)	mean_daily	1.09	0.79, 1.50	0.6
*glm(presence ~ max_daily*max_hum, data = camp_max, family = binomial)*	max_daily	0.93	0.61, 1.40	0.7
	max_hum	0.78	0.51, 1.17	0.2
	max_daily * max_hum	1.09	0.82, 1.45	0.5
glm(presence ~ mean_daily*mean_hum, data = camp_mean, family = binomial)	mean_daily	0.78	0.45, 1.34	0.4
	mean_hum	0.66	0.38, 1.14	0.14
	mean_daily * mean_hum	1.06	0.81, 1.38	0.7
glmer(presence ~ max_daily*max_hum +(1|camp), control = glmerControl(optimizer ="Nelder_Mead"), data = camp_max, family = binomial)	max_daily	2.57	0.66, 10.0	0.2
	max_hum	0.92	0.28, 3.08	0.9
	max_daily * max_hum	1.64	0.65, 4.15	0.3
*glmer(presence ~ mean_daily*mean_hum +(1|camp), control = glmerControl(optimizer ="Nelder_Mead"), data = camp_mean, family = binomial)*	mean_daily	1.6	0.30, 8.61	0.6
	mean_hum	0.71	0.17, 3.08	0.7
	mean_daily * mean_hum	1.39	0.61, 3.16	0.4
glm(presence ~ area, data = camp_max, family = binomial)	area	0.87	0.82, 0.92	<0.001

2.5 Discussion

I examined the microclimate of urban roosts of the endangered spectacled flying-fox in the tropical lowlands of Cairns in north-eastern Australia and found that roost occupancy was not predicted by maximum temperature or relative humidity. During the summers of 2021/2022 and 2022/2023, I observed that maximum roost temperatures were commonly 30-35 ^{o}C, with more excessive hot days (>35 ^{o}C) recorded at urban roosts than expected based on the most recent decade of available temperature data for the summer period (2013-2023). I recorded only one day when the urban roost temperature was greater than 40 ^{o}C. No period replicated the 2018 heatwave, which was characterised by six consecutive excessively hot days and exceptionally low humidity. I found a significantly negative relationship between ambient temperature and humidity at the roosts, where the hottest days coincided with those of the lowest humidity.

There is a limitation on using the Kestrel as a microclimate data collection for an animal living in the canopy and as a short visit per camp. The limitation is that the temperature and humidity were collected at human chest height. However, this approach was used with a very similar methodology before, where microclimate variables of forest fragments were collected at breast height with a 15-minute collection time (Magnago et al. 2015). Another paper used handheld meteorological stations to analyse the microclimate conditions for a volant species (Patten & Smith-Patten, 2012). I intended to use data loggers as demonstrated in the Sydney study on grey-headed flying-fox (Snoyman & Brown 2010) but the loggers placed in the analysed campsites were stolen several times, making that methodology unfeasible.

The 2018 Cairns heatwave was caused by warm, dry winds moving west from inland Australia and becoming established along the northeast coast (Bureau of Meteorology 2018). This weather pattern was highly unusual for the region, which is normally influenced by easterly winds that dissipate heat with cooler air and precipitation. Continental climate drivers, such as El Niño and Indian Ocean Dipole conditions, were not a strong influence on the heatwave, but a pulse of Madden-Julian oscillation appears to have contributed to the establishment of westerly winds, along with a low-pressure system in the southeast (Bureau of Meteorology 2018).

Heatwaves often intensify in a cycle, where dry areas heat up faster, causing even more moisture loss and further increasing temperatures. Despite occurring at the

beginning of the wet season in Cairns, the days prior to the heatwave registered below average rainfall in the northeast (Bureau of Meteorology 2018). This intensified the conditions that led to the exceptionally low humidity recorded during this period. These regional weather conditions may have been further exacerbated by the effect of urban heat islands, which act to raise the temperature of urban areas with respect to the surrounding areas (Ramsay et al. 2023). This may explain why the urban roost sites were slightly warmer than the airport records overall, over the same timeframe.

However, this trend was not significant, most likely due to the high inter-roost variability in recorded temperatures, which may be a result of the broad range of landscape and vegetation types within the study sites. It is worth noting that the hottest roost temperature I recorded (40.1 ^{o}C) was 7.8 ^{o}C higher than the temperature recorded at the airport for the same date, illustrating the importance of direct measurements of roost microclimates for predicting heatwave events at flying-fox roosts.

In Australia, flying-fox populations have been ravaged by heatwaves while at roosts (Welbergen et al. 2008; Welbergen 2012). Between 1994 and 2008, die-offs of at least 19 flying-fox populations were attributed to extreme temperatures (Janzen 1967; Welbergen 2012). The microclimate characteristics of flying-fox roosts are an important contributor to the ability of these species to cope with heat stress (Bartholomew, Leitner & Nelson 1964), and may also have a significant potential to buffer the effects of heat waves (De Frenne et al. 2021). Roost vegetation features can directly influence the success of thermoregulatory behaviours in flying-foxes. For example, wind permeability can influence the effectiveness of heat dispersion through wing fanning (Bartholomew, Leitner & Nelson 1964), vegetation structure provides shade (Rajasegaran et al. 2018), the evapotranspiration of larger trees actively cools the air, and plant cover in the understorey reduces latent heat (De Frenne et al. 2021). In a 2002 die-off event, Welbergen et al. (2008) recorded a progression of thermoregulatory behaviours presented by bats during the heatwave, starting with wing fanning, followed by shade-seeking, panting, and saliva-spreading.

As flying-foxes have a wide distribution across many different habitats, it is challenging to generalise from this study to roost preferences at a larger scale. I found that although spectacled flying-fox roost sites experienced more excessively hot days during the study period than average over the past decade, maximum temperature and humidity values alone did not predict roost occupancy. However, I found that occupied

roosts exhibited greater variation in temperature than unoccupied roosts, although this could be due to differences in vegetation type and the distance between sites, rather than a preference for some inherent habitat quality, as I did not find evidence that temperature and humidity influenced roost occupancy. This is in contrast to a study on grey-headed flying-foxes in Sydney, which found that bats were more likely to permanently occupy roosts with a slightly higher variance in daily temperature and humidity than other camps (Snoyman & Brown 2010).

As I consider a future where heatwaves are becoming more frequent, supporting flying-fox populations through roost management may be one of the most feasible and effective local options available. Previous suggestions to increase tolerance to heat stress during extreme heat events recommends cooling flying-foxes by vegetation spraying, misting the animals directly, and the use of ground-based sprinklers (Mo & Roache 2021). However, these responses may worsen tolerance to heat stress if spraying and the associated increased human presence leads to bat dispersal, an effect that could be exacerbated by the presence of young pups during the summer months which may be abandoned if roosts are disturbed (Stanvic et al. 2013).

Alternatively, a preventive forecast has been developed to predict the occurrence of flying-fox die-offs, with a 24-48 h window of confidence (Ratnayake et al. 2019). This "flying-fox forecast" uses the gridded temperature from the BOM's Australian Region domain of the 'Australian Community Climate and Earth-System Simulator' (ACCESS-R) Numerical Weather Prediction (NWP) system to evaluate air temperature in a particular area with a 42 ^{o}C temperature threshold to predict a heat event. However, as the results of this study demonstrate, roost temperatures can be substantially greater than those registered by the BOM, which may result in delayed preventive action or no action. Ultimately, a better understanding of the importance of the microclimate of urban roosts and the interactions between roost occupancy, local environmental features, and thermal tolerance will be needed to prevent future flying-fox mass mortality events. Improving thermal resistance to heatwaves through scientifically informed management policies, which may include the identification and monitoring of occupied roosts to reduce the risk of bats dying at these sites during heat waves. Further studies into how the composition and structure of roost vegetation can be managed to buffer the microclimate conditions of roosts would be beneficial in supporting the capacity of flying-foxes to cope with extreme heat events.

CHAPTER 3

Does the vegetation structure of spectacled flying-fox roosts affect microclimate and occupancy? Vegetation characteristics of Spectacled Flying-foxes (*Pteropus conspicillatus*) urban roosts in a lowland tropical city and their influence on roost microclimate and occupancy

---

Abstract

Understanding the influence of vegetation structure on the microclimate is becoming increasingly important for climate-change-sensitive species, especially in human-modified environments. The endangered spectacled flying-fox (*Pteropus conspicillatus*) is one such species that has become increasingly vulnerable to heat waves due to their preferential roosting in urban forest remnants. This study investigates the relationships between vegetation structure, microclimate, and roost occupancy across 20 urban roosts in Cairns, northeastern Australia. We employed field measurements and LiDAR-derived vegetation data to analyse canopy cover, tree height, and understorey characteristics, as well as their impact on local temperature and humidity. Microclimate data were collected over two summers, capturing variations across occupied and unoccupied camps. Occupied camps were characterised by slightly higher canopy cover (96.9%) and greater vertical complexity than unoccupied camps, although canopy cover was not a significant predictor of occupancy. Logistic regression and ordination analyses revealed a higher likelihood of occupancy for camps with taller trees (>20 m) and higher stem density in the understorey. Ground cover composition was also associated with occupancy, with greater levels of herbaceous vegetation recorded at occupied sites. Microclimate analyses indicated that structural features such as sapling density and canopy height modulate local temperature and humidity, with taller vegetation reducing maximum temperatures. These findings suggest that vegetation structure significantly influences roost microclimate, affecting spectacled flying-fox occupancy. Camps with complex vertical structures and lower humidity were more likely to be occupied, providing insights into habitat preferences and their potential vulnerability to extreme weather events. Conservation strategies should prioritise enhancing vertical complexity and managing microclimatic conditions to mitigate the impacts of climate change on this endangered species. Future

research should explore these dynamics further to inform urban planning and habitat restoration efforts.

3.2 Introduction

Bioclimate models that predict the onset of extreme weather events, such as heatwaves, can provide important early warnings for human safety and managing vulnerable wildlife species (Urban 2015; Evans et al. 2022). In Australia, the Flying-Fox Heat Stress Forecaster is a bioclimate model that uses a temperature threshold to predict heat stress and potential mortality of flying-foxes across the east coast of the continent (Ratnayake et al. 2019). In 2018, the Forecaster predicted a high mortality risk from extreme temperatures for spectacled flying-foxes in the Cairns region, northeastern Australia. This prediction proved correct, with approximately 23,000 bats perishing during this event; potentially comprising one-third of the species' population; (Ratnayake et al. 2019; Lopes et al. 2024). While the Forecaster was highly effective at predicting temperature at the coarse spatial scale of the Cairns region, it did not explain why some flying-fox camps were badly affected, and others in close proximity were not. This local-scale variability in temperature illustrates the potential importance of topography and vegetation in influencing microclimate. Furthermore, it demonstrates the critical role microclimate can have in sustaining refugial populations during extreme weather events (Suggitt et al. 2011; Evans et al. 2022; Finocchiaro et al. 2024) and the need to identify these differences.

Microclimate is associated with organisms' survival (Pincebourde et al. 2016; Wolfe et al. 2025), growth (Duchicela et al. 2021; Pandey et al. 2025), and reproduction rates (Huey et al. 2012; Smyser et al. 2024), which in turn influences species' occupancy (Varner & Dearing 2014; Ranius et al. 2024), and distribution (McGinn et al. 2023; Ismaeel et al. 2024). In forest ecosystems, the abiotic conditions inside forests can vary largely across space and time (Ismaeel et al. 2024) and will be influenced by climate change according to its capacity to buffer the extreme conditions presented outside of the forest (De Frenne et al. 2021).

Vegetation structure, topography, soil and water availability have been associated with changes in microclimate (De Frenne et al. 2021; Kemppinen et al. 2024). Tree height and canopy foliage density (Wang et al. 2023) also reduces temperature and humidity

extremes (Ziter et al. 2019). They influence local temperatures by absorbing and reflecting incoming shortwave radiation and cooling via evapotranspiration, which together can reduce forest understorey temperature by up to 4^{o}C on average globally (De Frenne et al. 2019) and up to 10^{o}C in tropical forests (Ismaeel et al. 2024). Furthermore, the complexity and density of stems and leaf architecture control the penetration of light and heat into the forest, diminishing as leaf area increases so that solar radiation at ground level is a fraction of the solar radiation affecting the canopy in closed forests (Scheffers et al. 2017; Atkins et al. 2018; Díaz-Calafat et al. 2023). Evapotranspiration is much higher in and just below the canopy, which actively cools the hottest part of the forest, along with winds which are generally faster and more persistent at canopy level (Vinod et al. 2022). If soils dry out during droughts or over summer periods, the cooling from evapotranspiration will diminish, especially where forests are deciduous and shed leaves to reduce drought stress (de Souza et al. 2020). Canopy cover also influences the understory plant density and composition, regulating light penetration and sapling colonisation (Lemenih et al. 2004; Ismaeel et al. 2024). The complexity and density of the stems at each forest strata affects the distribution of heat across the vertical axis in forests (De Frenne et al. 2019), with even ground cover reducing solar radiation and heat transfer to the soil (Zhao & Jackson 2014; Li et al. 2015).

Vegetation structure also influences the distribution of biodiversity in forests, including the preferred roost selection of flying-foxes (Dos Santos et al. 2016; Majumdar et al. 2016). Flying-foxes tend to roost in a wide variety of vegetation types from tall dense forests to short-statured mangroves, and even trees in well-watered parks. However, most of the reported roosts have been registered in urban areas, with Spectacled flying-fox' recognized roosts located in protected areas reduced to 13.9% (MacDonald et al. 2021; Timmiss et al. 2021). Land use change and habitat fragmentation have detrimentally affected flying-fox populations and roost availability (Timmiss et al. 2021), increasing bat roosting in urban areas. These urban roosts are often small forest remnants or planted trees that lack the vegetation complexity of intact forests and potentially provide fewer refugia buffering potential from extreme weather events (Majumdar et al. 2016; Morán-Ordóñez et al. 2018; González-Trujillo et al. 2023).

Due to the variety of habitats occupied by Australian flying-foxes, the current understanding of their habitat requirements is generally considered incomplete (Markus & Hall 2004; Páez et al. 2018; Boardman et al. 2021; Timmiss et al. 2021; Yabsley et al.

2021). The influence of vegetation structure and microclimate on flying-fox occupancy has been examined for grey-headed and little red flying-foxes. In southeastern NSW, the roosts with greater levels of occupancy experienced higher temperature variability than sites that did not (Snoyman & Brown 2010), whereas for the Little red flying-fox, the most nomadic species, a study analysed the roosts in a broad and local scale, assessing the vegetation structure and the main species composition in Queensland. This study found the roosts presented (1) a slightly taller canopy; (2) greater canopy and subcanopy cover, providing a complex structure to roost, although the association was considered to be weak (MacDonald et al. 2021). For the spectacled flying-fox, the most dedicated paper describes its roost as close to the rainforest (no more than 6.5km), with dense vegetation and seasonal populational movements between traditional sites and the Innisfail and Atherton area. It also points to the preference for roosting in the rainforest. However, nowadays, this information may not reflect reality (Richards 1990). Even though the little-red flying-fox study identified structural and environmental characteristics at site and landscape scales that are closely linked with known little red flying-fox (LRFF) roost locations, it couldn't pinpoint precise factors influencing their roosting choices (MacDonald et al. 2021). By demonstrating microclimate preferences for grey-headed flying-foxes and vegetation preferences for little red flying-foxes, these studies suggest that certain vegetation structures likely attract to/ retain these bat populations in specific areas.

Spectacled flying-foxes have even fewer studies than the other 3 mainland species of flying-foxes. They have the disadvantage of being the species with the smallest distribution being restricted to Coastal Queensland, from Tully to the tip of Cape York and the northern islands of Torres Strait; and outside Australia in Papua New Guinea (Hall & Richards 2000; Species Profile and Threats Database 2025). For the spectacled flying-fox, the most dedicated paper describes its roost as close to the rainforest (no more than 6.5km), with dense vegetation and seasonal populational movements between traditional sites and Innisfail and Atherton area. It also points to the preference for roosting in the rainforest. However, nowadays, this information may not reflect reality (Richards 1990).

This study investigates the vegetation structure of urban spectacled flying-fox roosts in Cairns, Australia, and its influence on roost microclimate and occupancy. Specifically, we aim to answer the following questions: (1) How does vegetation structure

differ among urban roost sites? (2) Does vegetation structure influence microclimate within roosts? (3) Is roost occupancy likelihood influenced by vegetation structure or microclimate? We hypothesise that roosts with taller trees and complex vertical structures provide better thermal buffering and will be more likely to be occupied. Additionally, we predict that sites with lower canopy cover will exhibit higher understorey temperatures due to increased light penetration. By combining field measurements with remote sensing data (LiDAR), this study provides insights into habitat preferences and conservation strategies for an endangered species facing increasing climatic stress understory will increase the likelihood of roost occupancy. These hypotheses were tested with field and remote sensing data structure.

3.3 Methods

The study was undertaken in the lowland tropical city of Cairns in northeastern Australia (16.92^{o}S, 145.78^{o}E). Cairns experiences a mean annual rainfall of ~2000 mm and a pronounced dry season (<100 mm month 1) from April to November. The monthly mean maximum temperature ranges from 25.8°C (winter) to 31.5°C (summer) (Bureau of Meteorology 2023).

Twenty urban roost sites were selected for this study from the spectacled flying-fox roost database managed by Cairns Regional Council and the Bats and Trees Society of Cairns. I selected sites based on occupancy, seeking to pair sites that were continuously occupied with those currently unoccupied from 2021 to 2023. The continuously occupied sites comprised males, females, and pups/juveniles during the studied season.

The roosts selected for this study span 40 km north to south and 10-20 km east of west around Cairns. The north-south extent of the urban roosts (16.78 ^{o}S, 145.68 ^{o}E to 17.09 ^{o}S,145.78 ^{o}E) covers an area of ~160 km^2 (Figure 3.1). Sites were selected in partnership with bat-caring organisations monitoring these sites since the dispersal of the traditional colony located in the Cairns CBD.

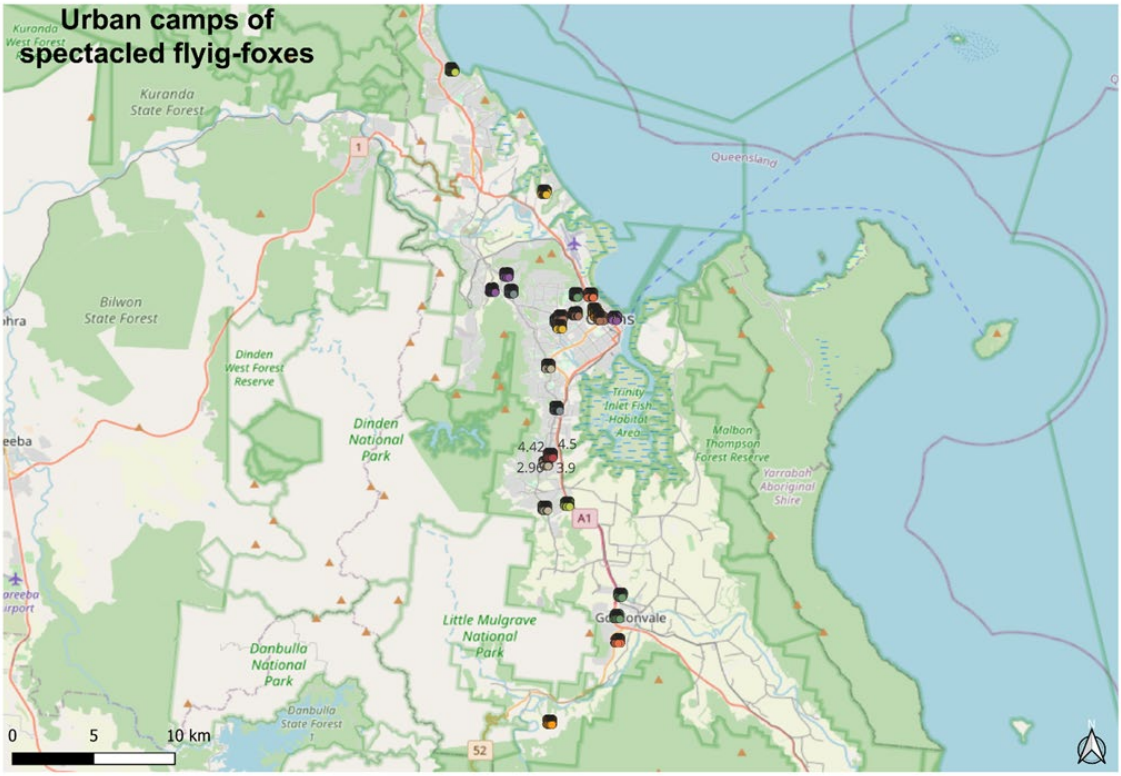


Figure 3.1: The location of spectacled flying-fox roost sites examined in this study. The roosts encompass various vegetation types related to habitat area (0.5 – 42 ha) and urban environments (houses, roads, walking paths, etc). In all the roosts, a heavy human presence could be inferred from observations of littering and garden debris.

3.3.1 Vegetation structure

3.3.1.1 Plot assessment

We assessed vegetation structure along transects 25 m long and 10 m wide (5 m each side of the centred line). The number of transects varied with the roost size: one transect per roost < 20 ha in area, and two transects per roost >20 ha. In cases where two transects were used, the resulting data were averaged.

We selected structural variables representative of habitat quality that could impact microclimate inside forest fragments (Blanchard et al. 2023). We measured the canopy cover using a spherical densiometer every 5 m of the transect. We counted the sky view corners and calculated the coverage percentage. Ground cover was assessed using a 1 m^2 squared grid divided into four 0.25 m^2 smaller grids. Every 5 m, we placed the grid on the ground and visually estimated the proportion of the ground cover in five categories (bare soil, leaf litter, grass, herbs, and wood plants) up to 100%.

The number of stems was counted every 5 m, on both sides of the transect, in a 5m line from the transect centre, and stem DBH (diameter at breast height – 1.3 m from the ground) was measured and tallied into four size classes: Small (<2.5 cm), Medium (2.5-5 cm), and Large Saplings (5-10 cm), and Trees (>10 cm). The DBH of trees was recorded individually and used as indicator of maturity. All the stems in that line were counted and classified as above.

3.3.1.2 Aerial LiDAR

Aerial *LiDAR* technology was utilised to assess the vegetation structure of entire roost area of the study sites. The *LiDAR* data were sourced from the *Elvis* - Elevation and Depth - Foundation Spatial Data open spatial repository between 2009 and 2011(Geoscience Australia, 2010) , and processed using R version 4.2.2 (R Core Team, 2023) with packages such as *sf* (Pebesma, 2018), *tidyverse (Wickham et al., 2019), lidR (Roussel et al., 2020),* and *terra (Hijmans, 2023).* The procedure involved loading the *LiDAR* files as a *LAScatalog* within the *lidR package* and applying a 200 m square buffer around the center of each flying-fox roost using the *sf package*. Each buffer was then clipped to the *LAScatalog* to generate a 200 m x 200 m las file per roost.

For each roost, the *las* file was normalised by removing the terrain using a Triangulated Irregular Network (TIN) within the *lidR package*. Building points (las class 6) were rasterised to a 1 m resolution and then converted to polygons with the *terra package*, removing all points within these polygons from the *las file*. The remaining data wer then height-smoothed using a 4 m square window and a two-sigma Gaussian method to eliminate outlying points.

After smoothing and normalising, points classified as unassigned, ground, low point, model key/reserved, rail, road surface, and overlap/reserved were filtered out, leaving only vegetation points. The filtered *las* file was analysed to calculate standard metrics using *lidR's 'pixel_metrics'* function with a 5 m resolution, representing the approximate diameter of a tree crown. Height intervals ranged from 1 to 35 meters were used. Finally, the processed data was converted into a raster stack, then into spatial points using the terra package, and exported as a shapefile and CSV file for further analysis.

The collected data is the percentage of point cloud data divided into height classes (1, 2, 5, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30 and 35m), showing the distribution

of the vegetation volume across the different strata. When analysing the point cloud data, we eliminated 40 and 45m columns due to the absence of data for most of the roosts.

3.3.2 Microclimate

For two summers, between November 2021 and January 2022, and December 2022 and February 2023, microclimate data was collected at roosts on non-rainy days between 11 am and 2 pm at breast height, avoiding direct sun exposure. Using a handheld meteorological station (Kestrel 3550), I collected air temperature and humidity at each of the 20 bat roosts over a 10-minute period at each roost. Each roost was sampled 4-6 times each season. For logistical reasons, we could not sample the camps on the same dates but this was acknowledged when choosing the statistical models, as stated below. The accuracy for ambient temperature (***T_a***) is ±0.5 °C and the resolution is ±0.1 °C, whilst for relative humidity (***Rh***) is ±3% and ±0.1%, respectively (Kestrel Weather Meters 2020).

3.3.3 Statistical analysis

To infer the main predictors influencing roost occupancy, I performed a non-metric multidimensional scaling (NMDS) (Oksanen et al. 2024) using the *vegan* package. The density, trunk diameter, canopy cover and microclimate data were transformed using the *scale* function in R, and the compositional data (vertical complexity and ground cover) was normalised using a centred-log ratio in the package *compositions* (van den Boogaart & Tolosana-Delgado 2008) . I used R software [version 4.4.0 (Team. R Core, 2021)] for all statistical data analysis.

I used a Wilcoxon Rank-Sum test to compare the medians in occupied and unoccupied roosts in order to analyse the association of canopy cover with roost occupancy and examined the likelihood of predictor variables associating with occupancy with logistic regression models using *tidy models*.

To investigate the relevance of ground cover in the prediction of roost occupancy, I used logistic regression with Lasso penalty using the package *glmnet* (Friedman et al. 2010; Tay et al. 2023). To predict the association of sapling and tree density with roost occupancy I performed a logistic regression using the Wilcoxon Rank-Sum test as a post-hoc test to compare the canopy cover medians in occupied and unoccupied roosts. The

same approach was used to predict the association between tree maturity and roost occupancy. To investigate the importance of vertical complexity in predicting roost occupancy, I analysed a transformed point cloud data using logistic regression with Lasso penalty, package *glmnet* (Friedman et al. 2010; Tay et al. 2023).

I investigated the association of vegetation structure with microclimate using generalised linear regression with the Lasso penalty. To investigate how understorey would be associated with microclimate, we used a multivariate additive model and a linear model with stem class and overall density as predictors. The data were transformed as stated at the beginning of this section, and using the package *mgcv* (Wood 2017) for the additive model due to the non-linear nature of the data. To investigate the association of tree height with roost microclimate, we used a multivariate general linear model with Lasso penalty using the package *glmnet* (Friedman et al. 2010; Tay et al. 2023).

Although microclimate data were collected on different days and at varying times, the use of scaled variables helped reduce the influence of measurement timing, allowing the models to focus on relative differences across roosts. Furthermore, the use of Lasso-penalised regression introduced a regularisation component that shrinks noisy or inconsistent predictors, such as those potentially influenced by day-to-day variation, toward zero. This approach provides robustness against incidental environmental fluctuations and supports the identification of structural predictors consistently associated with microclimate and occupancy, regardless of the exact time of data collection.

We investigated the odds ratio of each model to identify the variables with a higher association with the microclimatic variables.

3.4 Results

By the end of the study, 12 of the 20 flying-fox roosts studied were assessed as occupied, and eight were assessed as unoccupied. All the studied roosts showed varied degrees of human disturbance, including littering and proximity to houses and roads.

3.4.1 Vegetation characteristics of urban roosts

The NMDS (Non-metric multidimensional scaling) ordination compared the vegetation structure and environmental conditions across sampled roosts in the context of

roost occupancy (Figure 3.2). Overall, there is no clear separation with respect to site association with axes between occupied and unoccupied roosts, but there is an association between occupancy and environmental and structural factors.

The ordination illustrates the variation in vegetation structure and environmental conditions across sampled roosts. Significant vectors fitted to the ordination highlight key variables driving this variation. Specifically, vegetation above 10 meters (R^2=0.32, P=0.04), mean diameter at breast height (R^2=0.33, P=0.029), and herbaceous cover (R^2=0.2600, p=0.047) were strongly correlated with the NMDS axes.

These results indicate that a higher percentage of tree height above 10m, herbaceous cover, and three diameters contribute to the spatial variation in vegetation structure and species presence. These findings emphasise the importance of vegetation complexity in shaping the distribution patterns of species across the study area.

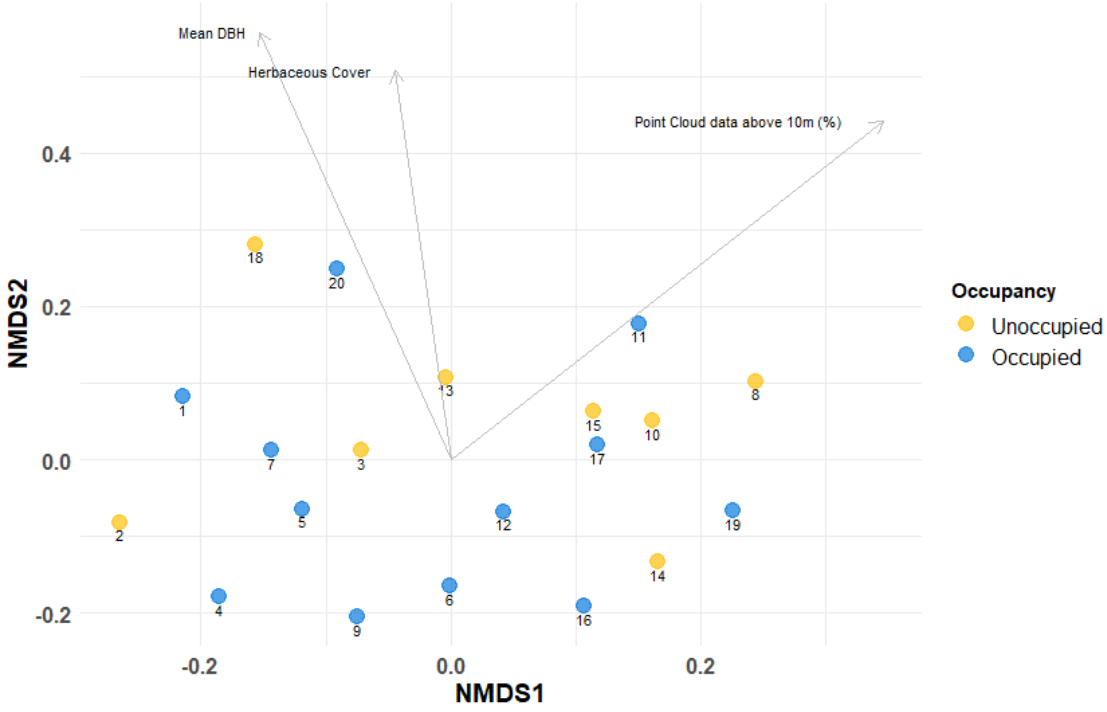


Figure 3.2 Non-metric Multidimensional Scaling (NMDS) ordination plot showing the significant factors predicting roost occupancy. Occupied (blue) and unoccupied (yellow) sites are separated based on significant environmental variables. Each point represents a roost, with proximity indicating similarity in environmental conditions. Arrows represent significant (P<0.05) environmental vectors, with their direction indicating the gradient of

the variable and their length representing the strength of the correlation with the NMDS axes.

3.4.2 Canopy cover

Canopy cover estimates were high for all sites but slightly lower overall for unoccupied roosts (Mean = 93.4 ± SD=5.4) than occupied roosts (95.5±5.0). We compared the median of the canopy cover of the analysed roosts. While occupied roosts showed a higher percentage median forest cover (96.9%) than unoccupied roosts (94.8%), this was not significantly different (Wilcoxon sum ranks test P<0.005, effect size r = 0.31; Figure 3.3). Not surprisingly, there was also no detectable effect of canopy cover on flying-fox occupancy (logistic regression, z value=-1.80, Pr (>|z) = -0.07).

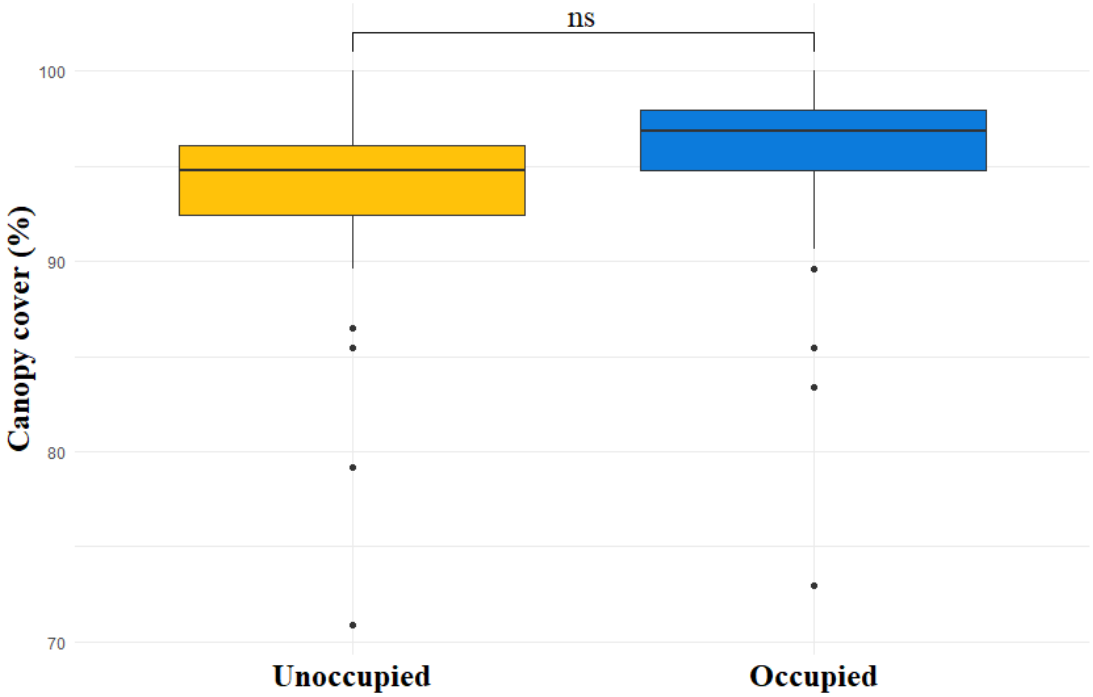


Figure 3.3 A comparison of canopy cover estimates between occupied and unoccupied flying-fox urban roosts in Cairns, Australia.

3.4.3 Ground cover

Overall, the structural features of ground cover differed between occupied and unoccupied roosts (Figure 3.4) with respect to the proportion of grass, exposed soil, herbs and woody plants. This difference between the sites was significantly associated with the

current occupancy of flying-foxes, with the likelihood of occupancy in roosts increasing 256 times with more herb cover and 7 times with more bare soils (Lasso Regression r2=0.19, P<0.005, df=4). More grass was associated with a small decrease in likelihood (0.33 times).

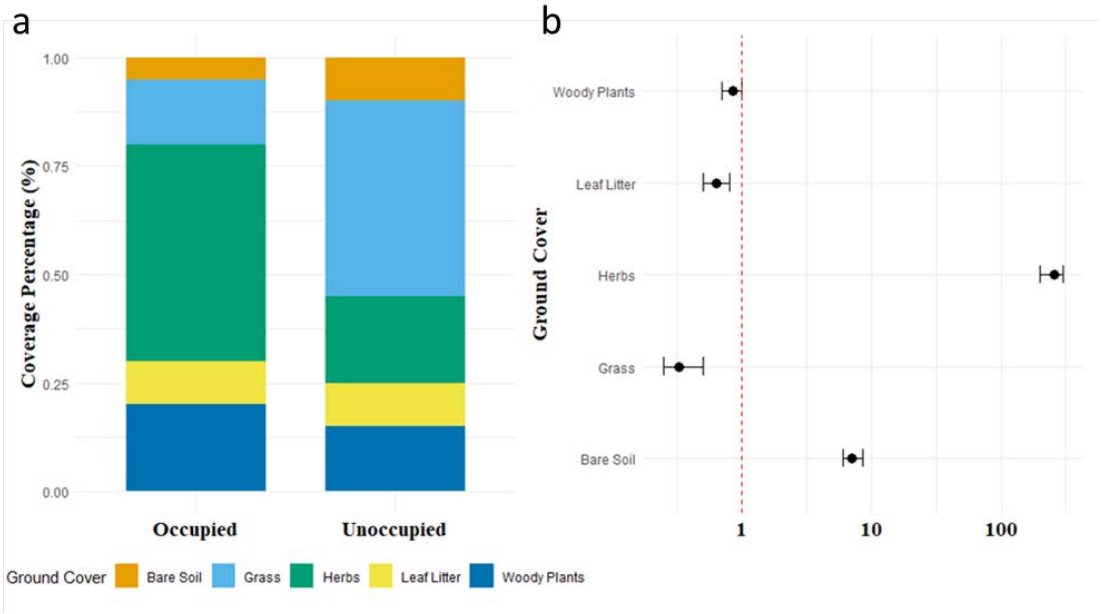


Figure 3.4 Ground cover composition in occupied and unoccupied flying-fox roosts and its association with roost occupancy.(a) Stacked bar plots show the proportional cover of five ground cover types (bare soil, grass, herbs, leaf litter, and woody plants) in occupied (left) and unoccupied (right) roosts. (b) Odds ratios from a logistic regression model indicate the likelihood of site occupancy as a function of each ground cover type. Odds ratios > 1 suggest a positive association with occupancy (e.g., woody plants, leaf litter), while values < 1 indicate a negative association (e.g., herbs, grass, bare soil). Error bars represent 95% confidence intervals. The red dashed line marks the neutral value (OR = 1).

3.4.4 Understory structure and roost occupancy

Ground cover is associated with variation in the microclimate of forest fragments by directly and indirectly affecting key environmental factors such as temperature, humidity, soil moisture, and wind dynamics.

Although I found that the median number of stems was higher in occupied sites compared to unoccupied for: small (occupied: unoccupied, 44(IQR=27):21 (IQR=31)); medium (6 (IQR=7):2 (IQR_6)); and large saplings (4(IQR=10):2(IQR=6)); and trees

(8(IQR=7):9(IQR=7)); there was no significant difference detected overall (Wilcoxon sum rank test: small saplings= -0.93; medium sapling = -0.52; large sapling = -0.48, trees = -0.63 and overall = -1.16; where all P > 0.05) (Figure 3.5).

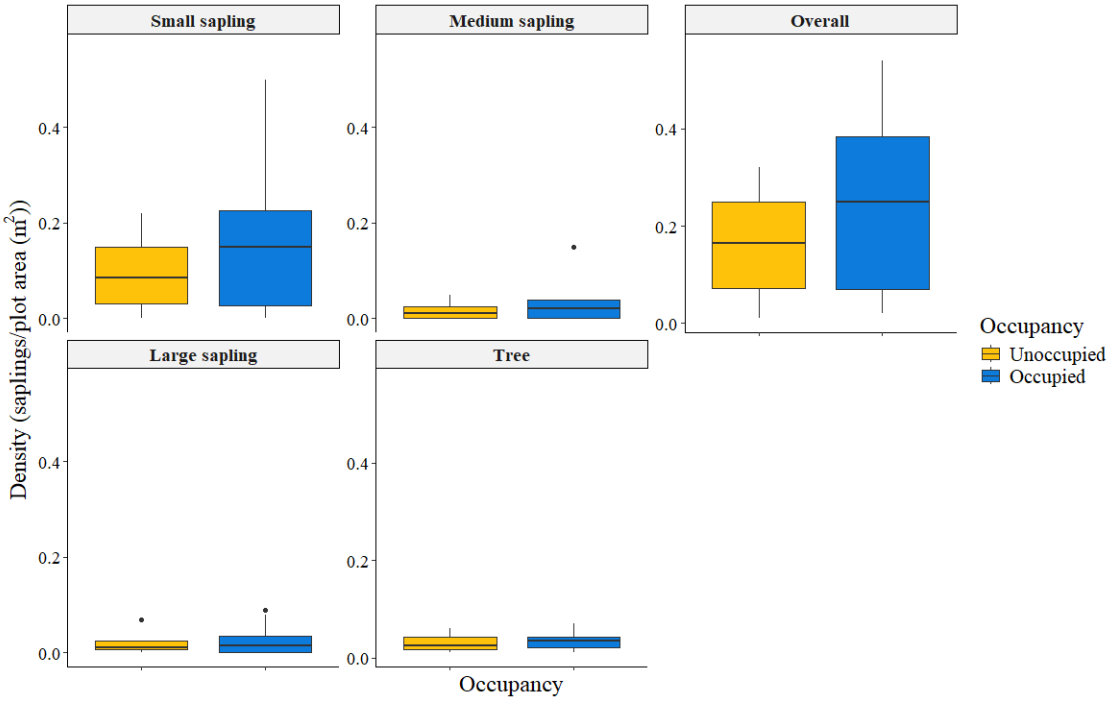


Figure 3.5 Boxplots comparing the density of vegetation categories (small saplings, medium saplings, large saplings, and trees) per plot area (m²) between occupied and unoccupied sites. The "Overall" panel aggregates all vegetation categories. Occupied sites (blue) exhibit higher density across most vegetation categories compared to unoccupied sites (yellow), particularly for small and medium saplings.

3.4.5 Tree diameter

The average tree diameter did not differ consistently between the occupied and unoccupied roosts (Wilcoxon Rank-Sum test W=3991, z-value=0.14, P=0.89; Figure. 3.6), despite a trend of slightly larger trees in unoccupied sites.

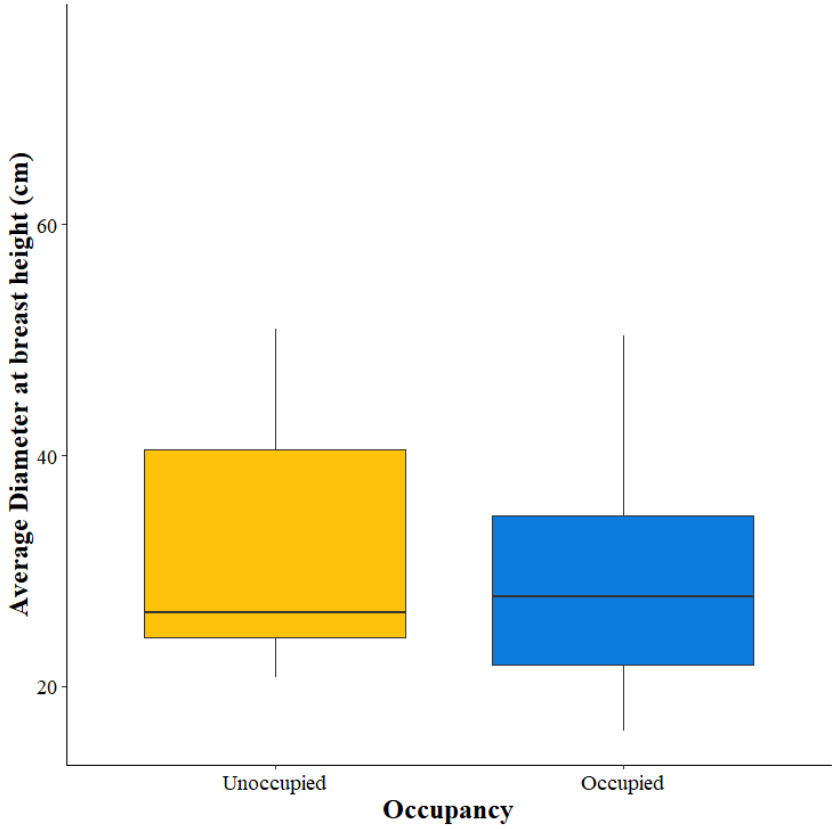


Figure 3.6: Boxplot comparing the average tree diameter between occupied and unoccupied roost sites and showing no difference between them. We investigated the association between tree maturity and roost occupancy on the probability of roost occupancy, testing the model against our data. There was a non-significant association between more mature trees and occupied roosts (β=18.38, z-value=0.55, P=0.58). This could suggest a slight trend but not a key factor in roost occupancy. We tested the model against the data, and it explains 50% of the results.

We also analysed the coefficient of variation between occupied and unoccupied roosts, but we could not find a significant difference (ΔCV = -6.92%, Levene's test: F(1,180)=0.26, P=0.612).

3.4.6 LiDAR data

LiDAR data from the study sites were used to estimate vegetation structure, including canopy density and maximum vegetation height, using point cloud returns across discrete height intervals from >1 m to >35 m. Although a few roost sites included

taller trees, with only four roosts having vegetation exceeding 25 m, and just one reaching over 35 m. Most of the structural complexity was concentrated in the lower height strata (Figure 3.7).

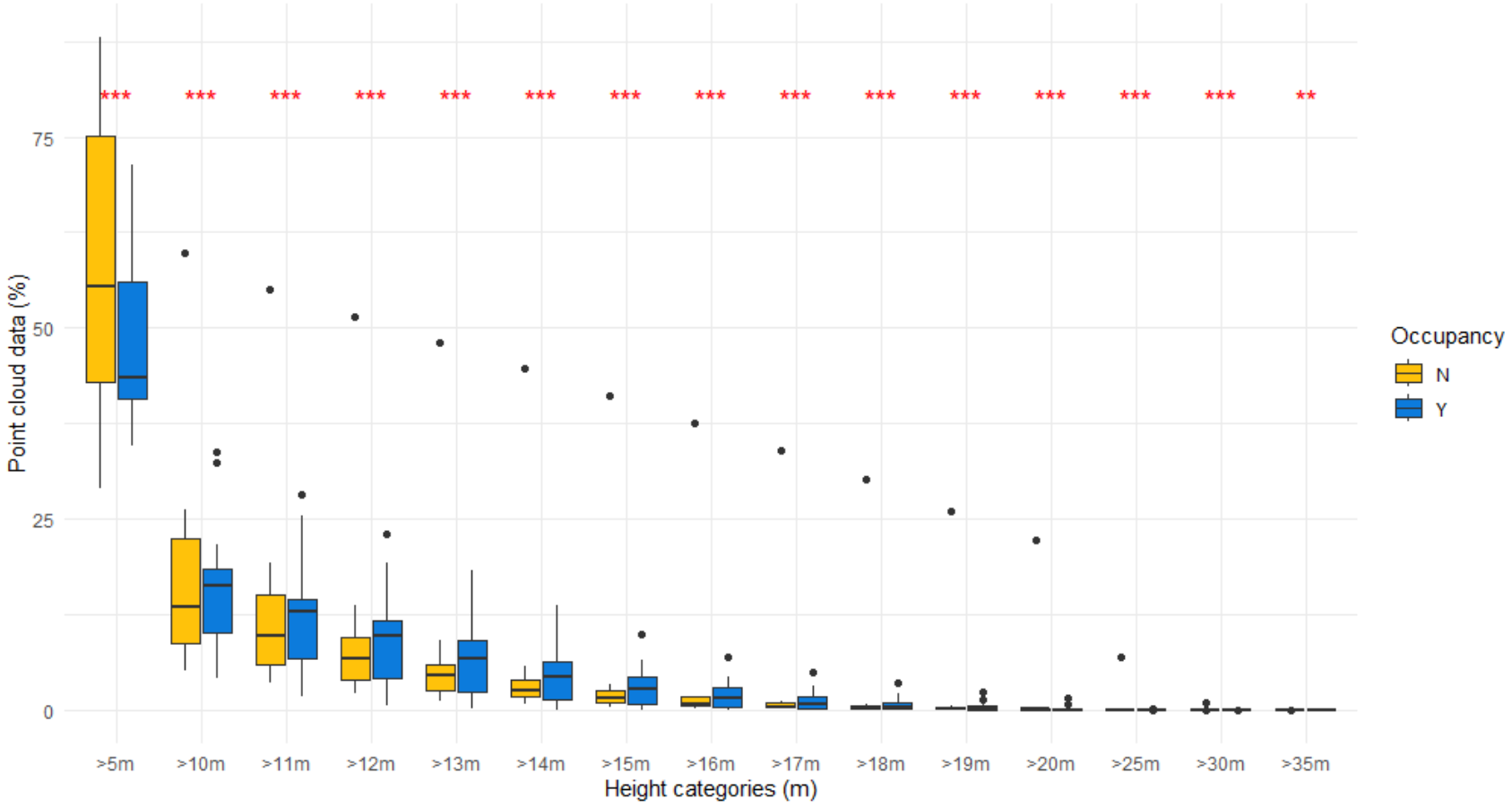

***
***
***
***
***
***
***
***
***
***
***
***
***
***
**
75
50
25
0
Point cloud data (%)
>5m
>10m
>11m
>12m
>13m
>14m
>15m
>16m
>17m
>18m
>19m
>20m
>25m
>30m
>35m
Height categories (m)
Occupancy
N
Y

Figure 3.7 Boxplots showing the proportion of vegetation across height categories (m) for occupied (Y, blue) and unoccupied (N, yellow) roosts. Each box represents the interquartile range (IQR), with the horizontal line indicating the median. Outliers are shown as individual black points beyond the whiskers, which extend to 1.5 times the IQR. Red asterisks (***, **, *) above each height category represent the significance levels of Wilcoxon rank-sum tests: ***$p < 0.001$, **$p < 0.01$, and *$p < 0.05$. The results indicate consistent differences between the two groups, particularly in lower height categories. Occupied camps are characterised by intermediate height (11–15 meters) compared to unoccupied camps, indicating a preference for vertical complexity in this range. Lower heights and fewer trees at the intermediate height characterise unoccupied camps.

Occupied camps have a significantly higher proportion of vegetation detected in the intermediate height categories (11–15 meters) than unoccupied camps, indicating a preference for vertical complexity in this range. Unoccupied camps show more evenly distributed trees across lower heights, with less emphasis on the intermediate heights, suggesting a difference in vegetation structure between the two groups. It seems reasonable that occupied camps have this structure as the canopy would be structured with a few emerging trees and a dense sub-canopy capable of providing shelter during heat events.

We performed a logistic regression with a Lasso penalty to identify which heights were associated with occupancy. Using a 10-fold cross-validation, Lasso showed 0.58 accuracy. The likelihood of roost occupancy significantly increased by 1.45 times in forests taller than 11 m (OR = 1.48, Lasso %deviance = 58%, MSE = 0.23, $P<0.05$) and by 1.38 times above 12 m (OR = 1.38). However, between heights of 13 and 14 m, no significant differences were observed between groups. Above 15 m, the likelihood of roost occupancy increased marginally (OR = 1.01) but began to decline at greater heights, with reductions observed between 17 m (OR = 0.61) and 25 m (OR = 0.19). Beyond 30 m, differences became statistically insignificant, likely due to the low percentage of data in this range (less than 5% of point cloud data recorded across all analysed roosts).

These results align with the NMDS preliminary analysis, which suggests bats favour vertical complexity in roosting environments. Roosts with a greater proportion of intermediate-height trees (10–14 m) appear to offer optimal roosting conditions.

Conversely, the reduced likelihood of roost occupancy at greater heights (above 15 m) may reflect limited habitat functionality for bat roosting, such as shading on hot days or reduced accessibility.

Both the graph and the regression converge on the association of intermediate heights (11–15 m) and vertical complexity with roost occupancy. However, the first analysis provides a more granular understanding of the likelihood of occupancy across all height ranges, while the second emphasises the structural differences between camps. Together, these findings suggest that vegetation structure, particularly the presence of a dense sub-canopy, is potentially associated with bats.

3.4.7 Vegetation characteristics of Spectacled flying-fox urban roosts and their influence on roost microclimate

To investigate the different associations between vegetation structure and microclimate, I analysed them separately, as intercorrelation between variables could mask important relationships. To achieve that, I divided the analysis into understory and canopy.

3.4.7.1 Understorey and microclimate

I used the dredge function to perform model selection for generalised additive models (GAMs), analysing the influence of vegetation structure on maximum and mean temperature, as well as maximum and mean humidity. Among all tested models, the only significant result was the effect of medium-sized stem density **on** maximum temperature. The best-supported model included a smoothing spline for medium-sized stem density, which significantly positively affected maximum temperature **(**$F = 5.21$, $P = 0.0095$, $edf = 2.73$**).** This model explained 53.2% of the deviance in maximum temperature, with **(**adjusted $R^2=0.45$**),** indicating a notable relationship between vegetation structure and microclimate. The results suggest that an increase in medium-sized stem density is associated with higher maximum temperatures in the study area.

Our findings suggest that the density of medium-sized saplings have important associations with roost maximum temperature.

We investigated the influence of tree heights on roost microclimate using the LiDAR point cloud data. We performed a generalised linear model with Lasso penalty on the normalised data. We performed a multivariate model including the heights collected (1, 2, 5, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25, 30, 35m) as predictors and microclimate variables as response. The percentage of detected vegetation using LiDAR point cloud data significantly affected only the maximum temperature. We found that roosts with a higher proportion of vegetation above 14 meters reduced temperatures by 23% (OR = 0.77, Lasso %deviance = 62.6, MSE = 1.19), suggesting that tall trees would help reduce the heat to reach lower areas of the roost. Roosts with higher point cloud density above 10 meters are also associated with a slight decrease in mean temperature, with each unit increase linked to an approximate 1% reduction (OR = 0.99) (Lasso %deviance = 29.68, MSE = 1.19).

Additionally, roosts with higher maximum point cloud data show a strong association with increased mean temperature, with each unit increasing altitude leading to an estimated 74% rise in mean temperature (OR = 1.74). Higher point cloud density above 10 meters was associated with a decrease in maximum humidity, with each unit increase linked to a 22% reduction (OR = 0.78). Similarly, point cloud density above 20 meters shows a minor association with lower maximum humidity, corresponding to a 2% decrease per unit increase (OR = 0.98). In contrast, higher average height has a positive association with maximum humidity, where each unit increase correlates with a 58% reduction in maximum humidity (OR = 0.42).

3.5 Discussion

In the urban roosts of Cairns, far north Queensland, I examined the relationship between vegetation structure, microclimate, and roost occupancy over two summer periods. The results showed a significant association between occupancy and some of these variables. Occupied roosts exhibited greater vertical complexity and a higher abundance of intermediate-height trees (11–15 m), with a 1.45 times higher likelihood of occupancy in roosts exceeding 11 meters. Canopy cover was high across all roosts but slightly higher in occupied sites (96.9%) compared to unoccupied sites (93.4%). However, logistic regression found no significant relationship between canopy cover and occupancy, suggesting that overall canopy density alone does not drive occupancy

patterns. Occupied roosts contained more herbaceous plants and woody vegetation, whereas unoccupied roosts had greater proportions of bare soil and grass.

The association between canopy height and flying-fox occupancy has been documented in other tropical flying-fox species. For example, *Pteropus giganteus* from the Indian subcontinent has been associated with roosting in tall trees with large canopy structures (Hahn et al. 2014). Similar to our findings, roosts of this species showed a higher density of trees in the mid-canopy layer (6–15 m) and a lower density in the upper canopy (Majumdar et al. 2016). The preference for trees in this height range has been hypothesised to accommodate the large colony sizes of this species (Hahn et al. 2014). Similarly, its conspecific, *Pteropus medius*, is associated with taller trees that provide extensive canopy cover and large, well-spaced crowns, as well as a greater diameter at breast height (Madala et al. 2022).

Vegetation structure significantly influenced microclimate conditions within urban roosts. This study partially supported the hypothesis that canopy cover influences microclimate through shading and light penetration (Gao et al. 2021). While canopy cover estimates were slightly higher in occupied roosts, the differences were not statistically significant. However, the LiDAR data suggest that intermediate canopy heights (10–14 m) measured at a larger scale were important in moderating temperature and humidity (Zhang et al. 2013; Gao et al. 2021; Smith-Tripp et al. 2022).

Roosts with greater point cloud density above 14 m were associated with a 23% reduction in maximum temperature, emphasising the role of tall trees in providing thermal buffering (Gao et al. 2021). It is also important to notice that the effects of vegetation structure are more noticeable during the hottest hours of the day, between 1400 and 1500h (Zhang et al. 2013). Although measurements were collected under the canopy and not directly beneath dense bat aggregations, we acknowledge that the presence of roosting animals may have contributed marginally to localised microclimate readings, and future studies could explore this potential effect more explicitly.

Structurally diverse vegetation reduces temperature through layers of stratification, where each layer has a cooling capacity, acting in the canopy and also in the littering layer, through soil cooling (Terschanski et al. 2024). Moreover, greater average tree height was associated with increased maximum humidity, suggesting that layered vegetation may retain moisture (Ismaeel et al. 2024; Terschanski et al. 2024).

Mid-story and ground vegetation offers protection from predators and human disturbances, which is relevant for the safety of roosting colonies (Hall & Richards 2000). This highlights the complex interactions between vegetation structure and microclimate regulation and underscores the ecological importance of preserving diverse vertical strata to enhance roost suitability.

Ground cover composition significantly differed between occupied and unoccupied roosts. Roost occupancy was associated with higher herbaceous cover and woody plants. Conversely, higher grass cover was negatively associated with occupancy; grass has high light requirements compared to herbs (Warneke et al. 2023), which is likely due to more sunlight reaching the forest floor through less dense forest cover (Randle et al. 2018). Therefore, the differences between occupied and unoccupied camps can be indirectly linked to canopy characteristics. However, the increased herbaceous layer in occupied camps is more likely a 33result of nutrient and seed input from bat guano. Rich in nitrogen, bat guano enhances soil fertility, promoting seed colonisation and potentially influencing the success of both native and invasive plant species (Dimande et al. 2023; Huang et al. 2023; Korn et al. 2023).

The positive association between medium-sized stem density and higher maximum temperatures can be explained ecologically by vegetation structure changes affecting microclimate. Medium-sized stems, often found in regenerating or transitional environments, provide less canopy cover than mature trees (Jiao et al. 2017), allowing more sunlight to reach the ground. In our study, most roosts are not continuous vegetation but parks and private areas. Additionally, their lower leaf area and reduced evapotranspiration compared to larger trees limit natural cooling, while the dense understory structure can trap heat and reduce air circulation. Combined with lower albedo from dense vegetation surfaces that absorb more solar radiation, these factors contribute to warmer microclimates in areas with high medium-sized stem density (Santos et al. 2024).

There were some important limitations to the broader interpretations of this study's results. First, the study only explored 20 urban camps in Far North Queensland, tropical Australia. While these camps varied in size and vegetation composition, reducing the likelihood of discovering definitive explanations for occupancy choices. Second, with the loss of canopy iButtons using a handheld meteorological station at only 1.4m high, the microclimate was not sampled at roosting height and may have underestimated the

climate bats were experiencing. In the future, a deeper study of the effects of microclimate on roost occupancy should use several data loggers per camp for a long period.

3.5.1 Implications for Roost Suitability

The results collectively suggest the importance of vertical complexity in vegetation structure for roost suitability. Intermediate-height trees (11–15 m) and a dense sub-canopy appear to provide optimal conditions for flying-foxes, offering thermal comfort, structural diversity and refugia during extreme temperature events. The reduced likelihood of occupancy in sites with greater tree heights or lower intermediate canopy density suggests that vertical stratification is associated with habitat preference. These findings are consistent with the NMDS ordination analysis, which identified tree height above 10 m and herbaceous cover as drivers of spatial variation in roost occupancy.

These findings have important implications for the conservation of spectacled flying-foxes in urban environments. Managing roost habitats to maintain intermediate canopy heights and enhance structural diversity could improve habitat suitability and support species conservation. Additionally, preserving vegetation layers that buffer microclimatic extremes may become increasingly important under climate change, as rising temperatures and altered humidity patterns could impact roost conditions.

Future research should investigate the long-term effects of vegetation management practices on roost occupancy and explore the interactions between microclimatic variables and other ecological factors, such as food availability and predation risk.

CHAPTER 4

The effects of roost vegetation and microclimate on estimates of bat temperatures

---

Abstract

Monitoring wildlife during extreme weather events is critical for understanding and mitigating the impacts of climate change on biodiversity. In this study, we demonstrate the value of infrared thermography for assessing relative bat temperature and evaluating the influence of microclimate and vegetation structure on thermal readings. During the 2018 heatwave in Cairns, approximately 23,000 Spectacled flying-foxes died from heat stress over three consecutive days. Interestingly, while some roosts were severely impacted, others remained unaffected. I hypothesise that vegetation structure and microclimate differences influenced bat survival across roost sites. I used LiDAR and fieldwork assessment to identify structural differences between roosts and infrared thermography to assess how these factors affect bat surface temperature. Our findings suggest that higher air temperature, open vegetation with increased solar exposure, and greater proportions of small saplings contribute to elevated thermal readings, particularly in camps with low canopy height and high herbaceous cover. In contrast, higher relative humidity, tall trees (above 20m), dense canopy cover, and specific ground cover like herbs, bare soil, and leaf litter mitigate thermal stress by creating cooler, more stable microclimates. Intermediate-to-tall trees (12–15m) further buffer against extreme temperatures, highlighting the critical role of vegetation structure and ground composition in shaping bat habitat microclimates. Targeted reforestation in areas prone to extreme heat, focusing on vegetation that promotes shading and moisture retention, can enhance habitat resilience and reduce the risk of heat-related mortality in bat populations.

4.2 Introduction

Monitoring wildlife during extreme weather events is crucial for understanding and mitigating the impacts of climate change on biodiversity (Ummenhofer & Meehl 2017). The approach can be indirect, where you forecast the future effects of weather on wildlife based on previous events (Ratnayake et al. 2019), or direct, where you can instantly measure the effects of the weather conditions on wildlife (Soravia et al. 2021). One direct approach is to evaluate the animal's body temperature on site. Among wildlife, homeotherms—organisms that maintain a stable internal body temperature—are particularly vulnerable to extreme weather as they have a narrow body temperature threshold, and extreme variations can be lethal (Mota-Rojas et al. 2021).

Measuring the impact of several environmental characteristics on the range variation of body temperature can teach us the determining variables involved and help us to develop mechanisms to avoid deadly consequences. The standard devices for monitoring wildlife temperature are either internal or contact types, such as rectal thermometers and thermocouples. The main disadvantage of these devices is the need to restrain the animal, involving mechanical and chemical methods (Jerem et al. 2015), resulting in animal distress. In this context, research to establish infrared thermography as a non-invasive alternative to access animal temperature, has evolved (Tattersall 2016; Wang et al. 2021). The farming industry uses it to monitor animal wellbeing (Brcko et al. 2020), assess infections (Bleul et al. 2021; Machado et al. 2021; Whittaker et al. 2023), and monitor the body temperature during extreme weather conditions (Čukić et al. 2023; Ghezzi et al. 2024). Additionally, to the farming industry, infrared thermography is useful in wildlife assessment and monitoring of ectotherms, such as molluscs (Seuront et al. 2018) and reptiles; and endotherms, such as birds (McCafferty et al. 2011), and mammals, including bats (Lancaster et al. 1997).

Modern infrared thermography operates on the principle that all objects emit infrared radiation proportional to their temperature, as described by the Stefan-Boltzmann law (Balaras & Argiriou 2002). Infrared thermographic devices capture this emitted radiation, typically within the 8–14μm wavelength range, and convert it into thermal images or temperature readings (Usamentiaga et al. 2014). By detecting the intensity of the emitted infrared radiation, these devices accurately measure the surface temperature

of objects without direct contact (Usamentiaga et al., 2014). The resulting data is often a colour or grayscale image, where different shades correspond tosarying temperatures (Fischer Verlag et al. 1998).

There are specific anatomical regions of the animal's body characterised by a complex vascular network and minimal or absent hair coverage, which optimise heat exchange with the environment. These specialised anatomical structures, known as thermal windows, also act in thermoregulation by facilitating efficient heat dissipation (Andrade 2015; Mota-Rojas et al. 2021). A comprehensive review by Mota-Rojas et al. (2022) examined various species and outlined the essential criteria for effectively applying infrared thermography (IRT) in monitoring these regions. Bats seemed to rely greatly on their limbs for thermal regulation. If the ambient temperature is below body temperature, the difference between rectal and skin temperature in bats can be as great as 12 °C (Rummel et al. 2019). However, as soon as the ambient temperature is above body temperature, evaporative cooling becomes the only way of dissipating heat (Rummel et al. 2019; Welman et al. 2017). The thermoregulatory capacity varies between species according to their roost type, where species roosting in warm spaces, such as tree hollows, have a higher evaporative cooling capacity compared to species roosting in more thermally stable and cooler roosts, such as caves (Czenze et al. 2020; de Mel et al. 2024).

Spectacled flying-foxes (Pteropus conspicillatus), for instance, typically roost in the canopy of dense vegetation in tropical regions (Pierson & Rainey W.E., 1992)> This typicallys exposes them to high ambient temperatures, direct solar radiation and in general, low thermal stability; when combined with their restricted distribution and the increasing frequency of extreme weather events in historically stable tropical zones, this significantly heightens their vulnerability to climate change impacts (Hall & Richards 2000).

Listed as endangered since 2013 (Roberts et al. 2020), the Spectacled flying-fox faces significant conservation threats, including extreme heat events, habitat loss, and declining food resources (Welbergen 2012; Tait et al. 2014; Lopes et al. 2024). Urban roost dispersal is driven by the community and political pressures (Roberts et al. 2021) further disrupts their habitats, while diseases such as cleft palate (McMichael et al. 2023) and tick paralysis (Buettner et al. 2013) overly affect juveniles and mothers. Furthermore, negative public perceptions, amplified by fears of coronavirus transmission (Lu et al. 2021), add complexity to conservation efforts.

These compounded threats are exacerbated by the physiological vulnerabilities and environmental constraints identified in climate vulnerability assessments. For example, the 2018 Cairns heatwave, which saw temperatures soar 10 to 12°C above the November average with unusually low humidity, killed 23,000 individuals (Bureau of Meteorology 2018; Lopes et al. 2024). In an already declining population, the dispersal of the main roost in the city centre in 2020 posed a new challenge to the studied population (Preece 2024). Under the current traits used to assess vulnerability to climate change, slow reproductive rates, limited distribution, potentially fragile habitats, and narrow physiological tolerances are key factors (Pacifici et al. 2015) pressuring this endangered species, reinforcing the need for a deep knowledge of its habitat requirements and how they influence its ability to survive increasingly frequent extreme events.

Ratnayake et al. (2019) developed a forecaster aiming for a predictive model for flying-fox mortality during extreme heat events. The methodology involved analysing gridded hourly air temperature forecasts from the Australian Bureau of Meteorology's ACCESS-R model and evaluating these predictions against in situ air temperature measurements and interpolated weather station data, focusing on a threshold of 42.0°C for flying-fox mortality. The outcome demonstrated that the 24- and 48-hour forecasts accurately predicted 77% and 73% of die-offs, respectively, indicating that the forecaster could reliably predict flying-fox mortality at a landscape scale, providing a valuable tool for biodiversity conservation in the face of climate change.

Until this moment, the focus on predicting flying-fox mortality has been driven by the analysis of climatic variables. However, the complex interaction between the habitat characteristics and their impact on bat temperature has not been investigated. Hence, I consider the main gaps in our understanding of how Spectacled flying-foxes respond to extreme temperatures as follows.

First, the limited research on spectacled flying-fox roost preferences stems from their restricted geographic range and the scarcity of species-specific studies. As a result, current knowledge often relies on generalisations from other Pteropus species, which may not accurately capture the ecological requirements of this endangered bat. Second, monitoring wildlife temperature poses methodological challenges, prompting interest in non-invasive techniques.

Previous analysis of climate trends in the urban areas where Spectacled flying-foxes form maternity camps has revealed a significant rise in the number of hot days exceeding 35°C (Lopes et al., 2024). This trend aligns with regional and global projections, indicating that heatwaves will become increasingly frequent and severe (Steffen et al., 2014).

In light of the current situation faced by spectacled flying foxes, this study was designed to address the following research questions: (1) Is infrared thermography a reliable tool for detecting bat surface temperature across different environments? (2) Do microclimatic risks vary between roost sites? (3) How do vegetation structure and microclimate influence bat surface temperature?

To address these questions, I examined the influence of roost characteristics on bat surface temperature and tested the use of a handheld infrared thermal camera as a non-invasive method for estimating temperature in free-ranging bats. The study focused on urban roosts in Cairns, where I documented variation in habitat structure and its effect on microclimate conditions. I hypothesised that both vegetation structure and microclimate would directly influence bat surface temperature. Ultimately, this research aims to establish a practical and non-intrusive tool for monitoring thermal stress in flying-foxes and to inform reforestation and habitat management efforts aimed at enhancing roost suitability in a warming climate.

4.3 Methods

This study was undertaken using field and remote sensing data in 20 urban camps across the Cairns, for six months, divided into two summers, 2021 and 2022. The camps were selected based on the availability of existing population data monitored by Cairns Regional Council (2024). Data collection was conducted on clear days, as humidity and cloud cover can influence the accuracy of the chosen methodology. The following section outlines the sampling procedures and methods employed throughout the study period.

4.3.1 Field collection

I visited 20 bat camps over two summers (Nov/2021-Jan/2022 and Dec/2022-Feb/2023). To standardise the image collection, 50 m transects were set in each camp, capturing thermal images every 5m.

4.3.2 Microclimate

The microclimate data were collected at roosts on non-rainy days between 11 am and 2 pm at 1.4 m above the ground for two summers, avoiding direct sun exposure at each of the 20 bat roosts over 10 minutes. A handheld meteorological station (Kestrel 3550ag®; Kestrel Weather Meters, 2020) was used to register air temperature and relative humidity. The accuracy for ambient temperature (Ta) is 0.5 °C, and the resolution is 0.1 °C, while relative humidity (Rh) is 3% and 0.1%, respectively. I sampled each roost 4-6 times each season.

4.3.3 Thermal camera

The thermal infrared (TIR) camera (384iM Thermal Imaging Camera, Turtle Tough) has an uncooled micro-bolometer sensor and converts infrared radiation readings into temperatures within the –20 to 150 °C range. For clarity throughout this chapter, I use the term *surface temperature* to refer to the data collected with the thermal camera, as it represents the temperature measured on the surface of the animal (Usamentiaga et al. 2014).

Thermal measurements were obtained from the whole bat, and the warmest areas were used as measurement targets. We analysed TIR images, assuming a uniform emissivity value of 0.98 across all surfaces (Zheng et al. 2022). This constant was adopted when examining variations in spatial thermal heterogeneity with the TIR. I estimated differences in relative temperatures across images of the same surface captured from various distances. For this purpose, we are confident that potential emissivity variations within the scenes did not cause the bias we observed. The TIR camera has a 384x288 pixels micro-bolometer focal plane array (384iM Thermal Imaging Camera, Turtle Tough (© 2024 Turtle Tough Pty Ltd. All 2024). The camera calibration was performed as described in Appendix B.

Over two summers, I collected thermal images of bats in Cairns' urban camps. The thermal images were collected from different angles due to the difference in the terrain and our ability to achieve a clear picture of the bats (without the interposition of leaves or branches), but over the same hours of the day, between 11 am and 2 pm. Each camp was visited four to six times, and the number of images captured varied according to the number of individuals and their positions in the trees.

Lily Creek has been excluded from the thermal analysis due to its insufficient sample size, with only three recorded data points. I used weighted analysis for the other camps to count for the different sample sizes between camps.

However, Lily Creek was retained for the vegetation structure analysis, as the sampling effort for this aspect was consistent across all camps. The study ensures that vegetation metrics remain comprehensive while refining the thermal dataset to include only camps with adequate data representation. This approach maintains the integrity of both analyses, allowing for robust conclusions on the role of vegetation in shaping microclimate and bat temperature regulation.

4.3.3.1 Thermal reading (capture/analysis)

Sampling was conducted exclusively on clear days due to the thermal camera's sensitivity to high humidity. To confirm the reliability of thermal imaging in distinguishing bat surface temperatures from the surrounding environment, the association between the target and its background was tested. This validation step ensured the robustness of the thermal data for accurately assessing bat surface temperatures.

At 5-metre intervals along each transect, the thermal camera was directed toward the nearest roosting tree, ensuring that direct sunlight did not affect the device. Sampling was standardised between 11:00 a.m. and 2:00 p.m. to minimise variation in solar incidence and radiation reflection. Effort was also adjusted based on animal visibility, as accurate surface temperature readings require a clear line of sight between the camera and the bat, unobstructed by foliage. Before image capture, camera settings were calibrated to match local relative humidity, a necessary input for enhancing the accuracy of thermal measurements.

The same number of bat and vegetation background data points were extracted using the software Infrared Report Express V2.1.5.0 (Turtle Tough, n.d.)

4.3.4 Vegetation structure: plot-based assessment

Vegetation structure was assessed using 25 m × 10 m transects (5 m on each side). Camp size determined transect number: one transect for camps <20 ha and two for camps >20 ha, with data averaged when applicable.

Stems were counted every 5 m within a 5 m band from the transect centre, and DBH was recorded, classified into four size classes: Small (<2.5 cm), Medium (2.5–5 cm), Large Sapling (5–10 cm), and Tree (>10 cm). To minimise disturbance, transects in occupied camps were placed away from roosting trees. Canopy cover was measured every 5 m using a spherical densiometer, calculating the percentage of sky view obscured. Ground cover was estimated using a 1 m² quadrat divided into four 0.25 m² sections, placed every 5 m along the transect. Cover types were visually estimated as percentages across five categories: bare soil, leaf litter, grass, herbs, and woody plants.

4.3.5 Vegetation structure: LiDAR scan

Aerial LiDAR technology was utilised to assess the vegetation structure of entire roosts in the greater Cairns area. This methodology was selected for its high accuracy, fine resolution, and ability to capture detailed tree height measurements (Gyawali et al. 2022).

The LiDAR data, sourced from the Elvis - Elevation and Depth - Foundation Spatial Data open spatial repository between 2009 and 2011, was processed using R version 4.2.2 (R Core Team 2023) with packages such as *sf (Pebesma, 2018), tidyverse* (Wickham et al. 2019), *lidR* (Roussel et al. 2020), and *terra* (Hijmans 2023). The procedure involved loading the LiDAR files as a LAScatalog and applying a 200m square buffer around the centre of each flying-fox camp using the sf package. Each buffer clipped the LAScatalog to generate a 200m x 200m *las* file per camp.

The *las* file was normalised for each camp by removing the terrain using a Triangulated Irregular Network (TIN) with the *lidR* (Roussel et al., 2020)package. Building points (*las* class 6) were rasterised to a 1 m resolution and then converted to polygons with the *terra (Hijmans, 2023)* package, removing all points within these polygons from the *las* file. The remaining data was then height smoothed using a 4 m square window and a two-sigma Gaussian method to eliminate outlying points.

After smoothing and normalising, points classified as unassigned, ground, low point, model key/reserved, rail, road surface, and overlap/reserved were filtered out,

leaving only vegetation points. The filtered *last* file was analysed to calculate standard metrics using *lidR's 'pixel_metrics'(Roussel et al., 2020)* function with a 5 m resolution, representing the approximate diameter of a tree crown. Various height intervals from 0 to 45 meters were used.

Finally, the *terra (Roussel et al., 2020)* package converted the processed data into a raster stack and spatial points. Then, it was exported as a shapefile and CSV file for further analysis.

4.3.6 Data analysis

I used R software [version 4.4.0 (R Core Team 2023)] for all statistical data analysis.

To perform the analysis, we scaled the numerical continuous data using the *scale* function in R and the compositional data was normalised using a centred-log ratio in the package *compositions* (van den Boogaart & Tolosana-Delgado 2008).

To address the research objectives, we conducted the following analyses to investigate the influence of microclimate and vegetation structure on bat thermal readings.

4.3.6.1 Thermal reading validation

We used a non-parametric test to verify the difference between the bats' thermal readings and the background. We expected the bats to appear hotter, as endotherms would thermoregulate to avoid fluctuations despite the changes in the environment around them, within a limit.

To analyse the temperature differences between bats and the background across various camps, we employed Wilcoxon Signed-Rank Tests for each camp. We employed this non-parametric test to compare thermal readings between bats and their background vegetation across different camps. This method was selected to account for variability and non-normality in the data, ensuring robust statistical comparisons.

I also performed controlled and field validation tests described in the supplementary material (Appendix B).

4.3.6.2 Extreme thermal risk

To assess the frequency and probability of bat surface temperatures exceeding 42°C, we inferred the frequency of the thermal readings above this threshold. This number is significant because it is a critical temperature for flying-foxes, beyond which they are at high risk of thermal stress or mortality (Bartholomew et al. 1964; Welbergen et al. 2008).

The goal is to identify camps where bats are more vulnerable to extreme thermal conditions and further understand the microclimatic factors contributing to this risk.

4.3.6.3 Environmental and vegetation influence on bat surface temperature

To investigate the influence of microclimatic factors on bat surface temperatures as measured by infrared thermography, we focused on key environmental variables such as humidity, ambient temperature, wind speed, and heat index. This helps us to understand how environmental conditions buffer or exacerbate thermal stress in bats.

To investigate this, I used a correlation matrix to examine pairwise relationships between microclimatic variables (e.g., humidity, wind speed) and bat surface temperature. Statistical significance was indicated for correlations with $|r| > 0.5$ and $p < 0.05$ (*), focusing on associations that could strongly influence bat temperatures.

I conducted an ordination analysis to explore patterns in bat thermal readings across camps. This method grouped camps based on their microclimate characteristics and thermal image data, providing insights into how environmental conditions shaped thermal variability among camps.

To further understand the influence of environmental variables, such as ambient temperature and relative humidity, on bat surface temperatures, we used a generalised linear model (GLM). This model quantified the contribution of these variables to observed thermal readings, aligning with our objective to identify key microclimatic factors influencing bat thermoregulation.

4.4 Results

I sampled bat surface temperature over six months divided between the summers of 2021/22 and 2022/23. In each roost, the sample effort was correlated to the sample size and ability to collect the thermal image.

4.4.1 Thermal readings and risk of extreme temperatures

4.4.1.1 Thermal reading validation

Across 10 urban camps, bat surface temperature estimates were obtained from 4,709 individuals. The thermal camera recorded a mean bat surface temperature of 36.4°C (±3.9 SD), with a maximum of 44.7°C. In all sampled sites, flying-foxes exhibited significantly higher surface temperatures than the surrounding vegetation (Table 4.1; Figure 4.1).

Table 4.1. Mean temperatures of bat and vegetation surfaces were compared with Wilcoxon signed-rank tests at 11 urban roost sites in Cairns, Australia.

Roost	DF	P-Value	x̄ Bat (°C)	x̄ Veg (°C)
Bulimba	122	<0.01	37.14 ± 5.6	34.41 ± 3.23
Cairns Villas	1111	<0.01	35.56 ± 3.58	33.86 ± 3.56
Chay Road	39	<0.01	40.17 ± 1.23	37.41 ± 1.5
Dunn St	121	<0.01	40.05 ± 0.95	37.72 ± 2.72
Farmer St	294	<0.01	36.26 ± 5.17	33.84 ± 5.36
Gordonvale	1617	<0.01	37.63 ± 5.05	34.59 ± 5.18
Harwood Cl	61	<0.01	36.75 ± 5.27	34.85 ± 5.52
Henley St	878	<0.01	37.4 ± 3.11	35.64 ± 3.87
Loridan Dr	322	<0.01	40.51 ± 2.08	38.61 ± 2.41
Waratah	179	<0.01	30.62 ± 2.04	29.39 ± 1.59

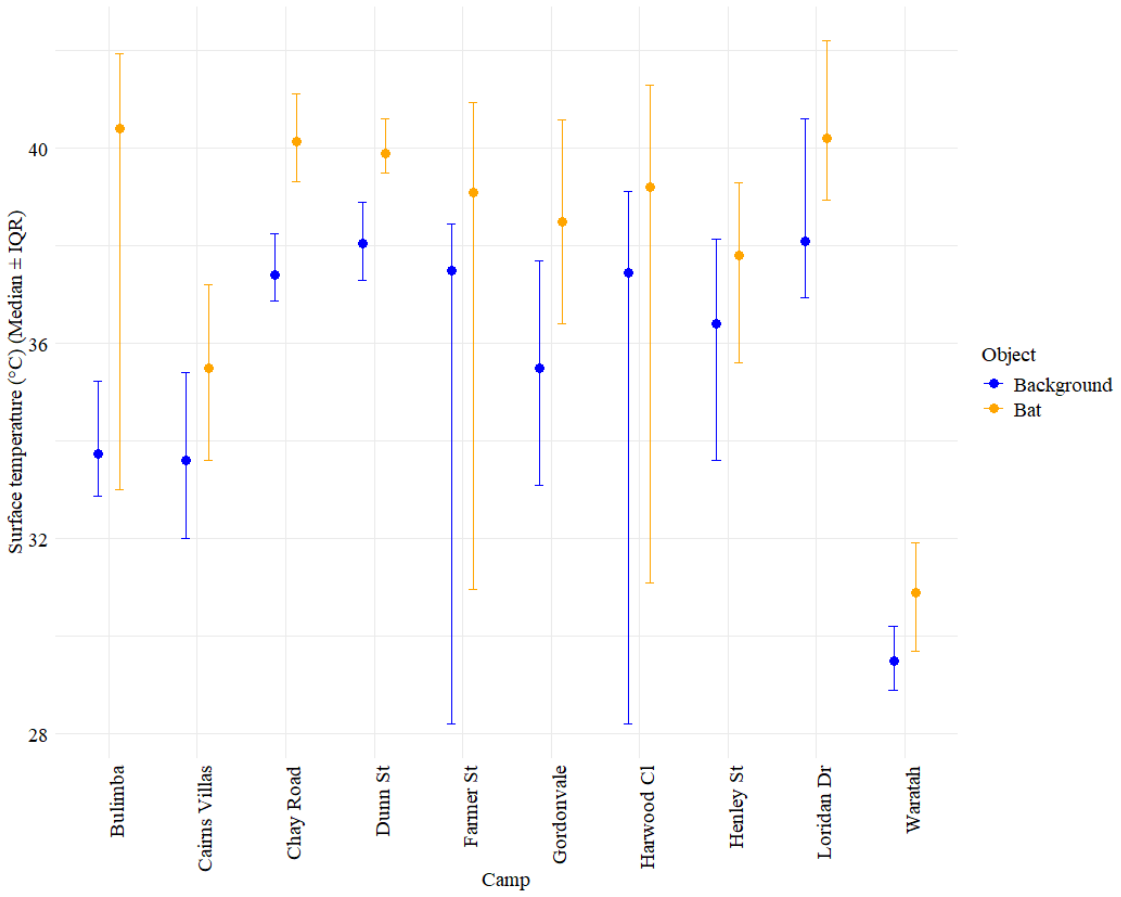


Figure 4.1. The interquartile range of bat and background temperature per camp. The blue lines show the interquartile range of bat temperature, and the yellow line shows the background. The dots represent the median, and the red asterisk shows the significance.

I analysed the influence of environmental variables on the relative difference between bat and background surface temperatures using linear, mixed and generalised models (Table 4.2). The models were designed to assess the relationship between these variables, with roost included as a random factor. Air temperature and relative humidity were treated as fixed factors, while the response variable was the temperature difference between the bat's surface and the background vegetation.

Table 4.2. Results of linear mixed and generalised models fitted to the difference between bat surface temperature and background ranked according to the Akaike Information Criterion (AIC).

Model	Formula	AIC	Random Effect (Camp)	Interaction Included	Air temperature	Relative humidity	Interaction	Random Effect SD	Residual SD
LMM (Model 2)	diff ~ tempc * relhum + (1 | camp)	13090	Yes	Yes	p < 0.001	p < 0.001	p < 0.001	0.3077	0.964
LMM (Model 4)	diff ~ tempc + relhum + (1 | camp)	13111	Yes	No	p < 0.001	p < 0.001		0.2966	0.966
GLM (Model 3)	diff ~ tempc + relhum	13393	No	No					1.00041
GLM (Model 1)	diff ~ tempc * relhum	13394	No	Yes					1.0004

Diff – difference between bat temperature and background vegetation

Tempc – ambient temperature (°C)

Relhum – Relative humidity

Camp – Roost site

Model 2 was the best-supported model (AIC = 13089.8), indicating that bat thermal balance is not solely dictated by air temperature but is strongly modulated by humidity levels. Higher air temperatures were associated with lower temperature differences between bats and their surroundings ($\beta = -0.196$, $p < 0.001$). Similarly, increased humidity reduced this difference more strongly ($\beta = -0.301$, $p < 0.001$). The interaction term ($\beta = 0.085$, $p < 0.001$) further suggests that under humid conditions, the negative effect of temperature on this thermal gradient is less pronounced. These results highlight the role of humidity in mitigating heat stress in roosting bats.

The random effect of camp ($\sigma^2 = 0.095$) suggests that roosts differ slightly in baseline temperature conditions, likely reflecting variation in vegetation structure, canopy cover, and microclimate buffering capacity. Despite this, the model had strong explanatory power (adjusted $R^2 = 0.93$, deviance explained = 95.1%), indicating that ambient temperature and humidity are key drivers of bat surface temperature relative to their environment. These findings emphasize the importance of roost-site characteristics in shaping bat thermoregulatory responses, reinforcing the role of vegetation complexity in reducing heat stress and supporting the use of thermal imaging as a tool for monitoring bat thermal ecology in changing climates.

The inclusion of camp as a random effect accounts for differences among roost sites, reflecting the role of localised environmental factors such as vegetation cover, wind exposure, and microclimatic variation. The random effect standard deviation (0.31) suggests that while site-level differences contribute to thermoregulatory variation, most of the observed differences occur within camps.

4.4.1.2 Extreme thermal risk

I investigated the extreme thermal risk of bat camps by quantifying the frequency of temperatures over 42°C during the two summer periods of this study. The proportion of observations in each camp where bat surface temperature is > 42°C was calculated by dividing the count of exceedances by the total observations for each camp and multiplying by 100. (Fig. 4). The ridgeline figure illustrates that there are a few camps, such as Waratah, that maintained cooler temperatures during the two summers of this study (Fig. 4A). Furthermore, in other camps, such as Cairns Villas and Gordonvale, the curve is overlong and low, showing higher variability in the bat surface temperature. Higher

variation in bat surface temperature can suggest environmental conditions that do not buffer variations in the ambient temperature. (Figure 4.2).

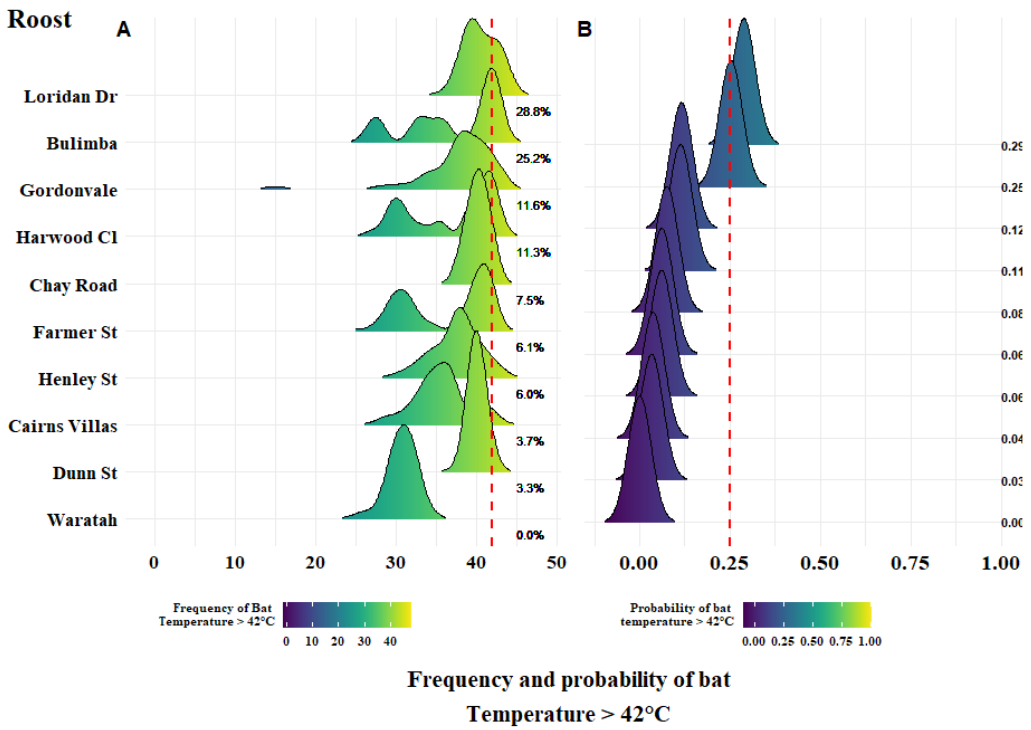


Figure 4.2 Comparison of the frequency (A) and probability (B) of bat temperatures exceeding 42°C across different campsites. Panel (A) displays the distribution of bat temperatures for each campsite, with the percentages representing the proportion of observations above 42°C. Panel (B) shows the modelled probabilities of bat temperatures exceeding 42°C based on logistic regression, with the red dashed line indicating that two (Loridan Dr and Bulimba) camps have a 25% chance of having temperatures above the threshold.

The linear mixed-effect model (bat_temp ~ (1 | camp)) was used to assess the extent to which bat surface temperatures vary across camps while accounting for within-group dependency. The model revealed that camp explained a small proportion of the total variance in bat temperature, with the standard deviation of the random intercept being $\sigma^2 = 3.397$. The within-camp residual variance was higher ($\sigma^2 = 16.794$), suggesting that most of the variation in bat temperatures occurs within rather than between camps.

This finding indicates that camp-level differences alone are not the primary drivers of temperature variability, and additional factors such as microclimate conditions or individual bat behaviour may be more influential.

To further explore camp-level differences, we bootstrapped the random intercepts to obtain 95% confidence intervals (CIs) for each camp's deviation from the overall mean. The results showed that Loridan Dr (95% CI: 0.1479, 0.2070) and Bulimba (95% CI: 0.0632, 0.1492) had significantly higher bat surface temperatures than the overall mean. Conversely, Waratah (95% CI: -0.1206, -0.0480) exhibited significantly lower temperatures than the overall average, while Cairns Villas (95% CI: -0.0811, -0.0417) and Dunn St (95% CI: -0.0978, -0.0130) were also cooler than average. The remaining camps had confidence intervals overlapping zero, suggesting no significant deviation from the overall mean.

Despite the observed camp-level differences, the relatively small variance in the random effect suggests that camp alone does not fully explain the observed variation in bat temperatures. Overall, while roost structures are associated with changes in bat surface temperatures, their effect appears secondary to within-site variation, highlighting the need for further investigation into the microclimatic and behavioural factors influencing thermal exposure in roosting bats.

4.4.2 Environmental and vegetation influence on bat surface temperature

Non-metric multidimensional scaling (NMDS) was used to visualise differences in environmental variables across roost camps. Despite not forming evident clusters, the NMDS ordination (Figure 4.3) revealed distinct patterns, indicating variation in environmental composition among camps. To statistically assess these differences, a permutational multivariate analysis of variance (PERMANOVA) was conducted using Euclidean distance (adonis test, 999 permutations). The PERMANOVA analysis confirmed significant differences in environmental variables between roost camps (R^2 = 0.50, p = 0.001), indicating that environmental conditions vary across sites. This suggests that camp-specific factors, such as temperature, humidity, and vegetation structure, may shape bat microhabitats. Environmental vectors fitted onto the NMDS plot (envfit()) identified key factors driving this variation, including temperature, humidity, vegetation height, and ground cover**.**

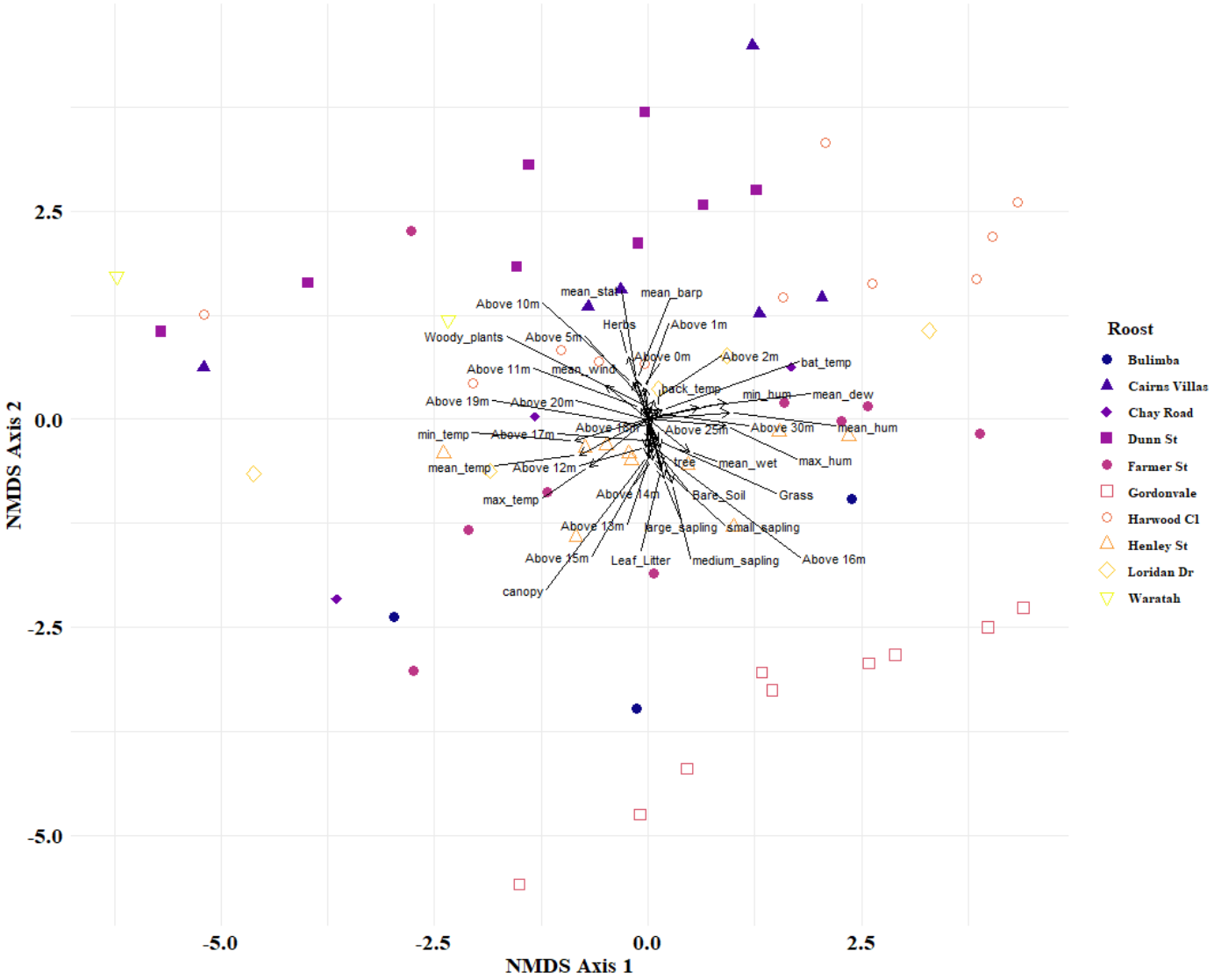

NMDS Axis 2
2.5
0.0
-2.5
-5.0
NMDS Axis 1
-5.0
-2.5
0.0
2.5
mean_stalk
mean_barp
Above 10m
Herbs
Above 1m
Woody_plants
Above 5m
Above 0m
Above 2m
bat_temp
Above 11m
mean_wind
back_temp
min_hum
mean_dew
Above 19m
Above 20m
Above 15m
Above 25m
Above 30m
mean_hum
min_temp
Above 17m
tree
mean_wet
max_hum
mean_temp
Above 12m
Above 14m
Bare_Soil
Grass
max_temp
Above 13m
large_sapling
small_sapling
Above 18m
Leaf_Litter
medium_sapling
Above 16m
canopy
Roost
Bulimba
Cairns Villas
Chay Road
Dunn St
Farmer St
Gordonvale
Harwood Cl
Henley St
Loridan Dr
Waratah

Figure 4.3. Non-metric multidimensional scaling (NMDS) ordination plot showing the variation in environmental conditions across roost camps. Each point represents a roost site, coloured and shaped according to its respective camp. The overlaid environmental vectors indicate significant factors ($p < 0.05$) influencing the ordination, with arrow lengths representing the strength of correlation. NMDS Axis 1 is primarily driven by humidity (mean, max, min) and temperature (mean, max, min)**,** while NMDS Axis 2 is associated with vegetation structure variables, including medium saplings, herbs, and canopy cover. Bat temperature does not significantly correlate with either NMDS axis ($p > 0.05$), suggesting that it is influenced by additional factors not captured by the ordination. The PERMANOVA analysis confirmed that environmental conditions significantly differ among camps **(**$R^2 = 0.50$, $p = 0.001$**),** indicating variation in habitat characteristics across sites.

To investigate how the roosts would group across a gradient of environmental variables, I did a constrained visualisation using the scores from the NMDS analysis and bat temperature as a gradient (Figure 4.4).

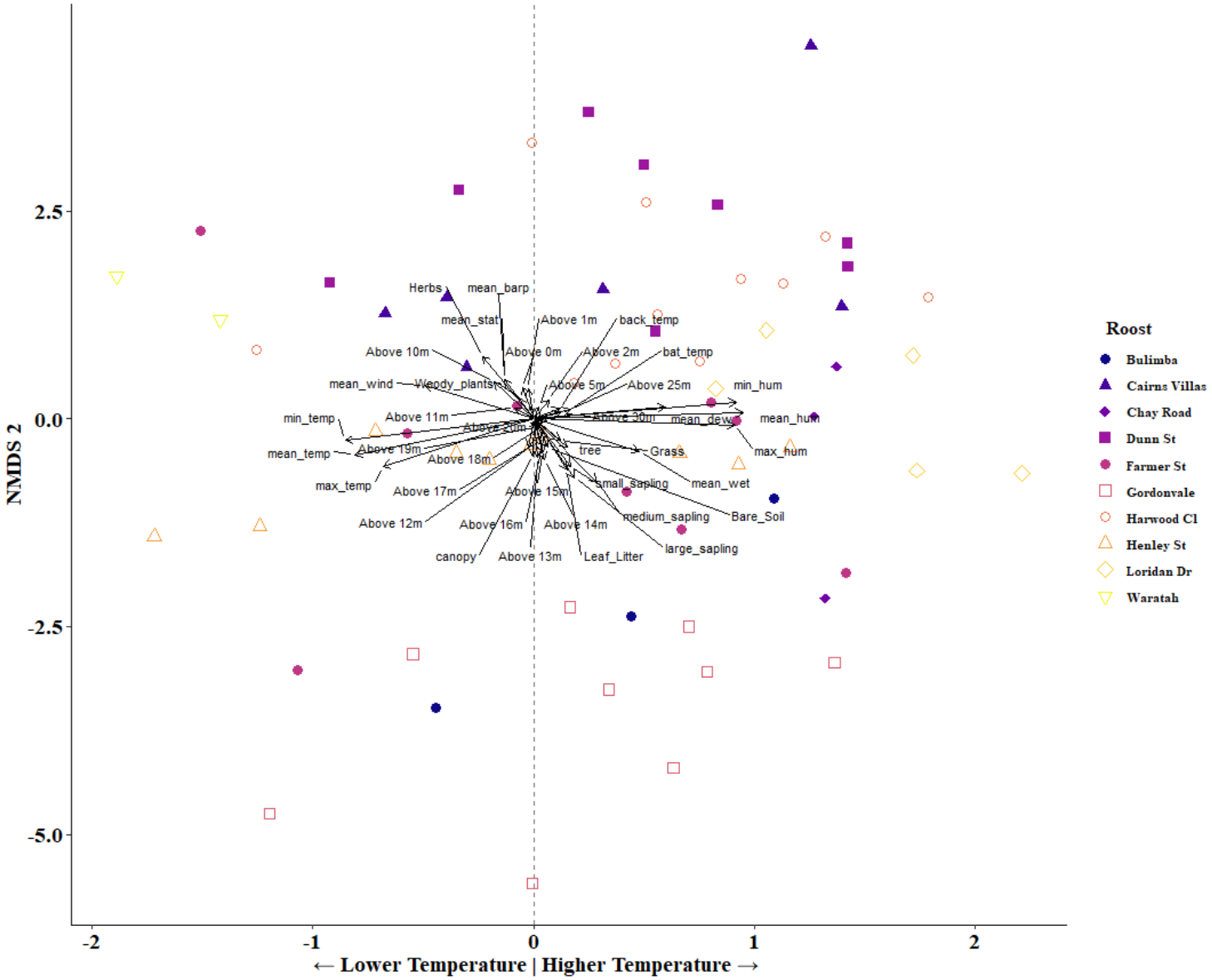

NMDS 2
2.5
0.0
-2.5
-5.0
-2
-1
0
1
2
← Lower Temperature | Higher Temperature →
Herbs
mean_barp
mean_stat
Above 1m
back_temp
Above 10m
Above 0m
Above 2m
bat_temp
mean_wind
Woody_plants
Above 5m
Above 25m
min_hum
min_temp
Above 11m
Above 30m
mean_dew
mean_hum
Above 19m
tree
Grass
max_hum
mean_temp
Above 18m
max_temp
Above 17m
Above 15m
small_sapling
mean_wet
Above 12m
Above 16m
Above 14m
medium_sapling
Bare_Soil
canopy
Above 13m
Leaf_Litter
large_sapling
Roost
Bulimba
Cairns Villas
Chay Road
Dunn St
Farmer St
Gordonvale
Harwood Cl
Henley St
Loridan Dr
Waratah

Figure 4.4 Constrained visualisation of roost sites based on environmental variables, with bat temperature as the primary axis**.** Camps on the right side of the plot are associated with higher bat temperatures and are influenced by factors such as bare soil, small saplings, and higher humidity**.** Camps on the left side experience lower bat temperatures and are more influenced by canopy cover, large saplings, and woody plants, which may buffer temperature fluctuations.

Based on this ordination, we identified some camps with the highest or lowest percentage of points on the lower or higher side of the bat temperature gradient (Table 4.3).

Table 4.3 Percentage of roost site data points in high and low bat temperature environments

Roost	**High (%)**	**Low (%)**
Chay Road	100	0
Loridan Dr	100	0
Harwood Cl	81.8	18.2
Dunn St	75	25
Bulimba	66.7	33.3
Gordonvale	66.7	33.3
Farmer St	55.6	44.4
Cairns Villas	50	50
Henley St	40	60
Waratah	0	100

Roost sites are ranked by the proportion of data points in higher (>0) and lower (<0) bat temperature categories**.** Chay Road and Loridan Dr (100%) are exclusively in high-temperature environments, while Waratah (100%) is entirely in a low-temperature environment. Harwood Cl, Dunn St, and Bulimba are predominantly high-temperature, whereas Henley St and Waratah have more points in cooler environments**.** Cairns Villas (50%) is evenly distributed between both conditions.

It is important to notice that Chay Road is the camp where the die-off happened in 2018, which shows that the conditions in this camp remain extremely dangerous for the bats. The most populated camps during my study period were Gordonvale, Dunn St, Farmer St, Cairns Villas and Henley St. Of the cited camps, just Henley St has less the 50% of the bat surface temperature on the higher end of this gradient.

4.4.3 Microclimate

Microclimate associations with bat surface temperatures was examined with linear mixed-effects model (LMM) with microclimatic variables as fixed effects and roost identity as a random effect. Bat surface temperatures were significantly influenced by environmental conditions with relative humidity having a strong negative effect ($\beta = -0.15$, $P < 0.05$), while air temperature had a significant positive effect ($\beta = 0.16$, $P < 0.05$). Wind speed showed a weak, non-significant negative effect ($\beta = -0.058$, $P = 0.18$). Roost-specific factors accounted for 67.9% of the variance in bat surface temperature, underscoring the role of local environmental conditions, while 32.1% remained unexplained. The model's conditional R^2 was 79.2%, with 43.8% of the variance explained by roost-specific factors and 35.4% by microclimatic predictors.

4.4.4 Vegetation structure

4.4.4.1 Tree height

To assess the influence of vegetation height on bat surface temperature, a linear mixed-effects model was applied, with camp included as a random effect to account for within-group variability. Analysis of the full set of LiDAR-derived vegetation structure data indicated that camp-level variation explained 20% of the observed temperature variability. However, none of the individual height categories (ranging from ground level to 35 m) had a statistically significant effect on thermal readings. Model selection followed an iterative refinement process to optimise fit while minimising complexity. The full model, incorporating all vegetation height predictors, yielded an AIC of 55.48.

Subsequent stepwise removal of non-significant variables, supported by Variance Inflation Factor (VIF) analysis to address collinearity, produced a series of simpler models with marginally higher AIC values but improved parsimony and interpretability.

The final selected model, Model 7, retained three significant vegetation height predictors: point cloud data above 12 m, 13 m, and 15 m. Although this model had a higher AIC value (101.73) compared to earlier versions, the statistical significance of its retained predictors supported its selection. Further variable removal did not substantially improve model fit, indicating that vegetation heights above 12 m, 13 m, and 15 m capture the most ecologically relevant variation in bat surface temperature. The random effect of site ("camp") was included in all models to account for site-level variability, although its contribution to overall variance was minimal (Table 4.4).

Table 4.4 Model selection results for the association between vegetation structure, here represented as point-cloud data above different height (fixed effects) and bat surface temperature, using LiDAR-derived point cloud data across height classes. The table shows degrees of freedom (df), Akaike Information Criterion (AIC), significance levels (., *, **, ***), and R^2 values.

Model	Predictors	df	AIC	p<0.005	Marginal R^2	Conditional R^2
1	~ above0m +above5m + above10m + above11m + above12m + above13m + above14m + above15m + above16m + above17m + above18m + above19m + above20m + above25m + above30m + above35m + (1 | camp)	3	5.48	-	0.84	0.85
2	~ above11m +above12m + above13m + above14m + above15m + above16m + above17m + above18m + above19m + above20m + above25m + (1 | camp)	3	6.64	-	0.61	0.89
3	~ above12m + above13m + above14m +above15m + above16m + above17m + above18m + above19m + above20m + (1 | camp)	3	5.01	-	0.84	0.84
4	~ above12m + above13m + above14m +above15m + above16m + above17m + above18m + above19m + (1 | camp)	3	5.9	-	0.75	0.84
5	~ above12m + above13m + above15m + above16m + above17m +(1 | camp)	0	7.57	-	0.84	0.84
6	~ above12m + above13m + above15m + above16m + (1 | camp)		5.63	./ **/*/NS	0.86	0.86
7	~ above12m +above13m + above15m + (1 | camp)		01.73	* */***/***	0.86	0.86

Model 7 explained 86% of the variance in bat surface temperature (R^2 = 0.86), with identical marginal and conditional R^2 values, indicating minimal contribution from the random effect of roost. The final model identified three significant vegetation height predictors: point cloud data above 12 m and 15 m were associated with lower bat surface temperatures, while vegetation above 13 m was associated with higher temperatures. These results suggest that structural variation within the 12–15 m height range influences microclimatic conditions relevant to bat thermoregulation.

4.4.4.2 Understory

I used a linear mixed-effect model where camp would be counted for between-group variability. The roost contributed with 0% in the variability, meaning the difference in the vegetation density between roosts is not significant for these predictors The generalised linear model revealed significant relationships between understory components and bat temperature readings, with positive and negative effects across different vegetation components (Multiple R^2=0.45, Adjusted R^2=0.29). Among the

ground cover components, Herbs (β= −4.11, df=32, P<0.05), Bare Soil (β= −7.02, df=32, P<0.05), and Leaf Litter (β= −1.96, df=32, P<0.05) showed significant negative effects, indicating that their increased proportions are associated with cooler microclimates. Grass also had a marginally negative impact (β= −1.65, df=32, P=0.09).

Small saplings (β=1.89, P<0.05) significantly positively associated with bat temperature readings, increasing. In contrast, canopy cover (β= −0.86, P<0.05) and medium saplings (β= −1.74, P=0.07) exhibited negative effects, although medium sapling was not significant. These results suggest that dense canopy cover and higher proportions of specific ground covers mitigate thermal stress, while small saplings' high density indicates more light and localised warming.

Overall, the variability in bat body temperature is significantly associated by the composition of vegetation structure and ground cover, highlighting the importance of these components in shaping the microclimatic conditions of bat habitats.

4.5 Discussion

In the urban roosts of Cairns, north Queensland, I used infrared thermography to examine the relative surface temperature of spectacled flying-foxes (*Pteropus conspicillatus*) along two summer periods. I demonstrated that urban roost characteristics, particularly vegetation structure and local microclimate, significantly influence the thermal exposure of the studied bats during summer in tropical Australia. Using infrared thermography, I identified large variation in bat surface temperatures across roost sites, with several camps consistently reaching or exceeding critical thermal thresholds. These findings emphasise the role of habitat structure in mitigating heat stress and highlight the potential of thermal imaging as a tool for evaluating roost suitability under climate change.

4.5.1 Microclimate strongly influences bat thermal stress

Bat surface temperatures were significantly associated with local microclimatic conditions. Relative humidity had a strong negative relationship with thermal readings, consistent with reduced evaporative heat loss under humid conditions (van Dyk et al., 2019). In contrast, air temperature had a positive effect on bat temperature, suggesting that elevated ambient conditions are directly translated into increased physiological heat

loads. Wind speed did not significantly influence surface temperature, likely due to low airflow within dense vegetation during sampling periods. These results reinforce previous findings that both temperature and humidity jointly constrain thermoregulatory performance in flying-foxes (Mella et al., 2024; Rubalcaba et al., 2022).

Critically, multiple roosts exhibited conditions that placed bats at risk of lethal heat stress. The constrained ordination analysis revealed that 7 out of 10 roosts had more than half of their average daily bat temperatures on the higher-temperature axis. Particularly, Chay Road, the site of a mass mortality event in 2018 (Lopes et al., 2024), recorded consistently elevated thermal readings. A ridge regression further confirmed that 90% of camps had bat temperatures exceeding 42°C — the presumed lethal threshold (Welbergen et al., 2008) — with 20% of those camps showing over 20% of individuals above that threshold. This suggests that some roosts may regularly expose flying-foxes to life-threatening conditions.

4.5.2 Vegetation structure modifies microclimate and buffers thermal extremes

Vegetation structure emerged as a key determinant of roost microclimate. Camps dominated by mid- to tall-canopy trees (12–15 m) consistently supported cooler bat surface temperatures. These findings align with evidence that taller trees and closed canopies reduce thermal stress by providing shade, lowering radiant heat load, and facilitating vertical air movement (Gillerot et al., 2024; Jucker et al., 2018a). Unexpectedly, vegetation cover at 13 m was associated with increased bat temperatures. This pattern may reflect discontinuities in the mid-canopy layer, which allow greater solar radiation to penetrate the roosting strata. Rather than height alone, these results suggest that vertical continuity and canopy density are factors moderating microclimatic conditions. The increase in temperature at 13m height can be due to gaps in the canopy where the solar radiation could be higher, influencing the thermal readings (Murakami et al., 2022).

Assessing the vegetation structure in its entirety, with consideration of all analysed strata as an integrated whole, roost sites characterised by mid-tall trees (12-15m), dense canopy, higher relative humidity, and specific understory compositions (leaf

litter, herbs, bare soil) provided cooler and more stable microclimates, reducing thermal risk. Conversely, sites with short, open vegetation and a high proportion of small saplings were hotter, posing increased heat stress risks. (Terschanski et al., 2024b; Zellweger et al., 2024).These findings highlight targeted habitat management, particularly reforestation with taller trees and structured understory vegetation, essential for enhancing habitat resilience against extreme heat events (Zabin et al., 2022).

Before examining the relationship between roost characteristics and bat surface temperature, I first evaluated the capacity of the thermal camera to reliably distinguish bats from the surrounding vegetation. This step was essential given the comparable emissivity values of bat fur (Playà-Montmany & Tattersall 2021) and foliage (Chen 2015) emissivity is very similar.

Analyses of the temperature differential between bats and background vegetation revealed that both air temperature and relative humidity significantly influenced this gradient. Higher ambient temperatures were generally associated with larger differences, whereas increased humidity reduced the gradient more strongly. The significant interaction term indicated that under humid conditions, the negative effect of temperature on the bat–background temperature gradient was attenuated, suggesting that humidity plays an important role in shaping thermal balance.

Although the random effect of camp accounted for only 9% of the variance, it nevertheless reflects consistent site-level differences in baseline thermal conditions, likely driven by variation in vegetation structure, canopy cover, and microclimate buffering capacity. The greater proportion of variation, however, was explained by within-site environmental fluctuations, reinforcing the importance of fine-scale microclimatic conditions in shaping thermal profiles. These findings are consistent with earlier results showing significant differences in median bat–background temperature differentials among camps, further underlining the influence of roost-site characteristics on thermoregulatory dynamics.

A likely mechanism underlying these patterns is the interaction between humidity and temperature. Elevated humidity can reduce the efficiency of evaporative cooling, leading to higher bat surface temperatures even under moderate ambient temperatures (van Dyk et al. 2019). Conversely, heat dissipation may be more effective in drier conditions, allowing bats to maintain a surface temperature closer to the background. This

is consistent with ecological expectations, as thermoregulation in endotherms often involves integrated behavioural and physiological strategies to mitigate heat stress across changing environmental conditions (Mota-Rojas et al. 2021; Rubalcaba et al. 2022; Mella et al. 2024).Taken together, these results highlight that, beyond macroclimatic influences, fine-scale microhabitat selection and individual behavioural adjustments are critical in shaping bat thermal ecology (Boyles et al. 2022; Chenery et al. 2022).

4.5.3 Roost microclimate and their influence on bat thermal readings

Different flying-fox species in Australia appear to have different thermal tolerances. A 1964 study examined the thermoregulation response of three species, two of them from the same *Pteropus* genus as spectacled flying-foxes. The grey-headed (*Pteropus poliocephalus*) demonstrated greater thermal tolerance by maintaining its internal temperature 1°C below the ambient temperature even when it reached 40°C but demonstrated thermoregulatory behaviours such as panting after 35°C. Additionally, the space between its wing and body was 10°C warmer than when exposed to cold conditions. Little-red flying-foxes (*Pteropus scapulatus*) showed a higher tolerance to mild hyperthermia, allowing their body temperature to reach 41°C before starting panting (Bartholomew, Leitner and Nelson 1964). Both thermoregulatory ranges are compatible with their distribution. spectacled flying-foxes thermal tolerance has not been established yet, but it would be expected to fall between these two species. This tolerance range between 35°C and 41°C can guide us in the best approach regarding the threshold of temperatures to start a heat stress response during an extreme weather event.

Exposure to temperatures exceeding the presumed lethal threshold for flying-foxes(42°C, Bartholomew, Leitner & Nelson 1964; Welbergen et al. 2008), was widespread across roost sites, with certain locations exhibiting recurrent extreme thermal conditions. Such patterns are consistent with observations in *Pteropus giganteus* in West Bengal, India, where elevated mortality was linked to periods of high temperature combined with low humidity (Dey, 2015). In both species, many individuals did not relocate despite adverse thermal conditions, suggesting a trade-off between conserving energy through site fidelity and the increased risk of mortality from heat stress.

Analysis of microclimate–temperature relationships further supports the role of roost-site characteristics in shaping thermal exposure. The linear mixed-effects model indicated that roost identity accounted for 35.4% of the variance in bat surface

temperature, reinforcing the observed differences in the likelihood of extreme heat events among sites. This finding parallel results from *P. giganteus*, where seasonal roosts maintained lower mean diurnal temperatures than year-round roosts (Hahn et al., 2014), suggesting that cooler roosts may offer a thermoregulatory advantage.

Collectively, these results underscore that roost-specific microclimatic conditions exert a strong influence on heat stress risk. Given the high degree of site fidelity observed in *P. conspicillatus* and related species, conservation strategies should prioritise enhancing the thermal buffering capacity of existing roosts. Approaches such as reforestation, the preservation of canopy complexity, and the protection of structural vegetation features are likely to be more effective than relying on relocation to cooler habitats. In the context of increasing frequency and intensity of extreme heat events under climate change, such targeted microclimate management represents a critical intervention to reduce mortality and sustain population viability.

4.5.4 Roost vegetation and their influence on bat thermal readings

Vegetation structure also showed an important association with bat surface temperature. Camps with taller trees and denser canopy cover (e.g., Henley Street and Waratah) exhibited cooler bat surface temperatures, likely due to increased shading and water retention (Wang et al. 2023; Yin et al. 2024). Conversely, camps with shorter vegetation and higher herbaceous cover (e.g., Cairns Villas and Dunn Street) recorded higher bat temperatures, suggesting that open vegetation increases solar exposure and thermal stress (Sharmin et al. 2023; Wujeska-Klause & Pfautsch 2020).

This is particularly evident at Waratah, where bat surface temperatures were consistently lower despite the roost being structurally simple, comprised mainly of tall *Eucalyptus* trees over open grass. Although lacking dense understory vegetation, the site benefits from the vertical stratification and shading provided by the tall canopy**,** which likely reduces radiant heat and facilitates convective airflow (Gillerot et al., 2024; Jucker et al., 2018b). Tall trees in tropical systems can mitigate thermal extremes by intercepting solar radiation and promoting vertical air movement, even when foliage is sparse. In addition, certain *Eucalyptus* traits such as leaf orientation and high reflectivity further reduce thermal loads in roosting strata (James & Bell, 2000). Waratah's open canopy structure may therefore provide a consistent thermal refuge for flying-foxes, despite its

minimal ground cover, emphasising that canopy height and openness can be equally or more important than shrub density (Bouwen et al., 2025) for roost cooling in tropical landscapes.

On the other hand, Loridan Dr and Bulimba had over 20% of bat surface temperature observations exceeding the 42°C threshold. These camps also exhibited a narrow range of temperature variation, which may suggest either a roost's ability to buffer ambient extremes or a vegetation structure that traps heat, resulting in consistently high temperatures. In contrast, camps that exhibit a wider temperature variation may reflect either a less complex vegetation structure**,** which provides limited buffering, or the influence of surrounding environmental factors that drive a broader range in ambient temperatures, ultimately affecting bat surface temperature. Notably, given that such high exceedance rates occur even in camps with relatively complex structures, it is plausible that camps with less structured or degraded vegetation would show an even higher proportion of extreme temperatures due to reduced thermal buffering capacity.

The results of this study are limited by the number of roost sites studied, the number of summer periods examined and the method used to estimate bat surface temperatures from afar. Given the varying distances and environmental conditions under which data were collected, the method serves primarily as a comparative tool rather than an absolute measure of temperature.

Future research should focus on long-term monitoring of bat surface temperatures, incorporating behavioural observations to understand thermoregulatory strategies better. Additionally, fine-scale habitat assessments, such as tree species composition and canopy density, could provide further insights into optimising roost environments in a warming climate and a long-term microclimate assessment at the canopy level.

CHAPTER 5

Critical analysis of management plans for flying-foxes in Queensland and an interdisciplinary proposal: public sector, Science and citizen Science working together

---

Abstract

Climate change intensifies ecological pressures on wildlife, particularly for species vulnerable to extreme heat events. The spectacled flying-fox (*Pteropus conspicillatus*), an endangered species in Queensland, faces increasing threats from habitat loss, human-wildlife conflict, and rising temperatures. However, current management approaches remain largely reactive, focusing on dispersal and post-event interventions rather than addressing the underlying environmental drivers of mortality. This study critically evaluated flying-fox management plans across Queensland, focusing on heat stress mitigation strategies, scientific integration, and the role of vegetation and microclimate in roost-site selection and survival. Using Cairns as a case study, empirical data on roost microclimate and vegetation structure were analysed to identify key factors influencing thermal resilience. Findings indicate that existing management plans do not incorporate predictive models or empirical-based strategies to mitigate heat stress. While some councils, such as Cairns and Ipswich, acknowledge the impact of extreme temperatures, their response remains reactive, relying on behavioural distress cues rather than preventive action. This study provides empirical evidence that canopy density, vegetation structure, and humidity regulation are essential in buffering flying-foxes against lethal heat events. Despite this, habitat-based cooling strategies and climate-adaptive planning are absent from current conservation policies. To address these gaps, this study proposes a shift toward a preventive management framework, integrating real-time microclimate monitoring, predictive heat stress thresholds, and habitat modifications that enhance thermal comfort in key roosts. By embedding empirical data into decision-making, councils can move beyond short-term conflict resolution and develop long-term conservation strategies that align with climate adaptation goals. These recommendations

offer a science-driven pathway to mitigate heat-related mortality and improve the resilience of spectacled flying-fox populations in an era of accelerating climate change.

5.2 Introduction

Climate change is a significant driver of ecological dynamics, particularly regarding niche swaps and overlaps among species (Jan et al. 2025). Rising global temperatures and shifting precipitation patterns force species to adapt by modifying their geographical ranges and ecological niches (Avidad et al. 2024). This often results in increased competition and interaction between native and non-native species and among species with previously non-overlapping distributions. (Haight et al. 2023; Chen et al. 2024).

Among the species most affected by climate change in Australia, the spectacled flying-fox (*Pteropus conspicillatus*) faces an increasing number of threats, including habitat loss, human-wildlife conflict, and extreme heat events (Steffen et al. 2014; Perkins-Kirkpatrick & Gibson 2017). Flying-foxes have an important ecological role as pollinators and seed dispersers**,** yet they are frequently targeted in urban areas due to concerns about noise, odour, and disease transmission (Hall & Richards 2000; Currey et al. 2018). These conflicts have led to widespread roost dispersals, which often disregard conservation priorities and fail to provide long-term solutions for species management. Conservation management is central to mitigating the impacts of climate change, but effective intervention requires the integration of ecological, social, and policy-driven factors(Keppel et al. 2024; Passos et al. 2024).

Historically, all native wildlife in Queensland has been legally protected, and any intervention—such as dispersing a flying-fox roost—required authorisation from the Queensland Department of Environment and Science (DES). However, a 2013 amendment to the Nature Conservation Act 1992 (Qld) shifted this authority to local governments, granting them control over flying-fox management within Urban Flying-Fox Management Areas (UFFMA)—designated zones where councils could intervene in roost locations without requiring state-level permits (Department of Environment and Science 2020).

While this policy change was intended to enhance local decision-making, it led to fragmented and inconsistent management approaches across councils. A review of 48

dispersal attempts between 1992 and 2020 found that: 25% of displaced roosts were critical for threatened species. Only four dispersals were deemed successful, all requiring extensive habitat removal and high financial costs (e.g., Bundall dispersal: $250,000) (Roberts et al. 2021).

In many cases, dispersal resulted in fragmented, smaller roosts across urban areas, increasing conflicts rather than resolving them (Calcino 2020; Lunn et al. 2021; Roberts et al. 2021). This reactive management approach fails to address underlying ecological issues and exacerbates risks to spectacled flying-fox populations.

Beyond direct human-wildlife conflicts, climate change is becoming an even more immediate and severe threat to spectacled flying-fox populations(Welbergen et al. 2008; Welbergen 2012). In 2018, a single heatwave in Cairns resulted in the death of one-third of the local population, with mortality concentrated at a single roost in Edmonton (Chay Road). Other roosts in the city experienced similar temperatures but far lower mortality rates, suggesting that microclimate conditions and habitat characteristics may play a crucial role in survival outcomes. Despite the clear risk posed by extreme heat events, current management strategies remain largely reactive, focusing on dispersal and post-event responses rather than addressing the underlying environmental drivers of mortality.

This research critically evaluated existing flying-fox management plans in Queensland, focusing on their reliance on scientific data, their approach to heat stress mitigation, and the role of vegetation and microclimate in roost-site selection and mortality risk. By analysing policies across multiple councils, this study identified key gaps in current approaches and assessed how conservation strategies incorporate empirical evidence. Additionally, by integrating vegetation structure and microclimate data from spectacled flying-fox roosts in Cairns, this research provided direct ecological insights into the factors that influence thermal resilience. The findings highlight the need to shift from reactive to preventive management, advocating for strategies integrating real-time microclimate monitoring, predictive heat stress thresholds, and habitat modifications to buffer flying-fox populations from extreme heat.

Ultimately, this study argued for a climate-adaptive, evidence-based management framework that prioritises long-term conservation over short-term conflict resolution. By embedding empirical ecological data into decision-making, councils can move beyond

ineffective dispersal tactics and implement proactive solutions that ensure the survival of spectacled flying-foxes in an era of accelerating climate change.

5.3 Methods

5.3.1 Study Design

This study examines flying-fox management plans across Local Government Areas (LGAs) in Queensland, Australia, focusing on management objectives, the use of scientific evidence, and the presence of heat stress mitigation strategies. By comparing these plans, this study evaluates their effectiveness in balancing conservation and conflict resolution and recommends evidence-based improvements.

5.3.2 Data Collection

5.3.2.1 Identification of Management Plans

A list of all 78 LGAs in Queensland was obtained from the Queensland Government directory. In August 2023, the official websites of all 78 councils were searched using internal search engines with the keywords:"flying-fox","bat(s)". Relevant documents, including: Flying-Fox Management Plans, Statements of Management Intent, Meeting announcements, Educational resources, and Wildlife policies, were reviewed for their inclusion of flying-fox roost management strategies.

5.3.2.2 Inclusion Criteria

Only finalised and publicly available documents were included to ensure the relevance and comparability of the management plans. Out of 28 LGAs that had documents related to flying-fox roost management, 8 LGAs had finalised management plans, of which 7 were selected for analysis due to their completeness and alignment with this study’s objectives. The included management plans cover the following areas: Cairns (Cairns Regional), Banana Shire, Sunshine Coast (Sunshine Coast Regional), Ipswich (Ipswich City), Gladstone (Gladstone Regional), Whitsunday (Whitsunday Regional) and Central Highlands Regional (Queensland government map Appendix C).

5.3.3 Data Analysis

Each management plan was assessed using a standardised classification system (Table 5.1), which categorised key components into the following variables.

Table 5.1 Variables assessed and key components analysed.

Variables	**Observed aspects**
Objectives	Whether the plan prioritizes conservation, conflict resolution, or both
Roost Classification	Use of structured risk-based categorization, where
Scientific Foundation	Presence of empirical data, research collaborations, and decision-support tools.
Management Strategies	– Evaluation of deterrence, habitat modification, and relocation efforts.
Heat Stress Management	Presence and type of mitigation strategies, or studies pointing towards a roost management to improve thermal comfort

5.4 Results and Discussion

5.4.1 Roost Risk Management Across Different Plans

Roost risk management strategies vary significantly among the studied councils, ranging from structured decision frameworks to reactive assessments based on public complaints. Ipswich and Cairns employ a tiered risk-based approach, categorising roosts into high, medium, and low conflict zones, which guide the level of intervention. This hierarchical framework enables councils to allocate resources efficiently while minimising unnecessary disturbance to the species. The Sunshine Coast and Banana Shire rely on a decision support tool that integrates ecological and human factors to determine intervention strategies. In contrast, Gladstone and Whitsunday adopt a more reactive, case-by-case approach, responding to emergent community concerns without prior risk categorisation. The Central Highlands employs a hybrid approach, combining roost risk assessment with mitigation strategies to strike a balance between conservation and human concerns.

5.4.2 Determining Levels of Intervention

The decision-making process for interventions is often informed by roost categorisation, proximity to urban areas, and community conflict levels. Banana Shire and Cairns integrate ecological principles into their decision trees, prioritising non-intrusive management before progressing to active deterrents or dispersal. Ipswich and Sunshine Coast consider residential proximity, where sites within 100–300m of human dwellings trigger escalated interventions such as buffer creation, vegetation removal, or dispersal. Whitsunday and Gladstone focus more on community-reported conflicts, often responding only when a threshold of complaints is reached, rather than implementing proactive measures. The Cairns strategy stands out due to its multi-faceted evaluation framework, which weighs historical data, ongoing monitoring, and projected roost movements, ensuring that interventions are guided by scientific evidence rather than immediate public pressure.

The dispersal of spectacled flying-foxes from the Cairns City Library, carried out by the Cairns Regional Council (CRC) in 2020, aimed to reduce human-wildlife conflict, protect heritage-listed trees, and lower pup mortality rates. The council intended to

relocate the bats to the Cairns Central Swamp, a historically used roost site with 30 hectares of remnant rainforest and paperbark swamp. However, the flying-foxes did not establish themselves there, and instead, many moved to other urban areas, such as Manoora, creating unintended but predictable consequences (Calcino 2020). Conservationists criticised the operation as "farcical," arguing that it could harm the endangered species and questioning the effectiveness of using deterrents such as sound cannons and light (Cox 2020). Despite these concerns, the council continues deterrent efforts in the Central Business District (CBD), employing non-lethal methods like torches, pool noodles, and intermittent noise to prevent recolonisation (Kentwell 2023).

While the strategy promotes in-situ management and long-term monitoring, as stated in the Cairns Management Strategy, the 2020 dispersal primarily sought immediate conflict resolution, with limited success in relocating bats to an ecologically suitable site (Kentwell 2023). This contrast highlights the complexity of wildlife management and the difficulty of aligning theoretical conservation strategies with practical outcomes.

5.4.3 Collaboration with Researchers

Scientific collaboration is the basis of more effective flying-fox management, with Cairns, Ipswich, and Sunshine Coast demonstrating direct partnerships with ecological researchers and bat conservation groups. The Cairns plan incorporates the findings of bat ecology consultants (NRA Environmental Consultants) and integrates long-term citizen science from organisations such as the Bats and Trees Society of Cairns. Ipswich has actively collaborated with universities and conservationists to develop heat stress mitigation plans, reflecting a broader ecological commitment that extends beyond human-flying-fox conflict resolution. However, the website mentioned in their management plan as a reference for heat stress mitigation strategy does not lead anywhere. I assume they would revise it in a future version of this document.

Sunshine Coast also incorporates research findings into its adaptive management strategies, adjusting conservation actions based on new ecological insights. Conversely, Banana Shire, Central Highlands, Gladstone, and Whitsunday show limited direct research collaboration, relying more on government guidelines and internal assessments rather than active scientific partnerships. This disparity highlights a gap in empirical

evidence integration, where some councils prioritise community-driven responses over research-informed decision-making.

5.4.4 Regular Roost Monitoring

Continuous monitoring is a crucial aspect of sustainable flying-fox management, with Ipswich, Cairns, and Sunshine Coast implementing structured monitoring programs. Ipswich employs a quarterly monitoring schedule, supplemented by conflict-based evaluations when public complaints rise. Cairns follows a deterrent action log, tracking changes in roost occupancy in key areas, such as the City Library roost and Brinsmead Reserve. Sunshine Coast integrates GIS-based habitat mapping to anticipate future roost shifts and minimise potential conflicts. In contrast, Banana Shire, Gladstone, and Whitsunday lack formalised monitoring programs, instead assessing roosts on an as-needed basis, usually in response to complaints. Roost monitoring is an important aspect of bat conservation and conflict resolution. Over time, the seasonal migration data can help the responsible authorities to predict on conflicts and act in advance.

5.4.5 Primary Focus: Conservation vs. Conflict Resolution

The balance between bat conservation and human conflict mitigation varies among councils, influencing policy decisions and intervention strategies. Ipswich, Cairns, and Sunshine Coast exhibit a dual focus, acknowledging both the ecological importance of flying-foxes and the need to manage human-wildlife interactions. These councils incorporate community education programs, non-intrusive mitigation methods, and habitat protection into their broader conservation strategies. Conversely, Gladstone and Whitsunday lean more heavily towards conflict resolution, prioritising human concerns over conservation imperatives. This focus is evident in their reliance on dispersal techniques rather than long-term habitat management. Banana Shire and Central Highlands take an intermediate stance, recognising flying-foxes' ecological role while maintaining a flexible management approach based on community tolerance levels.

5.4.6 Analysis of Heat Stress Management in Queensland Flying-Fox Management Plans

The analysis of flying-fox management plans across Queensland revealed varying approaches to heat stress management, with most plans adopting a reactive strategy rather than a proactive, predictive model. Cairns Regional Council is the only LGA with a dedicated *Flying-Fox Emergency Action Plan – Heat Stress Event* separate from its general management plan. This plan provides a structured response framework, assigning specific responsibilities to agencies and wildlife carers, and coordinating responses with Queensland Health and local disaster management teams. The Cairns plan includes trigger points based on temperature thresholds and flying-fox behaviour, with interventions such as water spraying and public communication campaigns.

Other councils, including Ipswich and Banana Shire, acknowledge the risk of heat stress events but primarily focus on response rather than prevention. Ipswich, for example, identifies extreme heat as a key species management issue and advises public education on handling stressed or deceased bats. It recognises signs of heat stress, such as fanning, seeking shade, panting, and saliva spreading, but only initiates action once these signs are visible. The council collaborates with wildlife carers to mitigate heat stress impacts, but lacks a structured, preventive intervention plan.

Similarly, Banana Shire's management plan addresses environmental stress events, including heatwaves, cyclones, and droughts, but focuses primarily on cleanup efforts and post-event response. The plan mentions coordination with wildlife rescue services and monitoring for stress signals in bats but does not incorporate predictive measures to mitigate extreme heat impacts before they escalate.

A key limitation of most management plans is their reliance on observable stress behaviours rather than proactive intervention strategies. Current response mechanisms are triggered when bats exhibit distress, such as wing fanning, shade-seeking, licking their wings, and panting. This reactive approach does not prevent mortality events but instead seeks to manage their outcome. While more comprehensive, Cairns' heat stress plan still uses behavioural cues as activation triggers rather than a predictive model based on microclimate conditions and long-term climatic forecasts.

This study highlights the need for a shift towards predictive heat stress management. By integrating microclimate monitoring data, councils can establish early

warning systems based on temperature and humidity trends, enabling targeted interventions before heat stress symptoms appear. Such an approach could include proactive microclimate manipulation, such as strategic irrigation or vegetation management, to increase canopy cover and reduce temperature extremes within roosts.

5.4.7 Data-Driven Conservation: A Missing Element

Most flying-fox management plans lack structured, data-driven methodologies, relying instead on reactive measures to address human-wildlife conflicts. For instance, plans such as those implemented in Cairns, Ipswich, and Gladstone do not incorporate experimental data or decision-support tools, which are essential for adaptive management based on ecological evidence (Parsons et al. 2011). The absence of rigorous scientific assessments, such as population viability analyses and roost dynamics studies, undermines the ability of these plans to develop long-term, sustainable solutions (Roberts et al. 2012).

Species-specific considerations are also often overlooked. While some plans, such as Whitsunday and Banana Shire, identify the species they aim to manage—such as the Little Red Flying-Fox (*Pteropus scapulatus*), Black Flying-Fox (*Pteropus alecto*), and Grey-Headed Flying-Fox (*Pteropus poliocephalus*)—they lack detailed ecological studies on species-specific behaviour, population dynamics, and migratory patterns. These gaps in knowledge reduce the effectiveness of conservation and management strategies, as flying-foxes exhibit complex seasonal and resource-driven movements that require a landscape-scale approach to roost and habitat management (Tidemann & Nelson 2011). Without empirical data, management plans risk implementing ineffective or counterproductive actions that fail to address the ecological drivers of flying-fox distribution and roost selection.

An ecologically driven flying-fox management approach would mitigate human-wildlife conflicts and provide municipalities with data-driven urban landscaping and habitat management recommendations. By incorporating ecological research on flying-fox foraging behaviour and roosting site selection, councils could strategically select ornamental plants that do not attract flying-foxes to urban areas, thereby reducing roost establishment near residential zones (Hall & Richards 2000; Eby & Law 2008). Additionally, this approach could guide homeowners on planting species that deter flying-

foxes, such as those with low nectar production or strong aromatic compounds that are unappealing to bats. This aligns with urban ecological management principles, where modifying habitat structure and food availability can influence wildlife distribution without the need for direct intervention such as a dispersal (Buckton et al. 2023). By integrating ecological knowledge into city planning and public awareness programs, councils could foster coexistence while minimizing conflict and preserving flying-fox populations' critical ecological roles in pollination and seed dispersal.

5.4.7.1 Cairns management plan

This amendment proposes a shift from an avoidance-based approach to an active conservation strategy in managing spectacled flying-fox roosts in the Cairns LGA. While the current plan prioritises conflict avoidance to the detriment of flying-fox conservation and well-being, prioritising dispersal in high-conflict areas, conservation-based approaches can provide long-term solutions that mitigate human-wildlife conflict while ensuring the stability of flying-fox populations. This proposal emphasises habitat enhancement, structured roost management, and community engagement to improve coexistence outcomes.

The existing management strategy largely relies on deterrence and dispersal to mitigate human-flying-fox conflict. However, these strategies have led to unintended consequences, such as the relocation of flying-foxes to new urban areas, increasing community dissatisfaction and failing to provide stable roosting sites. Instead of resolving human-wildlife conflict, dispersal efforts have displaced colonies into residential areas, commercial zones, and schools, intensifying community opposition and creating ongoing management challenges.

Additionally, deterrence measures can cause stress to flying-fox populations, leading to disrupted breeding cycles, increased pup mortality, and heightened physiological stress (Edwards et al. 2019).

The sudden displacement of large numbers of flying-foxes can reduce foraging efficiency and expose individuals to increased predation and environmental hazards (Welbergen et al. 2020). These disturbances also risk amplifying disease transmission due to higher population densities in suboptimal alternative roosting locations (Lunn et al. 2021).

While the management plan acknowledges the ecological importance of flying-foxes, its primary focus remains on human-centric conflict mitigation, rather than proactive conservation-based solutions. The plan does not sufficiently prioritise in-situ habitat improvement or long-term roost stabilisation, which are crucial for maintaining healthy populations. Furthermore, dispersal methods—especially without a viable alternative habitat—result in repeated relocation attempts, making management costly, resource-intensive, and ineffective in the long term.

The failure to successfully relocate flying-foxes to the designated Cairns Central Swamp underscores the need for a more evidence-based and ecologically informed approach. Habitat suitability assessments should be conducted before implementing deterrence measures, ensuring that any targeted relocation efforts align with ecological and behavioural factors that influence roost site selection. Without integrating habitat conservation, dispersal efforts will continue to create a cycle of displacement, ecological disruption, and community conflict rather than achieving sustainable coexistence.

To replace avoidance strategies, the following conservation-based actions are recommended:

- Designated Roost Habitat Enhancement:

Identify and restore key roost sites with optimal microclimatic conditions, such as those with dense canopy cover, adequate shade, and higher humidity levels. This thesis provided the structural aspects that increase thermal comfort. The next step should be a vegetation composition assessment to describe the species composition. Allied to this, the long-term plan should focus on reforestation of the areas using species with a higher coolant effect at the canopy level, such as trees with higher leaf-area index to provide a better below-canopy surface cooling(Rahman et al. 2020). Also, broad-leaf species have a high stomatal conductance during a heatwave, increasing the humidity through evapotranspiration (Marchin et al. 2023).

- Heat stress, an urgent management aspect

Over the past decades, the frequency, intensity, and duration of heatwaves in Australia have significantly increased, posing a major threat to flying-fox populations (Steffen et al. 2014; Perkins-Kirkpatrick & Gibson 2017). Heat stress events have led to mass mortality incidents, particularly affecting vulnerable species such as the Spectacled flying-fox (*Pteropus conspicillatus*), whose habitat characteristics play a crucial role in

determining mortality levels (Welbergen et al. 2008). Despite this growing risk, most flying-fox management plans lack proactive heatwave mitigation strategies. Among the analyzed plans, only Cairns provides a detailed toolkit for responding to heat stress events, while Ipswich acknowledges their occurrence but does not specify responsible personnel or provide a structured decision-making framework.

The current approach to heat stress management remains predominantly reactive, focusing on emergency response rather than preventing conditions that exacerbate flying-fox vulnerability. Research indicates that mass die-offs occur when extreme temperatures persist for consecutive days, as observed in past events in Cairns and Ipswich (Shields 2014; Lopes et al. 2024). The physiological mechanisms underlying heat-related mortality remain a subject of scientific debate. Some studies attribute deaths to extreme dehydration due to excessive evaporative water loss (Czenze et al. 2020), while others suggest that exhaustion from repeated heat stress without adequate recovery time plays a critical role (Ratnayake, 2019). Given these uncertainties, ecologically informed management plans should incorporate predictive modelling, habitat modifications, and long-term mitigation strategies to reduce the frequency and severity of heat stress mortality in flying-fox populations.

5.4.7.2 Forecasting High-Risk Events

In Chapter 2, I provided a long-term analysis indicating the rapid increase in temperatures above 35°C during the summer in Cairns. I analysed long-term weather data from BOM and observed an increase in the frequency of extreme temperatures. I also showed the duration of the heatwave, and the dry heat are more likely to be associated with the flying-foxes' death than just the temperature.

The Cairns Region Council Flying-Fox Emergency Action Plan: Heat Stress Event mapped the urban roosts in Cairns and established a monitoring and action plan. However, the action plan remains predominantly reactive, relying on observed bat distress behaviours (e.g., wing fanning, clustering) and temperature thresholds (above 37°C) to initiate responses rather than proactively preventing heat stress. While the plan acknowledges the risks of extreme heat, it does not incorporate real-time microclimate monitoring or predictive strategies to anticipate high-risk roosts in advance.

A more effective and proactive strategy would involve integrating the microclimate and vegetation data provided in this thesis to refine forecast-based interventions. This study identified key structural aspects to increase thermal comfort in roosts, including the role of vegetation complexity, canopy density, and tree species composition in modulating microclimate conditions. More importantly, this study evidences that flying-foxes will roost in different vegetation structures regardless of the risk of high-risk temperature. This evidences that dispersals or forest corridors tend to be ineffective for this species, and the best solution for species conservation is the reforestation of the hottest camps, providing the buffering conditions to avoid heat stress and incorporating monitoring tools, as I will describe below.

To shift towards a predictive heat stress management approach, the following measures should be considered:

- Microclimate Monitoring: Install permanent meteorological sensors/data loggers at key roost sites to collect real-time temperature and humidity data. This would provide early warning indicators for approaching heat stress conditions. Correlate this data with the weather data to describe the association between the BOM data and the roost data.
- Threshold-Based Preventive Actions: Use empirical data to establish risk thresholds, triggering proactive interventions before distress behaviours appear.
- Portable Irrigation Systems: Based on findings from Melbourne's Yarra Bend Park, where a misting system was installed at canopy height to cool roosts on hot days, similar portable irrigation systems could be deployed in Cairns before extreme heat events. These systems could be tested initially in unoccupied areas to assess their effectiveness and potential disturbance levels before being implemented in active roosts.
- Habitat Modifications: Reforestation efforts should focus on plant species with a high cooling effect at the canopy level. Trees with a higher leaf-area index provide increased below-canopy cooling, and broad-leaved species with high stomatal conductance can increase humidity through evapotranspiration, further reducing heat stress risks.
- Testing & Implementation of Preventive Irrigation System: To optimise the effectiveness of portable irrigation systems, controlled trials should assess the ideal timing and duration of irrigation to ensure microclimate stability without

excessive water consumption. These trials should also evaluate the impact of irrigation on humidity levels and temperature within occupied roosts to determine its effectiveness in mitigating heat stress. Additionally, potential disturbance effects on flying-fox behaviour must be examined to ensure that irrigation interventions minimise stress while maximising their cooling benefits.

5.4.8 Cross-Sectoral Applications for Climate Adaptation

Beyond flying-fox conservation, the microclimate data collected in this study and the suggested monitoring methodology has broader applications for urban development and climate adaptation. Understanding the cooling effects of vegetation in roost sites provides valuable insights into the role of the existing urban parks in mitigating heat stress. This information can be leveraged across multiple government departments, including:

- Urban Planning & Development: Designing city landscapes that optimise thermal comfort, integrating green infrastructure to reduce urban heat stress.
- Public Health & Heat Mitigation: Enhancing thermal regulation strategies in public spaces to protect vulnerable human populations from extreme heat.
- Disaster Risk Reduction & Emergency Management: Developing a forecast-based action plan for extreme heat events that extends beyond wildlife management, contributing to a broader climate resilience framework.

By incorporating predictive microclimate models into conservation and urban planning efforts, proactive solutions can be implemented before extreme temperatures reach lethal thresholds, ensuring a more sustainable and climate-resilient approach to both wildlife and human well-being.

CHAPTER 6

6.1 Conclusions

This study provides a multidisciplinary perspective on the impact of climate change on flying-foxes. It highlights thermal imaging as a practical tool for assessing how habitat characteristics buffer extreme temperatures and influence bat surface temperature. Throughout the chapters, this thesis explores the increasing occurrence of extreme temperatures in Cairns, the role of microclimate and vegetation structure in flying-fox occupancy, and the effects of roost characteristics on bat surface temperature. Additionally, it draws on empirical data to offer guidance on heat stress management, providing valuable insights for conservation strategies.

In **Chapter 2**, we examined the impact of climate change on extreme temperature events in Cairns and analysed whether roost microclimate conditions could predict roost occupancy. The results indicated that microclimate conditions vary significantly across roosting sites while temperature trends increase. However, roost occupancy was not determined by temperature, vegetation characteristics, and human disturbance factors.

Building on this, **Chapter 3** provided a more detailed analysis of predicting roost occupancy by incorporating multiple ecological variables, including vegetation structure, microclimate factors, and spatial patterns. The findings demonstrated that occupied roosts tended to have greater structural complexity, particularly a higher proportion of intermediate-height trees (11–15 m), which increased the likelihood of occupancy. This suggests that vertical stratification within roosts is one of the roost requirements in site selection, potentially providing both thermal buffering and enhanced roosting opportunities. While canopy cover was consistently high across all roosts, its slight variation between occupied and unoccupied sites was not statistically significant in predicting occupancy, indicating that factors beyond overall canopy coverage may be more influential in roost selection. Additionally, ground cover composition differed between sites, with occupied roosts exhibiting a higher prevalence of herbaceous and woody vegetation, while unoccupied sites had more exposed soil and grass cover. These patterns highlight the importance of habitat heterogeneity in supporting flying-fox roosting preferences and reinforce the need for conservation strategies that maintain diverse vegetation structures.

Furthering this investigation, **Chapter 4** assessed the effectiveness of thermal cameras in measuring bat surface temperature across different roosts. This comparative tool provided valuable insight into which environmental conditions exert the most influence on heat stress, reinforcing that roost selection is driven by a complex interaction between microclimate conditions and broader landscape factors. Using infrared thermography, I identified high thermal risk in at least three roosts, with Chay Road experiencing the most extreme temperatures, while sites with taller trees and dense canopy cover, such as Henley Street and Waratah, provided cooler microclimates. Higher humidity reduced bat surface temperatures, whereas open vegetation increased thermal stress. Given the species' strong roost fidelity, conservation strategies should focus on reforestation and structured understory management to mitigate extreme heat exposure. While temperature estimates have limitations, this study reinforces thermal imaging as a valuable monitoring tool, advocating for long-term microclimate assessments and habitat restoration to enhance flying-fox resilience in a warming climate.

In **Chapter 5,** I used empirical data gathered during this thesis to inform amendments to the Cairns Regional Council's flying-fox management plan. The proposed strategies advocate for a shift from reactive to predictive heat stress mitigation, incorporating reforestation efforts, wildlife corridors, and preventive irrigation before heatwaves. By integrating these elements with the Flying-Fox Forecaster, councils can develop proactive intervention strategies that reduce mortality risks while minimising conflict with urban populations. These findings underscore the necessity of aligning management plans with empirical data to improve conservation outcomes and ensure sustainable cohabitation between flying-foxes and urban communities.

In summary, the main findings suggest that spectacled flying-foxes' will continue to roost in these areas, regardless of the offered conditions. From a conservation perspective, the empirical data showed the vegetation structure and microclimate necessary to buffer extreme temperatures. The management plan team should work alongside the reforestation team to improve the existing roosts and reinforce the important ecological role portrayed by this endangered species.

6.2 Study Limitations and Future Directions

Despite its comprehensive methodology, this study has certain limitations. First, while the analysis incorporated multiple roosts, the temporal scope was limited, and longer-term monitoring could provide stronger validation of findings. Additionally, behavioural factors influencing roost occupancy were not fully explored, as microclimate and vegetation structure alone may not capture the complexity of species movement dynamics.

Future research should focus on longitudinal studies that assess seasonal shifts in roost selection, integrating behavioural ecology with habitat conditions. Moreover, incorporating remote sensing technologies, such as LiDAR and drone-based thermal imaging, could enhance the accuracy of microclimate assessments. Expanding predictive models by incorporating species-specific behavioural responses to environmental stressors would further refine conservation strategies.

Additionally, exploring the influence of social behaviours on roost formation could provide deeper insights into site fidelity and movement patterns. Finally, further collaboration with policymakers is necessary to translate scientific insights into standardised management frameworks**,** ensuring that empirical data directly informs conservation policies at a broader scale.

REFERENCES

Andrade, D. V. (2015). Thermal windows and heat exchange. *Temperature*, *2*(4), 451. https://doi.org/10.1080/23328940.2015.1040945.

Atkins, J. W., Fahey, R. T., Hardiman, B. H., & Gough, C. M. (2018). Forest Canopy Structural Complexity and Light Absorption Relationships at the Subcontinental Scale. *Journal of Geophysical Research: Biogeosciences*, *123*(4), 1387–1405. https://doi.org/10.1002/2017JG004256.

Avidad, P. M., Clavero, M., & Viana, D. S. (2024). Climate and Land-Use Change Leading to Niche Expansion and Shifts in Birds. *Journal of Biogeography*. https://doi.org/10.1111/jbi.15045.

Bailey, A. M., Ober, H. K., Reichert, B. E., & McCleery, R. A. (2019). Canopy Cover Shapes Bat Diversity across an Urban and Agricultural Landscape Mosaic. *Environmental Conservation*, *46*(3), 193–200. https://doi.org/10.1017/S0376892919000109.

Bailey, L. D., Ens, B. J., Both, C., Heg, D., Oosterbeek, K., & van de Pol, M. (2019). Habitat selection can reduce effects of extreme climatic events in a long-lived shorebird. *Journal of Animal Ecology*, *88*(10), 1474–1485. https://doi.org/10.1111/1365-2656.13041.

Balaras, C. A., & Argiriou, A. A. (2002). Infrared thermography for building diagnostics. *Energy and Buildings*, *34*(2), 171–183. https://doi.org/https://doi.org/10.1016/S0378-7788(01)00105-0.

Bartholomew, G. A., Leitner, P., & Nelson, J. E. (1964). Body Temperature, Oxygen Consumption, and Heart Rate in Three Species of Australian Flying-foxes. *Physiological Zoology*, 37(2), 179–198. JSTOR. https://doi.org/10.2307/30152330.

Blanchard, G., Barbier, N., Vieilledent, G., Ibanez, T., Hequet, V., McCoy, S., & Birnbaum, P. (2023). UAV-Lidar reveals that canopy structure mediates the influence of edge effects on forest diversity, function and microclimate. *Journal of Ecology*, *111*(7), 1411–1427. https://doi.org/10.1111/1365-2745.14105.

Bleul, U., Hässig, M., & Kluser, F. (2021). Screening of febrile cows using a small handheld infrared thermography device. *Tierarztliche Praxis Ausgabe G: Grosstiere - Nutztiere*, *49*(1), 12–20. https://doi.org/10.1055/a-1307-9993.

Boardman, W. S. J., Roshier, D., Reardon, T., Burbidge, K., McKeown, A., Westcott, D. A., Caraguel, C. G. B., & Prowse, T. A. A. (2021). Spring foraging movements of an urban population of grey-headed flying-foxes (*Pteropus poliocephalus*). *Journal of Urban Ecology*, *7*(1). https://doi.org/10.1093/jue/juaa034.

Boyles, J. G., Johnson, E. M., Fuller, N. W., Silas, K. A., Hou, L., Frick, W. F., & McGuire, L. P. (2022). Behavioural microclimate selection and physiological responses to environmental conditions in a hibernating bat. *Canadian Journal of Zoology*, *100*(3), 233–238. https://doi.org/10.1139/cjz-2021-0193.

Brcko, C. C., Silva, J. A. R. da, Martorano, L. G., Vilela, R. A., Nahúm, B. de S., Silva, A. G. M., Barbosa, A. V. C., Bezerra, A. S., & Lourenço Júnior, J. de B. (2020). Infrared Thermography to Assess Thermoregulatory Reactions of Female Buffaloes in a Humid Tropical Environment. *Frontiers in Veterinary Science*, *7*. https://doi.org/10.3389/fvets.2020.00180.

Brooke, A. P., Solek, C., & Tualaulelei, A. (2008). Roosting Behavior of Colonial and Solitary Flying-foxes in American Samoa (Chiroptera: Pteropodidae). *The Association for Tropical Biology and Conservation Stable*, *32*(2), 338–350.

Buckton, S. J., Ioan Fazey, Sharpe, B., Eugyen Suzanne Om, Doherty, B., Ball, P., Denby, K., Bryant, M., Lait, R., Bridle, S., Cain, M., Carmen, E., Collins, L., Nixon, N., Yap, C., Connolly, A., Fletcher, B., Frankowska, A., Gardner, G., & James, A. (2023). The Regenerative Lens: A conceptual framework for regenerative social-ecological systems. *One Earth*, *6*(7). https://doi.org/10.1016/j.oneear.2023.06.006.

Buettner, P. G., Westcott, D. A., Maclean, J., Brown, L., McKeown, A., Johnson, A., Wilson, K., Blair, D., Luly, J., Skerratt, L., Muller, R., & Speare, R. (2013). Tick Paralysis in Spectacled Flying-Foxes (Pteropus conspicillatus) in North Queensland, Australia: Impact of a Ground-Dwelling Ectoparasite Finding an Arboreal Host. *PLoS ONE*, *8*(9). https://doi.org/10.1371/journal.pone.0073078.

Bureau of Meteorology. (2007). *Warmest May and autumn on record in eastern Australia.* http://www.bom.gov.au/climate/current/statements/scs12.pdf.

Bureau of Meteorology. (2009). *Exceptional winter heat over large parts of Australia.*

Bureau of Meteorology. (2018). *An extreme heatwave on the tropical Queensland coast*.

Bureau of Meteorology. (2023). *Climate Data Online*. Http://Www.Bom.Gov.Au/Climate/Data/.

Cai, Z., Cui, J., Yuan, H., & Cheng, M. (2023). Application and research progress of infrared thermography in temperature measurement of livestock and poultry animals: A review. *Computers and Electronics in Agriculture*, *205*, 107586. https://doi.org/10.1016/j.compag.2022.107586.

Cairns Council (2024). *Flying-Fox-Emergency-Action-Plan-Heat-Stress-Event-V10*.

Calcino, C. (2020). Cairns flying-fox dispersal sends bats to new Manoora home. The Cairns Post.

Camargo, J. L. & Kapos, V. (1995). Complex edge effects on soil moisture and microclimate in central Amazonian Forest. *Journal of Tropical Ecology*, *11*(2), 205–221. https://doi.org/10.1017/S026646740000866X.

Camacho, A., Rodrigues, M. T., Jayyusi, R., Harun, M., Geraci, M., Carretero, M. A., Vinagre, C., & Tejedo, M. (2024). Does heat tolerance actually predict animals' geographic thermal limits? *Science of the Total Environment*, *917*. https://doi.org/10.1016/j.scitotenv.2024.170165.

Carter, T., Leemans, R., Lal, M., Whetton, P., Hay, L., Jones, R., Katz, R., Kittel, T., Smith, J., & Wilby, R. (2001). *IPCC third assessment report: climate change 2001- working group I: the scientific basis.*

Chen C. (2015). Determining the leaf emissivity of three crops by infrared thermometry. *Sensors (Basel). 15*;15(5):11387-401. doi: 10.3390/s150511387. PMID: 25988870; PMCID: PMC4481894.

Chen, P., Shen, C., Tao, Z., Qin, W., Huang, W., & Siemann, E. (2024). Deterministic responses of biodiversity to climate change through exotic species invasions. *Nature Plants*, *10*(10), 1464–1472. https://doi.org/10.1038/s41477-024-01797-7.

Chenery, M., Geiser, F., & Stawski, C. (2022). Thermal biology and roost selection of free-ranging male little forest bats, *Vespadelus vulturnus*, during winter. *Journal of Mammalogy*, *103*(4), 826–834. https://doi.org/10.1093/jmammal/gyac022.

Coates, L., Haynes, K., O'Brien, J., McAneney, J., & De Oliveira, F. D. (2014). Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844-2010.

Environmental Science and Policy, *42*, 33–44. https://doi.org/10.1016/j.envsci.2014.05.003.

Cox, L. (2020). Dispersal of flying-foxes from centre of Cairns “farcical”, wildlife groups say. The Guardian.

Čukić, A., Rakonjac, S., Djoković, R., Cincović, M., Bogosavljević-Bošković, S., Petrović, M., Savić, Ž., Andjušić, L., & Andjelić, B. (2023). Influence of Heat Stress on Body Temperatures Measured by Infrared Thermography, Blood Metabolic Parameters and Its Correlation in Sheep. *Metabolites*, *13*(8). https://doi.org/10.3390/metabo13080957.

Currey, K., Kendal, D., van der Ree, R., & Lentini, P. E. (2018). Land manager perspectives on conflict mitigation strategies for urban flying-fox camps. *Diversity*, *10*(2). https://doi.org/10.3390/D10020039.

Czenze, Z. J., Naidoo, S., Kotze, A., & McKechnie, A. E. (2020). Bat thermoregulation in the heat: Limits to evaporative cooling capacity in three southern African bats. *Journal of Thermal Biology*, *89*. https://doi.org/10.1016/j.jtherbio.2020.102542.

De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B. R., Hylander, K., Luoto, M., Vellend, M., Verheyen, K., & Lenoir, J. (2019). Global buffering of temperatures under forest canopies. *Nature Ecology and Evolution*, *3*(5), 744–749. https://doi.org/10.1038/s41559-019-0842-1.

De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B., Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A., Jucker, T., Klinges, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., & Meeussen, C. (2021). Forest microclimates and climate change: Importance, drivers and future research agenda. *Global Change Biology*, 27(11), 2279–2297. https://doi.org/10.1111/gcb.15569.

de Mel, R. K., Moseby, K. E., Stewart, K. A., Rankin, K. E., & Czenze, Z. J. (2024). The heat is on: Thermoregulatory and evaporative cooling patterns of desert-dwelling bats. *Journal of Thermal Biology*, *123*. https://doi.org/10.1016/j.jtherbio.2024.103919.

de Souza, B. C., Carvalho, E. C. D., Oliveira, R. S., de Araujo, F. S., de Lima, A. L. A., & Rodal, M. J. N. (2020). Drought response strategies of deciduous and evergreen woody species in a seasonally dry neotropical forest. *Oecologia*, *194*(1–2), 221–236. https://doi.org/10.1007/s00442-020-04760-3.

Department of Environment and Science. (2020). *Code of practice: Ecologically sustainable management of flying-fox roosts*. Department of Environment and Science.

Dey, S. (2015). Effect of heat wave on the Indian Flying-fox *Pteropus giganteus* (Mammalia: Chiroptera: Pteropodidae) population from Purulia District of West Bengal, India. *Journal of Threatened Taxa*, *7*(3), 7029–7033. https://doi.org/10.11609/jott.1905.7029-7033.

Díaz-Calafat, J., Uria-Diez, J., Brunet, J., De Frenne, P., Vangansbeke, P., Felton, A., Öckinger, E., Cousins, S. A. O., Bauhus, J., Ponette, Q., & Hedwall, P. O. (2023). From broadleaves to conifers: The effect of tree composition and density on understory microclimate across latitudes. *Agricultural and Forest Meteorology*, *341*. https://doi.org/10.1016/j.agrformet.2023.109684.

Dimande, P., Arrobas, M., & Rodrigues, M. Â. (2023). Under a Tropical Climate and in Sandy Soils, Bat Guano Mineralises Very Quickly, Behaving More like a Mineral Fertiliser than a Conventional Farmyard Manure. *Agronomy*, *13*(5). https://doi.org/10.3390/agronomy13051367.

Domeisen, D. I. V, Eltahir, A. B. E., Fischer, E. M., Knutti, R., Perkins-Kirkpatrick, S. E., Schar, C., Seneviratne, S. I., Weisheimer, A., & Wernli, H. (2023). Prediction and projection of heatwaves. *Nature Reviews Earth & Environment*, *4*, 36–50.

dos Santos, A. J., Vieira, T. B., & Faria, K. de C. (2016). Effects of vegetation structure on the diversity of bats in remnants of Brazilian Cerrado savanna. *Basic and Applied Ecology*, *17*(8), 720–730. https://doi.org/10.1016/j.baae.2016.09.004.

Duchicela, S. A., Cuesta, F., Tovar, C., Muriel, P., Jaramillo, R., Salazar, E., & Pinto, E. (2021). Microclimatic Warming Leads to a Decrease in Species and Growth Form Diversity: Insights from a Tropical Alpine Grassland. *Frontiers in Ecology and Evolution*, *9*. https://doi.org/10.3389/fevo.2021.673655.

Eby, P., & Law, B. (2008). Ranking the feeding habitats of Grey-headed flying-foxes for conservation management.

Edwards, K. L., Edes, A. N., & Brown, J. L. (2019). Stress, Well-Being and Reproductive Success. *Reproductive Sciences in Animal Conservation*, 91–162. https://doi.org/10.1007/978-3-030-23633-5_5.

Edzer Pebesma, by. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. *The R Journal*, *10*(1).

Elmore, R. D., Carroll, J. M., Tanner, E. P., Hovick, T. J., Grisham, B. A., Fuhlendorf, S. D., & Windels, S. K. (2017). Implications of the thermal environment for terrestrial wildlife management. *Wildlife Society Bulletin*, *41*(2), 183–193. https://doi.org/10.1002/wsb.772.

Enchéry, F., & Horvat, B. (2017). Understanding the interaction between henipaviruses and their natural host, fruit bats: Paving the way toward control of highly lethal infection in humans. *International Reviews of Immunology*, *36*(2), 108–121. https://doi.org/10.1080/08830185.2016.1255883.

Evans, L. C., Melero, Y., Schmucki, R., Boersch-Supan, P. H., Brotons, L., Fontaine, C., Jiguet, F., Kuussaari, M., Massimino, D., Robinson, R. A., Roy, D. B., Schweiger, O., Settele, J., Stefanescu, C., van Turnhout, C. A. M., & Oliver, T. H. (2022). Bioclimatic context of species' populations determines community stability. *Global Ecology and Biogeography*, *31*(8), 1542–1555. https://doi.org/10.1111/geb.13527.

Finocchiaro, M., Médail, F., Saatkamp, A., Diadema, K., Pavon, D., Brousset, L., & Meineri, E. (2024). Microrefugia and microclimate: Unraveling decoupling potential and resistance to heatwaves. *Science of the Total Environment*, *924*. https://doi.org/10.1016/j.scitotenv.2024.171696.

Fischer Verlag, G., Speakman, J. R., & Ward, S. (1998). Infrared thermography: principles and applications. In *ZOOLOGY* (Vol. 101).

Friedman, J., Hastie, T., & Tibshirani, R. (2010). Regularization Paths for Generalized Linear Models via Coordinate Descent. *Journal of Statistical Software*, *33*(1). https://doi.org/10.18637/jss.v033.i01.

Fuller, A., Mitchell, D., Maloney, S. K., Hetem, R. S., Fons ca, V. F. C., Meyer, L. C. R., Ven, T. M. F. N. V., & Snelling, E. P. (2021). How dryland mammals will respond to climate change: The effects of body size, heat load and a lack of food and water. *Journal of Experimental Biology*, *224*. https://doi.org/10.1242/jeb.238113.

Gao, X., Li, C., Cai, Y., Ye, L., Xiao, L., Zhou, G., & Zhou, Y. (2021). Influence of scale effect of canopy projection on understory microclimate in three subtropical urban broad-leaved forests. *Remote Sensing*, *13*(18). https://doi.org/10.3390/rs13183786.

Geoscience Australia. (2010). "ELVIS: ELVIS-Elevation and Depth – Foundation Spatial Data.

Ghalambor, C. K. (2006). Are mountain passes higher in the tropics? janzen's hypothesis revisited. *Integrative and Comparative Biology*, *46*(1), 5–17. https://doi.org/10.1093/icb/icj003.

Ghezzi, M. D., Napolitano, F., Casas-Alvarado, A., Hernández-Ávalos, I., Domínguez-Oliva, A., Olmos-Hernández, A., & Pereira, A. M. F. (2024). Utilization of Infrared Thermography in Assessing Thermal Responses of Farm Animals under Heat Stress. *Animals: An Open Access Journal from MDPI, 14*(4), 616. https://doi.org/10.3390/ani14040616.

Gibson, L., McNeill, A., Tores, P. de, Wayne, A., & Yates, C. (2010). Will future climate change threaten a range restricted endemic species, the quokka (*Setonix brachyurus*), in south west Australia? *Biological Conservation*, *143*(11), 2453–2461. https://doi.org/10.1016/j.biocon.2010.06.011.

González-Trujillo, J. D., Román-Cuesta, R. M., Muñiz-Castillo, A. I., Amaral, C. H., & Araújo, M. B. (2023). Multiple dimensions of extreme weather events and their impacts on biodiversity. In *Climatic Change* (Vol. 176, Issue 11). Springer Science and Business Media B.V. https://doi.org/10.1007/s10584-023-03622-0.

Gulraiz, T. L., Javid, A., Mahmood-Ul-Hassan, M., Maqbool, A., Ashraf, S., Hussain, M., & Daud, S. (2015). Roost characteristics and habitat preferences of Indian flying-fox (*Pteropus giganteus*) in urban areas of Lahore, Pakistan. *Turkish Journal of Zoology*, *39*(3), 388–394. https://doi.org/10.3906/zoo-1401-71.

Gyawali, A., Aalto, M., Peuhkurinen, J., Villikka, M., & Ranta, T. (2022). Comparison of Individual Tree Height Estimated from LiDAR and Digital Aerial Photogrammetry in Young Forests. *Sustainability (Switzerland), 14*(7). https://doi.org/10.3390/su14073720.

Hahn, M. B., Epstein, J. H., Gurley, E. S., Islam, M. S., Luby, S. P., Daszak, P., & Patz, J. A. (2014). Roosting behaviour and habitat selection of Pteropus giganteus reveal potential links to Nipah virus epidemiology. *Journal of Applied Ecology*, *51*(2), 376–387. https://doi.org/10.1111/1365-2664.12212.

Haight, J. D., Hall, S. J., Fidino, M., Adalsteinsson, S. A., Ahlers, A. A., Angstmann, J., Anthonysamy, W. J. B., Biro, E., Collins, M. K., Dugelby, B., Gallo, T., Green, A. M., Hartley, L., Jordan, M. J., Kay, C. A. M., Lehrer, E. W., Long, R. A., MacDougall, B., Magle, S. B., & Minier, D. E. (2023). Urbanization, climate and species traits shape mammal communities from local to continental scales. *Nature Ecology & Evolution*, 1–13. https://doi.org/10.1038/s41559-023-02166-x.

Hall, L. S., & Richards, G. (2000). *Flying-foxes and fruit and blossom bats of Australia*. University of New South Wales Press.

Han, Q., Sun, S., Liu, Z., Xu, W., & Shi, P. (2022). Accelerated exacerbation of global extreme heatwaves under warming scenarios. *International Journal of Climatology*, *42*(11), 5430–5441. https://doi.org/10.1002/joc.7541.

Hijmans, R. J. (2023). *The terra package*.

Hovick, T. J., Elmore, R. D., Wallred, B., Fuhlendorf, S. D., & Dahlgren, D. K. (2014). Landscapes as a moderator of thermal extremes: A case study from an imperiled grouse. *Ecosphere*, *5*(3). https://doi.org/10.1890/ES13-00340.1.

Huang, L., Liao, M., Liao, H., Liu, Z., Cai, H., Zhou, W., Xu, Z., Ouyang, K., Yang, W., & Jian, S. (2023). High phosphorus availability and low light intensity reduce the competitive ability of the invasive plant *Chromolaena odorata* in tropical coral islands. *Biological Invasions*. https://doi.org/10.1007/s10530-023-03186-1.

Huey, R. B., Kearney, M. R., Krockenberger, A., Holtum, J. A. M., Jess, M., & Williams, S. E. (2012). Predicting organismal vulnerability to climate warming: Roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1596), 1665–1679. https://doi.org/10.1098/rstb.2012.0005.

Ibáñez, C., Moreno-Manrique, M., Villagrá, A., Bueso-Ródenas, J., & Mínguez, C. (2024). Evaluation of Non-Contact Device to Measure Body Temperature in Sheep. *Animals*, *14*(1). https://doi.org/10.3390/ani14010098.

Ismaeel, A., Tai, A. P. K., Santos, E. G., Maraia, H., Aalto, I., Altman, J., Doležal, J., Lembrechts, J. J., Camargo, J. L., Aalto, J., Sam, K., Avelino do Nascimento, L. C., Kopecký, M., Svátek, M., Nunes, M. H., Matula, R., Plichta, R., Abera, T., & Maeda, E. E. (2024). Patterns of tropical forest understory temperatures. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-44734-0.

Jan, A., Arismendi, I., & Giannico, G. (2025). Double trouble for native species under climate change: habitat loss and increased environmental overlap with non-native species. *Global Change Biology*, *31*(1). https://doi.org/10.1111/gcb.70040.

Janzen, D. H. (1967). Why Mountain Passes are Higher in the Tropics WHY MOUNTAIN PASSES ARE HIGHER IN THE TROPICS*. In *Source: The American Naturalist* (Vol. 101, Issue 919).

Jason Bittel. (2019). *A Heat Wave in Australia Killed 23,000 Spectacled Flying-foxes*. NRDC. In: https://www.nrdc.org/stories/heat-wave-australia-killed-23000-spectacled-flying-foxes.

Jerem, P., Herborn, K., McCafferty, D., McKeegan, D., & Nager, R. (2015). Thermal imaging to study stress non-invasively in unrestrained birds. *Journal of Visualized Experiments, 2015*(105). https://doi.org/10.3791/53184.

Jiao, M., Zhou, W., Zheng, Z., Wang, J., & Qian, Y. (2017). Patch size of trees affects its cooling effectiveness: A perspective from shading and transpiration processes. *Agricultural and Forest Meteorology*, *247*, 293–299. https://doi.org/10.1016/j.agrformet.2017.08.013.

Kemppinen, J., Lembrechts, J. J., Koenraad Van Meerbeek, Jofre Carnicer, Nathalie Isabelle Chardon, Kardol, P., Lenoir, J., Liu, D., Maclean, I., Pergl, J., Saccone, P., Senior, R. A., Shen, T., Słowińska, S., Vigdis Vandvik, Jonathan von Oppen, Aalto, J., Ayalew, B., Bates, O., & Bertelsmeier, C. (2024). Microclimate, an important part of ecology and biogeography. *Global Ecology and Biogeography*, 33(6). https://doi.org/10.1111/geb.13834.

Kentwell, M. (2023). Flying-fox Management Strategy-Cairns LGA Community Life Branch.

Keppel, G., Stralberg, D., Morelli, T. L., & Bátori, Z. (2024). Managing climate-change refugia to prevent extinctions. *Trends in Ecology and Evolution, 39*(9), 800–808. https://doi.org/10.1016/j.tree.2024.05.002.

Kestrel Weather Meters. (2020). *Product Specifications for Kestrel Weather Meters, Model Numbers 1000-3550 SENSORS*.

Korn, L., Ngang, C., Ader, D. R., & Srean, P. (2023). Bat Guano Application Rate in Horticulture in Cambodia: An Experiment with Tomato. *Journal of Agricultural Science*, *15*(11), 24. https://doi.org/10.5539/jas.v15n11p24.

Kumar, R., & Elangovan, V. (2019). Effect of tree characteristics on roost selection of the Indian flying-fox, Pteropus giganteus. *Barbastella*, *12*(1). https://doi.org/10.14709/barbj.12.1.2019.13.

Lancaster, W. C., Thomson, S. C., & Speakman, J. R. (1997). Wing temperature in flying bats measured by infrared thermography. *Journal of Thermal Biology*, *22*(2), 109–116. https://doi.org/10.1016/S0306-4565(96)00039-3.

Lee, W. V. (2014). Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). *Natural Hazards*, *70*(2), 1453–1505. https://doi.org/10.1007/s11069-013-0884-7.

Lemenih, M., Gidyelew, T., & Teketay, D. (2004). Effects of canopy cover and understory environment of tree plantations on richness, density and size of colonizing woody species in southern Ethiopia. *Forest Ecology and Management*, *194*(1–3), 1–10. https://doi.org/10.1016/j.foreco.2004.01.050.

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., & Li, S. (2015). Local cooling and warming effects of forests based on satellite observations. *Nature Communications*, *6*. https://doi.org/10.1038/ncomms7603.

Li, Y., Fan, S., Li, K., Zhang, Y., & Dong, L. (2020). Microclimate in an urban park and its influencing factors: a case study of Tiantan Park in Beijing, China. *Urban Ecosystems*. https://doi.org/10.1007/s11252-020-01073-4.

Lopes, C., Firth, C., & Laurance, S. G. W. (2024). Occupancy of urban roosts by spectacled flying-foxes (*Pteropus conspicillatus*) is not affected by diurnal microclimate. *Austral Ecology*, *49*(2). https://doi.org/10.1111/aec.13487.

Lu, M., Wang, X., Ye, H., Wang, H., Qiu, S., Zhang, H., Liu, Y., Luo, J., & Feng, J. (2021). Does public fear that bats spread COVID-19 jeopardize bat conservation? *Biological Conservation, 254*. https://doi.org/10.1016/j.biocon.2021.108952.

Lunn, T. J., Eby, P., Brooks, R., McCallum, H., Plowright, R. K., Kessler, M. K., & Peel, A. J. (2021). Conventional wisdom on roosting behavior of Australian flying-foxes—A critical review, and evaluation using new data. *Ecology and Evolution*, *11*(19), 13532–13558. https://doi.org/10.1002/ece3.8079.

Luskin, M. S. (2010). Flying-foxes prefer to forage in farmland in a tropical dry forest landscape mosaic in Fiji. *Biotropica*, *42*(2), 246–250. https://doi.org/10.1111/j.1744-7429.2009.00577.x.

MacDonald, S. L., Bradford, M., McKeown, A., Vanderduys, E., Hoskins, A., & Westcott, D. (2021). Camp site habitat preferences of the little red flying-fox (*Pteropus scapulatus*) in Queensland. *Australian Journal of Zoology*, *68*(6), 234–253. https://doi.org/10.1071/ZO20079.

Machado, N. A. F., Da Costa, L. B. S., Barbosa-Filho, J. A. D., De Oliveira, K. P. L., De Sampaio, L. C., Peixoto, M. S. M., & Damasceno, F. A. (2021). Using infrared thermography to detect subclinical mastitis in dairy cows in compost barn systems. *Journal of Thermal Biology*, *97*. https://doi.org/10.1016/j.jtherbio.2021.102881.

Madala, M. F., Guna, C., Pradeepan, A., & Chalil, A. K. (2022). Roost tree characteristics of *Pteropus medius* (Chiroptera: Pteropodidae) in the midland laterite hillocks of northern Kerala, India. *Journal of Asia-Pacific Biodiversity*, *15*(4), 465–472. https://doi.org/10.1016/j.japb.2022.04.011.

Magnago, L. F. S., Rocha, M. F., Meyer, L., Martins, S. V., & Meira-Neto, J. A. A. (2015). Microclimatic conditions at forest edges have significant impacts on vegetation structure in large Atlantic Forest fragments. *Biodiversity and Conservation*, *24*(9), 2305–2318. https://doi.org/10.1007/s10531-015-0961-1.

Majumdar, K., Majumder, J., & Datta, B. K. (2016). Vegetation composition, structure and distribution status of trees used by two tropical fruit bat species in degraded habitats of Northeast India. *Zoology and Ecology*, *26*(2), 63–76. https://doi.org/10.1080/21658005.2016.1148978.

Marchin, R. M., Medlyn, B. E., Tjoelker, M. G., & Ellsworth, D. S. (2023). Decoupling between stomatal conductance and photosynthesis occurs under extreme heat in broadleaf tree species regardless of water access. *Global Change Biology*, *29*(22), 6319–6335. https://doi.org/10.1111/gcb.16929.

Markus, N., & Hall, L. (2004). Foraging behaviour of the black flying-fox (*Pteropus alecto*) in the urban landscape of Brisbane, Queensland. *Wildlife Research*, *31*(3), 345–355. https://doi.org/10.1071/WR01117.

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor e T. Waterfield (2018). An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *Cambridge University Press, Cambridge, UK and New York, NY, USA*, pp. 3-24. https://doi.org/10.1017/9781009157940.001.

McAlpine, C. A., Syktus, J., Ryan, J. G., Deo, R. C., McKeon, G. M., McGowan, H. A., & Phinn, S. R. (2009). A continent under stress: Interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology*, *15*(9), 2206–2223. https://doi.org/10.1111/j.1365-2486.2009.01939.x.

McCafferty, D. J., Gilbert, C., Paterson, W., Pomeroy, P. P., Thompson, D., Currie, J. I., & Ancel, A. (2011). Estimating metabolic heat loss in birds and mammals by combining infrared thermography with biophysical modelling. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 158(3), 337–345. https://doi.org/10.1016/j.cbpa.2010.09.012.

McCafferty, D. J., Gallon, S., & Nord, A. (2015). Challenges of measuring body temperatures of free-ranging birds and mammals. *Animal Biotelemetry*, *3*(1), 1–10. https://doi.org/10.1186/s40317-015-0075-2.

McGinn, K. A., Peery, M. Z., Zulla, C. J., Berigan, W. J., Wilkinson, Z. A., Barry, J. M., Keane, J. J., & Zuckerberg, B. (2023). A climate-vulnerable species uses cooler forest microclimates during heat waves. *Biological Conservation*, *283*. https://doi.org/10.1016/j.biocon.2023.110132.

McMichael, L., Mclean, J., Taylor, J., Martinez, Y., & Meers, J. (2023). Cleft Palate Syndrome in the Endangered Spectacled Flying-fox (*Pteropus conspicillatus*): Implications for Conservation and Comparative Research. *Veterinary Sciences*, *10*(1). https://doi.org/10.3390/vetsci10010038.

Mella, V. S. A., Cooper, C. E., Karr, M., Krockenberger, A., Madani, G., Webb, E. B., & Krockenberger, M. B. (2024). Hot climate, hot koalas: the role of weather, behaviour and disease on thermoregulation. *Conservation Physiology*, *12*(1). https://doi.org/10.1093/conphys/coae032.

Mo, M., & Roache, M. (2021). A review of intervention methods used to reduce flying-fox mortalities in heat stress events. *Australian Mammalogy*, *43*(2), 137–150. https://doi.org/10.1071/AM20038.

Mo, M., Roache, M., Davies, J., Hopper, J., Pitty, H., Foster, N., Guy, S., Parry-Jones, K., Francis, G., Koosmen, A., Colefax, L., Costello, C., Stokes, J., Curran, S., Smith, M., Daly, G., Simmons, C.-M., Hansen, R., Prophet, D., Welbergen, J. A. (2021). Estimating flying-fox mortality associated with abandonments of pups and extreme heat events during the austral summer of 2019–20. *Pacific Conservation Biology*. https://doi.org/10.1071/pc21003.

Morán-Ordóñez, A., Briscoe, N. J., & Wintle, B. A. (2018). Modelling species responses to extreme weather provides new insights into constraints on range and likely climate change impacts for Australian mammals. *Ecography*, *41*(2), 308–320. https://doi.org/10.1111/ecog.02850.

Mota-Rojas, D., Pereira, A. M. F., Wang, D., Martínez-Burnes, J., Ghezzi, M., Hernández-Avalos, I., Lendez, P., Mora-Medina, P., Casas, A., Olmos-Hernández, A., Domínguez, A., Bertoni, A., & Geraldo, A. de M. (2021). Clinical Applications and Factors Involved in Validating Thermal Windows Used in Infrared Thermography in Cattle and River Buffalo to Assess Health and Productivity. *Animals: An Open Access Journal from MDPI*, *11*(8), 2247. https://doi.org/10.3390/ani11082247.

Mota-Rojas, D., Titto, C. G., Orihuela, A., Martínez-Burnes, J., Gómez-Prado, J., Torres-Bernal, F., Flores-Padilla, K., Carvajal-de la Fuente, V., & Wang, D. (2021). Physiological and Behavioral Mechanisms of Thermoregulation in Mammals. *Animals*, *11*(6), 1733. https://doi.org/10.3390/ani11061733.

Mota-Rojas, D., Pereira, A. M. F., Martínez-Burnes, J., Domínguez-Oliva, A., Mora-Medina, P., Casas-Alvarado, A., Rios-Sandoval, J., de Mira Geraldo, A., & Wang, D. (2022). Thermal Imaging to Assess the Health Status in Wildlife Animals under Human Care: Limitations and Perspectives. *Animals*, *12*(24), 3558. https://doi.org/10.3390/ani12243558.

Murcia, C. (1995). Edge effects in fragmented forests: implications for conservation. *Trends in Ecology & Evolution* 10: 58-62. https://doi.org/10.1016/S0169-5347(00)88977-6.

Oksanen, J., Simpson GL, Blanchet FG, Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., & Evangelista, H. (2024). *"vegan": Community Ecology Package*. https://github.com/vegandevs/vegan.

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., Hole, D. G., Martin, T. G., Akçakaya, H. R., Corlett, R. T., Huntley, B., Bickford, D., Carr, J. A., Hoffmann, A. A., Midgley, G. F., Pearce-Kelly, P., Pearson, R. G., Williams, S. E., & Willis, S. G. (2015). Assessing species vulnerability to climate change. *Nature Climate Change*, *5*(3), 215–224. https://doi.org/10.1038/nclimate2448.

Páez, D. J., Restif, O., Eby, P., & Plowright, R. K. (2018). Optimal foraging in seasonal environments: Implications for residency of australian flying-foxes in food-subsidized

urban landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1745). https://doi.org/10.1098/rstb.2017.0097.

Palmer, C., Price, O., & Bach, C. (2000). Foraging ecology of the black flying-fox (*Pteropus alecto*) in the seasonal tropics of the Northern Territory, Australia. *Wildlife Research*, *27*(2), 169–178. https://doi.org/10.1071/WR97126.

Pandey, U., Wanwey, S. R., Gandhi, N., Ram, S., Borgaonkar, H. P., & Sangode, S. (2025). Tree growth responses to the climate variability within the Pir Panjal Range evidenced by tree-rings of Abies pindrow (Royle ex D. Don) Royle. *Theoretical and Applied Climatology*, *156*(2), 91. https://doi.org/10.1007/s00704-024-05302-0.

Parsons, J. G., Cairns, A., Johnson, C. N., Robson, S. K. A., Shilton, L. A., & Westcott, D. A. (2006). Dietary variation in spectacled flying-foxes (*Pteropus conspicillatus*) of the Australian Wet Tropics. *Australian Journal of Zoology*, *54*(6), 417–428. https://doi.org/10.1071/ZO06092.

Parsons, J. G., Robson, S. K. A., & Shilton, L. A. (2011). Roost fidelity in spectacled flying-foxes Pteropus conspicillatus: Implications for conservation and management. *Australian Zoologist*, *35*(SPEC. ISSUE), 66–71. https://doi.org/10.7882/fs.2011.009.

Passos, I., Figueiredo, A., Almeida, A. M., & Ribeiro, M. M. (2024). Uncertainties in Plant Species Niche Modeling under Climate Change Scenarios. *Ecologies*, *5*(3), 402–419. https://doi.org/10.3390/ecologies5030025.

Patten, M. A., & Smith-Patten, B. D. (2012). Testing the microclimate hypothesis: Light environment and population trends of Neotropical birds. *Biological Conservation*, *155*, 85–93. https://doi.org/10.1016/j.biocon.2012.06.004.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. In *Science* (Vol. 355, Issue 6332). *American Association for the Advancement of Science.* https://doi.org/10.1126/science.aai9214.

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, *39*(20). https://doi.org/10.1029/2012GL053361.

Perkins-Kirkpatrick, S. E., & Gibson, P. B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports, 7*(1). https://doi.org/10.1038/s41598-017-12520-2.

Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020). Increasing trends in regional heatwaves. *Nature Communications, 11*(1). https://doi.org/10.1038/s41467-020-16970-7.

Pincebourde, S., Murdock, C. C., Vickers, M., & Sears, M. W. (2016). Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integrative and Comparative Biology, 56*(1), 45–61. https://doi.org/10.1093/icb/icw016.

Playà-Montmany, N., & Tattersall, G. J. (2021). Spot size, distance and emissivity errors in field applications of infrared thermography. *Methods in Ecology and Evolution, 12*(5), 828-840. https://doi.org/10.1111/2041-210X.13563.

Plotly Technologies Inc. (2015). *Collaborative data science Publisher: Plotly Technologies Inc.*

Polato, Gill B.A., Shah, A.A., Gray, M.M., Casner, K.L., Barthelet, A., Messer, P.W., Simmons, M.P., Guayasamin, J.M., Encalada, A.C., Kondratieff, B.C., Flecker, A.S., Thomas, S.A., Ghalambor, C.K., LeRoy Poff, N., Funk, W.C. & Zamudio, K.R. (2018). Narrow thermal tolerance and low dispersal drive higher speciation in tropical mountains. *PNAS., 115*(49), 12471–12476. https://doi.org/10.5061/dryad.m728c47.

Preece, N. (2023). Spectacled Flying-fox conflicts—tucker, totem, taunt and threat. *Integrative Conservation, 2*(3), 112–118. https://doi.org/10.1002/inc3.26.

Preece, N. (2024). Endangered Spectacled Flying-fox: a review of past and current knowledge and future needs to re-start its recovery. *Australian Zoologist*. https://doi.org/10.7882/az.2024.007

R Core Team. (2023). *R: A Language and Environment for Statistical Computing* (4.2.2). R Foundation for Statistical Computing.

Rahman, M. A., Hartmann, C., Moser-Reischl, A., von Strachwitz, M. F., Paeth, H., Pretzsch, H., Pauleit, S., & Rötzer, T. (2020). Tree cooling effects and human thermal comfort under contrasting species and sites. *Agricultural and Forest Meteorology*, 287. https://doi.org/10.1016/j.agrformet.2020.107947.

Rajasegaran, P., Shazali, N., & Khan, F. A. A. (2018). Microclimate and Physiological Effects in the Roosts of Cave Dwelling Bats: Implications in Roost Selection and Conservation in Sarawak, Malaysian Borneo. *Zoological Science*, *35*(6), 521–527. https://doi.org/10.2108/zs170144.

Rakoto, P. Y., Deilami, K., Hurley, J., Amati, M., & Sun, Q. (Chayn). (2021). Revisiting the cooling effects of urban greening: Planning implications of vegetation types and spatial configuration. *Urban Forestry and Urban Greening*, *64*. https://doi.org/10.1016/j.ufug.2021.127266.

Ramsay, E. E., Duffy, G. A., Burge, K., Taruc, R. R., Fleming, G. M., Faber, P. A., & Chown, S. L. (2023). Spatio-temporal development of the urban heat island in a socioeconomically diverse tropical city. *Environmental Pollution*, *316*. https://doi.org/10.1016/j.envpol.2022.120443.

Randle, M., Stevens, N., & Midgley, G. (2018). Comparing the differential effects of canopy shading by Dichrostachys cinerea and Terminalia sericea on grass biomass. *South African Journal of Botany*, *119*, 271–277. https://doi.org/10.1016/j.sajb.2018.09.026.

Ranius, T., Gibbons, P., & Lindenmayer, D. (2024). Habitat requirements of deadwood-dependent invertebrates that occupy tree hollows. *Biological Reviews*. https://doi.org/10.1111/brv.13110.

Ratcliffe, J. M., & Ter Hofstede, H. M. (2005). Roosts as information centres: Social learning of food preferences in bats. *Biology Letters*, *1*(1), 72–74. https://doi.org/10.1098/rsbl.2004.0252.

Ratnayake, H. U., Kearney, M. R., Govekar, P., Karoly, D., & Welbergen, J. A. (2019). Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, *22*(4), 386–395. https://doi.org/10.1111/acv.12476.

Ratnayake, H. U., Welbergen, J. A., Van Der Ree, R., & Kearney, M. R. (2021). Variation in fur properties may explain differences in heat-related mortality among Australian flying-foxes. *Australian Journal of Zoology*, *68*(6), 285–295. https://doi.org/10.1071/ZO20040.

Richards, G. (1990). The spectacled flying-fox, *Pteropus conspicillatus* (Chiroptera: Pteropodidae), in north Queensland. 2. Diet, seed dispersal and feeding ecology. *Australian Mammalogy*, *13* (April 1981), 25–31.

Richards, G. C. (1990). The spectacled flying-fox, *Pteropus conspicillatus*, (Chiroptera: Pteropodidae) in North Queensland 1. Roost sites and distribution patterns. *Australian Mammalogy*, *13*, 17–24.

Roberts, B. J., Catterall, C. P., Eby, P., & Kanowski, J. (2012). Long-distance and frequent movements of the flying-fox *Pteropus poliocephalus*: Implications for management. *PLoS ONE*, *7*(8). https://doi.org/10.1371/journal.pone.0042532.

Roberts, B., Eby, P. &, Westcott, D. (2020). *Pteropus conspicillatus*, Spectacled Flying-fox. https://doi.org/10.2305/IUCN.UK.2020.

Roberts, B. J., Mo, M., Roache, M., & Eby, P. (2021). Review of dispersal attempts at flying-fox camps in Australia. In *Australian Journal of Zoology 68*(6), 254–27. https://doi.org/10.1071/ZO20043.

Roussel, J.-R., Auty, D., Coops, N. C., Tompalski, P., Goodbody, T. R. H., Meador, A. S., Bourdon, J.-F., de Boissieu, F., & Achim, A. (2020). lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. *Remote Sensing of Environment*, *251*, 112061. https://doi.org/10.1016/j.rse.2020.112061.

Roy, K., Saha, G. K., & Mazumdar, S. (2020). Seasonal influence on the diurnal roosting behaviour of free-ranging Indian flying-fox *Pteropus giganteus* in an urban landscape, India. *Biologia*, *75*(11), 1955–1961. https://doi.org/10.2478/s11756-020-00472-4.

Rubalcaba, J. G., Gouveia, S. F., Villalobos, F., Cruz-Neto, A. P., Castro, M. G., Amado, T. F., Martinez, P. A., Navas, C. A., Dobrovolski, R., Alexandre Felizola Diniz-Filho, J., & Olalla-T arraga, M. A. (2022). *Physical constraints on thermoregulation and flight drive morphological evolution in bats.* https://doi.org/10.1073/pnas.

Rummel, A. D., Swartz, S. M., & Marsh, R. L. (2019). Warm bodies, cool wings: Regional heterothermy in flying bats. *Biology Letters*, *15*(9). https://doi.org/10.1098/rsbl.2019.0530.

Santos, E. G., Svátek, M., Nunes, M. H., Aalto, J., Senior, R. A., Matula, R., Plichta, R., & Maeda, E. E. (2024). Structural changes caused by selective logging undermine the thermal buffering capacity of tropical forests. *Agricultural and Forest Meteorology*, *348*. https://doi.org/10.1016/j.agrformet.2024.109912.

Scheffers, B. R., Edwards, D. P., Diesmos, A., Williams, S. E., & Evans, T. A. (2014). Microhabitats reduce animal's exposure to climate extremes. *Global Change Biology*, *20*(2), 495–503. https://doi.org/10.1111/gcb.12439.

Scheffers, B. R., Edwards, D. P., Macdonald, S. L., Senior, R. A., Andriamahohatra, L. R., Roslan, N., Rogers, A. M., Haugaasen, T., Wright, P., & Williams, S. E. (2017). Extreme thermal heterogeneity in structurally complex tropical rain forests. *Biotropica*, *49*(1), 35–44. https://doi.org/10.1111/btp.12355.

Seidel, S. D., & Yang, D. (2020). The lightness of water vapor helps to stabilize tropical climate. In *Sci. Adv* (Vol. 6). https://www.science.org.

Seuront, L., Ng, T. P. T., & Lathlean, J. A. (2018). A review of the thermal biology and ecology of molluscs, and of the use of infrared thermography in molluscan research. *Journal of Molluscan Studies*, *84*(3), 203–232. https://doi.org/10.1093/mollus/eyy023.

Sharmin, M., Tjoelker, M. G., Pfautsch, S., Esperon-Rodriguez, M., Rymer, P. D., & Power, S. A. (2023). Tree crown traits and planting context contribute to reducing urban heat. Urban Forestry & Urban Greening, 83, 127913. https://doi.org/10.1016/j.ufug.2023.127913.

Shields, T. (2014). Key Components for a Flying-fox Management Plan to cover Ipswich City Council.

Smith-Tripp, S. M., Eskelson, B. N. I., Coops, N. C., & Schwartz, N. B. (2022). Canopy height impacts on the growing season and monthly microclimate in a burned forest of British Columbia, Canada. *Agricultural and Forest Meteorology*, *323*. https://doi.org/10.1016/j.agrformet.2022.109067.

Smyser, T. J., Hardy, M. A., Davis, A. J., Preston, W. L., & Tietje, W. D. (2024). Downed wood removal effects on survival and site fidelity of woodrats in a California oak woodland. *Journal of Wildlife Management*, *88*(5). https://doi.org/10.1002/jwmg.22590.

Snoyman, S., & Brown, C. (2010). Microclimate preferences of the grey-headed flying-fox (*Pteropus poliocephalus*) in the Sydney region. *Australian Journal of Zoology*, *58*(6), 376–383. https://doi.org/10.1071/ZO10062.

Soravia, C., Ashton, B. J., Thornton, A., & Ridley, A. R. (2021). The impacts of heat stress on animal cognition: Implications for adaptation to a changing climate. *WIREs Climate Change*, *12*(4). https://doi.org/10.1002/wcc.713.

Species Profile and Threats Database. (2025). *Pteropus conspicillatus* - Spectacled flying-fox. Species Profile and Threats Database - Department of Climate Change, Energy, the Environment and Water.

Staff, N. R. Council. (1995). *Effects of Past Global Change on Life*. National Academies Press. https://www.ncbi.nlm.nih.gov/books/NBK231950/https://www.ncbi.nlm.nih.gov/books/NBK231950/

Stanvic, S., Mcdonald, V., & Collins, L. (2013). *Managing Heat Stress in Flying-foxes Colonies*.

Steffen, W., Hughes, L., & Perkins, S. (2014). Heatwaves: Hotter, Longer, More Often. http://www.climatecouncil.org.au/uploads/9901f6614a2cac7b2b888f55b4dff9cc.pdf.

Stevens, G. C. (1989). The Latitudinal Gradient in Geographical Range: How so Many Species Coexist in the Tropics. In *Source: The American Naturalist* (Vol. 133, Issue 2). https://about.jstor.org/terms.

Suggitt, A. J., Gillingham, P. K., Hill, J. K., Huntley, B., Kunin, W. E., Roy, D. B., & Thomas, C. D. (2011). Habitat microclimates drive fine-scale variation in extreme temperatures. *Oikos*, *120*(1), 1–8. https://doi.org/10.1111/j.1600-0706.2010.18270.x.

Tait, J., Perotto-Baldivieso, H. L., McKeown, A., & Westcott, D. A. (2014). Are flying-foxes coming to town? Urbanisation of the spectacled flying-fox (*Pteropus conspicillatus*) in Australia. *PLoS ONE*, *9*(10). https://doi.org/10.1371/journal.pone.0109810.

Tattersall, G. J. (2016). Infrared thermography: A non-invasive window into thermal physiology. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology*, 202, 78–98. https://doi.org/10.1016/j.cbpa.2016.02.022.

Tay, J. K., Narasimhan, B., & Hastie, T. (2023). Elastic Net Regularization Paths for All Generalized Linear Models. *Journal of Statistical Software*, *106*(1). https://doi.org/10.18637/jss.v106.i01.

Team. R Core. (2021). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*.

Terschanski, J., Nunes, M. H., Aalto, I., Pellikka, P., Wekesa, C., & Maeda, E. E. (2024). The role of vegetation structural diversity in regulating the microclimate of human-modified tropical ecosystems. *Journal of Environmental Management*, *360*. https://doi.org/10.1016/j.jenvman.2024.121128.

Threatened species & ecological communities (2019). *Conservation Advice Pteropus conspicillatus spectacled flying-fox*. http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl.

Tidemann, C. R., & Nelson, J. E. (2011). Life expectancy, causes of death and movements of the grey-headed flying-fox (*Pteropus poliocephalus*) inferred from banding. *Acta Chiropterologica*, *13*(2), 419–429. https://doi.org/10.3161/150811011X624901.

TSSC - Threatened Species Scientific Committee (2021). *Pteropus poliocephalus (*Grey-headed Flying-fox) - Advice to the Minister for the Environment and Heritage from the Threatened Species Scientific Committee (TSSC) on Amendments to the list of Threatened Species under the Environment Protection and Biodiversity Conservation *Act 1999 (EPBC Act)*. Department of Climate Change, Energy, the Environment and Water. https://www.dcceew.gov.au/environment/biodiversity/threatened/conservation-advices/pteropus-poliocephalus.

Timmiss, L. A., Martin, J. M., Murray, N. J., Welbergen, J. A., Westcott, D., McKeown, A., & Kingsford, R. T. (2021). Threatened but not conserved: Flying-fox roosting and foraging habitat in Australia. *Australian Journal of Zoology*, *68*(6), 226–233. https://doi.org/10.1071/ZO20086.

Turtle Tough. (n.d.). *Infrared Report Express* (2.1.5.0).

Ummenhofer, C. C., & Meehl, G. A. (2017). Extreme weather and climate events with ecological relevance: A review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1723). https://doi.org/10.1098/rstb.2016.0135.

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571–573. https://doi.org/10.1126/science.aaa4984.

Usamentiaga, R., Venegas, P., Guerediaga, J., Vega, L., Molleda, J., & Bulnes, F. (2014). Infrared Thermography for Temperature Measurement and Non-Destructive Testing. *Sensors*, 14(7), 12305–12348. https://doi.org/10.3390/s140712305.

van den Boogaart, K. G., & Tolosana-Delgado, R. (2008). "compositions": A unified R package to analyze compositional data. *Computers and Geosciences*, *34*(4), 320–338. https://doi.org/10.1016/j.cageo.2006.11.017.

Varner, J., & Dearing, M. D. (2014). The Importance of Biologically Relevant Microclimates in Habitat Suitability Assessments. *PLoS ONE*, *9*(8), 104648. https://doi.org/10.1371/journal.pone.0104648.t001.

van Dyk, M., Noakes, M. J., & McKechnie, A. E. (2019). Interactions between humidity and evaporative heat dissipation in a passerine bird. *Journal of Comparative*

Physiology B: Biochemical, Systemic, and Environmental Physiology, *189*(2), 299–308. https://doi.org/10.1007/s00360-019-01210-2.

Vinod, N., Slot, M., McGregor, I. R., Ordway, E. M., Smith, M. N., Taylor, T. C., Sack, L., Buckley, T. N., & Anderson-Teixeira, K. J. (2022). Thermal sensitivity across forest vertical profiles: patterns, mechanisms, and ecological implications. *New Phytologist.* https://doi.org/10.1111/nph.18539.

Wagner, B., Baker, P. J., Stewart, S. B., Lumsden, L. F., Nelson, J. L., Cripps, J. K., Durkin, L. K., Scroggie, M. P., & Nitschke, C. R. (2020). Climate change drives habitat contraction of a nocturnal arboreal marsupial at its physiological limits. *Ecosphere*, *11*(10). https://doi.org/10.1002/ecs2.3262.

Wang, F. K., Shih, J. Y., Juan, P. H., Su, Y. C., & Wang, Y. C. (2021). Non-invasive cattle body temperature measurement using infrared thermography and auxiliary sensors. *Sensors*, *21*(7). https://doi.org/10.3390/s21072425.

Wang, X., Rahman, M. A., Mokroš, M., Rötzer, T., Pattnaik, N., Pang, Y., Zhang, Y., Da, L., & Song, K. (2023). The influence of vertical canopy structure on the cooling and humidifying urban microclimate during hot summer days. *Landscape and Urban Planning*, *238*. https://doi.org/10.1016/j.landurbplan.2023.104841.

Warneke, C., Brudvig, L. A., Gregg, M., McDaniel, S., & Yelenik, S. (2023). Elevation, canopy cover and grass cover structure patterns of seedling establishment in a subtropical post-fire restoration. *Ecological Solutions and Evidence*, *4*(4). https://doi.org/10.1002/2688-8319.12280.

Welbergen, J. A., Klose, S. M., Markus, N., & Eby, P. (2008). Climate change and the effects of temperature extremes on Australian flying-foxes. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1633), 419–425. https://doi.org/10.1098/rspb.2007.1385.

Welbergen, J. (2012). The impacts of extreme events on biodiversity - lessons from die-offs in flying-foxes. *Proceedings of the International Symposium on the Importance of Bats as Bioindicators*, *December*, 60–64.

Welbergen, J. A., Meade, J., Field, H. E., Edson, D., McMichael, L., Shoo, L. P., Praszczalek, J., Smith, C., & Martin, J. M. (2020). Extreme mobility of the world's largest flying mammals creates key challenges for management and conservation. *BMC Biology*, *18*(1), 1–13. https://doi.org/10.1186/s12915-020-00829-w.

Welman, S., Tuen, A. A., & Lovegrove, B. G. (2017). Using thermoregulatory profiles to assess climate change vulnerability in an arboreal tropical bat: Heterothermy may be a pre-adaptive advantage. *Climate Research*, *74*(2), 161–170. https://doi.org/10.3354/cr01496.

Whittaker, A. L., Muns, R., Wang, D., Martínez-Burnes, J., Hernández-Ávalos, I., Casas-Alvarado, A., Domínguez-Oliva, A., & Mota-Rojas, D. (2023). Assessment of Pain and Inflammation in Domestic Animals Using Infrared Thermography: A Narrative Review. *Animals*, *13*(13), 2065–2065. https://doi.org/10.3390/ani13132065.

Wickham H. (2016). ggplot2: Elegant Graphics for Data Analysis. *Springer-Verlag New York.*

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., & Takahashi, K. (2019). Welcome to the Tidyverse. *Journal of Open-Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686.

Wiens, J. J. (2016). Climate-related local extinctions are already widespread among plant and animal species. *PLoS Biology*, *14*(12). https://doi.org/10.1371/journal.pbio.2001104.

Wolfe, J. D., Luther, D. A., Jirinec, V., Collings, J., Johnson, E. I., Bierregaard, R. O., & Stouffer, P. C. (2025). Climate change aggravates bird mortality in pristine tropical forests. *Science Advances*, *11*, 8086. https://www.science.org.

Wood N., S. (2017). GAMs in Practice: mgcv. In *Generalized Additive Models* (2nd ed., pp. 325–398). CRC Press. https://doi.org/https://doi.org/10.1201/9781315370279.

Wujeska-Klause, A., & Pfautsch, S. (2020). The Best Urban Trees for Daytime Cooling Leave Nights Slightly Warmer. *Forests*, *11*(9), 945. https://doi.org/10.3390/f11090945.

Yabsley, S. H., Meade, J., Martin, J. M., & Welbergen, J. A. (2021). Human-modified landscapes provide key foraging areas for a threatened flying mammal: The grey-headed flying-fox. *PLoS ONE*, *16*(November). https://doi.org/10.1371/journal.pone.0259395.

Yin, Y., Li, S., Xing, X., Zhou, X., Kang, Y., Hu, Q., & Li, Y. (2024). Cooling Benefits of Urban Tree Canopy: A Systematic Review. *Sustainability*, *16*(12), 4955. https://doi.org/10.3390/su16124955.

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., & Vejre, H. (2020). Critical review on the cooling effect of urban blue-green space: A threshold-size perspective. In *Urban Forestry*

and Urban Greening (Vol. 49). Elsevier GmbH. https://doi.org/10.1016/j.ufug.2020.126630.

Zhang, Z., Lv, Y., & Pan, H. (2013). Cooling and humidifying effect of plant communities in subtropical urban parks. *Urban Forestry and Urban Greening*, *12*(3), 323–329. https://doi.org/10.1016/j.ufug.2013.03.010.

Zhao, K., & Jackson, R. B. (2014). Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecological Monographs*, *84*(2), 329–353. https://doi.org/10.1890/12-1705.1.

Zheng, S., Zhou, C., Jiang, X., Huang, J., & Xu, D. (2022). Progress on Infrared Imaging Technology in Animal Production: A Review. *Sensors*, *22*(3), 705. https://doi.org/10.3390/s22030705.

Ziter, C. D., Pedersen, E. J., Kucharik, C. J., & Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(15), 7575–7580. https://doi.org/10.1073/pnas.1817561116.

APPENDIX A

Supplementary Material to Chapter 1

Supplementary Table:

The urban roost locations of spectacled flying-foxes and their area in Cairns.

Roost site	Coordinates	Area (ha)
Bulimba Crescent, Mount Sheridan	-16.9995, 145.7378	1.70
Cairns Cemetery (Relocation site)	-16.9099, 145.7523	24.20
Cairns Central Swamp (Relocation site)	-16.9175, 145.7522	36.90
Cairns Villas	-16.9223, 145.7416	2.52
Chay Road, Edmonton	-17.0300, 145.7346	2.90
Dunn Street Cairns North	-16.9156, 145.7632	0.70
Farmer Street, Edmonton	-17.0277, 145.7475	1.60
Goomboora Park, Brinsmead	-16.9039, 145.7041	31.90
Gordonvale SHS, Gordonvale	-17.0927, 145.7761	5.00
Guginy Reserve, Manunda	-16.9196, 145.7438	2.00
Harwood Close, Brinsmead	-16.9048, 145.7151	3.50
Henley Street Park, Earlville	-16.9480, 145.7366	0.90
Holloways	-16.8473, 145.7343	42.20
Kewarra Resort	-16.7765, 145.6810	16.00
Les Davies Park, North Cairns	-16.9068, 145.7611	2.70
Lily Creek, Parramatta Park	-16.9182, 145.7647	0.70
Loridan Drive, Brinsmead	-16.8952, 145.7124	1.70
Minnie Street, Parramatta Park	-16.9204, 145.7668	0.60
Quail Close, Woree	-16.9723, 145.7414	0.80
Waratah Dr	-16.9251, 145.7431	0.46

APPENDIX B

Supplementary Material to Chapter 5

Recording body temperature in spectacled flying-foxes, a thermal image approach

Objective: Validate the relationship between iButtons and thermal image cameras using a test body in a controlled and wild environment and analyse the influence of ambient temperature and humidity on the thermal camera reading.

Methods: The iButtons were used as benchmarks when comparing the measurements with a handheld thermal camera. A handheld meteorological station was used to record the environmental variables influencing the radioactive heat captured by the infrared thermography.

Results: There is a stronger correlation between the thermal camera temperature and iButton measurements in lower temperatures, but the agreement tends to cease after 35°C.

Introduction

Body temperature is a relevant marker on an animal wellbeing as it reflects physiological status and potential stress responses. Thermoregulatory responses can be triggered not only by fluctuations in environmental temperature but also by various physiological conditions, such as age, fasting, food consumption, stress, and inflammation. These factors can lead to alterations in internal body temperature, which in turn affect the temperature at the body's surface (McCafferty 2007; Schou et al. 2021; Arfuso et al. 2022; Lezama-García et al. 2022; Wang et al. 2023).

There are two main methodologies to assess body temperatures, contact-based and non-contact-based methods. Rectal thermometry is the standard method for veterinary patients(Smith et al., 2023).

Infrared thermography has been used as an alternative to invasive methods in farm and captive animals (Adam et al. 2018; Brcko et al. 2020; Bleul et al. 2021; Wang et al. 2021; Ghezzi et al. 2024);.

In body measurements are too stressful when analysing spectacled flying-foxes, as the species is endangered. To evaluate a bat body temperature, the capture effort could cause distress into the individual and in the entire group, as they are social gathered animals easily disturbed.

During the past few years, the number of heat stress events involving flying-foxes, and, specifically spectacled flying-foxes, led us to pursue a non-invasive methodology capable of monitoring their temperature during the hottest months of the year.

This study aims to compare the temperature registered by data-loggers against the temperature recorded by the infrared thermal camera.

Methods

Thermal camera

The thermal infrared (TIR) camera (384iM Thermal Imaging Camera, Turtle Tough) is equipped with uncooled micro-bolometer sensors and converts infrared radiation readings into temperatures within the –20 to 150 °C range. TIR images were analyzed under the assumption of a uniform emissivity value of 0.98 across all surfaces. This constant was adopted when examining variations in spatial thermal heterogeneity with the TIR. I estimated differences in relative temperatures across images of the same surface captured from various distances. For this purpose, we are confident that potential emissivity variations within the scenes did not cause the bias we observed (Faye et al., 2016). The TIR camera was equipped with a 384x288 pixels micro-bolometer focal plane array (384iM Thermal Imaging Camera, Turtle Tough, (© 2024 Turtle Tough Pty Ltd. All 2024).

iButton

The iButton captures the test-body temperature primarily through conduction, where the heat from the test body is transferred directly to the sensor. This heat transfer causes a change in the sensor's properties, which is then read and recorded as temperature. In this study, we used DS1922E-F5 (Thermochron iButton 15°C thru +140°C) (Maxim Integrated Products, 2013).

Device testing

We performed three experiments to examine the effects of climate and distance on thermal estimates from the TIR camera. Two indoor experiments were in the controlled environment facilities at the Environmental Research Complex (James Cook University, Cairns, Australia) and one outdoor experiment was undertaken on JCU campus under similar environmental conditions to the bat roosts during the summer months.

A flying-fox model was created with a test body of similar size made from a silicone ice/hot gel pack, painted with matte black spray paint, and fixed with a peg in a PVC pipe. The test body had an iButton fixed to the front and the back. The back iButton registered the contact temperature without the incidence of any external heat source or wind. The iButtons were covered by tape to avoid direct sunlight and interference with the thermal image capture due to their high reflectance.

The first experiment simulated the effects of a tropical environment on the bat model, with high temperature and high humidity, (39.2 ◦C and 75% relative humidity) similar to the conditions recorded during field surveys. The test body was acclimatized for 1 hour prior to study. The second experiment simulated a hot, dry environment with high temperature and low humidity environment, (39.2 ◦C and 33% relative humidity). Due to the limitations of the facilities, the thermal images from all the indoor experiments were captured at 3m from the test body.

We examined the effects of distance on TIR thermal values by capturing images of the flying-fox model at every 1 m from 1-10 m and at 15 and 18 m. The experiment was performed outdoors during the summer between 11 am and 2 pm, simulating the field surveys.

Results

Glasshouse results

For the glasshouse we performed 3 pictures of the test body in each of the conditions with a total of 9 points per condition for the test body and 30 points per condition of the background.

To understand the influence of each variable on the thermal image readings, we performed a correlation. A strong positive correlation ($r = 0.701$, $p < 0.0001$) was observed between thermal image and iButton temperatures. A strong negative correlation ($r = -0.680$, $p < 0.0001$) was verified between thermal image and humidity, indicating that higher humidity levels are associated with lower thermal image temperatures in a controlled environment (Figure 1).

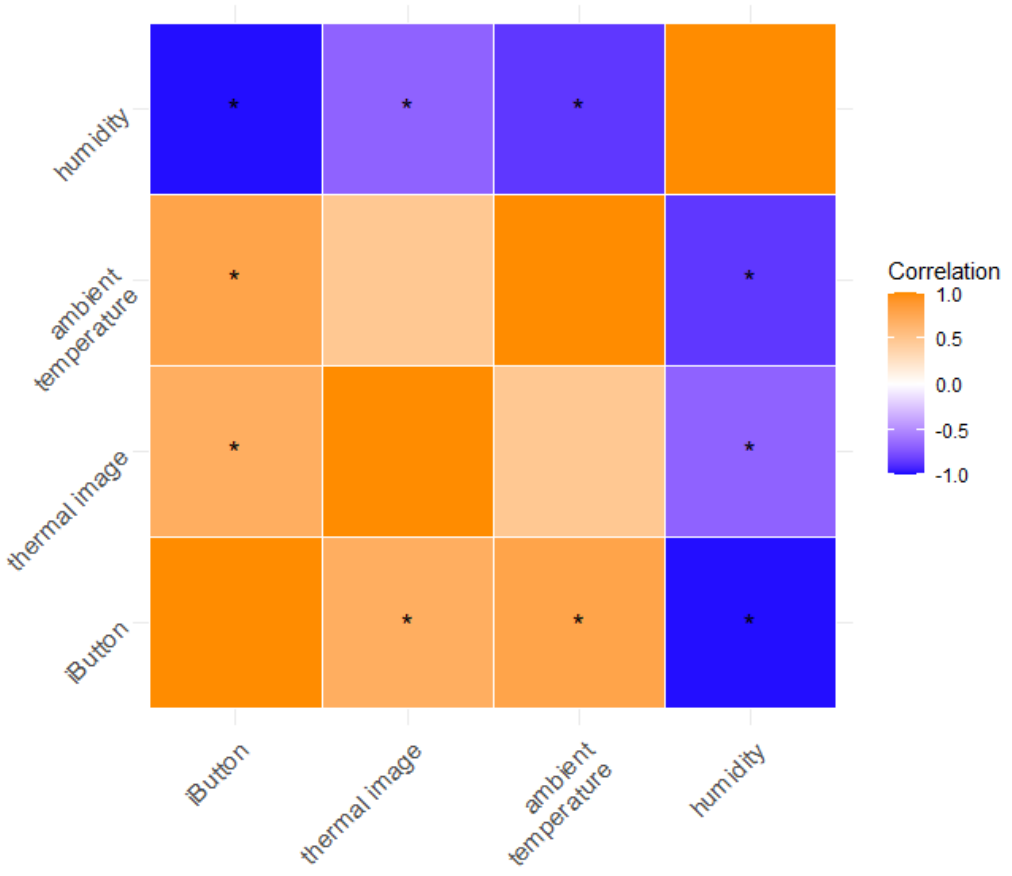


Figure 1: Correlation map between ambient variables and temperature readings for the glasshouse experiment. The (*) identify the correlations where $r > 0.5$ and $p < 0.05$ and where $-0.5 > r > -1.0$, concomitantly.

Still, we tested the difference in temperature readings in thermal image ($t = -5.0$, $df = 17.8$, $p < 0.01$) and iButton ($t = -21.6$, $df = 9$, $p < 0.01$) in the two different conditions established in the glasshouse and they were significant and corroborate the correlation result (Figure 2).

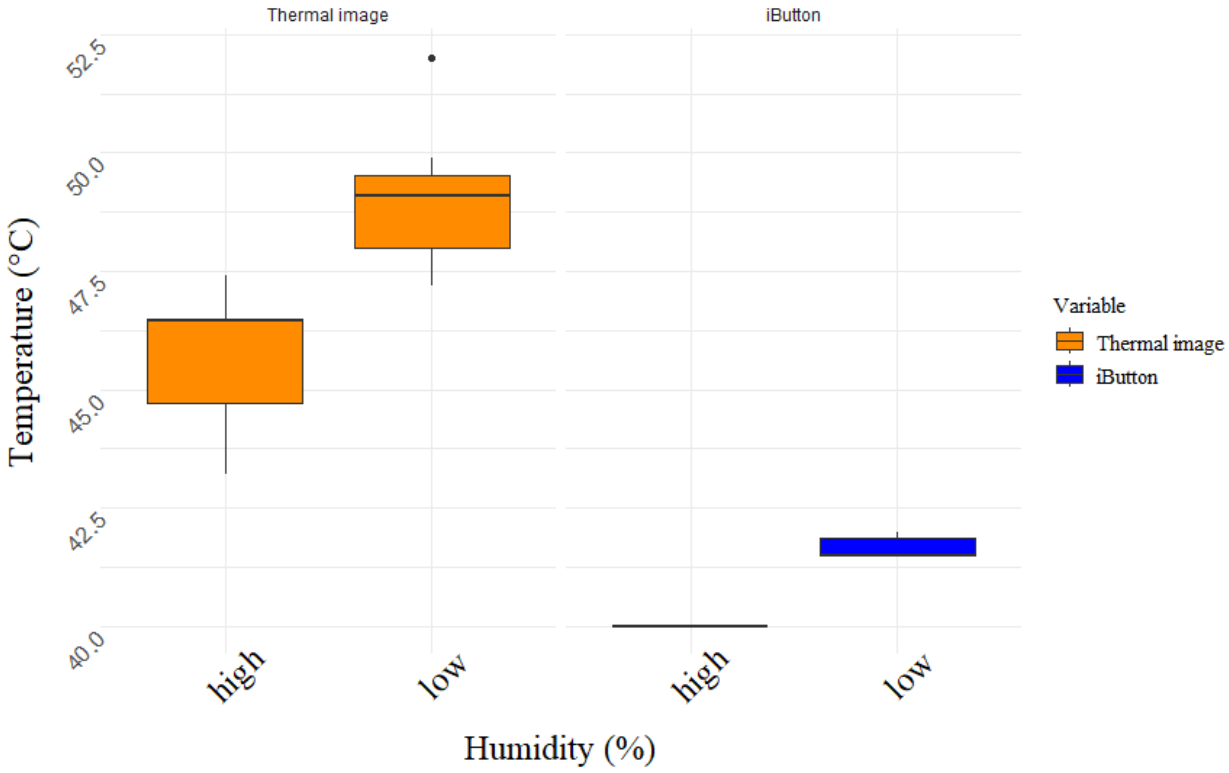


Figure 2: Boxplot displaying median and interquartile range of thermal image temperature and iButton temperature in two humidity conditions, low and high.

The GLM analysis revealed that the average temperature measured the *i*Buttons was a significant predictor of the average temperature capture using thermal imaging. The iButton was highly significant ($B = 1.767$, $SE = 0.234$, $t(59) = 7.552$, $p < .001$) on predicting the temperatures registered by the thermal camera. Specifically, for each unit increase in the iButton, there was an associated increase of 1.767 units in thermal imaging ($p < .001$) (Figure 3).

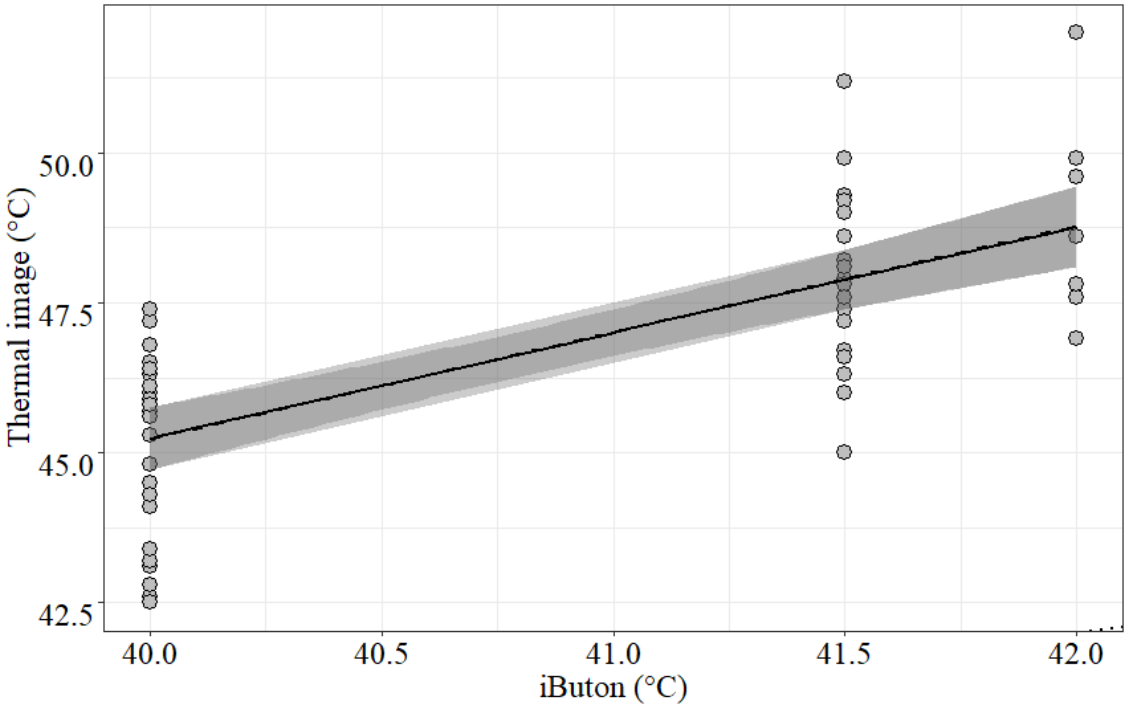


Figure 3: Generalised linear model plot evidencing a smaller variation in thermal image when iButton registers the lower temperatures (42.5-47.5°C) when compared to the variation (46-54°C) when the logger temperatures are higher.

To understand the impact of ambient temperature and humidity in the observed pattern, we examined the influence of ambient temperature and humidity in the thermal image readings.

We used Non-metric Multidimensional Scaling (NMDS) to address multicollinearity between the two methodologies and the ambient variables. NMDS1 as significantly correlated with ambient temperature (r = 0.85) and iButton (r = 0.75), and inversely with relative humidity (r = -0.65) (Figure 4A).

Both axes significantly relate to thermal image temperature, with higher temperatures and lower humidity driving higher thermal readings.

As the Generalized Linear Model (GLM) represented better the agreement between the two devices, we also used this model to explain a significant non-linear relationship between NMDS1 and thermal image temperature (R^2=0.42, p<0.001) (Figure 4B), with the model explaining 51.3 % of the variance in thermal image (R^2=0.51, p<0.001).

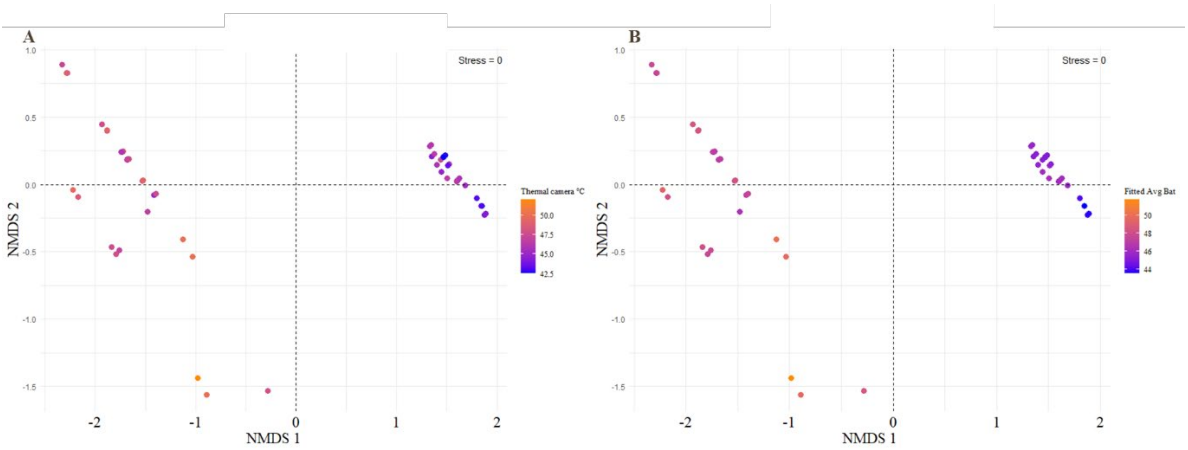


Figure 4: Non-metric Multidimensional Scaling (NMDS) plot showing the relationship between NMDS1 and NMDS2 axes, with points coloured according to the thermal camera temperature (°C). A- Coloured according to actual average bat temperature, B- Coloured according fitted average bat temperature derived from the Generalized Linear Model (GLM).

External validation

The external experiment had one more variable, the distance between the camera and the test body. This experiment aims to validate the measurements taken in the field, as the camera was exposed to a variable microclimate condition. We performed a correlation analysis to evaluate the impact and significance of each variable on the thermal image reading and the relationship between the thermal image and the iButton temperature. A strong positive correlation ($r = 0.86$, $p < 0.0001$) was found between thermal image and iButton temperatures, indicating a reliable relationship between the two devices. A strong negative correlation ($r = -0.84$, $p < 0.0001$) was observed between thermal image temperature and distance, suggesting that greater distances are associated with lower thermal image readings. Lastly, a strong positive correlation ($r = 0.88$, $p < 0.001$) was identified between thermal image and humidity, suggesting that higher humidity levels are associated with higher thermal image temperatures. These findings highlight the significant impact of environmental conditions and distance on thermal image readings, with ambient temperature having a relatively minor negative effect (Figure 5).

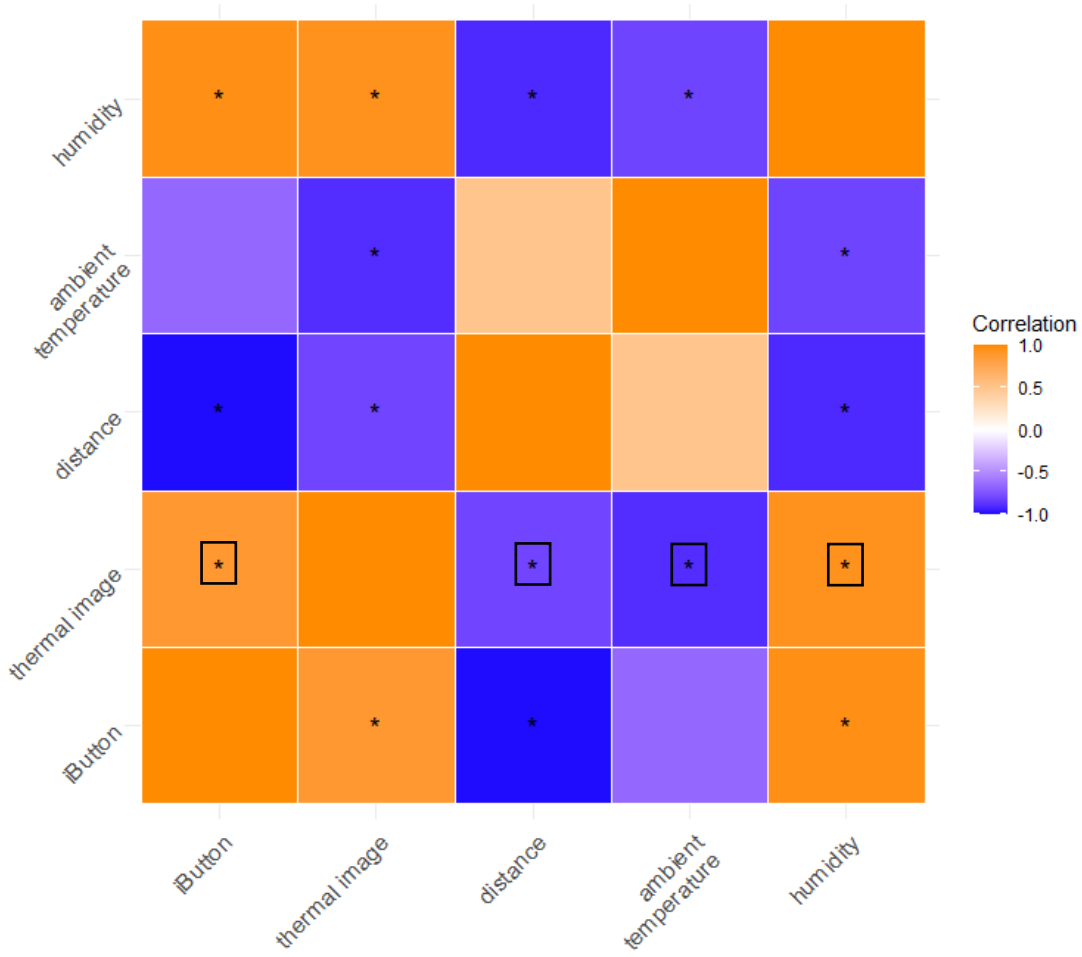


Figure 5: Correlation map between ambient variables and temperature readings for the outdoor experiment. The (*) identify the correlations where r > 0.5 and p < 0.05 and where -0.5 > r > -1.0, concomitantly.

The correlation map evidenced the correlations between distance, ambient temperature and humidity on thermal readings. We used a linear model to understand how much those variables influence the thermal readings. Here we see a higher variation in the thermal readings in the extremes of the logger temperature ranges, with a higher variability of TIR when DL=33°C (TIR= 35.7±SD1.1) and DL=36°C (TIR= 39.9±SD1.4). In the middle of the temperatures there was a very small variation for TIR (DL=34, TIR=36±0.3; DL=35, TIR=37.3±0.3) (Figure 6).

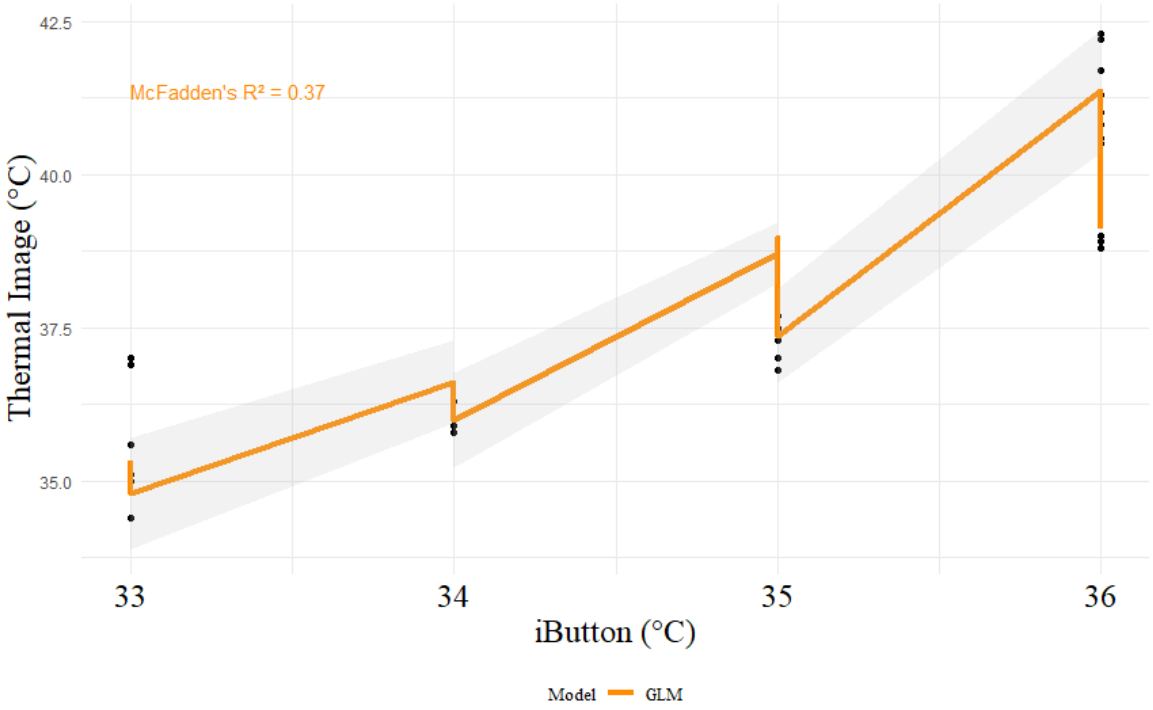


Figure 6: Generalized Linear Model multivariate plot showing the relationship between the temperature registered by the logger and the thermal readings with the influence of ambient temperature, humidity, and distance.

We investigated the impact of each variable in the TIR, and our data shows that humidity has the major contribution ($R2=0.28$, $P<0.01$) in increasing the registered temperatures. The other variables do not significantly influence TIR.

Specificity

It is also extremely important the camera to be able to distinguish between the background and the object we want to measure the temperature. We investigated if the ambient variables would have an impact in the difference between the TIR obtained from the test body and the background.

The average difference between background temperature and test body was of 7.5 °C (±0.8°C), with the test body showing an average temperature of 38.3 (±2.1°C) and the background showing an average of 30.7 °C (±1.7°C).

We then tested if that difference was significant to understand the ability of the thermal camera to detect the test body in a field environment with a complex background ($F(1, 88) = 1125$, $R^2=0.93$, $P < 0.001$). We then tested an interaction linear model to check if this relationship and it varied across the distances ($F(3, 86) = 402.4$, $R^2=0.93$, $P < 0.001$) and it was (Figure 7).

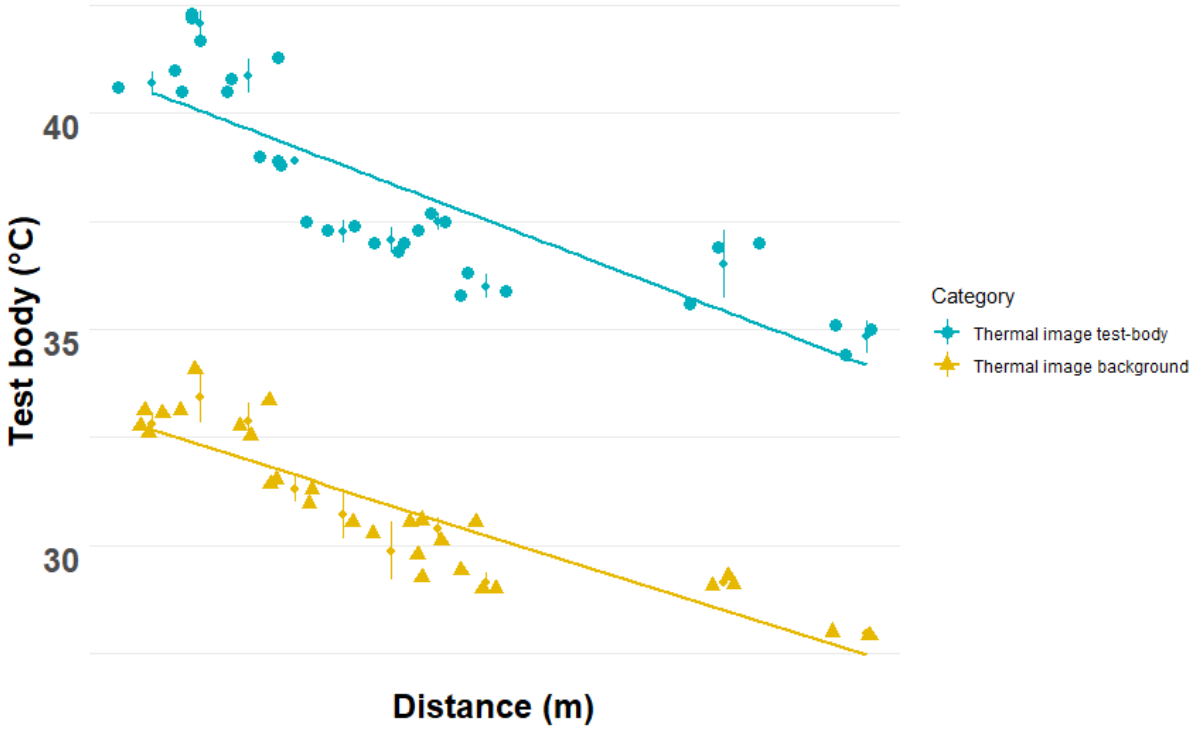


Figure 7: Average temperature registered by an iButton and the thermal camera along 18m.

This model suggests a strong linear relationship between the test-body and background temperatures, with a slope of 1.23472 indicating that for every unit increase in the background temperature, the test-body temperature increases by approximately 1.23 units in the first 5 meters. This equivalence doesn't hold as the distance of the thermal camera increases.

Discussion

The results showed that the relationship between the two methodologies here tested is not linear and can be influenced by environmental factors. Each experiment had a major influence of a different variable, evidencing that TIR responds to environmental variations differently depending on the conditions.

Under constant and controlled conditions, the ambient temperature showed a higher influence, while under. the external condition was influenced more by the humidity. The distance decreased the TIR of the test body and the background, but not at the same rate.

These findings demonstrate that thermal imaging in similar wild settings should be interpreted as a comparative rather than an absolute measure of animal temperature. While infrared thermography offers a non-invasive means to assess relative thermal patterns among individuals or roost sites, it does not provide precise estimates of core body temperature. In this study, thermal readings were used to compare relative surface temperatures of bats across different roost environments, allowing inference on the influence of habitat characteristics on thermal exposure, rather than reporting exact physiological temperatures.

APPENDIX C

Supplementary Material to Chapter 5

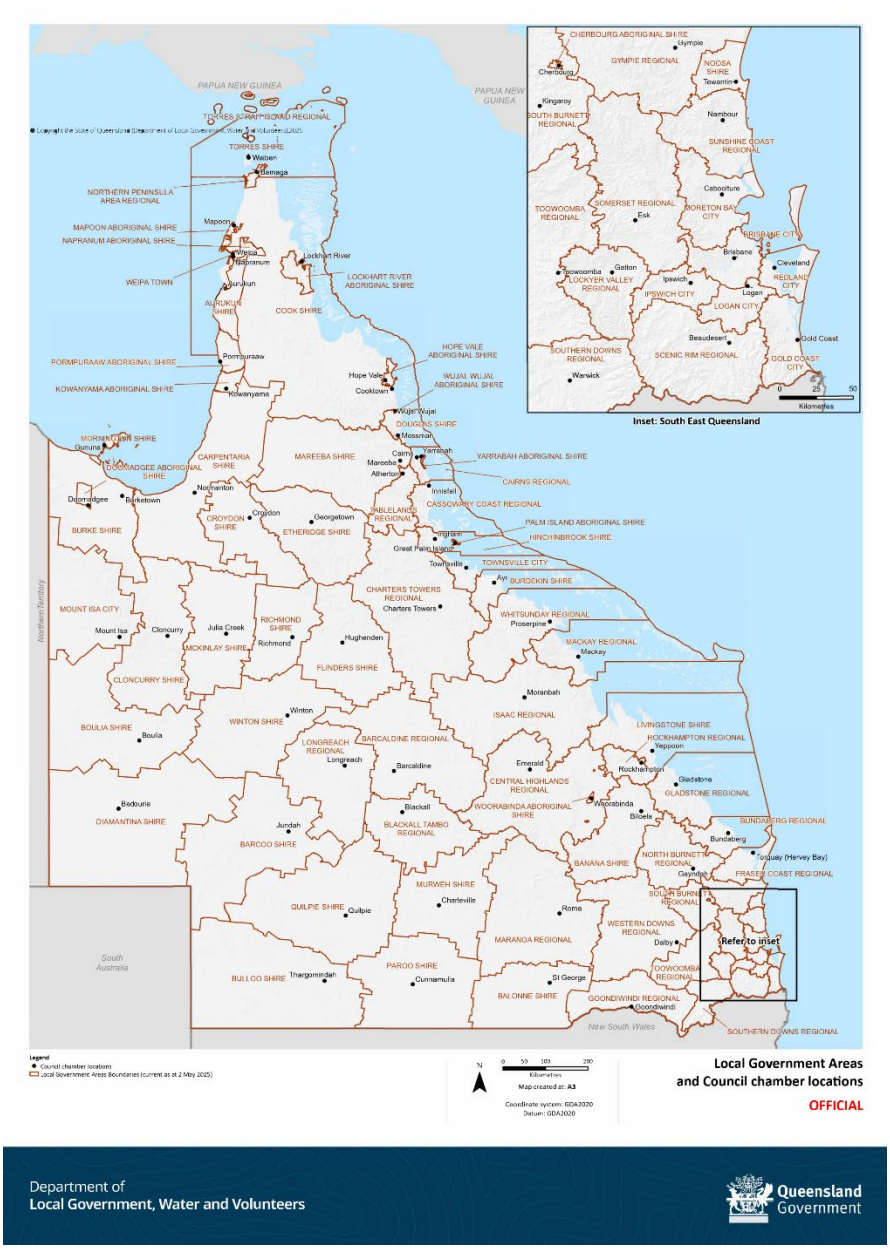


Figure 1: Local government areas, map extracted from https://www.localgovernment.qld.gov.au/for-councils/resources/maps

References

© 2024 Turtle Tough Pty Ltd. All. (2024). *Turtle Tough Sensors*. https://www.turtletoughsensors.com/products/thermography/infrared-cameras/tt384im-thermal-imaging-camera-detail

Adam, D., Beard, L., Johnston, S. D., Nicolson, V., Lisle, A., McKinnon, A., Larkin, R., Theilemann, P., Gillett, A., Brackin, K., FitzGibbon, S., Barth, B., & Ellis, W. (2018). Recording body temperature in koalas (Phascolarctos cinereus): a comparison of techniques. *Australian Veterinary Journal*, *96*(8), 308–311. https://doi.org/10.1111/avj.12719

Andrade, D. V. (2015). Thermal windows and heat exchange. *Temperature*, *2*(4), 451. https://doi.org/10.1080/23328940.2015.1040945

Arfuso, F., Acri, G., Piccione, G., Sansotta, C., Fazio, F., Giudice, E., & Giannetto, C. (2022). Eye surface infrared thermography usefulness as a noninvasive method of measuring stress response in sheep during shearing: Correlations with serum cortisol and rectal temperature values. *Physiology and Behavior*, *250*. https://doi.org/10.1016/j.physbeh.2022.113781

Atkins, J. W., Fahey, R. T., Hardiman, B. H., & Gough, C. M. (2018). Forest Canopy Structural Complexity and Light Absorption Relationships at the Subcontinental Scale. *Journal of Geophysical Research: Biogeosciences*, *123*(4), 1387–1405. https://doi.org/10.1002/2017JG004256

Avidad, P. M., Clavero, M., & Viana, D. S. (2024). Climate and Land-Use Change Leading to Niche Expansion and Shifts in Birds. *Journal of Biogeography*. https://doi.org/10.1111/jbi.15045

Bailey, A. M., Ober, H. K., Reichert, B. E., & McCleery, R. A. (2019). Canopy Cover Shapes Bat Diversity across an Urban and Agricultural Landscape Mosaic. *Environmental Conservation*, *46*(3), 193–200. https://doi.org/10.1017/S0376892919000109

Balaras, C. A., & Argiriou, A. A. (2002). Infrared thermography for building diagnostics. *Energy and Buildings*, *34*(2), 171–183. https://doi.org/https://doi.org/10.1016/S0378-7788(01)00105-0

Bartholomew, G. A., Leitner, P., & Nelson, J. E. (1964). Body Temperature, Oxygen Consumption, and Heart Rate in Three Species of Australian Flying Foxes. In *Source: Physiological Zoology* (Vol. 37, Issue 2).

Bartholomew, GA; Leitner, P and Nelson, J. (1964). *Body Temperature, Oxygen Consumption, and Heart Rate in Three Species of Australian flying foxes. 37*(2), 179–198. http://www.jstor.org/stable/30152330 .

Beall, E. B., Askegaard, L., Berkesch, J., Adolph, A. C., Hinnerichs, C. M., & Schmidt, M. (2022). *Principles and test methods of non-contact body thermometry*. https://doi.org/10.1101/2022.01.28.22269746

Blanchard, G., Barbier, N., Vieilledent, G., Ibanez, T., Hequet, V., McCoy, S., & Birnbaum, P. (2023). UAV-Lidar reveals that canopy structure mediates the influence of edge effects on forest diversity, function and microclimate. *Journal of Ecology*, *111*(7), 1411–1427. https://doi.org/10.1111/1365-2745.14105

Bleul, U., Hässig, M., & Kluser, F. (2021). Screening of febrile cows using a small handheld infrared thermography device. *Tierarztliche Praxis Ausgabe G: Grosstiere - Nutztiere*, *49*(1), 12–20. https://doi.org/10.1055/a-1307-9993

Boardman, W. S. J., Roshier, D., Reardon, T., Burbidge, K., McKeown, A., Westcott, D. A., Caraguel, C. G. B., & Prowse, T. A. A. (2021a). Spring foraging movements of an urban population of grey-headed flying foxes (Pteropus poliocephalus). *Journal of Urban Ecology*, *7*(1). https://doi.org/10.1093/jue/juaa034

Boardman, W. S. J., Roshier, D., Reardon, T., Burbidge, K., McKeown, A., Westcott, D. A., Caraguel, C. G. B., & Prowse, T. A. A. (2021b). Spring foraging movements of an urban population of grey-headed flying foxes (Pteropus poliocephalus). *Journal of Urban Ecology*, *7*(1), 1–10. https://doi.org/10.1093/jue/juaa034

Bouwen, K., Domec, J.-C., Charru, M., & Ogée, J. (2025). The impact of forest canopy structure on the understory microclimate: a physics-based approach and sensitivity analysis. In *EGU General Assembly 2024*. EGU General Assembly 2024. https://doi.org/10.5194/egusphere-egu24-10808

Boyles, J. G., Johnson, E. M., Fuller, N. W., Silas, K. A., Hou, L., Frick, W. F., & McGuire, L. P. (2022). Behavioural microclimate selection and physiological responses to environmental conditions in a hibernating bat. In *Canadian Journal of Zoology* (Vol. 100, Issue 3, pp. 233–238). Canadian Science Publishing. https://doi.org/10.1139/cjz-2021-0193

Brcko, C. C., Silva, J. A. R. da, Martorano, L. G., Vilela, R. A., Nahúm, B. de S., Silva, A. G. M., Barbosa, A. V. C., Bezerra, A. S., & Lourenço Júnior, J. de B. (2020).

Infrared Thermography to Assess Thermoregulatory Reactions of Female Buffaloes in a Humid Tropical Environment. *Frontiers in Veterinary Science*, *7*. https://doi.org/10.3389/fvets.2020.00180

Brooke, A. P., Solek, C., & Tualaulelei, A. (2008). *Roosting Behavior of Colonial and Solitary Flying Foxes in American Samoa (Chiroptera : Pteropodidae) Published by : The Association for Tropical Biology and Conservation Stable URL : http://www.jstor.org/stable/2663863*. *32*(2), 338–350.

Buckton, S. J., Fazey, I., Sharpe, B., Om, E. S., Doherty, B., Ball, P., Denby, K., Bryant, M., Lait, R., Bridle, S., Cain, M., Carmen, E., Collins, L., Nixon, N., Yap, C., Connolly, A., Fletcher, B., Frankowska, A., Gardner, G., … Sinclair, M. (2023). The Regenerative Lens: A conceptual framework for regenerative social-ecological systems. In *One Earth* (Vol. 6, Issue 7, pp. 824–842). Cell Press. https://doi.org/10.1016/j.oneear.2023.06.006

Buettner, P. G., Westcott, D. A., Maclean, J., Brown, L., McKeown, A., Johnson, A., Wilson, K., Blair, D., Luly, J., Skerratt, L., Muller, R., & Speare, R. (2013). Tick Paralysis in Spectacled Flying-Foxes (Pteropus conspicillatus) in North Queensland, Australia: Impact of a Ground-Dwelling Ectoparasite Finding an Arboreal Host. *PLoS ONE*, *8*(9). https://doi.org/10.1371/journal.pone.0073078

Bureau of Meteorology. (2007). *Warmest May and autumn on record in eastern Australia*. http://www.bom.gov.au/climate/current/statements/scs12.pdf

Bureau of Meteorology. (2009). *Exceptional winter heat over large parts of Australia*.

Bureau of Meteorology. (2018). *An extreme heatwave on the tropical Queensland coast*.

Bureau of Meteorology. (2023, March). *Climate Data Online*. Http://Www.Bom.Gov.Au/Climate/Data/.

Cai, Z., Cui, J., Yuan, H., & Cheng, M. (2023). Application and research progress of infrared thermography in temperature measurement of livestock and poultry animals: A review. In *Computers and Electronics in Agriculture* (Vol. 205). Elsevier B.V. https://doi.org/10.1016/j.compag.2022.107586

Calcino, C. (2020, August 14). Cairns flying fox dispersal sends bats to new Manoora home. *The Cairns Post*.

Camacho, A., Rodrigues, M. T., Jayyusi, R., Harun, M., Geraci, M., Carretero, M. A., Vinagre, C., & Tejedo, M. (2024). Does heat tolerance actually predict animals' geographic thermal limits? *Science of the Total Environment*, *917*. https://doi.org/10.1016/j.scitotenv.2024.170165

Camargo, J. L., & Kapos, V. (1995a). Complex edge effects on soil moisture and microclimate in central Amazonian forest. *Journal of Tropical Ecology*, *11*(2), 205–221. https://doi.org/10.1017/S026646740000866X

Camargo, J. L., & Kapos, V. (1995b). Complex edge effects on soil moisture and microclimate in central Amazonian forest. *Journal of Tropical Ecology*, *11*(2), 205–221. https://doi.org/10.1017/S026646740000866X

Carter, T., Leemans, R., Lal, M., Whetton, P., Hay, L., Jones, R., Katz, R., Kittel, T., Smith, J., & Wilby, R. (2001). *IPCC third assessment report: climate change 2001- working group I: the scientific basis.*

Chen, P., Shen, C., Tao, Z., Qin, W., Huang, W., & Siemann, E. (2024). Deterministic responses of biodiversity to climate change through exotic species invasions. *Nature Plants, 10*(10), 1464–1472. https://doi.org/10.1038/s41477-024-01797-7

Chen, S., Xiao, Y., Xiao, Z., Ma, D., Li, J., & Herrera-Ulloa, A. (2024). Prediction of suitable habitat shifts and assessment of ecological niche overlaps for three Tridentiger species with intertidal and subtidal characteristics under future climate changes. *Marine Pollution Bulletin, 198.* https://doi.org/10.1016/j.marpolbul.2023.115827

Chenery, M., Geiser, F., & Stawski, C. (2022). Thermal biology and roost selection of free-ranging male little forest bats, Vespadelus vulturnus, during winter. *Journal of Mammalogy*, *103*(4), 826–834. https://doi.org/10.1093/jmammal/gyac022

Coates, L., Haynes, K., O'Brien, J., McAneney, J., & De Oliveira, F. D. (2014). Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844-2010. *Environmental Science and Policy*, *42*, 33–44. https://doi.org/10.1016/j.envsci.2014.05.003

Cox, L. (2020, June 15). Dispersal of flying foxes from centre of Cairns "farcical", wildlife groups say. *The Guardian*.

Čukić, A., Rakonjac, S., Djoković, R., Cincović, M., Bogosavljević-Bošković, S., Petrović, M., Savić, Ž., Andjušić, L., & Andjelić, B. (2023). Influence of Heat Stress on Body Temperatures Measured by Infrared Thermography, Blood Metabolic Parameters and Its Correlation in Sheep. *Metabolites*, *13*(8). https://doi.org/10.3390/metabo13080957

Currey, K., Kendal, D., van der Ree, R., & Lentini, P. E. (2018). Land manager perspectives on conflict mitigation strategies for urban flying-fox camps. *Diversity*, *10*(2). https://doi.org/10.3390/D10020039

Czenze, Z. J., Naidoo, S., Kotze, A., & McKechnie, A. E. (2020). Bat thermoregulation in the heat: Limits to evaporative cooling capacity in three southern African bats. *Journal of Thermal Biology*, *89*. https://doi.org/10.1016/j.jtherbio.2020.102542

De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B., Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A., Jucker, T., Klinges, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., … Hylander, K. (2021a). Forest microclimates and climate change: Importance, drivers and future research agenda. In *Global Change Biology* (Vol. 27, Issue 11, pp. 2279–2297). Blackwell Publishing Ltd. https://doi.org/10.1111/gcb.15569

De Frenne, P., Lenoir, J., Luoto, M., Scheffers, B. R., Zellweger, F., Aalto, J., Ashcroft, M. B., Christiansen, D. M., Decocq, G., De Pauw, K., Govaert, S., Greiser, C., Gril, E., Hampe, A., Jucker, T., Klinges, D. H., Koelemeijer, I. A., Lembrechts, J. J., Marrec, R., … Hylander, K. (2021b). Forest microclimates and climate change: Importance, drivers and future research agenda. In *Global Change Biology* (Vol. 27, Issue 11, pp. 2279–2297). Blackwell Publishing Ltd. https://doi.org/10.1111/gcb.15569

De Frenne, P., Zellweger, F., Rodríguez-Sánchez, F., Scheffers, B. R., Hylander, K., Luoto, M., Vellend, M., Verheyen, K., & Lenoir, J. (2019). Global buffering of temperatures under forest canopies. *Nature Ecology and Evolution*, *3*(5), 744–749. https://doi.org/10.1038/s41559-019-0842-1

de Mel, R. K., Moseby, K. E., Stewart, K. A., Rankin, K. E., & Czenze, Z. J. (2024). The heat is on: Thermoregulatory and evaporative cooling patterns of desert-dwelling bats. *Journal of Thermal Biology, 123*. https://doi.org/10.1016/j.jtherbio.2024.103919

de Souza, B. C., Carvalho, E. C. D., Oliveira, R. S., de Araujo, F. S., de Lima, A. L. A., & Rodal, M. J. N. (2020). Drought response strategies of deciduous and evergreen woody species in a seasonally dry neotropical forest. *Oecologia*, *194*(1–2), 221–236. https://doi.org/10.1007/s00442-020-04760-3

Department of Environment and Science. (2020). *Code of practice - Ecologically sustainable management of flying-fox roosts*.

Dey, S. (2015). Effect of heat wave on the Indian Flying Fox Pteropus giganteus (Mammalia: Chiroptera: Pteropodidae) population from Purulia District of West Bengal, India. *Journal of Threatened Taxa, 7*(3), 7029–7033. https://doi.org/10.11609/jott.1905.7029-7033

Díaz-Calafat, J., Uria-Diez, J., Brunet, J., De Frenne, P., Vangansbeke, P., Felton, A., Öckinger, E., Cousins, S. A. O., Bauhus, J., Ponette, Q., & Hedwall, P. O. (2023). From broadleaves to conifers: The effect of tree composition and density on understory microclimate across latitudes. *Agricultural and Forest Meteorology, 341*. https://doi.org/10.1016/j.agrformet.2023.109684

Dimande, P., Arrobas, M., & Rodrigues, M. Â. (2023). Under a Tropical Climate and in Sandy Soils, Bat Guano Mineralises Very Quickly, Behaving More like a Mineral Fertiliser than a Conventional Farmyard Manure. *Agronomy, 13*(5). https://doi.org/10.3390/agronomy13051367

Domeisen, D. I. V, Eltahir, A. B. E., Fischer, E. M., Knutti, R., Perkins-Kirkpatrick, S. E., Schar, C., Seneviratne, S. I., Weisheimer, A., & Wernli, H. (2023). Prediction and projection of heatwaves. *Nature Reviews Earth & Environment*, *4*, 36–50.

dos Santos, A. J., Vieira, T. B., & Faria, K. de C. (2016a). Effects of vegetation structure on the diversity of bats in remnants of Brazilian Cerrado savanna. *Basic and Applied Ecology*, *17*(8), 720–730. https://doi.org/10.1016/j.baae.2016.09.004

dos Santos, A. J., Vieira, T. B., & Faria, K. de C. (2016b). Effects of vegetation structure on the diversity of bats in remnants of Brazilian Cerrado savanna. *Basic and Applied Ecology*, *17*(8), 720–730. https://doi.org/10.1016/j.baae.2016.09.004

Duchicela, S. A., Cuesta, F., Tovar, C., Muriel, P., Jaramillo, R., Salazar, E., & Pinto, E. (2021a). Microclimatic Warming Leads to a Decrease in Species and Growth Form Diversity: Insights From a Tropical Alpine Grassland. *Frontiers in Ecology and Evolution*, *9*. https://doi.org/10.3389/fevo.2021.673655

Duchicela, S. A., Cuesta, F., Tovar, C., Muriel, P., Jaramillo, R., Salazar, E., & Pinto, E. (2021b). Microclimatic Warming Leads to a Decrease in Species and Growth Form Diversity: Insights From a Tropical Alpine Grassland. *Frontiers in Ecology and Evolution*, *9*. https://doi.org/10.3389/fevo.2021.673655

Eby, P., & Law, B. (2008). *Ranking the feeding habitats of Grey-headed flying foxes for conservation management*.

Edwards, K., Edes, A., & Brown, J. (2019). Stress, Well-Being and Reproductive Success. In P. Comizzoli, J. Brown, & W. Holt (Eds.), *Reproductive Sciences in Animal Conservation. Advances in Experimental Medicine and Biology*, (2nd ed.,

Vol. 1200, pp. 91–162). Springer, Cham. https://doi.org/https://doi.org/10.1007/978-3-030-23633-5_5

Elmore, R. D., Carroll, J. M., Tanner, E. P., Hovick, T. J., Grisham, B. A., Fuhlendorf, S. D., & Windels, S. K. (2017). Implications of the thermal environment for terrestrial wildlife management. *Wildlife Society Bulletin*, *41*(2), 183–193. https://doi.org/10.1002/wsb.772

Enchéry, F., & Horvat, B. (2017a). Understanding the interaction between henipaviruses and their natural host, fruit bats: Paving the way toward control of highly lethal infection in humans. *International Reviews of Immunology*, *36*(2), 108–121. https://doi.org/10.1080/08830185.2016.1255883

Enchéry, F., & Horvat, B. (2017b). Understanding the interaction between henipaviruses and their natural host, fruit bats: Paving the way toward control of highly lethal infection in humans. *International Reviews of Immunology*, *36*(2), 108–121. https://doi.org/10.1080/08830185.2016.1255883

Environment Protection and Biodiversity Conservation Act 1999, Federal Register of Legislation 1 (2021). https://www.legislation.gov.au/Details/C2021C00182

Evans, L. C., Melero, Y., Schmucki, R., Boersch-Supan, P. H., Brotons, L., Fontaine, C., Jiguet, F., Kuussaari, M., Massimino, D., Robinson, R. A., Roy, D. B., Schweiger, O., Settele, J., Stefanescu, C., van Turnhout, C. A. M., & Oliver, T. H. (2022). Bioclimatic context of species' populations determines community stability. *Global Ecology and Biogeography*, *31*(8), 1542–1555. https://doi.org/10.1111/geb.13527

Faye, E., Dangles, O., & Pincebourde, S. (2016). Distance makes the difference in thermography for ecological studies. *Journal of Thermal Biology*, *56*, 1–9. https://doi.org/10.1016/j.jtherbio.2015.11.011

Finocchiaro, M., Médail, F., Saatkamp, A., Diadema, K., Pavon, D., Brousset, L., & Meineri, E. (2024). Microrefugia and microclimate: Unraveling decoupling potential and resistance to heatwaves. *Science of the Total Environment*, *924*. https://doi.org/10.1016/j.scitotenv.2024.171696

Fischer Verlag, G., Speakman, J. R., & Ward, S. (1998). Infrared thermography: principles and applications. In *ZOOLOGY* (Vol. 101).

Friedman, J., Hastie, T., & Tibshirani, R. (2010). Regularization Paths for Generalized Linear Models via Coordinate Descent. *Journal of Statistical Software*, *33*(1). https://doi.org/10.18637/jss.v033.i01

Fuller, A., Mitchell, D., Maloney, S. K., Hetem, R. S., Fons ca, V. F. C., Meyer, L. C. R., Ven, T. M. F. N. V., & Snelling, E. P. (2021). How dryland mammals will respond to climate change: The effects of body size, heat load and a lack of food and water. *Journal of Experimental Biology*, *224*. https://doi.org/10.1242/jeb.238113

Gao, X., Li, C., Cai, Y., Ye, L., Xiao, L., Zhou, G., & Zhou, Y. (2021). Influence of scale effect of canopy projection on understory microclimate in three subtropical urban broad-leaved forests. *Remote Sensing*, *13*(18). https://doi.org/10.3390/rs13183786

Geoscience Australia. (2010). *"ELVIS: ELVIS-Elevation and Depth – Foundation Spatial Data*.

Ghalambor, C. K. (2006). Are mountain passes higher in the tropics? janzen's hypothesis revisited. *Integrative and Comparative Biology*, *46*(1), 5–17. https://doi.org/10.1093/icb/icj003

Ghezzi, M. D., Napolitano, F., Casas-Alvarado, A., Hernández-Ávalos, I., Domínguez-Oliva, A., Olmos-Hernández, A., & Pereira, A. M. F. (2024). Utilization of Infrared Thermography in Assessing Thermal Responses of Farm Animals under Heat Stress. In *Animals* (Vol. 14, Issue 4). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/ani14040616

Gibson, L., McNeill, A., Tores, P. de, Wayne, A., & Yates, C. (2010). Will future climate change threaten a range restricted endemic species, the quokka (Setonix brachyurus), in south west Australia? *Biological Conservation*, *143*(11), 2453–2461. https://doi.org/10.1016/j.biocon.2010.06.011

Gillerot, L., Landuyt, D., De Frenne, P., Muys, B., & Verheyen, K. (2024). Urban tree canopies drive human heat stress mitigation. *Urban Forestry and Urban Greening*, *92*. https://doi.org/10.1016/j.ufug.2023.128192

González-Trujillo, J. D., Román-Cuesta, R. M., Muñiz-Castillo, A. I., Amaral, C. H., & Araújo, M. B. (2023a). Multiple dimensions of extreme weather events and their impacts on biodiversity. In *Climatic Change* (Vol. 176, Issue 11). Springer Science and Business Media B.V. https://doi.org/10.1007/s10584-023-03622-0

González-Trujillo, J. D., Román-Cuesta, R. M., Muñiz-Castillo, A. I., Amaral, C. H., & Araújo, M. B. (2023b). Multiple dimensions of extreme weather events and their impacts on biodiversity. In *Climatic Change* (Vol. 176, Issue 11). Springer Science and Business Media B.V. https://doi.org/10.1007/s10584-023-03622-0

Gulraiz, T. L., Javid, A., Mahmood-Ul-Hassan, M., Maqbool, A., Ashraf, S., Hussain, M., & Daud, S. (2015). Roost characteristics and habitat preferences of Indian flying fox (Pteropus giganteus) in urban areas of Lahore, Pakistan. *Turkish Journal of Zoology*, *39*(3), 388–394. https://doi.org/10.3906/zoo-1401-71

Gyawali, A., Aalto, M., Peuhkurinen, J., Villikka, M., & Ranta, T. (2022). Comparison of Individual Tree Height Estimated from LiDAR and Digital Aerial Photogrammetry in Young Forests. *Sustainability (Switzerland)*, *14*(7). https://doi.org/10.3390/su14073720

Hahn, M. B., Epstein, J. H., Gurley, E. S., Islam, M. S., Luby, S. P., Daszak, P., & Patz, J. A. (2014). Roosting behaviour and habitat selection of Pteropus giganteus reveal potential links to Nipah virus epidemiology. *Journal of Applied Ecology*, *51*(2), 376–387. https://doi.org/10.1111/1365-2664.12212

Haight, J. D., Hall, S. J., Fidino, M., Adalsteinsson, S. A., Ahlers, A. A., Angstmann, J., Anthonysamy, W. J. B., Biro, E., Collins, M. K., Dugelby, B., Gallo, T., Green, A. M., Hartley, L., Jordan, M. J., Kay, C. A. M., Lehrer, E. W., Long, R. A., MacDougall, B., Magle, S. B., … Lewis, J. S. (2023). Urbanization, climate and species traits shape mammal communities from local to continental scales. *Nature Ecology and Evolution*, *7*(10), 1654–1666. https://doi.org/10.1038/s41559-023-02166-x

Hall, L. S., & Richards, G. (2000a). *Flying foxes: Fruit and Blosson Bats of Australia*. University of NSW.

Hall, L. S., & Richards, G. (2000b). *Flying-foxes and fruit and blossom bats of Australia*. University of New South Wales Press.

Han, Q., Sun, S., Liu, Z., Xu, W., & Shi, P. (2022). Accelerated exacerbation of global extreme heatwaves under warming scenarios. *International Journal of Climatology*, *42*(11), 5430–5441. https://doi.org/10.1002/joc.7541

Hijmans, R. J. (2023). *The terra package*.

Huang, L., Liao, M., Liao, H., Liu, Z., Cai, H., Zhou, W., Xu, Z., Ouyang, K., Yang, W., & Jian, S. (2023). High phosphorus availability and low light intensity reduce the competitive ability of the invasive plant Chromolaena odorata in tropical coral islands. *Biological Invasions*. https://doi.org/10.1007/s10530-023-03186-1

Huey, R. B., Kearney, M. R., Krockenberger, A., Holtum, J. A. M., Jess, M., & Williams, S. E. (2012). Predicting organismal vulnerability to climate warming: Roles of behaviour, physiology and adaptation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1596), 1665–1679. https://doi.org/10.1098/rstb.2012.0005

Ibáñez, C., Moreno-Manrique, M., Villagrá, A., Bueso-Ródenas, J., & Mínguez, C. (2024). Evaluation of Non-Contact Device to Measure Body Temperature in Sheep. *Animals*, *14*(1). https://doi.org/10.3390/ani14010098

Indooroopilly Island Conservation Park. (1999).

Ismaeel, A., Tai, A. P. K., Santos, E. G., Maraia, H., Aalto, I., Altman, J., Doležal, J., Lembrechts, J. J., Camargo, J. L., Aalto, J., Sam, K., Avelino do Nascimento, L. C., Kopecký, M., Svátek, M., Nunes, M. H., Matula, R., Plichta, R., Abera, T., & Maeda, E. E. (2024a). Patterns of tropical forest understory temperatures. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-44734-0

Ismaeel, A., Tai, A. P. K., Santos, E. G., Maraia, H., Aalto, I., Altman, J., Doležal, J., Lembrechts, J. J., Camargo, J. L., Aalto, J., Sam, K., Avelino do Nascimento, L. C., Kopecký, M., Svátek, M., Nunes, M. H., Matula, R., Plichta, R., Abera, T., & Maeda, E. E. (2024b). Patterns of tropical forest understory temperatures. *Nature Communications*, *15*(1). https://doi.org/10.1038/s41467-024-44734-0

James, S. A., & Bell, D. (2000). Leaf orientation, light interception and stomatal conductance of Eucalyptus globulus ssp. globulus leaves. *Tree Physiology*, *20*, 815–823. https://doi.org/https://doi.org/10.1093/TREEPHYS/20.12.815

Jan, A., Arismendi, I., & Giannico, G. (2025). Double Trouble for Native Species Under Climate Change: Habitat Loss and Increased Environmental Overlap With Non-Native Species. *Global Change Biology*, *31*(1). https://doi.org/10.1111/gcb.70040

Janzen, D. H. (1967). Why Mountain Passes are Higher in the Tropics WHY MOUNTAIN PASSES ARE HIGHER IN THE TROPICS*. In *Source: The American Naturalist* (Vol. 101, Issue 919).

Jason Bittel. (2019, April 10). *A Heat Wave in Australia Killed 23,000 Spectacled Flying Foxes*. NRDC. https://www.nrdc.org/stories/heat-wave-australia-killed-23000-spectacled-flying-foxes#:~:text=The%20die%2Doff%E2%80%94which%20wiped,but%20it%20may%20become%20so.

Jerem, P., Herborn, K., McCafferty, D., McKeegan, D., & Nager, R. (2015). Thermal imaging to study stress non-invasively in unrestrained birds. *Journal of Visualized Experiments*, *2015*(105). https://doi.org/10.3791/53184

Jiao, M., Zhou, W., Zheng, Z., Wang, J., & Qian, Y. (2017). Patch size of trees affects its cooling effectiveness: A perspective from shading and transpiration processes. *Agricultural and Forest Meteorology*, *247*, 293–299. https://doi.org/10.1016/j.agrformet.2017.08.013

Jucker, T., Hardwick, S. R., Both, S., Elias, D. M. O., Ewers, R. M., Milodowski, D. T., Swinfield, T., & Coomes, D. A. (2018a). Canopy structure and topography jointly constrain the microclimate of human-modified tropical landscapes. *Global Change Biology*, *24*(11), 5243–5258. https://doi.org/10.1111/gcb.14415

Jucker, T., Hardwick, S. R., Both, S., Elias, D. M. O., Ewers, R. M., Milodowski, D. T., Swinfield, T., & Coomes, D. A. (2018b). Canopy structure and topography jointly constrain the microclimate of human-modified tropical landscapes. *Global Change Biology*, *24*(11), 5243–5258. https://doi.org/10.1111/gcb.14415

Kemppinen, J., Lembrechts, J. J., Van Meerbeek, K., Carnicer, J., Chardon, N. I., Kardol, P., Lenoir, J., Liu, D., Maclean, I., Pergl, J., Saccone, P., Senior, R. A., Shen, T., Słowińska, S., Vandvik, V., von Oppen, J., Aalto, J., Ayalew, B., Bates, O., … De Frenne, P. (2024). Microclimate, an important part of ecology and biogeography. *Global Ecology and Biogeography*, *33*(6). https://doi.org/10.1111/geb.13834

Kentwell, M. (2023). *Flying-fox Management Strategy-Cairns LGA Community Life Branch*.

Keppel, G., Stralberg, D., Morelli, T. L., & Bátori, Z. (2024). Managing climate-change refugia to prevent extinctions. *Trends in Ecology and Evolution*, *39*(9), 800–808. https://doi.org/10.1016/j.tree.2024.05.002

Kestrel Weather Meters. (2020). *Product Specifications for Kestrel Weather Meters, Model Numbers 1000-3550 SENSORS.*

Korn, L., Ngang, C., Ader, D. R., & Srean, P. (2023). Bat Guano Application Rate in Horticulture in Cambodia: An Experiment With Tomato. *Journal of Agricultural Science*, *15*(11), 24. https://doi.org/10.5539/jas.v15n11p24

Kumar, R., & Elangovan, V. (2019). Effect of tree characteristics on roost selection of the Indian flying fox, Pteropus giganteus. *Barbastella*, *12*(1). https://doi.org/10.14709/barbj.12.1.2019.13

Lancaster, W. C., Thomson, S. C., & Speakman, J. R. (1997a). Wing temperature in flying bats measured by infrared thermography. *Journal of Thermal Biology*, *22*(2), 109–116. https://doi.org/10.1016/S0306-4565(96)00039-3

Lancaster, W. C., Thomson, S. C., & Speakman, J. R. (1997b). Wing temperature in flying bats measured by infrared thermography. *Journal of Thermal Biology*, *22*(2), 109–116. https://doi.org/10.1016/S0306-4565(96)00039-3

Lee, W. V. (2014). Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). *Natural Hazards*, *70*(2), 1453–1505. https://doi.org/10.1007/s11069-013-0884-7

Lemenih, M., Gidyelew, T., & Teketay, D. (2004). Effects of canopy cover and understory environment of tree plantations on richness, density and size of colonizing woody species in southern Ethiopia. *Forest Ecology and Management*, *194*(1–3), 1–10. https://doi.org/10.1016/j.foreco.2004.01.050

Lezama-García, K., Martínez-Burnes, J., Marcet-Rius, M., Gazzano, A., Olmos-Hernández, A., Mora-Medina, P., Domínguez-Oliva, A., Pereira, A. M. F., Hernández-Ávalos, I., Baqueiro-Espinosa, U., Geraldo, A. de M., Casas-Alvarado, A., & Mota-Rojas, D. (2022). Is the Weight of the Newborn Puppy Related to Its Thermal Balance? *Animals*, *12*(24). https://doi.org/10.3390/ani12243536

Li, Y., Fan, S., Li, K., Zhang, Y., & Dong, L. (n.d.-a). *Microclimate in an urban park and its influencing factors: a case study of Tiantan Park in Beijing, China*. https://doi.org/10.1007/s11252-020-01073-4/Published

Li, Y., Fan, S., Li, K., Zhang, Y., & Dong, L. (n.d.-b). *Microclimate in an urban park and its influencing factors: a case study of Tiantan Park in Beijing, China*. https://doi.org/10.1007/s11252-020-01073-4/Published

Li, Y., Zhao, M., Motesharrei, S., Mu, Q., Kalnay, E., & Li, S. (2015). Local cooling and warming effects of forests based on satellite observations. *Nature Communications*, *6*. https://doi.org/10.1038/ncomms7603

Lopes, C., Firth, C., & Laurance, S. G. W. (2024a). Occupancy of urban roosts by spectacled flying-foxes (Pteropus conspicillatus) is not affected by diurnal microclimate. *Austral Ecology*, *49*(2). https://doi.org/10.1111/aec.13487

Lopes, C., Firth, C., & Laurance, S. G. W. (2024b). Occupancy of urban roosts by spectacled flying-foxes (Pteropus conspicillatus) is not affected by diurnal microclimate. *Austral Ecology*, *49*(2). https://doi.org/10.1111/aec.13487

Lu, M., Wang, X., Ye, H., Wang, H., Qiu, S., Zhang, H., Liu, Y., Luo, J., & Feng, J. (2021). Does public fear that bats spread COVID-19 jeopardize bat conservation? *Biological Conservation*, *254*. https://doi.org/10.1016/j.biocon.2021.108952

Lunn, T. J., Eby, P., Brooks, R., McCallum, H., Plowright, R. K., Kessler, M. K., & Peel, A. J. (2021). Conventional wisdom on roosting behavior of Australian flying-foxes—A critical review, and evaluation using new data. *Ecology and Evolution*, *11*(19), 13532–13558. https://doi.org/10.1002/ece3.8079

Lunn, T. J., Peel, A. J., McCallum, H., Eby, P., Kessler, M. K., Plowright, R. K., & Restif, O. (2021). Spatial dynamics of pathogen transmission in communally roosting species: Impacts of changing habitats on bat-virus dynamics. *Journal of Animal Ecology*, *90*(11), 2609–2622. https://doi.org/10.1111/1365-2656.13566

Luskin, M. S. (2010). Flying foxes prefer to forage in farmland in a tropical dry forest landscape mosaic in Fiji. *Biotropica*, *42*(2), 246–250. https://doi.org/10.1111/j.1744-7429.2009.00577.x

MacDonald, S. L., Bradford, M., McKeown, A., Vanderduys, E., Hoskins, A., & Westcott, D. (2021). Camp site habitat preferences of the little red flying-fox (Pteropus scapulatus) in Queensland. *Australian Journal of Zoology*, *68*(6), 234–253. https://doi.org/10.1071/ZO20079

Machado, N. A. F., Da Costa, L. B. S., Barbosa-Filho, J. A. D., De Oliveira, K. P. L., De Sampaio, L. C., Peixoto, M. S. M., & Damasceno, F. A. (2021). Using infrared thermography to detect subclinical mastitis in dairy cows in compost barn systems. *Journal of Thermal Biology*, *97*. https://doi.org/10.1016/j.jtherbio.2021.102881

Madala, M. F., Guna, C., Pradeepan, A., & Chalil, A. K. (2022). Roost tree characteristics of Pteropus medius (Chiroptera: Pteropodidae) in the midland laterite hillocks of northern Kerala, India. *Journal of Asia-Pacific Biodiversity*, *15*(4), 465–472. https://doi.org/10.1016/j.japb.2022.04.011

Magnago, L. F. S., Rocha, M. F., Meyer, L., Martins, S. V., & Meira-Neto, J. A. A. (2015). Microclimatic conditions at forest edges have significant impacts on vegetation structure in large Atlantic forest fragments. *Biodiversity and Conservation*, *24*(9), 2305–2318. https://doi.org/10.1007/s10531-015-0961-1

Majumdar, K., Majumder, J., & Datta, B. K. (2016a). Vegetation composition, structure and distribution status of trees used by two tropical fruit bat species in degraded habitats of Northeast India. *Zoology and Ecology*, *26*(2), 63–76. https://doi.org/10.1080/21658005.2016.1148978

Majumdar, K., Majumder, J., & Datta, B. K. (2016b). Vegetation composition, structure and distribution status of trees used by two tropical fruit bat species in degraded habitats of Northeast India. *Zoology and Ecology*, *26*(2), 63–76. https://doi.org/10.1080/21658005.2016.1148978

Marchin, R. M., Medlyn, B. E., Tjoelker, M. G., & Ellsworth, D. S. (2023). Decoupling between stomatal conductance and photosynthesis occurs under extreme heat in broadleaf tree species regardless of water access. *Global Change Biology, 29*(22), 6319–6335. https://doi.org/10.1111/gcb.16929

Markus, N., & Hall, L. (2004a). Foraging behaviour of the black flying-fox (Pteropus alecto) in the urban landscape of Brisbane, Queensland. *Wildlife Research, 31*(3), 345–355. https://doi.org/10.1071/WR01117

Markus, N., & Hall, L. (2004b). Foraging behaviour of the black flying-fox (Pteropus alecto) in the urban landscape of Brisbane, Queensland. *Wildlife Research, 31*(3), 345–355. https://doi.org/10.1071/WR01117

Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. S. P. R. S. A. P. W. M.-O. C. P. R. P. S. C. J. B. R. M. Y. C. X. Z. M. I. G. E. L. T. M. M. T. and, & T. Waterfield. (2018). *IPCC, 2018: Summary for policymakers. in: global warming of 1.5°c. an ipcc special report on the impacts of global warming of 1.5°c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SPM_version_report_LR.pdf

Maxim Integrated Products. (2013). *DS1922E iButton High-Temperature Logger with 8KB Data-Log Memory General Description* (pp. 1–44). www.maximintegrated.com.

McAlpine, C. A., Syktus, J., Ryan, J. G., Deo, R. C., McKeon, G. M., McGowan, H. A., & Phinn, S. R. (2009). A continent under stress: Interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology*, *15*(9), 2206–2223. https://doi.org/10.1111/j.1365-2486.2009.01939.x

McCafferty, D. J. (2007). The value of infrared thermography for research on mammals: Previous applications and future directions. *Mammal Review*, *37*(3), 207–223. https://doi.org/10.1111/j.1365-2907.2007.00111.x

McCafferty, D. J., Gallon, S., & Nord, A. (2015). Challenges of measuring body temperatures of free-ranging birds and mammals. *Animal Biotelemetry*, *3*(1), 1–10. https://doi.org/10.1186/s40317-015-0075-2

McCafferty, D. J., Gilbert, C., Paterson, W., Pomeroy, P., Thompson, D., Currie, J. I., & Ancel, A. (2011). Estimating metabolic heat loss in birds and mammals by combining infrared thermography with biophysical modelling. In *Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology* (Vol. 158, Issue 3, pp. 337–345). Elsevier Inc. https://doi.org/10.1016/j.cbpa.2010.09.012

McGinn, K. A., Peery, M. Z., Zulla, C. J., Berigan, W. J., Wilkinson, Z. A., Barry, J. M., Keane, J. J., & Zuckerberg, B. (2023a). A climate-vulnerable species uses cooler forest microclimates during heat waves. *Biological Conservation, 283*. https://doi.org/10.1016/j.biocon.2023.110132

McGinn, K. A., Peery, M. Z., Zulla, C. J., Berigan, W. J., Wilkinson, Z. A., Barry, J. M., Keane, J. J., & Zuckerberg, B. (2023b). A climate-vulnerable species uses cooler forest microclimates during heat waves. *Biological Conservation, 283*. https://doi.org/10.1016/j.biocon.2023.110132

McMichael, L., Mclean, J., Taylor, J., Martinez, Y., & Meers, J. (2023). Cleft Palate Syndrome in the Endangered Spectacled Flying Fox (Pteropus conspicillatus): Implications for Conservation and Comparative Research. *Veterinary Sciences, 10*(1). https://doi.org/10.3390/vetsci10010038

Mella, V. S. A., Cooper, C. E., Karr, M., Krockenberger, A., Madani, G., Webb, E. B., & Krockenberger, M. B. (2024). Hot climate, hot koalas: the role of weather, behaviour and disease on thermoregulation. *Conservation Physiology, 12*(1). https://doi.org/10.1093/conphys/coae032

Minnaar, I. A., Bennett, N. C., Chimimba, C. T., & Mckechnie, A. E. (2014). Partitioning of evaporative water loss into respiratory and Cutaneous pathways in

Wahlberg's Epauletted fruit bats (Epomophorus wahlbergi). *Physiological and Biochemical Zoology*, *87*(3), 475–485. https://doi.org/10.1086/675342

Mo, M., & Roache, M. (2021a). A review of intervention methods used to reduce flying-fox mortalities in heat stress events. In *Australian Mammalogy* (Vol. 43, Issue 2, pp. 137–150). CSIRO. https://doi.org/10.1071/AM20038

Mo, M., & Roache, M. (2021b). A review of intervention methods used to reduce flying-fox mortalities in heat stress events. *Australian Mammalogy*, *43*(2), 137–150. https://doi.org/10.1071/AM20038

Mo, M., Roache, M., Davies, J., Hopper, J., Pitty, H., Foster, N., Guy, S., Parry-Jones, K., Francis, G., Koosmen, A., Colefax, L., Costello, C., Stokes, J., Curran, S., Smith, M., Daly, G., Simmons, C.-M., Hansen, R., Prophet, D., … Welbergen, J. A. (2021). Estimating flying-fox mortality associated with abandonments of pups and extreme heat events during the austral summer of 2019–20. *Pacific Conservation Biology*. https://doi.org/10.1071/pc21003

Morán-Ordóñez, A., Briscoe, N. J., & Wintle, B. A. (2018a). Modelling species responses to extreme weather provides new insights into constraints on range and likely climate change impacts for Australian mammals. *Ecography*, *41*(2), 308–320. https://doi.org/10.1111/ecog.02850

Morán-Ordóñez, A., Briscoe, N. J., & Wintle, B. A. (2018b). Modelling species responses to extreme weather provides new insights into constraints on range and likely climate change impacts for Australian mammals. *Ecography*, *41*(2), 308–320. https://doi.org/10.1111/ecog.02850

Mota-Rojas, D., Pereira, A. M. F., Martínez-Burnes, J., Domínguez-Oliva, A., Mora-Medina, P., Casas-Alvarado, A., Rios-Sandoval, J., de Mira Geraldo, A., & Wang, D. (2022). Thermal Imaging to Assess the Health Status in Wildlife Animals under Human Care: Limitations and Perspectives. In *Animals* (Vol. 12, Issue 24). MDPI. https://doi.org/10.3390/ani12243558

Mota-Rojas, D., Pereira, A. M. F., Wang, D., Martínez-Burnes, J., Ghezzi, M., Hernández-Avalos, I., Lendez, P., Mora-Medina, P., Casas, A., Olmos-Hernández, A., Domínguez, A., Bertoni, A., & Geraldo, A. de M. (2021). Clinical applications and factors involved in validating thermal windows used in infrared thermography in cattle and river Buffalo to assess health and productivity. In *Animals* (Vol. 11, Issue 8). MDPI AG. https://doi.org/10.3390/ani11082247

Mota-Rojas, D., Titto, C. G., Orihuela, A., Martínez-Burnes, J., Gómez-Prado, J., Torres-Bernal, F., Flores-Padilla, K., Carvajal-De la Fuente, V., & Wang, D. (2021). Physiological and behavioral mechanisms of thermoregulation in mammals. In *Animals* (Vol. 11, Issue 6). MDPI AG. https://doi.org/10.3390/ani11061733

Murakami, M., Nunes Ramos, F., Durand, M., Ashton, R., & Batke, S. P. (2022). Quantification and Variation of Microclimatic Variables Within Tree Canopies - Considerations for Epiphyte Research. *Frontiers in Forests and Global Change, 5*. https://doi.org/10.3389/ffgc.2022.828725

Murcia, C. (1995). *Edge effects in fragmented forests: implications for conservation.*

Norin, T., & Metcalfe, N. B. (2019). Ecological and evolutionary consequences of metabolic rate plasticity in response to environmental change. In *Philosophical*

Transactions of the Royal Society B: Biological Sciences (Vol. 374, Issue 1768). Royal Society Publishing. https://doi.org/10.1098/rstb.2018.0180

Oksanen, J., Simpson GL, Blanchet FG, Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., & Evangelista, H. (2024). *"vegan": Community Ecology Package*. https://github.com/vegandevs/vegan

Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., Hole, D. G., Martin, T. G., Akçakaya, H. R., Corlett, R. T., Huntley, B., Bickford, D., Carr, J. A., Hoffmann, A. A., Midgley, G. F., Pearce-Kelly, P., Pearson, R. G., Williams, S. E., … Rondinini, C. (2015). Assessing species vulnerability to climate change. In *Nature Climate Change* (Vol. 5, Issue 3, pp. 215–225). Nature Publishing Group. https://doi.org/10.1038/nclimate2448

Páez, D. J., Restif, O., Eby, P., & Plowright, R. K. (2018a). Optimal foraging in seasonal environments: Implications for residency of australian flying foxes in food-subsidized urban landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1745). https://doi.org/10.1098/rstb.2017.0097

Páez, D. J., Restif, O., Eby, P., & Plowright, R. K. (2018b). Optimal foraging in seasonal environments: Implications for residency of australian flying foxes in food-subsidized urban landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1745). https://doi.org/10.1098/rstb.2017.0097

Páez, D. J., Restif, O., Eby, P., & Plowright, R. K. (2018c). Optimal foraging in seasonal environments: Implications for residency of australian flying foxes in

food-subsidized urban landscapes. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1745). https://doi.org/10.1098/rstb.2017.0097

Palmer, C., Price, O., & Bach, C. (2000). Foraging ecology of the black flying fox (Pteropus alecto) in the seasonal tropics of the Northern Territory, Australia. *Wildlife Research*, *27*(2), 169–178. https://doi.org/10.1071/WR97126

Pandey, U., Wanwey, S. R., Gandhi, N., Ram, S., Borgaonkar, H. P., & Sangode, S. (2025). Tree growth responses to the climate variability within the Pir Panjal Range evidenced by tree-rings of Abies pindrow (Royle ex D. Don) Royle. *Theoretical and Applied Climatology*, *156*(2), 91. https://doi.org/10.1007/s00704-024-05302-0

Parsons, J. G., Cairns, A., Johnson, C. N., Robson, S. K. A., Shilton, L. A., & Westcott, D. A. (2006). Dietary variation in spectacled flying foxes (Pteropus conspicillatus) of the Australian Wet Tropics. *Australian Journal of Zoology*, *54*(6), 417–428. https://doi.org/10.1071/ZO06092

Parsons, J. G., Robson, S. K. A., & Shilton, L. A. (2011). Roost fidelity in spectacled flying-foxes Pteropus conspicillatus: Implications for conservation and management. *Australian Zoologist*, *35*(SPEC. ISSUE), 66–71. https://doi.org/10.7882/fs.2011.009

Passos, I., Figueiredo, A., Almeida, A. M., & Ribeiro, M. M. (2024). Uncertainties in Plant Species Niche Modeling under Climate Change Scenarios. *Ecologies*, *5*(3), 402–419. https://doi.org/10.3390/ecologies5030025

Patten, M. A., & Smith-Patten, B. D. (2012). Testing the microclimate hypothesis: Light environment and population trends of Neotropical birds. *Biological Conservation*, *155*, 85–93. https://doi.org/10.1016/j.biocon.2012.06.004

Pebesma, E. (2018). Simple Features for R: Standardized Support for Spatial Vector Data. In *The R Journal* (Vol. 10, Issue 1, pp. 439–446).

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I. C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. In *Science* (Vol. 355, Issue 6332). American Association for the Advancement of Science. https://doi.org/10.1126/science.aai9214

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, *39*(20). https://doi.org/10.1029/2012GL053361

Perkins-Kirkpatrick, S. E., & Gibson, P. B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-12520-2

Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020a). Increasing trends in regional heatwaves. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-16970-7

Perkins-Kirkpatrick, S. E., & Lewis, S. C. (2020b). Increasing trends in regional heatwaves. *Nature Communications*, *11*(1), 1–8. https://doi.org/10.1038/s41467-020-16970-7

Pierson, E. D., & Rainey W.E. (1992). The biology of flying foxes of the genus Pteropus: a review. *Biological Report - US Fish & Wildlife Service*, *90*(23), 1–17.

Pincebourde, S., Murdock, C. C., Vickers, M., & Sears, M. W. (2016a). Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integrative and Comparative Biology*, *56*(1), 45–61. https://doi.org/10.1093/icb/icw016

Pincebourde, S., Murdock, C. C., Vickers, M., & Sears, M. W. (2016b). Fine-scale microclimatic variation can shape the responses of organisms to global change in both natural and urban environments. *Integrative and Comparative Biology*, *56*(1), 45–61. https://doi.org/10.1093/icb/icw016

Plotly Technologies Inc. (2015). *Collaborative data science Publisher: Plotly Technologies Inc*.

Polato NR, Gill BA, Shah AA, Gray MM, Casner KL, Barthelet A, Messer PW, Simmons MP, Guayasamin JM, Encalada AC, Kondratieff BC, Flecker AS, Thomas SA, Ghalambor CK, LeRoy Poff N, Funk WC, & Zamudio KR. (2018). Narrow thermal tolerance and low dispersal drive higher speciation in tropical mountains. *PNAS.*, *115*(49), 12471–12476. https://doi.org/10.5061/dryad.m728c47

Preece, N. (2023). Spectacled Flying-fox conflicts—tucker, totem, taunt and threat. *Integrative Conservation*, *2*(3), 112–118. https://doi.org/10.1002/inc3.26

Preece, N. (2024). Endangered Spectacled Flying-fox: a review of past and current knowledge and future needs to re-start its recovery. *Australian Zoologist*. https://doi.org/10.7882/az.2024.007

Queensland Goverment. (2021). *Nature Conservation Act 1992* (Issue July).

R Core Team. (2023). *R: A Language and Environment for Statistical Computing* (4.2.2). R Foundation for Statistical Computing.

Rahman, M. A., Hartmann, C., Moser-Reischl, A., von Strachwitz, M. F., Paeth, H., Pretzsch, H., Pauleit, S., & Rötzer, T. (2020). Tree cooling effects and human thermal comfort under contrasting species and sites. *Agricultural and Forest Meteorology*, *287*. https://doi.org/10.1016/j.agrformet.2020.107947

Rajasegaran, P., Shazali, N., & Khan, F. A. A. (2018). Microclimate and Physiological Effects in the Roosts of Cave Dwelling Bats: Implications in Roost Selection and Conservation in Sarawak, Malaysian Borneo. *Zoological Science*, *35*(6), 521–527. https://doi.org/10.2108/zs170144

Rakoto, P. Y., Deilami, K., Hurley, J., Amati, M., & Sun, Q. (Chayn). (2021). Revisiting the cooling effects of urban greening: Planning implications of vegetation types and spatial configuration. *Urban Forestry and Urban Greening*, *64*. https://doi.org/10.1016/j.ufug.2021.127266

Ramsay, E. E., Duffy, G. A., Burge, K., Taruc, R. R., Fleming, G. M., Faber, P. A., & Chown, S. L. (2023). Spatio-temporal development of the urban heat island in a socioeconomically diverse tropical city. *Environmental Pollution*, *316*. https://doi.org/10.1016/j.envpol.2022.120443

Randle, M., Stevens, N., & Midgley, G. (2018). Comparing the differential effects of canopy shading by Dichrostachys cinerea and Terminalia sericea on grass biomass. *South African Journal of Botany, 119*, 271–277. https://doi.org/10.1016/j.sajb.2018.09.026

Ranius, T., Gibbons, P., & Lindenmayer, D. (2024). Habitat requirements of deadwood-dependent invertebrates that occupy tree hollows. *Biological Reviews.* https://doi.org/10.1111/brv.13110

Ratcliffe, J. M., & Ter Hofstede, H. M. (2005a). Roosts as information centres: Social learning of food preferences in bats. *Biology Letters*, *1*(1), 72–74. https://doi.org/10.1098/rsbl.2004.0252

Ratcliffe, J. M., & Ter Hofstede, H. M. (2005b). Roosts as information centres: Social learning of food preferences in bats. *Biology Letters*, *1*(1), 72–74. https://doi.org/10.1098/rsbl.2004.0252

Ratnayake, H. U., Kearney, M. R., Govekar, P., Karoly, D., & Welbergen, J. A. (2019a). Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, *22*(4), 386–395. https://doi.org/10.1111/acv.12476

Ratnayake, H. U., Kearney, M. R., Govekar, P., Karoly, D., & Welbergen, J. A. (2019b). Forecasting wildlife die-offs from extreme heat events. *Animal Conservation*, *22*(4), 386–395. https://doi.org/10.1111/acv.12476

Ratnayake, H. U., Welbergen, J. A., Van Der Ree, R., & Kearney, M. R. (2021). Variation in fur properties may explain differences in heat-related mortality among Australian flying-foxes. *Australian Journal of Zoology*, *68*(6), 285–295. https://doi.org/10.1071/ZO20040

Remmers, S., Dausmann, K., Schoroth, M., Rabarison, H., & Reher, S. (2025). Intraspecific variation in metabolic responses to diverse environmental conditions in the Malagasy bat Triaenops menamena. *Journal of Comparative Physiology B: Biochemical, Systemic, and Environmental Physiology*, *195*(2), 247–262. https://doi.org/10.1007/s00360-025-01608-1

Richards, G. (1990). The spectacled flying fox, Pteropus conspicillatus (Chiroptera: Pteropodidae), in north Queensland. 2. Diet, seed dispersal and feeding ecology. *Australian Mammalogy*, *13*(April 1981), 25–31.

Richards, G. C. (1990). The spectacled flying-fox, Pteropus conspicillatus, (Chiroptera: pteropodidae) in North Queensland 1. Roost sites and distribution patterns. *Australian Mammalogy*, *13*, 17–24.

Roberts, B., Eby, P. &, & Westcott, D. (2020). *Pteropus conspicillatus, Spectacled Flying Fox*. https://doi.org/10.2305/IUCN.UK.2020

Roberts, B. J., Catterall, C. P., Eby, P., & Kanowski, J. (2012). Long-distance and frequent movements of the flying-fox Pteropus poliocephalus: Implications for management. *PLoS ONE*, *7*(8). https://doi.org/10.1371/journal.pone.0042532

Roberts, B. J., Mo, M., Roache, M., & Eby, P. (2021a). Review of dispersal attempts at flying-fox camps in Australia. In *Australian Journal of Zoology* (Vol. 68, Issue 6, pp. 254–272). CSIRO. https://doi.org/10.1071/ZO20043

Roberts, B. J., Mo, M., Roache, M., & Eby, P. (2021b). Review of dispersal attempts at flying-fox camps in Australia. *Australian Journal of Zoology*. https://doi.org/10.1071/ZO20043

Roussel, J. R., Auty, D., Coops, N. C., Tompalski, P., Goodbody, T. R. H., Meador, A. S., Bourdon, J. F., de Boissieu, F., & Achim, A. (2020). lidR: An R package for analysis of Airborne Laser Scanning (ALS) data. In *Remote Sensing of Environment* (Vol. 251). Elsevier Inc. https://doi.org/10.1016/j.rse.2020.112061

Roy, K., Saha, G. K., & Mazumdar, S. (2020). Seasonal influence on the diurnal roosting behaviour of free-ranging Indian flying fox Pteropus giganteus in an urban landscape, India. *Biologia, 75*(11), 1955–1961. https://doi.org/10.2478/s11756-020-00472-4

Rubalcaba, J. G., Gouveia, S. F., Villalobos, F., Cruz-Neto, A. P., Castro, M. G., Amado, T. F., Martinez, P. A., Navas, C. A., Dobrovolski, R., Alexandre Felizola Diniz-Filho, J., & Olalla-T arraga, M. A. (2022). *Physical constraints on thermoregulation and flight drive morphological evolution in bats.* https://doi.org/10.1073/pnas

Rummel, A. D., Swartz, S. M., & Marsh, R. L. (2019a). Warm bodies, cool wings: Regional heterothermy in flying bats. *Biology Letters*, *15*(9). https://doi.org/10.1098/rsbl.2019.0530

Rummel, A. D., Swartz, S. M., & Marsh, R. L. (2019b). Warm bodies, cool wings: Regional heterothermy in flying bats. *Biology Letters*, *15*(9). https://doi.org/10.1098/rsbl.2019.0530

Santos, E. G., Svátek, M., Nunes, M. H., Aalto, J., Senior, R. A., Matula, R., Plichta, R., & Maeda, E. E. (2024). Structural changes caused by selective logging undermine the thermal buffering capacity of tropical forests. *Agricultural and Forest Meteorology*, *348*. https://doi.org/10.1016/j.agrformet.2024.109912

Scheffers, B. R., Edwards, D. P., Diesmos, A., Williams, S. E., & Evans, T. A. (2014). Microhabitats reduce animal's exposure to climate extremes. *Global Change Biology*, *20*(2), 495–503. https://doi.org/10.1111/gcb.12439

Scheffers, B. R., Edwards, D. P., Macdonald, S. L., Senior, R. A., Andriamahohatra, L. R., Roslan, N., Rogers, A. M., Haugaasen, T., Wright, P., & Williams, S. E. (2017). Extreme thermal heterogeneity in structurally complex tropical rain forests. *Biotropica*, *49*(1), 35–44. https://doi.org/10.1111/btp.12355

Schou, M. F., Bonato, M., Engelbrecht, A., Brand, Z., Svensson, E. I., Melgar, J., Muvhali, P. T., Cloete, S. W. P., & Cornwallis, C. K. (2021). Extreme temperatures compromise male and female fertility in a large desert bird. *Nature Communications*, *12*(1). https://doi.org/10.1038/s41467-021-20937-7

Seidel, S. D., & Yang, D. (2020a). The lightness of water vapor helps to stabilize tropical climate. In *Sci. Adv* (Vol. 6). https://www.science.org

Seidel, S. D., & Yang, D. (2020b). The lightness of water vapor helps to stabilize tropical climate. In *Sci. Adv* (Vol. 6). https://www.science.org

Seuront, L., Ng, T. P. T., & Lathlean, J. A. (2018a). A review of the thermal biology and ecology of molluscs, and of the use of infrared thermography in molluscan research. *Journal of Molluscan Studies*, *84*(3), 203–232. https://doi.org/10.1093/mollus/eyy023

Seuront, L., Ng, T. P. T., & Lathlean, J. A. (2018b). A review of the thermal biology and ecology of molluscs, and of the use of infrared thermography in molluscan research. In *Journal of Molluscan Studies* (Vol. 84, Issue 3, pp. 203–232). Oxford University Press. https://doi.org/10.1093/mollus/eyy023

Shields, T. (2014). *Key Components for a Flying-fox Management Plan to cover Ipswich City Council*.

Smith, R., Mastrocco, A., Prittie, J., & Weltman, J. (2023). Comparison of Aural and Rectal Temperature in Dogs Presenting to an Emergency Room. *Veterinary Medicine: Research and Reports*, *Volume 14*, 125–131. https://doi.org/10.2147/vmrr.s411935

Smith-Tripp, S. M., Eskelson, B. N. I., Coops, N. C., & Schwartz, N. B. (2022). Canopy height impacts on the growing season and monthly microclimate in a burned forest of British Columbia, Canada. *Agricultural and Forest Meteorology*, *323*. https://doi.org/10.1016/j.agrformet.2022.109067

Smyser, T. J., Hardy, M. A., Davis, A. J., Preston, W. L., & Tietje, W. D. (2024). Downed wood removal effects on survival and site fidelity of woodrats in a California oak woodland. *Journal of Wildlife Management*, *88*(5). https://doi.org/10.1002/jwmg.22590

Snoyman, S., & Brown, C. (2010a). Microclimate preferences of the grey-headed flying fox (Pteropus poliocephalus) in the Sydney region. *Australian Journal of Zoology*, *58*(6), 376–383. https://doi.org/10.1071/ZO10062

Snoyman, S., & Brown, C. (2010b). Microclimate preferences of the grey-headed flying fox (Pteropus poliocephalus) in the Sydney region. *Australian Journal of Zoology*, *58*(6), 376–383. https://doi.org/10.1071/ZO10062

Soravia, C., Ashton, B. J., Thornton, A., & Ridley, A. R. (2021). The impacts of heat stress on animal cognition: Implications for adaptation to a changing climate. In

Wiley Interdisciplinary Reviews: Climate Change (Vol. 12, Issue 4). John Wiley and Sons Inc. https://doi.org/10.1002/wcc.713

Species Profile and Threats Database. (2025, January 19). *Pteropus conspicillatus - Spectacled flying-fox*. Species Profile and Threats Database - Department of Climate Change, Energy, the Environment and Water.

Staff, N. R. Council. (1995a). *Effects of Past Global Change on Life*. National Academies Press. https://www.ncbi.nlm.nih.gov/books/NBK231950/https://www.ncbi.nlm.nih.gov/books/NBK231950/

Staff, N. R. Council. (1995b). *Effects of Past Global Change on Life*. National Academies Press.

Stanvic, S., Mcdonald, V., & Collins, L. (2013). *Managing Heat Stress in Flying-foxes Colonies*.

Steffen, W., Hughes, L., & Perkins, S. (2014). *Heatwaves : Hotter, Longer, More Often.* http://www.climatecouncil.org.au/uploads/9901f6614a2cac7b2b888f55b4dff9cc.pdf

Stevens, G. C. (1989a). The Latitudinal Gradient in Geographical Range: How so Many Species Coexist in the Tropics. In *Source: The American Naturalist* (Vol. 133, Issue 2).

Stevens, G. C. (1989b). The Latitudinal Gradient in Geographical Range: How so Many Species Coexist in the Tropics. In *Source: The American Naturalist* (Vol. 133, Issue 2). https://about.jstor.org/terms

Suggitt, A. J., Gillingham, P. K., Hill, J. K., Huntley, B., Kunin, W. E., Roy, D. B., & Thomas, C. D. (2011). Habitat microclimates drive fine-scale variation in extreme temperatures. *Oikos*, *120*(1), 1–8. https://doi.org/10.1111/j.1600-0706.2010.18270.x

Tait, J., Perotto-Baldivieso, H. L., McKeown, A., & Westcott, D. A. (2014). Are flying-foxes coming to town? Urbanisation of the spectacled flying-fox (Pteropus conspicillatus) in Australia. *PLoS ONE*, *9*(10). https://doi.org/10.1371/journal.pone.0109810

Tattersall, G. J. (2016a). Infrared thermography: A non-invasive window into thermal physiology. In *Comparative Biochemistry and Physiology -Part A : Molecular and Integrative Physiology* (Vol. 202, pp. 78–98). Elsevier Inc. https://doi.org/10.1016/j.cbpa.2016.02.022

Tattersall, G. J. (2016b). Infrared thermography: A non-invasive window into thermal physiology. In *Comparative Biochemistry and Physiology -Part A : Molecular and Integrative Physiology* (Vol. 202, pp. 78–98). Elsevier Inc. https://doi.org/10.1016/j.cbpa.2016.02.022

Tay, J. K., Narasimhan, B., & Hastie, T. (2023). Elastic Net Regularization Paths for All Generalized Linear Models. *Journal of Statistical Software*, *106*(1). https://doi.org/10.18637/jss.v106.i01

Team. R Core. (2021). R: A language and environment for statistical computing. *R Foundation for Statistical Computing*.

Terschanski, J., Nunes, M. H., Aalto, I., Pellikka, P., Wekesa, C., & Maeda, E. E. (2024a). The role of vegetation structural diversity in regulating the microclimate

of human-modified tropical ecosystems. *Journal of Environmental Management, 360*. https://doi.org/10.1016/j.jenvman.2024.121128

Terschanski, J., Nunes, M. H., Aalto, I., Pellikka, P., Wekesa, C., & Maeda, E. E. (2024b). The role of vegetation structural diversity in regulating the microclimate of human-modified tropical ecosystems. *Journal of Environmental Management, 360*. https://doi.org/10.1016/j.jenvman.2024.121128

Threatened species & ecological communities (TS. (2019). *Conservation Advice Pteropus conspicillatus spectacled flying-fox*. http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl

Tidemann, C. R., & Nelson, J. E. (2011). Life expectancy, causes of death and movements of the grey-headed flying-fox (Pteropus poliocephalus) inferred from banding. *Acta Chiropterologica*, *13*(2), 419–429. https://doi.org/10.3161/150811011X624901

Timmiss, L. A., Martin, J. M., Murray, N. J., Welbergen, J. A., Westcott, D., McKeown, A., & Kingsford, R. T. (2021a). Threatened but not conserved: Flying-fox roosting and foraging habitat in Australia. *Australian Journal of Zoology*, *68*(6), 226–233. https://doi.org/10.1071/ZO20086

Timmiss, L. A., Martin, J. M., Murray, N. J., Welbergen, J. A., Westcott, D., McKeown, A., & Kingsford, R. T. (2021b). Threatened but not conserved: Flying-fox roosting and foraging habitat in Australia. *Australian Journal of Zoology*, *68*(6), 226–233. https://doi.org/10.1071/ZO20086

Turbill, C., Walker, M., Boardman, W., Martin, J. M., McKeown, A., Meade, J., & Welbergen, J. A. (2024). Torpor use in the wild by one of the world's largest bats.

Proceedings of the Royal Society B: Biological Sciences, *291*(2026). https://doi.org/10.1098/rspb.2024.1137

Turtle Tough. (n.d.). *Infrared Report Express* (2.1.5.0).

Ummenhofer, C. C., & Meehl, G. A. (2017). Extreme weather and climate events with ecological relevance: A review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1723). https://doi.org/10.1098/rstb.2016.0135

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571–573. https://doi.org/10.1126/science.aaa4984

Usamentiaga, R., Venegas, P., Guerediaga, J., Vega, L., Molleda, J., & Bulnes, F. G. (2014). Infrared thermography for temperature measurement and non-destructive testing. In *Sensors (Switzerland)* (Vol. 14, Issue 7, pp. 12305–12348). MDPI AG. https://doi.org/10.3390/s140712305

van den Boogaart, K. G., & Tolosana-Delgado, R. (2008). "compositions": A unified R package to analyze compositional data. *Computers and Geosciences*, *34*(4), 320–338. https://doi.org/10.1016/j.cageo.2006.11.017

van Dyk, M., Noakes, M. J., & McKechnie, A. E. (2019). Interactions between humidity and evaporative heat dissipation in a passerine bird. *Journal of Comparative Physiology B: Biochemical, Systemic, and Environmental Physiology*, *189*(2), 299–308. https://doi.org/10.1007/s00360-019-01210-2

Varner, J., & Dearing, M. D. (2014a). The Importance of Biologically Relevant Microclimates in Habitat Suitability Assessments. *PLoS ONE*, *9*(8), 104648. https://doi.org/10.1371/journal.pone.0104648.t001

Varner, J., & Dearing, M. D. (2014b). The Importance of Biologically Relevant Microclimates in Habitat Suitability Assessments. *PLoS ONE*, *9*(8), 104648. https://doi.org/10.1371/journal.pone.0104648.t001

Vinod, N., Slot, M., McGregor, I. R., Ordway, E. M., Smith, M. N., Taylor, T. C., Sack, L., Buckley, T. N., & Anderson-Teixeira, K. J. (2023). Thermal sensitivity across forest vertical profiles: patterns, mechanisms, and ecological implications. In *New Phytologist* (Vol. 237, Issue 1, pp. 22–47). John Wiley and Sons Inc. https://doi.org/10.1111/nph.18539

Wagner, B., Baker, P. J., Stewart, S. B., Lumsden, L. F., Nelson, J. L., Cripps, J. K., Durkin, L. K., Scroggie, M. P., & Nitschke, C. R. (2020). Climate change drives habitat contraction of a nocturnal arboreal marsupial at its physiological limits. *Ecosphere*, *11*(10). https://doi.org/10.1002/ecs2.3262

Wang, F. K., Shih, J. Y., Juan, P. H., Su, Y. C., & Wang, Y. C. (2021). Non-invasive cattle body temperature measurement using infrared thermography and auxiliary sensors. *Sensors*, *21*(7). https://doi.org/10.3390/s21072425

Wang, X., Rahman, M. A., Mokroš, M., Rötzer, T., Pattnaik, N., Pang, Y., Zhang, Y., Da, L., & Song, K. (2023a). The influence of vertical canopy structure on the cooling and humidifying urban microclimate during hot summer days. *Landscape and Urban Planning*, *238*. https://doi.org/10.1016/j.landurbplan.2023.104841

Wang, X., Rahman, M. A., Mokroš, M., Rötzer, T., Pattnaik, N., Pang, Y., Zhang, Y., Da, L., & Song, K. (2023b). The influence of vertical canopy structure on the cooling and humidifying urban microclimate during hot summer days. *Landscape and Urban Planning*, *238*. https://doi.org/10.1016/j.landurbplan.2023.104841

Wang, Y., Li, Q., Chu, M., Kang, X., & Liu, G. (2023). Application of infrared thermography and machine learning techniques in cattle health assessments: A review. In *Biosystems Engineering* (Vol. 230, pp. 361–387). Academic Press. https://doi.org/10.1016/j.biosystemseng.2023.05.002

Warneke, C., Brudvig, L. A., Gregg, M., McDaniel, S., & Yelenik, S. (2023). Elevation, canopy cover and grass cover structure patterns of seedling establishment in a subtropical post-fire restoration. *Ecological Solutions and Evidence*, *4*(4). https://doi.org/10.1002/2688-8319.12280

Welbergen, J. (2012). The impacts of extreme events on biodiversity - lessons from die-offs in flying-foxes. *Proceedings of the International Symposium on the Importance of Bats as Bioindicators*, *December*, 60–64.

Welbergen, J. A., Klose, S. M., Markus, N., & Eby, P. (2008a). Climate change and the effects of temperature extremes on Australian flying-foxes. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1633), 419–425. https://doi.org/10.1098/rspb.2007.1385

Welbergen, J. A., Klose, S. M., Markus, N., & Eby, P. (2008b). Climate change and the effects of temperature extremes on Australian flying-foxes. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1633), 419–425. https://doi.org/10.1098/rspb.2007.1385

Welbergen, J. A., Meade, J., Field, H. E., Edson, D., McMichael, L., Shoo, L. P., Praszczalek, J., Smith, C., & Martin, J. M. (2020). Extreme mobility of the world's largest flying mammals creates key challenges for management and conservation. *BMC Biology*, *18*(1), 1–13. https://doi.org/10.1186/s12915-020-00829-w

Welman, S., Tuen, A. A., & Lovegrove, B. G. (2017). Using thermoregulatory profiles to assess climate change vulnerability in an arboreal tropical bat: Heterothermy may be a pre-adaptive advantage. *Climate Research*, *74*(2), 161–170. https://doi.org/10.3354/cr01496

Whittaker, A. L., Muns, R., Wang, D., Martínez-Burnes, J., Hernández-Ávalos, I., Casas-Alvarado, A., Domínguez-Oliva, A., & Mota-Rojas, D. (2023). Assessment of Pain and Inflammation in Domestic Animals Using Infrared Thermography: A Narrative Review. In *Animals* (Vol. 13, Issue 13). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/ani13132065

Wickham H. (2016). ggplot2: Elegant Graphics for Data Analysis. . *Springer-Verlag New York.*

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019a). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., … Yutani, H. (2019b). Welcome to the Tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wiens, J. J. (2016). Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLoS Biology*, *14*(12). https://doi.org/10.1371/journal.pbio.2001104

Wolfe, J. D., Luther, D. A., Jirinec, V., Collings, J., Johnson, E. I., Bierregaard, R. O., & Stouffer, P. C. (2025). Climate change aggravates bird mortality in pristine tropical forests. *Science Advances*, *11*, 8086. https://www.science.org

Wood N., S. (2017). GAMs in Practice: mgcv. In *Generalized Additive Models* (2nd ed., pp. 325–398). CRC Press. https://doi.org/https://doi.org/10.1201/9781315370279

Yabsley, S. H., Meade, J., Martin, J. M., & Welbergen, J. A. (2021a). Human-modified landscapes provide key foraging areas for a threatened flying mammal: The grey-headed flying-fox. *PLoS ONE*, *16*(November). https://doi.org/10.1371/journal.pone.0259395

Yabsley, S. H., Meade, J., Martin, J. M., & Welbergen, J. A. (2021b). Human-modified landscapes provide key foraging areas for a threatened flying mammal: The grey-headed flying-fox. *PLoS ONE*, *16*(November), 1–19. https://doi.org/10.1371/journal.pone.0259395

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., & Vejre, H. (2020a). Critical review on the cooling effect of urban blue-green space: A threshold-size perspective. In *Urban Forestry and Urban Greening* (Vol. 49). Elsevier GmbH. https://doi.org/10.1016/j.ufug.2020.126630

Yu, Z., Yang, G., Zuo, S., Jørgensen, G., Koga, M., & Vejre, H. (2020b). Critical review on the cooling effect of urban blue-green space: A threshold-size

perspective. In *Urban Forestry and Urban Greening* (Vol. 49). Elsevier GmbH. https://doi.org/10.1016/j.ufug.2020.126630

Zabin, C. J., Jurgens, L. J., Bible, J. M., Patten, M. V., Chang, A. L., Grosholz, E. D., & Boyer, K. E. (2022). Increasing the resilience of ecological restoration to extreme climatic events. In *Frontiers in Ecology and the Environment* (Vol. 20, Issue 5, pp. 310–318). John Wiley and Sons Inc. https://doi.org/10.1002/fee.2471

Zellweger, F., Sulmoni, E., Malle, J. T., Baltensweiler, A., Jonas, T., Zimmermann, N. E., Ginzler, C., Karger, D. N., De Frenne, P., Frey, D., & Webster, C. (2024). Microclimate mapping using novel radiative transfer modelling. *Biogeosciences*, *21*(2), 605–623. https://doi.org/10.5194/bg-21-605-2024

Zhang, Z., Lv, Y., & Pan, H. (2013). Cooling and humidifying effect of plant communities in subtropical urban parks. *Urban Forestry and Urban Greening*, *12*(3), 323–329. https://doi.org/10.1016/j.ufug.2013.03.010

Zhao, K., & Jackson, R. B. (2014). Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecological Monographs*, *84*(2), 329–353. https://doi.org/10.1890/12-1705.1

Zheng, S., Zhou, C., Jiang, X., Huang, J., & Xu, D. (2022). Progress on Infrared Imaging Technology in Animal Production: A Review. In *Sensors* (Vol. 22, Issue 3). MDPI. https://doi.org/10.3390/s22030705

Ziter, C. D., Pedersen, E. J., Kucharik, C. J., & Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the*

United States of America, 116(15), 7575–7580.

https://doi.org/10.1073/pnas.1817561116