The Conservation Biology of the Monteiro's Storm-Petrel and Band-Rumped Storm-Petrel on Ilhéu da Praia, Azores

This thesis is being submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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July 2022

Front cover photographs: top left (Ilhéu da Praia; Ben Porter), top right (Monteiro's storm-petrel adult; Hannah Hereward), second from top right (band-rumped storm-petrel; Ben Porter), second from top left (chick being weighed; Ben Porter), third from top right (sunset from the islet; Hannah Hereward), second from bottom left (bespoke nest camera deployed on artificial nest; Hannah Hereward), second from bottom middle (a video still of an adult and chick in the nest; Hannah Hereward), second from bottom right (GPS tag and band-rumped storm-petrel; Ben Porter), bottom left (band-rumped storm-petrel in nest with Monteiro's storm-petrel chick; Hannah Hereward), four on bottom right (Barolo shearwater, ants + ant eggs, Madeiran wall lizard, Cory's shearwater; Ben Porter).

Summary

This thesis addresses the conservation of two species of seabird (Monteiro's and band-rumped storm-petrels) that breed on the same islet in the Azores Archipelago, but at different times of year. **Chapter 1** provides a General Introduction to the thesis, and **Chapter 2** sets out the General Methods used.

Chapter 3 addresses the biotic and abiotic drivers of long-term changes in breeding success, phenology and chick growth. A major concerning finding is that breeding success has declined in both species over the 20-year study period, with this decline being most substantial (~1% per year) for the endemic Monteiro's storm-petrel. Possible causes of this decline include interacting weather variables (air temperature, wind speed and rainfall) and other species implicated in nesting failures (Barolo Shearwater, Cory's Shearwater, other storm-petrel species, Madeiran Wall Lizard, and ants).

The remaining data chapters combine novel technologies to aid in describing behaviours in the nest and at sea to inform conservation action.

Chapter 4 details the development and successful deployment of a cheap but reliable bespoke nest camera system, providing a highly flexible tool for monitoring burrow-nesting birds in remote locations.

Chapter 5 utilises this camera technology to quantify both storm-petrel species' daily and seasonal routines of behaviour, and three categories of threats. Of the two species, Monteiro's storm-petrel chicks experienced more frequent interactions with all three categories of threats.

Chapter 6 is a proof-of-concept study that demonstrates the powerful combination of GPS tracking, camera monitoring and chick weighing, to examine the inter-relation of foraging behaviour and breeding success. This could be deployed in future studies of breeding seabirds to address ongoing conservation challenges.

The **General Discussion** describes the urgent need for conservation action to address the substantial decline in breeding success of the endemic Monteiro's storm-petrel, highlighting a range of achievable and potentially effective conservation management actions.

Acknowledgements

The last 3 years 9 months have been an incredible marathon!
I have revelled in the highs, pushed through the lows and determinedly strode out in the middle times. I realise that writing a five-page acknowledgement might seem excessive or extravagant, but whilst I have led this crazy rollercoaster journey, I would not have reached the finish line without the many who have supported, helped and cheered me on along the way and I would like to take the time to thank them.

Whether named or unnamed – thank you!

My PhD was two years in the planning, which first started to take root when I met **Dr Robert Thomas**, **Dr Renata Medeiros-Mirra and Dr Frank Hailer** at the beautiful A Rocha centre in Portugal - Cruzinha. In the two years, my PhD proposal was jointly put together with these supervisors and also drew in additional supervisors, namely **Dr Verónica Neves and Dr Sean Rands** and two advisors **Dr Mark Bolton and Dr Joël Bried**. A huge thank you to all seven of you for persevering in pushing my PhD proposal through to funding and supporting me in the various ways you have over the last four years!

To my primary supervisor – **Rob** - it has been a delight and privilege to have you as my primary supervisor! Thank you for keeping me going with a continual string of cracking dad jokes, reminding me that a PhD is a 'marathon not a snickers' (Thomas, 2018), asking what my morale score is, honest sharing of life in its highs and lows, as well as academically honing, explaining and supporting. I have also really appreciated sharing the interest in creation care and the A Rocha family - and excited to see what happens in this next season.

To **Rob, Renata and Frank** - thank you for being willing to develop and pursue PhD funding with me for this project and seeing something in me worth keeping. Thank you for the many meetings, chats, time and care throughout my PhD (including many a coffee and ice cream trip and late nights on the cliffs, storm-petrel ringing).

Sean - thank you for your support and many calls and in person catch ups over coffee. I am so thankful for your ability to ask the right questions at the right time and the broader background you bring in wider behaviour studies and technology applications.

Mark, Renata, Verónica and Joël - thank you for welcoming me into the group of people who study the Monteiro's storm-petrel! It has been a delight to be part of this amazing group of researchers and I am so thankful for your willingness to share previous years of data and to share and discuss ideas. And **Verónica** - thank you for hosting me on Faial, introducing me to the many and varied researchers, welcoming me onto the islet and sharing such a special place and your knowledge of it and the species that call it home.

A huge thank you to my funders - **NERC GW4+** Doctoral Training Partnership studentship and especially to **Sara Tonge** and **Emeliana Palk** for your incredible help and support negotiating the last four years! I have also had the privilege of undertaking a 3-month career development placement during my DTP, and I'm so thankful to **Dr Robert Sluka and family** for hosting me! It was so great to spend time with you all again and to get stuck in with the various projects A Rocha USA - Florida do and take part in.

On the islet, power was an important feature for both charging powerpacks to run the cameras and also to keep us in touch with the outside world. So, a huge thank you to **GB-Sol** who gifted me some solar panels to take on fieldwork – without these, we could not have deployed as many cameras as we did or indeed have kept in touch with those off islet! Thank you for your generosity and interest in my project! Also, a huge thank you to **Pathtrack** for the GPS tag support!

It has been a delight and privilege to have fitted in a year and a bit of fieldwork for my PhD (especially considering the covid-19 travel restrictions due to which I missed out on 3 months of fieldwork). For this fieldwork I moved to the beautiful, small, otherwise uninhabited volcanic islet and enlisted the help of fieldwork assistants, friends and family to help gather the huge amount of data I have collected in a relatively short amount of time. A huge thank you to the amazing Natural Park team (particularly to **Dr Pedro Raposo, Luís Aguiar, Joana Lourenço** and **Beatriz Cunha**) who kept us connected to the outside world with many boat trips (in all weathers) and food and water runs. Special thanks to **Pedro and his family** for welcoming us for delicious and rejuvenating dinners when on the mainland! And to **Peter and Christiana and the community on Graciosa** for hosting myself and all the teams whilst on the mainland.

Fieldwork assistants, friends and family (in order of appearance): **Alyssa Sargent, Zoe Deakin, Alys Perry, Eike Usher, Sara Roda, Sarah Long, Julian Benedikt, Sarah Gronefeld, Matthew Couldwell, Emma Renshaw, Katie Shaw, Lisa and Catherine, Anthony Hereward, Pauline Hereward, Bernado Neto, Viola Ross-Smith, Jack Devlin, Ben Porter, Kirstin Jones, Jonathan Biddle, Dimitri Dujardin, Jodie Henderson, Miriam Cuesta, Gary Hanock, Alice Edney** and **Max Levy**. Also thanks to **those who were due to join fieldwork in early Summer 2020 when travel was not possible**. Thank you to all of you for being willing to maroon yourselves on the islet and get stuck into all aspects of islet life - from the various fieldwork activities to sharing life together - so many memories of daily nest checks including 'guess the chick weight', star gazing whilst also waiting for birds to drop in the mist-net, mapping nests and habitats, late night GPS tracker retrieval (especially when in the morning we saw on the camera that the birds came after we'd gone to sleep!), trips to watch the sunset and to listen to the day-to-night shift in bird calls, playing card games or watching an occasional film/tv series, opening a corked wine bottle without a corkscrew (yes it did work!), winter boat trips (each trip has its own story), almost cabin fever after two straight days of rain, the triumphant return to the islet in August 2020! The list goes on, but I best move on.
To you all - thank you :).

Various of those who joined me on the islet took photographs and videos and some drew too. But two who have contributed many of the photographs and the artwork in my thesis are **Ben Porter** (www.benporterwildlife.co.uk) and **Sarah Long** (Seafarer Sarah Artwork). **Sarah** - it was great fun to talk through the different commission ideas in the context of the two epic field seasons you assisted on ☺, thank you for creating such beautiful paintings! **Ben** – thank you for joining the crazy adventure, taking time to listen to ideas and (as ever) seizing the opportunities when photographic moments presented themselves amidst the day-to-day islet life and varied fieldwork!

A special thank you to two Cardiff University students I co-supervised, who took on smaller projects that fitted within my thesis – **Christa Emmett** and **Laura Astbury** thank you for your motivation and determination, particularly for the many hours of video watching, as well as the chats and calls discussing all the different aspects of your respective projects!

As I'm sure will be the case for many other PhD'ers in the last and coming few years, covid-19 changed a lot of 'plans' many times. Amidst the uncertainties and rollercoaster that is PhD life (regardless of international pandemics), I am so thankful to PhD friends, non-PhD friends, and family for cheering me on.

To the amazingly supportive community within the **School of Biosciences and especially the Organisms and Environment Division** – I am so thankful for the times I have had online and in person, to meet, chat and listen with all those I have. Thank you to those behind-the-scenes-answers to lots of different emails and requests! Special thanks to **Bethan Griffiths** and **Francisca Aslin** for their dyslexia study skills support – it has been invaluable for keeping me on track! To **PhD friends**, thank you for sharing the highs and lows of PhD life together. **To those in my year and cohort** (at Cardiff and across GW4+ DTP) – a huge thank you! **My first-year office buddies, Dr Sarah Christophodies, Dr Jez Smith, Dr Richard J. Facey and Dr Sophie Lee-Williams** - thank you for being on hand to answer 'where/what/how' questions and for supplying chocolate when needed and for catch ups in the latter years when I have been back. Special thanks to **Jez** and **Rich** for pep talks (and pub trips) in the latter years, and to Rich for introducing me to the delights of Raspberry Pi – thank you for all the remote, troubleshooting help! Huge thanks to those in our **research on behaviour group** and especially the **Cardiff Uni Stormie team** (**Zoe Deakin, Dr Alex McCubbin, Annelea Beard and Ben Porter**). Also thank you to **those from other floors across the four years** who welcomed me in for coffee/lunch chats and walks ☺.

To my **non-PhD friends, family friends, church and A Rocha families and to my family** – named or unnamed, thank you for keeping me sane, messaging me, and where possible, meeting up in person! Special thanks to **Abi B, Sarah T, Georgina B, Ben P, Will and Claudia E-C, Katie S, Soph M, the Strattons, Aimee L, Kate P, Hannah E, Abbie M, Alice M** and my amazing **small group**! Huge thanks to the amazing **Leadbetters** for hosting and welcoming me into their family so many times! Special thanks to our **Dutch family** for giving me a base to write up for a few weeks - thankful for the walks, chats and space in the garden to listen to swifts and write! Huge thanks to our dogs, **Piran** and now **Branok**, for the many walks, runs and cuddles. And to my **family at home and beyond** – there are not enough words, but thank you for the many meals, walks, calls, chats and encouragement :).

I leave the biggest and also most emotional thank you to write for last - **mum and dad**. Thank you for encouraging and nurturing in me your God-given adventurous spirit, curiosity and care! It has taken you both to some incredible places and I'm thankful for all the places it has already taken me and I'm looking forward to seeing what's next! Thank you for your continual encouragement, listening ear, willingness to walk/run and talk and to celebrate the small and big things, whilst also sharing in the grief and loss of the last four years. It has been quite a four years, and I'm so thankful to have been home when I needed to be and away when I could.

There are so many different quotes and phrases that have summarised different parts of the last four years, but I would like to return to a PhD being a marathon.

PhD life, as with the Christian life, can be described as a race, as a marathon to be enjoyed but with the highs and lows that it brings. It's a chance to cheer each other on - and I'm thankful for those named and unnamed for cheering me on and I hope I have done so in return. As in every race there are people at different stages, and some are already ahead and finished (be it the PhD journey or life as a whole). For me this quote below encourages me that although, over the last four years I have seen and shared in considerable emotional strains and heart-breaking loss, I am thankful to know that those no longer with us are these pioneers who have blazed the way ahead of me, still cheering me on.

To those no longer with us (especially Miranda, Piran, Grandma, David)
- you are sorely missed,
but I'm so thankful for the memories and legacies you have left behind.

"The fundamental fact of existence is that this trust in God, this faith, is the firm foundation under everything that makes life worth living. It's our handle on what we can't see...
Do you see what this means—all these pioneers who blazed the way, all these veterans cheering us on? It means we'd better get on with it. Strip down, start running—and never quit!" (Hebrews 11:1, 12:1)

"… I got to my feet and stared around the sea again. — Nothing — nothing but water and sky !

Presently a long way off I saw the small dark shape of a bird skimming low down over the swell. When it came quite close I saw it was a Stormy Petrel. I tried to talk to it, to see if it could give me news. But unluckily I hadn't learned much seabird language and I couldn't even attract its attention, much less make it understand what I wanted.

Twice it circled round my raft, lazily, with hardly a flip of the wing. And I could not help wondering, in spite of the distress I was in, where it had spent last night — how it, or any other living thing, had weathered such a smashing storm. It made me realise the great big difference between different creatures; and that size and strength are not everything. To this petrel, a frail little thing of feathers, much smaller and weaker than I, the Sea could do anything she liked, it seemed; and his only answer was a lazy, saucy flip of the wing ! *He* was the one who should be called the *able seaman*. For, come raging gale, come sunlit calm, this wilderness of water was his home.

After swooping over the sea around me (just looking for food, I supposed) he went off in the direction from which he had come. And I was alone once more. …"
(Tommy Stubbins in *The Voyages of Doctor Dolittle*, by Hugh Lofting, p206).

Collaborators

This PhD was funded through a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council [NE/L002434/1] with additional support from the project CASE partner, Eco-explore Community Interest Company. I helped developed the project alongside supervisors and advisors who then proposed the project, namely Dr Robert J. Thomas, Dr Renata Medeiros-Mirra, Dr Frank Hailer, Dr Verónica Neves, Dr Sean A. Rands and Dr Mark Bolton and Dr Joël Bried. All have contributed to each chapter of this PhD. However, additional collaborators have also contributed to the completion of my PhD, especially in the development of papers - now published or in preparation.

Chapter 3. I led the fieldwork for the 2019-2020 seasons, the consolidation of the data from other years, the data analysis and write up. The previous years of fieldwork research were led by: Mark Bolton and Renata Medeiros-Mirra (2000-2001), Joël Bried and Verónica Neves (2002-2017), Verónica Neves, Petra Quillfeldt, Wiebke Schaefer (2018-2019) (This fieldwork was funded by various other grants: Fundação de Ciência e Tecnologia, Small Project Grant from RSPB/BirdLife, FCT grant, Programmes "MARMAC" I and II, OKEANOS-Marine Sciences Institute, MARE). Robert J. Thomas assisted in data analysis. Fieldwork assistants aided in data collection throughout the 20 years of fieldwork: Luís Dias, Ana Mendes, Luís Aguiar, Colin Beale, C. Picanço, P. Pedro, M.C. Magalhães, C. Nava, Lucia Gomes, Miguel Tarita da Silva, Théo Châteugiron, Jake Taylor-Bruce, Martin Austad, Juan Masello, Thiemo Karwinkel, Alyssa Sargent, Zoe Deakin, Alys Perry, Eike Usher, Sara Roda, Sarah Long, Julian Benedikt, Sarah Gronefeld, Matthew Couldwell, Emma Renshaw, Katie Shaw, Lisa and Catherine, Anthony Hereward, Pauline Hereward, Bernado Neto, Viola Ross-Smith, Jack Devlin, Ben Porter, Kirstin Jones, Jonathan Biddle, Dimitri Dujardin, Jodie Henderson, Miriam Cuesta, Gary Hanock, Alice Edney and Max Levy. All supervisors and advisors contributed to manuscript shaping and development.

Chapter 4. I led the development of the bespoke camera and housing, in field deployments, video analysis method, analysis of videos, data analysis and write up. The concept was also conceived by Richard J. Facey and Robert J. Thomas. Richard J. Facey also co-built the camera and developed the programme scripts, assisted by Luke Maggs. Alyssa J. Sargent aided in developing the camera housing in-field, with trouble-shooting advice provided by Richard J. Facey. Additional assistants contributed to in-field camera deployment and initial video analysis: Alyssa J. Sargent, Sara Roda, Matthew L. Couldwell, Emma L. Renshaw, Katie H. Shaw, Jack J. Devlin, Sarah E. Long, Ben J. Porter and Jodie M. Henderson. Ben J. Porter contributed photographs. Robert J. Thomas, Christa L. Emmett and Laura Astbury also contributed towards developing the video analysis and data processing methods. Christa L. Emmett also analysed Monteiro's storm-petrel season videos and Laura Astbury analysed the band-rumped storm-petrel season videos. Robert J. Thomas and Richard J. Facey also initially contributed to developing the manuscript. Sean A. Rands contributed to subsequent manuscript shaping and development.
This chapter is already published under the same name in Ecology and Evolution.

Chapter 5. I led the development of the concept, in field deployments, video analysis method, analysis of videos, data analysis and write up.
The concept was also conceived by Richard J. Facey and Robert J. Thomas. Trouble shooting advice was provided by Richard J. Facey. Additional assistants contributed to in-field camera deployment and initial video analysis: Alyssa J. Sargent, Verónica Neves, Sara Roda, Matthew L. Couldwell, Emma L. Renshaw, Katie H. Shaw, Jack J. Devlin, Sarah E. Long, Ben J. Porter and Jodie M. Henderson. Robert J. Thomas, Christa L. Emmett and Laura Astbury also contributed to the development of the image analysis and data processing methods and R Scripts. Christa L. Emmett also analysed Monteiro's storm-petrel season videos and Laura Astbury analysed the band-rumped storm-petrel season videos. Robert J. Thomas assisted in developing and finalising statistical analysis. The manuscript was initially developed from Christa L. Emmett's and Laura Astbury's respective undergraduate and master's dissertations, aided by Robert J. Thomas. All supervisors and advisors contributed to manuscript shaping and development.

Chapter 6. I led the development of the concept, coordinated fieldwork (including deployment of cameras and GPS tags), the analysis (of videos, GPS tracks and data) and write up.
The concept was also conceived by Robert J. Thomas. Trouble shooting advice for cameras was provided by Richard J. Facey. Additional assistants contributed to in-field camera deployments and initial video analysis: Ben J. Porter, Jodie M. Henderson, Alice Edney and Max A. Levy. Christa L. Emmett analysed Monteiro's storm-petrel season videos, Laura Astbury analysed the band-rumped storm-petrel season videos and Jodie M. Henderson analysed near-nest videos. GPS tracking deployment methods were guided by Verónica Neves. GPS tag deployments were also undertaken by Verónica Neves, Ben Porter and in collaboration with Wiebke Schaefer and Petra Quillfeldt, with assistance from Alice Edney and Max Levy. Robert J. Thomas aided in initially developing the manuscript. Sean A. Rands and Joël Bried contributed to manuscript shaping and development.

Licences

All fieldwork was conducted under appropriate licencing. Specific licencing to conduct fieldwork on Ilhéu da Praia was granted by the Direção Regional do Ambiente, Região Autónoma dos Açores (HFRH licence numbers: 40/2019/DRA, SAI-DRA/2019/1821 Proc. 116.14.03/43 and 83/2020/DRA - SAI-DRA/2020/3569 Proc. 116.14.03/43). Bird ringing licences were granted by the Instituto da Conservação da Natureza e das Florestas (HFRH licence numbers: No. 71/2019 and No. 74/2020).

All fieldwork methods were designed to be compatible with Cardiff University ethical regulations and the ASAB Guidelines for the Treatment of Animals in Behavioural Research and Teaching (Buchanan et al. 2012).

Reference:

Buchanan, K., Burt de Perera, T., Carere, C., Carter, T., Hailey, A., Hubrecht, R., Jennings, D., Metcalfe, N., Pitcher, T., Peron, F. and Sneddon, L., 2012. Guidelines for the treatment of animals in behavioural research and teaching. *Animal Behaviour*, *83*(1), pp.301-309.

Publications

Publications directly arising from this project:

- **Hannah F. R. Hereward**, Richard J. Facey, Alyssa J. Sargent, Sara Roda, Matthew L. Couldwell, Emma L. Renshaw, Katie H. Shaw, Jack J. Devlin, Sarah E. Long, Ben J. Porter, Jodie M. Henderson, Christa Emmett, Laura Astbury, Luke Maggs, Sean A. Rands, Robert J. Thomas, 2021. Raspberry Pi nest cameras: an affordable tool for remote behavioural and conservation monitoring of bird nests. *Ecology and Evolution*. 11(21): 14585-14597. https://doi.org/10.1002/ece3.8127 *First Author*

- Deployment data and python scripts archived with Dryad: **Hereward, Hannah** et al. (2021), Raspberry Pi nest cameras: an affordable tool for remote behavioural and conservation monitoring of bird nests, Dryad, Dataset, https://doi.org/10.5061/dryad.9w0vt4bfb

Publications arising from work completed alongside this project:

- **Hannah F. R. Hereward**, Richard J. Facey, Anthony Caravaggi, Sean A. Rands, Robert J. Thomas. Single-board, modular computers as low-cost, bespoke camera trap systems for ecological and conservation research. *Remote Sensing in Ecology and Conservation*. [Rejected with invitation to resubmit]. *1st Author*

- Bethany L. Clark, … **Hannah F. R. Hereward**, … & Maria P. Dias. Global assessment of plastic encounter risk for marine birds. *Nature*. [Under Review]. *One of many middle co-authors*

- Sarah E. Long, Jack J. Devlin, Pedro Raposo, Ben J. Porter and **Hannah F. R. Hereward**. Habitat Categorisation and Mapping of a Seabird Reserve: Ilhéu da Praia, Azores. *Seabird*. 33(2021): 53-65. *Last Author*

Student Supervision

- Christa L. Emmett, 2020. Investigating the impact of invasive lizard and ant species on the breeding success of Monteiro's storm-petrels (*Hydrobates monteiroi*). BSc Final Year Project.

- Laura Astbury, 2020. A detailed comparison of the nest success and within-nest behaviour of two Storm-Petrel species in the Azores. MSc Final Project Report.

- Hannah Gagliardi, 2021-2022. Professional Training Year student with EcoExplore.

- Led the development of the Raspberry Pi cameras to deploy them in pied flycatcher nest boxes (deployed in Spring 2021 and 2022). EcoExplore.

Presentations

- **Hannah. F. R. Hereward**, Renata Medeiros-Mirra, Joël Bried, Verónica Neves, Wiebke Schaefer, Petra Quillfeldt, Robert J. Thomas, Frank Hailer, Mark Bolton. *A comparison across two decades, of the breeding biology of two sibling species of procellariiformes.* BOU 2022 Annual Conference, 12th-14th April 2022, Virtual international conference.

- **Hannah. F. R. Hereward**, Renata Medeiros, Verónica Neves, Frank Hailer, Richard Facey, Robert Thomas. *Exploring sibling storm-petrel species (Hydrobates sp.) breeding ecology, utilising both traditional and modern approaches.* 3rd World Seabird Conference, 4th-8th October 2021, Virtual international conference.

- Wiebke Schäfer, Gemma Carroll, **Hannah Hereward**, Petra Quillfeldt, Verónica Neves. *Foraging and at-sea distribution of a vulnerable and endemic storm-petrel.* 3rd World Seabird Conference 4th-8th October 2021, Virtual international conference.

- **Hannah F. R. Hereward**, Richard J. Facey, Sean A. Rands, Robert J. Thomas. *Behaviours, threats and conservation implications of two sibling species of seabird (storm-petrels).* Wessex Congress 2021, 6th-8th September 2021, UKRI, UK. Virtual conference.

- **Hannah F. R. Hereward**, Richard J. Facey, Sean A. Rands, Robert J. Thomas. *The use of a bespoke Raspberry Pi nest camera to monitor behavioural and possible threat interactions in nocturnal burrow-nesting seabirds*. Cardiff University, Organisms and Environment division Annual Away Day 7th May 2021, Cardiff University, UK. Virtual conference.

- **Hannah F. R. Hereward**, Richard J. Facey, Sean A. Rands, Robert J. Thomas. *The use of a bespoke Raspberry Pi nest camera to monitor behavioural and inter-species interactions in nocturnal burrow-nesting seabirds*. ASAB Easter virtual meeting 14th-16th April 2021, University of Bristol, UK. Virtual conference.

- **Hereward, H.F.R.,** 2019. *The conservation implications of climatic and trophic interactions on population change in the Monteiro's Storm-petrel and its sister species***.** Wessex DTN 2019, 20th March, Blavatnik School of Government, Oxford, UK. In person conference.

- **Hereward, H.F.R.,** 2018. *The conservation implications of climatic and trophic interactions on population change in the Monteiro's Storm-petrel and its sister species***.** WEEN Wales Ecology & Evolution Network Conference, 24th November, Centre for Alternative Technology, Powys, Wales, UK. In person conference.

Outreach

- I co-presented a talk for the 'Life on the Edge, Exploring the Ocean through Science and Faith' (www.lifeontheedge.info) at Wadebridge Town Hall, 4th November 2021. Talk title: "Studying, protecting, and restoring marine habitats"

- My winter 2019-2020 fieldwork team and I wrote a short film (edited by Ben Porter) for the World Seabird Union's series on "World of Seabirds": "World of Seabirds: Praia Islet, Azores" https://www.youtube.com/watch?v=8QJUNrn5-rA&t=42s

- Myself and one of my team gave an interview on this short film: "World of Seabirds: Interview with Ben Porter and Hannah Hereward, Cardiff University" https://www.youtube.com/watch?v=gcTr6dB_Ej8&t=0s

- I contributed a research summary to the Seabirds.net 'Highlighted researcher' page (April 2021).

- Various other films of the PhD fieldwork (and islet life) were created by Ben Porter and can be found here:
  "Return of the Cagarro":
  https://www.youtube.com/watch?v=6QErodQSuqw;

  "Flight of the Stormie chick":
  https://www.youtube.com/watch?v=9N9RtPao5UE;

  "GPS tracking Madeiran Storm-petrels":
  https://www.youtube.com/watch?v=rq0R3zTgoLs

Carbon Offsetting

Carbon costs incurred from this PhD have been offset through Climate Stewards (www.climatestewards.org; see details in certificate below).

Climate Stewards

Date of issue: 22 June 2022

This is to certify

Hannah F. R. Hereward

has offset her carbon costs incurred from her NERC GW4+ DTP funded PhD

with Climate Stewards.

Total emissions offset: 33.00 tCO_2e.

Summary of emissions:

Activity	Emissions	Offset cost
Electricity	1.27 tCO_2e	£25.48
Land Travel	3.58 tCO_2e	£71.58
Air Travel	20.34 tCO_2e	£406.78
Food	6.65 tCO_2e	£132.98
Other Expenditure	1.16 tCO_2e	£23.28
Total	**33.00 tCO_2e**	**£660.10**

Climate Stewards offsets emissions at £20 per tonne CO_2e.

Offsetting through Climate Stewards supports community-based carbon projects in the global south. Each project brings multiple local benefits such as improved health, livelihoods, and biodiversity.

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Chapter 1. General Introduction

Photographs: top (Ilhéu da Praia; Ben Porter), bottom left (Monteiro's storm-petrel adult; Hannah Hereward), bottom right (band-rumped storm-petrel; Ben Porter).

1.1. Background

The loss of biological diversity is a global issue; this is exemplified in the increased rate of recent species extinctions (estimated 200 vertebrate species lost over the last 100 years, compared to an estimated background rate of loss of 200 vertebrate species over the last 10,000 years; Ceballos et al. 2017; Dueñas et al. 2021). In 1992, the Convention on Biological Diversity (United Nations) was established; one of its three main aims is to aid in conserving biodiversity. Over the last 30 years since this convention, various key questions in ecology and biological diversity have been identified and – in many cases - addressed (Sutherland et al. 2009, 2021; Lepczyk et al. 2017; Dey et al. 2020). Many successful conservation projects result from conservation science (e.g. through studying breeding biology, ecology and drivers of population change) being translated into conservation practice (Sutherland et al. 2009).

Across the five main vertebrate groups (fishes, amphibians, reptiles, mammals and birds), not only has the rate of overall extinction increased, but range contractions and population declines of these species have also increased (Ceballos et al. 2017). Range contractions and population declines provide early indications of the risk of extirpation and final extinction events, and so are critical to monitor, especially when intending to conserve a species (Ceballos et al. 2017). Specifically, an estimated 30% of bird species have decreasing population trends. However, this is not (yet) reflected in their overall IUCN Red List designations, as almost 55% of bird species are still being designated as "Low Concern" (Ceballos et al. 2017). Seabirds are considered to be one of the most threatened avian groups at a global scale, and are important indicators of marine ecosystem health (Croxall et al. 2012; Dias et al. 2019). Seabird monitoring programmes therefore provide valuable data for understanding the demographic, climatic and trophic drivers of change (Burger and Gochfeld 2004; Mallory et al. 2010; Xiao et al. 2017; Table 1.1). The specific drivers of change may include: competition for nests (Bolton et al. 2004), predator-prey dynamics, energy costs of reproduction (Robert et al. 2012) and oceanographic conditions (Amorim et al. 2008; Robert et al. 2012). Anthropogenic threats may include: urban development, agriculture and aquaculture, energy production and mining, transportation and service corridors, biological resource use, human intrusions and disturbance, natural system modifications, invasive and other problematic species, genes

and diseases, pollution, geological events, as well as climate change and severe weather events (Mallory et al. 2010; Lavers et al. 2014; Hart et al. 2016; Mejías et al. 2017; IUCN 2018; Table 1.1). The most recent reviews on assessing overall threats to seabird populations have all concluded that of this wide diversity of threats, the top three threat categories are: invasive alien species, bycatch from fisheries and climate change / severe weather (Croxall et al. 2012; Dias et al. 2019; Lees et al. 2022).

The ability of species to adapt to these natural processes and anthropogenic stressors, through phenotypic plasticity and microevolutionary processes, can be aided by human intervention / action in the form of conservation actions (Burger and Gochfeld 2004; Jenouvrier et al. 2005; Mallory et al. 2010). Various conservation actions can be highly effective in addressing the top three threat categories, particularly through the removal of non-native species from islands (Buxton et al. 2016; Jones et al. 2016). Examples of these include: feral cat eradication on Ascension Island (Ratcliffe et al. 2010), eradication of Norway rats (*Rattus norvegicus*) on a Mediterranean island (Canale et al. 2019) and eradication of black rats (*Rattus rattus*) and the European rabbit (*Oryctolagus cuniculus*) in the Azores (Bried et al. 2009; Amaral et al. 2010), to name but a few. Furthermore, some mitigation techniques have been trialled to aid in reducing bycatch for seabirds (see review by Løkkeborg, 2011). These have included: using bird scaring-lines and the strategic management of fish waste (Bull 2009; Melvin et al. 2014), and more recently for long-line fishing by using "Hookpods" (Sullivan et al. 2018) and by illuminating gillnets (Mangel et al. 2018). However, further work is still needed to assess threats such as the impacts of problematic invertebrates on seabird populations, and also in terms of climate change where impacts are unknown or, as yet, only projected (Dias et al. 2019), but see review by Sydeman et al. (2012).

Table 1.1. Biotic, Abiotic and Anthropogenic factors influencing seabird breeding success and/or survival

	Sea or Land	Specific Factor	Comments and References
Biotic	Land	Inter-species competition for nests	Monteiro and Furness (1998); Bolton et al. (2004)
	Land	Predator-Prey Dynamics	Bolton et al. (2004); Monteiro and Furness (1998); Bried (2003)
	Land	Habitat loss	Monteiro et al. (1996a)
	Land	Reproduction	The costs of reproduction to adult survival are mostly energetic costs and decreased immune function during breeding on land. As a consequence, mortality often occurs at sea after breeding but is caused by a reduced immune function (Robert et al. 2012). This mortality is often more pronounced in unsuccessful breeders.
	Sea	Chlorophyll a (Chl a)	The demographic rates (e.g. adult survival and breeding success) are shaped by oceanic conditions – biotic factors = Chlorophyll a, abiotic factors = SST and North Atlantic Oscillation (Amorim et al. 2008; Robert et al. 2012; Fagundes et al. 2016)
Abiotic	Sea	Sea Surface Temperature (SST)	
Anthropogenic - Climatic	Sea	Increases in storm frequency and intensity	Orgeret et al. (2022)
	Sea	Increases in heat wave frequency and intensity	Jones et al. (2018)
	Sea	Increases in SST / changes in Chl a dynamics	See SST and Chl a above
Anthropogenic – non-climatic	Sea	Pollution	At sea (Hart et al. 2016); artificial light pollution (Rodríguez and Rodríguez 2009; Rodríguez et al.

			2012; Raine et al. 2017); in-nest marine debris (Merlino et al. 2018)
	Sea	Commercial fishing	Hart et al. (2016); competition with fisheries (Monteiro et al. 1996a; Sugishita et al. 2015)
	Land/Sea	Human disturbance	Disturbance (Monteiro et al. 1996a; Bried et al. 2009); exploitation (Monteiro et al. 1996a)
	Land	Non-native species introductions (Hart et al. 2016)	E.g. Monteiro et al. (1996a); Monteiro et al. (1999); Bradley and Marzluff (2003); Bried et al. (2009); Amaral et al. (2010); Ratcliffe et al. (2010); Mejías et al. (2017); Neves et al. (2017)

Seabirds are long-lived species, and so require long-term monitoring to truly assess and identify these drivers of change, which in turn aid in determining whether conservation actions are required, and what these should be (Clutton-Brock and Sheldon 2010; Croxall et al. 2012; Paleczny et al. 2015; Dias et al. 2019; Rodríguez et al. 2019). Traditionally, monitoring has been conducted through in-person visits to seabird colonies throughout their breeding periods (Paleczny et al. 2015). Information collected on these visits generally includes overall breeding success rates, egg and chick development, threats and causes of mortality, and identifying the timings of breeding events such as laying, hatching and fledging (e.g. Allan 1962; Harris 1969; Boersma et al. 1980; Boersma 1986; Monteiro and Furness 1998; Mauck and Ricklefs 2005). In addition, capture-mark-recapture approaches are also used, such as mist-netting (Libois et al. 2012; Robert et al. 2015), although conducting censuses at colonies is often easier than using capture-mark-recapture methods for the adults (Sutherland et al. 2004). However, the combination of traditional monitoring techniques with novel technologies is being increasingly used within ecological fields. This is because such combinations provide opportunities for broader questions to be asked and knowledge gaps to be filled (Allan et al. 2018), especially in terms of the specific behavioural and demographic mechanisms behind population changes, in light of climatic and trophic drivers, both at the nest (Masello et al. 2001; Gladbach et al. 2009a,b; Sugishita et al. 2017) and at sea (Sugishita et al. 2017; Bolton 2021).

1.2. Storm-petrels

Of the 24 species of storm-petrels assessed by the IUCN in 2018 (IUCN 2018), 37% were classified as Near Threatened or higher on the IUCN Red List (Figure 1.1A), 75% had either a declining or unknown population trend (Figure 1.1B), and almost 80% of these species were threatened by invasive non-native species / diseases and/or problematic native species / diseases, and 50% were threatened by pollution (Figure 1.1C; IUCN 2018).

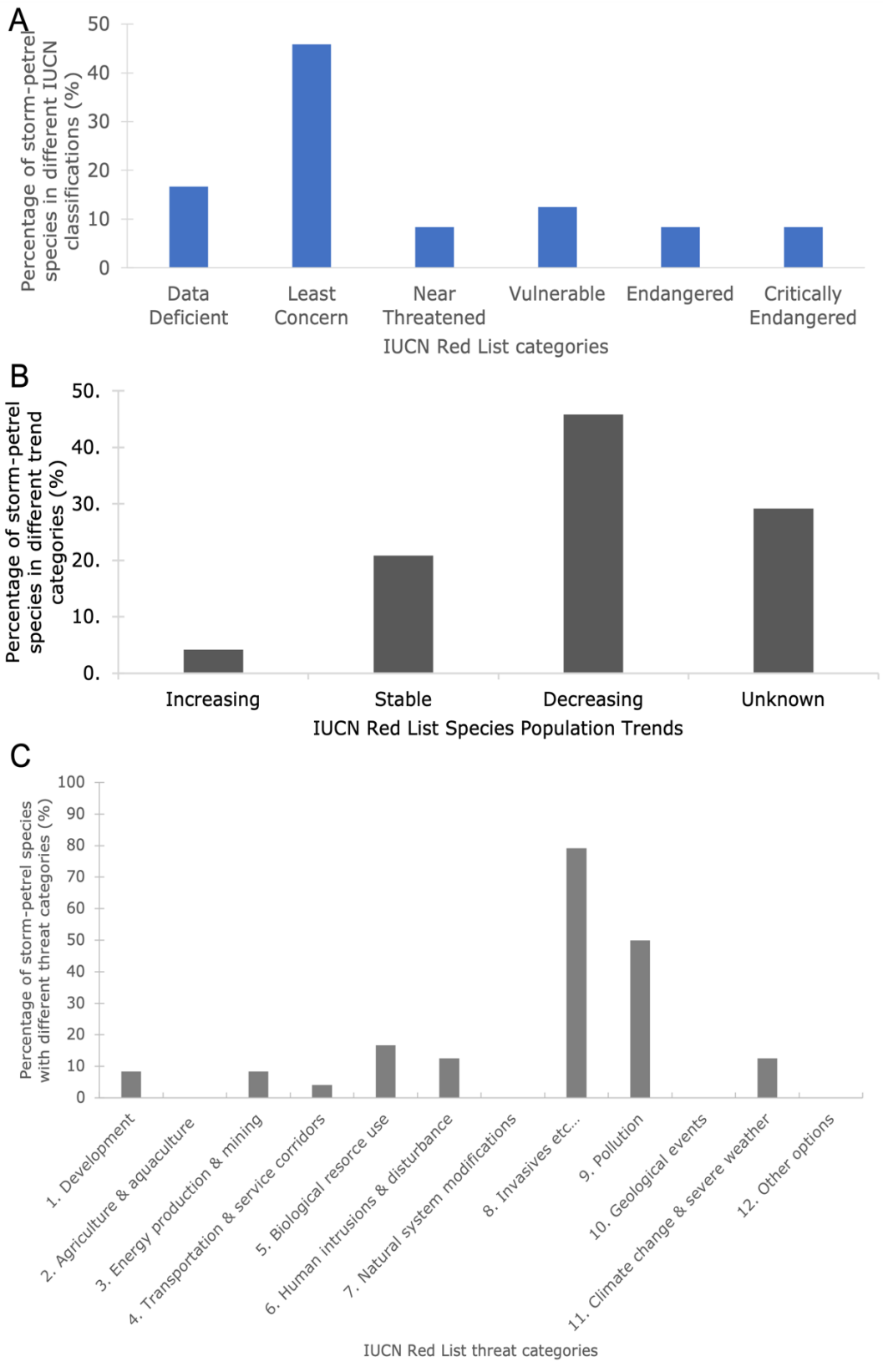


Figure 1.1. Summaries of 24 species of storm-petrel from the IUCN Red List (based on data compiled in 2018) as a: A) Percentage of species in each IUCN Red List classification. B) Percentage of the population trends of each species. C) Percentage occurrence of each threat identified for each species. NB. Full category names for 1 = Residential and commercial development and 8 = Invasive species and other problematic species, genes and diseases.

The geographical ranges of these 24 species of storm-petrel vary from single-island endemics to ocean-wide species-complexes (Warham 1990; Brooke 2004; IUCN 2018). One of these species-complexes is the band-rumped storm-petrel (*Hydrobates castro* complex; Warham 1990; Brooke 2004; Friesen et al. 2007). This species is widely distributed, breeding on islands across the Atlantic and Pacific Oceans. In at least five archipelagos, the species breeds on the same islands in different seasons. In one of these island archipelagos, the Azores, this has led to species-level genetic and phenotypic divergence between birds breeding during the hot season compared to the cool season, resulting in the evolution of two distinct species (Bolton et al. 2008; Silva et al. 2016). Competition for nest sites, avoidance of predators, and seasonal variation in food availability have all been suggested as potential drivers of this speciation event, and as potential constraints on current population sizes (Robert et al. 2012), but the selective forces driving temporal and genetic segregation, and population change remain poorly understood.

1.3. The Azores

The Azores Archipelago is a global hotspot for marine and terrestrial biodiversity. Despite having a generally low ocean productivity, across the archipelago there are localised upwellings and many underwater seamounts (Monteiro et al. 1996a,b; Magalhães et al. 2008; Paiva et al. 2010). Ecologically, the marine habitats around the Azores are important reproduction, migration and foraging grounds for various marine mammals and fish (Monteiro et al. 1996a). Alongside this, the terrestrial habitats (especially the surrounding islets) are also important for a great variety of seabirds that use both the terrestrial habitats as breeding grounds as well as the surrounding marine habitats for feeding (Monteiro et al. 1996a). These species include: Monteiro's and band-rumped storm-petrels (*Hydrobates monteiroi* and *H. castro*), Bulwer's petrel (*Bulweria bulwerii*), common and roseate terns (*Sterna hirundo* and *S. dougallii*), sooty terns (*Onychoprion fuscatus*), Cory's shearwaters (*Calonectris borealis*), the Macronesian / North Atlantic little / Barolo) shearwater (*Puffinus lherminieri baroli*, hereafter referred to as Barolo shearwater) and Manx shearwaters (*Puffinus puffinus*) (Monteiro et al. 1996a; Bolton et al. 2008).

1.3.1. Storm-petrels on the Azores

The storm-petrels breeding on the Azores have been studied for more than two decades (e.g. Monteiro et al. 1996b; Bolton et al. 2004; Robert et al. 2015). Prior to 2008 they were classified as "hot" and "cool" season individuals of the band-rumped storm-petrel complex (*Hydrobates castro* complex; Monteiro and Furness 1998). However, since 2008, they have been reclassified as two separate sibling species, where the "hot season" species are the newly classified Monteiro's storm-petrel (*H*. *monteiroi*) and its sibling species is the "cool season", band-rumped storm-petrel (*H*. *castro*; Monteiro and Furness 1998; Bolton et al. 2008; Robert et al. 2015; Silva et al. 2016). While they have only relatively recently been reclassified, genetic analysis has shown that they likely diverged 125,000-300,000 years ago from populations in the Pacific, 70,000-350,000 years ago from other populations within the North Atlantic, and 110,000-180,000 years ago from each other (Friesen et al. 2007; Smith et al. 2007). The Monteiro's storm-petrel is endemic to the Azores and is currently listed as "Vulnerable" on the IUCN Red List, with a reportedly stable population trend (BirdLife International 2018b). This "Vulnerable" classification is due to its small population size (<400 breeding pairs) and narrow geographic distribution, meaning they are susceptible to stochastic events, human disturbance and invasive/non-native species (BirdLife International 2018b). In comparison, the band-rumped storm-petrel is widespread across the Atlantic and Pacific Oceans (Raine et al. 2017), listed as "Least Concern" on the IUCN Red List, but with a decreasing population trend (BirdLife International 2018a). This decreasing population trend is due to predation by non-natives/invasive species and being grounded due to light pollution (Boersma and Groom 1993; Monteiro et al. 1999; Rodríguez and Rodríguez 2009; Raine et al. 2017).

1.3.2. Previous conservation efforts on Ilhéu da Praia

All known Monteiro's storm-petrel populations breed on five small islets off Graciosa and Flores Islands in the Azores Archipelago (Monteiro et al. 1999; Bolton et al. 2008). The largest known breeding site for both species of storm-petrel in the Azores is on Ilhéu da Praia, off the east coast of Graciosa Island (Monteiro's storm-petrel ~178 breeding pairs, band-rumped storm-petrel ~200 breeding pairs; Bolton et al. 2004, 2008). Since 1997, conservation efforts have been implemented to improve the islet's habitat. Initially this focused on reducing soil erosion and decreasing competition for nesting

burrows through successful eradication of rabbits (*Oryctolagus cuniculus*) in 1997 (Bried et al. 2009). Further conservation efforts to increase breeding habitat options were implemented through the deployment of 150 artificial breeding chambers, in which breeding success was higher than in natural nest sites (Bolton et al. 2004). In addition, reductions in human disturbance were implemented by stopping agricultural practices and *ad hoc* visits from local people (Monteiro et al. 1996a), through Ilhéu da Praia being brought under the management of Graciosa Natural Park Authority, due to the implementation of several designations of the islet: as an Important Bird Area (BirdLife International 2022a) as a nucleus for the Graciosa Biosphere Reserve (designated in 2007; UNESCO 2020) and as a Special Protected Area (designated under the Natura 2008 programme; European Commission 2000). Finally, the restoration of native plant species (Bried et al. 2009) has led to a dramatic increase in native flora habitats across the islet, meaning that natural nest site options for the various Procellariiform species have increased, although soil erosion in some parts of the islet has also increased (Long et al. 2021). More recent research has raised concerns about a potential new threat arising from predation on the storm-petrels by the non-native/naturalised Madeiran wall lizard (*Podarcis dugesii* formally *Teira dugesii or Lacerta dugesii*, hereafter referred to as *Podarcis dugesii*; Neves et al. 2017). A recent Species Action Plan for the Monteiro's storm-petrel specifically mentions this emerging threat from the Madeiran wall lizards, and the need to gather rigorous evidence on the impact it has on the storm-petrel species (SPEA, 2018 unpublished data).

1.4. Overall aims and objectives

These two sympatric sibling species, one of which is a vulnerable endemic species, breeding on the same islet but at different times of year, provide an interesting and distinctive case study system in which to examine the drivers of population change in an important conservation context. This has been conducted through combining traditional and novel monitoring techniques to aid in understanding the climatic and biological drivers of long-term changes in breeding success and other demographic parameters, whilst also aiding in describing the breeding behaviours of the two species, and to identify any new threats through in-person and remote monitoring of nests.

Consequently, the aim of this PhD thesis is to draw together traditional behavioural study techniques, modern remote monitoring technologies (specifically nest cameras and GPS tracking) and future projection modelling to answer ecological questions to fill these knowledge gaps, in order to inform conservation management actions. Here I follow these two species in this well studied study system, to investigate long-term changes in the two populations over a 20 year period (Chapter 3), developing a novel technology - a bespoke in-nest camera system (Chapter 4), then I detail the in-nest behaviours and threats identified from deployments of these cameras during the chick rearing stage (Chapter 5) and end with a proof of concept example of combining these traditional and novel techniques (Chapter 6).

The results of this study are important in their own right, to ensure effective conservation of the two storm-petrel species including the Azores-endemic Monteiro's storm-petrel, but could also be applied to other seabird colonies where long-term monitoring will be important in assessing the drivers of population change and addressing conservation challenges.

Chapter 2. General Methods

Photographs: top left (chick being weighed; Ben Porter), top right (Hannah Hereward taking notes holding a chick; Ben Porter), bottom left inset (Hannah Hereward checking a nest; Ben Porter), bottom right (a line of artificial nests when covered; Hannah Hereward).

2.1. Study site

Following on from previous research, this study's fieldwork site was on Ilhéu da Praia, an uninhabited volcanic islet (~ 12 ha) situated 1.2 km east of Graciosa Island, Azores, Portugal (39°03'N, 27°57'W; Figure 2.1; Bolton et al. 2004). From 2000 to 2001, 150 artificial nest boxes were installed on the islet (Bolton et al. 2004), and in 2015 an additional 14 nests were installed (VN personal communication), to expand possible breeding areas for the two sibling species of storm-petrels that breed on the islet. The two species often breed in the same nest sites, but at different times of year (Bolton et al. 2004). As of the time of my PhD fieldwork there were a total of 160 usable artificial nest boxes across the islet (Bolton et al. 2004; Bried et al. 2009; Figure 2.1).

For all of the data presented in this PhD thesis, two types of nest monitoring occurred across a 20-year period. There were two periods of intensive data collection, where nests were checked daily, and chicks weighed daily. The first of these periods was: Spring 2000 to end of Summer season 2001 (Mid-April 2000 – September 2001, with some significant periods when no data was collected, and 6th-14th October 2000, 10th December 2000-16th January 2001, 12th March-12th April 2001) (Bolton et al. 2004). The second period of intensive monitoring was: Winter 2018 to end Summer 2020 (September 2018 – September 2020, with some significant periods where no data were collected: 29th November-7th December 2018, 11th-15th January 2019, 18th February 2019 – 3rd March 2019, 3rd March 2019- 22nd March 2019, 22nd March 2019 – 30th April 2019, 20th-25th September 2019, 30th September-5th October 2019, 8th December 2019 – 3rd January 2020, 16th March – 17th June 2020, 10th – 21st August 2020) (Hereward et al. 2021; Long et al. 2021). For Chapter 3, all of these years were included, and for the remaining data chapters only the latter period of intensive study was included (specifically end of April 2019- September 2020).

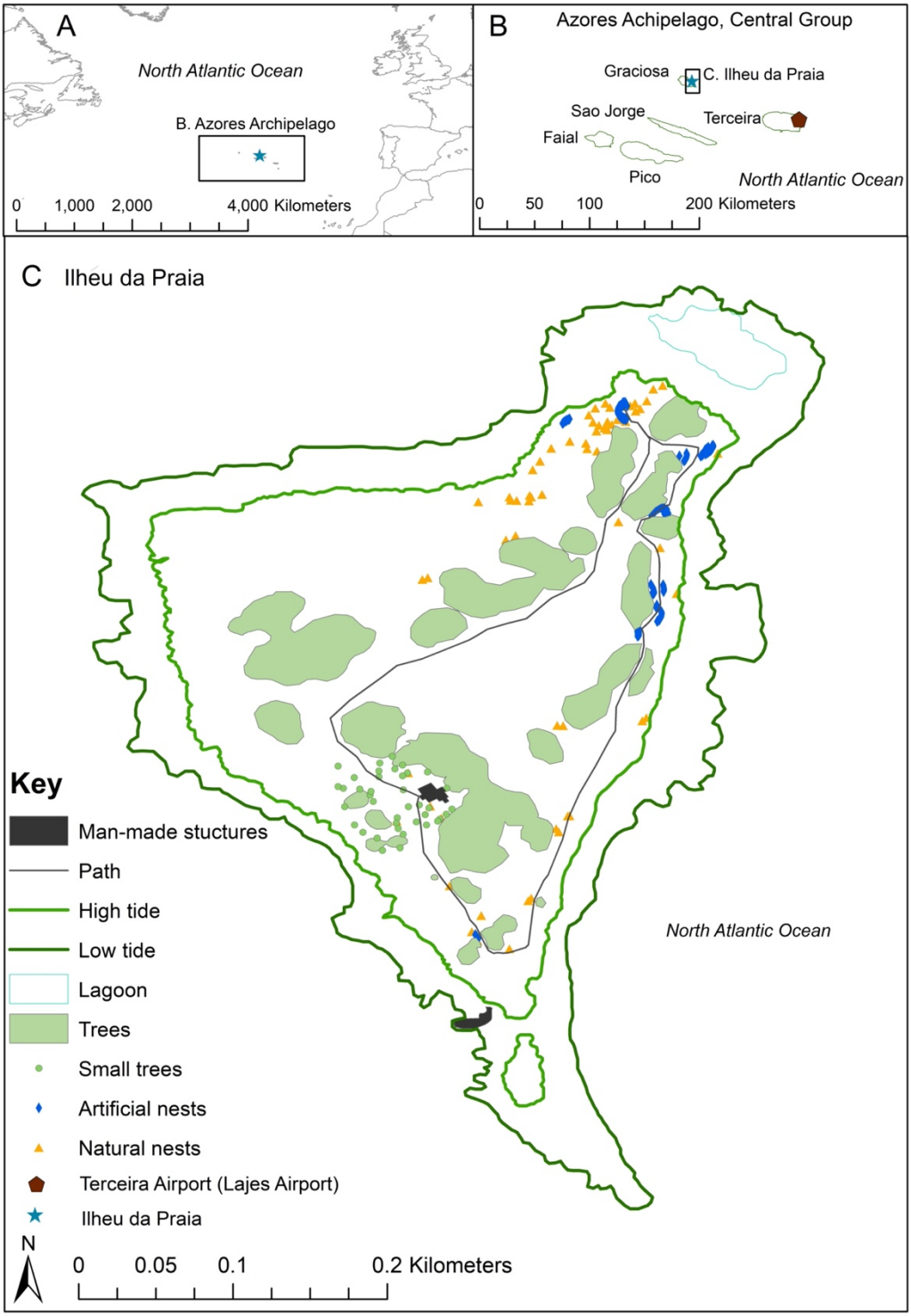


Figure 2.1. Map of A) the North Atlantic Ocean marking the Azores Archipelago with a black square and Ilhéu da Praia with a blue star, B) the Azores Archipelago central group of islands, marking Ilhéu da Praia with a black box and blue star and Terceira airport with a brown pentagon and C) Ilhéu da Praia, including high and low tide lines and lagoon, man-made structures and path, trees, artificial nests (blue diamond) and natural nests (orange triangle). Data compiled by Hereward, Long and Devlin. Map created in ArcGIS version 10.8.1. Base layer for world map was "UIA world countries boundaries" downloaded from hub.arcgis.com.

2.2. Nest monitoring

During the periods of intensive study, at the beginning of each breeding season, all artificial nests and previously identified natural nests were inspected. Any adults present were temporarily removed from the nest and processed - recording typical ringing biometrics (e.g. wing length, tarsus length, mass, brood patch; Harris 1969; Monteiro and Furness 1998; Bolton et al. 2008). If they had a ring/band (hereafter stated as ring) number already, this was recorded, if not, a unique ring was fitted to the tarsus for future identification. Once breeding pairs were established, non-toxic paint (www.edding.com/en-uk/) was used to individually mark each bird, to minimise the need for further handling of the adults in future visits (following Bolton et al. 2004). Once occupied, artificial nest boxes were typically checked daily through the rest of the breeding season (unoccupied boxes continued to be checked once or twice a week), and the natural nests were checked less frequently (Figure 2.1). Near the end of the Monteiro's storm-petrel breeding season, non-parent storm-petrel adults (most likely to be band-rumped storm-petrels) would start inspecting nests. When the new bird was already ringed, the ring number was read, and the species identity clarified. If the new individual was not already ringed, the same process of ringing and measuring was followed as above and where possible, the species clarified through biometric differences, as described in Bolton et al. (2008). Chick body mass was measured daily (to 0.1g), using a pan balance ("AccuWeight" scale, accurate to 0.1g; www.accuweigh.co.uk), to monitor their growth rate (Monteiro and Furness 1998). Wing length and tarsus length of chicks were measured only when the chick was alone in the nest (i.e. with parents absent), to minimise handling time when parents were present.

2.3. Weather data

Daily air temperature, precipitation (primarily rainfall) and wind speed data were extracted to compare the changes across this 20-year period (Figure 2.2). Data was accessed through the R package GSODR (Global Surface Summary Of The Day). The raw data for wind speed is the mean daily wind speed converted to m s^{-1} and air temperature is the mean daily air temperature converted to °C (both are individually collated from a variety of reports ranging from 4 hours to 24 hours of reports per day, missing=NA). Rainfall is the total precipitation reported during each day, converted to mm

day^{-1} (collated from a variety of reports: 1-6 report(s) of a 6-hour precipitation amount, 1-2 report(s) of a 12-hour precipitation amount, or 1 report of a 24-hour precipitation amount).

Wind speed measurements were extracted at the regional level (across 12 weather stations that had extractable data from across the Azores Archipelago) and air temperature and rainfall measurements were extracted at the local level (i.e. Terceira airport – deemed to be the closest to the islet in term of orientation and location, and that had data from across all years of the 20-year study period; Figure 2.1B).

These data were processed to produce annual summaries for each species' breeding season. The Monteiro's storm-petrel breeding season was deemed to be March-September inclusive (Julian days used: 60-273), and the band-rumped storm-petrel breeding season was deemed to be July of the year in which breeding was initiated, to March of the following year, inclusive (Julian days used: 182-366, 1-90 - an additional 365 was added to the day 1-90 values, as this is the latter part of the breeding year; this is to include all parts of the breeding season from the pre-laying/incubation exodus through to the latest fledging events). For visualising the models of regional weather, prediction lines were based on Terceira Airport ("LAJES"), as this is the closest weather station to Ilhéu da Praia, with the same geographical orientation, and has the most complete data for 2000-2020.

Long-term variations in air temperature (local), rainfall (local) and wind speed (regional) were analysed separately for each species' breeding season. For each weather variable / species, three models were conducted and plotted on the same graph. The models were variations of a GAM model, with Julian day (always smoothed with the default thin plate regression spline method; "tp") and year (either modelled as a straight line, or a smoothed line, or as a categorical variable, depending on the model), with the Gaussian error family and log link function. Prediction lines were based on the central Julian day for each species' breeding season (Monteiro's storm-petrel = day 166.5, band-rumped storm-petrel = day 318.5). The first model extracted a linear trend across the years with year left without a smoother. The second model extracted a wiggly line trend across the years with year smoothed (by "tp"). The third model extracted yearly averages – where year was a factor.

Air temperature increased across the 20-year period, with average breeding season air temperatures being ~ 2 °C higher in the Monteiro's storm-petrel breeding season compared to the band-rumped storm-petrel breeding season. Rainfall decreased slightly across the 20-year period, with generally higher levels of rainfall during the band-rumped storm-petrel breeding season, compared to the Monteiro's storm-petrel breeding season. Wind speed stayed very similar across the 20-year period, with marginally higher wind speeds during the band-rumped storm-petrel breeding season, and particularly calm conditions during the breeding seasons of both species in 2000 (NB: When this year was removed and the model re run, there was little change in the overall model result - not shown).

2.4. Statistical analysis

All statistical analyses were carried out using *R* 4.2.0 (R Core Team 2022) and implemented in RStudio version 2022.2.2.485 (RStudio Team 2022), using a variety of packages (Table 2.1), unless otherwise stated in the specific Data Chapters.

Table 2.1. Names and references of all packages used for statistical analysis

Package name	Package reference
GSODR	v3.1.5 (Sparks et al. 2017)
mgcv	v1.8-31 (Wood 2003; Wood 2017)
lme4	v1.1-29 (Bates et al. 2015)
nlme	v3.1-157 (Pinheiro and Bates 2000; Pinheiro et al. 2022)
EMbC	v2.0.3 (Garriga et al. 2019)
lubridate	v1.8.0 (Grolemund and Wickham 2011)
segmented	v5.1-0 (Muggeo 2003; Muggeo 2008; Muggeo 2016; Muggeo 2017)
tidyverse	v1.3.1 (Wickham et al. 2019)
AICcmodavg	v2.3-1 (Mazerolle 2020)
latex2exp	v0.9.4 (Meschiari 2022)

Where chick age was used in analysis, this was extracted by subtracting the Julian hatch date from the Julian observation date, and adding one day. Thus, chick hatch day 1 is the day the chick emerged from the egg. In Chapter 3, Julian day one = 1st January for that year, but for band-rumped storm-petrels

which hatched in the following year, 365 was added to the Julian hatch date. In Chapter 5, Julian day one = 1st January 2019 for the Monteiro's storm-petrel season and 1st October 2019 for the band-rumped storm-petrel breeding season.

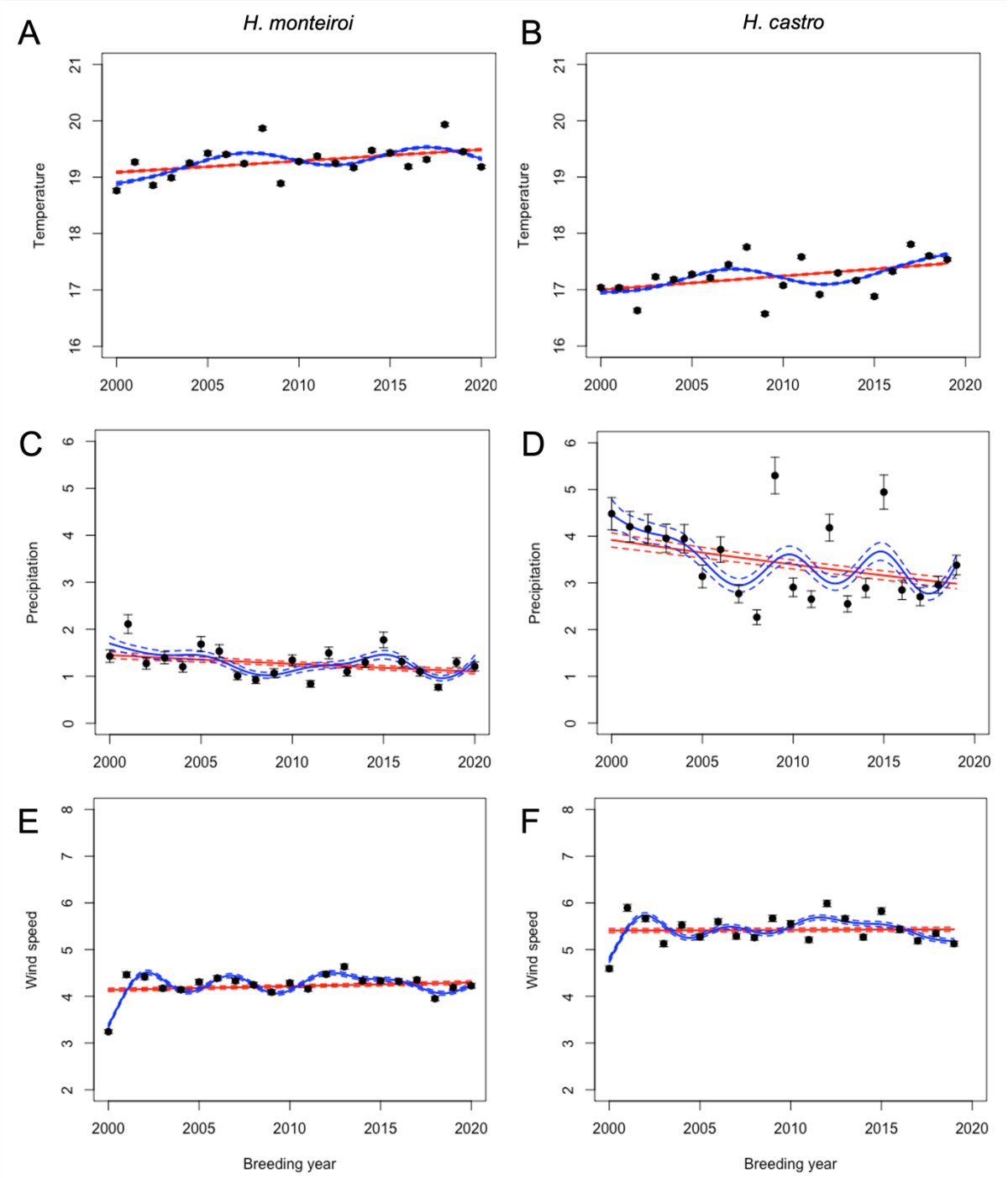


Figure 2.2. Average air temperature, rainfall and wind speed during both species' breeding seasons, across the 20-year study period. Black dots are the yearly average ± SE. Red lines = GLM analysis, blue lines = GAM analysis, where year and Julian day are variables in each model.

Chapter 3.

Long-Term Decreases in Breeding Productivity of Monteiro's and Band-Rumped Storm-Petrels on Ilhéu da Praia, Azores – Decade Scale and Seasonal Comparisons

This chapter is in prep. for submission for publication.

Photographs: top left (chick being weighed; Ben Porter), top right (Renata Medeiros-Mirra deploying artificial nest boxes in 2000; Renata Medeiros-Mirra), bottom right (Hannah Hereward at same nests as Renata Medeiros-Mirra above, in 2020; Ben Porter). Artwork details: (bottom left): Madeiran wall lizard + storm-petrel egg, Barolo shearwater, ants and band-rumped storm-petrel (Seafarer Sarah Artwork).

Summary

Long-term nest monitoring studies can be important in identifying changes in seabird breeding productivity and population dynamics in relation to the changing environment, and in guiding conservation actions. Here we compare, across two decades, the breeding productivity and demography of two sibling species of storm-petrel that breed in the same location (Ilhéu da Praia in the Azores Archipelago), but at different times of year. The Azores-endemic Monteiro's storm-petrel (*Hydrobates monteiroi*) breeds in summer (April-September), and the band-rumped storm-petrel (*Hydrobates castro*) breeds in winter (September-March). For each species across two time periods (2000-2001 and 2018-2020), artificial nest-boxes were checked daily, to monitor the fate of the eggs and chicks, and to measure chick growth. Less detailed productivity data were collected in the intervening years (2002-2017). Overall, the summer breeding Monteiro's storm-petrel had a lower productivity than the winter breeding band-rumped storm-petrel, but both species' productivity has declined significantly. Monteiro's storm-petrel breeding success showed a more pronounced decline than for band-rumped storm-petrel, driven largely by a substantial reduction in fledging success. Compared to the 2000-2001 period, Monteiro's storm-petrel breeding attempts in the 2019-2020 period were more likely to fail at both the egg and chick stages due to disturbance by native and non-native species, which (albeit to a lesser extent) was also observed for the band-rumped storm-petrel. While chick growth patterns do not explain the decline in breeding success, variation in breeding performance of both species across the two decades was associated with the interactive effects of regional weather conditions (air temperature, rainfall and wind speed). In particular, the breeding success of Monteiro's storm-petrel was negatively associated with warmer and drier summers, and the breeding success of the band-rumped storm-petrel was negatively associated with warmer and wetter winters. Preliminary VORTEX Population Viability Analysis for past and current levels of productivity identified that current demographic parameter values are insufficient to maintain a stable population for the Monteiro's storm-petrel. Consequently, this Chapter aids in understanding species' responses to decade-scale environmental changes, informs conservation actions to address the rapid decline in breeding productivity of both species, and suggests that a re-evaluation of the Red List classification of the endemic Monteiro's storm-petrel is needed.

3.1. Introduction

Seabirds are long-lived, but are considered one of the most threatened avian groups at a global scale and they are important indicators of marine ecosystem health. Robust, long-term seabird productivity monitoring programmes therefore provide valuable data for understanding the environmental drivers of demographic and population change (Chapter 1, Table 1.1). Such data in turn aid in determining whether conservation actions are required, and what these should entail (Clutton-Brock and Sheldon 2010; Croxall et al. 2012; Paleczny et al. 2015; Dias et al. 2019; Rodríguez et al. 2019).

The study of demographic drivers of seabird population change often involves following seabird nest histories throughout their breeding periods (Paleczny et al. 2015), and calculating overall breeding success, hatching and fledging success, measuring egg and chick development, and identifying timings of breeding events (e.g. Allan 1962; Harris 1969; Boersma et al. 1980; Boersma 1986; Monteiro and Furness 1998; Mauck and Ricklefs 2005). Studies across multiple years can aid in identifying changes in these demographic parameters over time, such as changes in overall breeding success (e.g. Simons 1981; Chastel et al. 1993; Slater and Byrd 2009; Cuthbert et al. 2014; Dunn et al. 2016; Hart et al. 2016; Mejías et al. 2017), duration of the incubation and nestling stages (Harris 1969), or phenological shifts in the form of lay and/or hatch dates (Keogan et al. 2018). An additional aspect of monitoring demographic drivers is assessing population size and survival rates (which are important parameters in assessing population dynamics of long-lived species; Sæther and Bakke 2000). These are often assessed through capture-mark-recapture approaches, such as mist-netting and ringing (Libois et al. 2012; Robert et al. 2015). However, conducting censuses at colonies is often easier than using capture-mark-recapture of the adults (Sutherland et al. 2004).

From the demographic and population changes identified, an assessment can be made to determine whether the level of change is variation around a stable long-term mean (e.g. Chastel et al. 1993; Dunn et al. 2016) or defined as a long-term increase or decline (e.g. Cuthbert et al. 2014). If the population is declining, climatic and trophic drivers can be assessed to determine possible causes (see reviews: Croxall et al. 2012; Dias et al. 2019; Rodríguez et al. 2019). Climatic drivers include rainfall (Boersma et al. 1980; Bolton et al.

2004), air temperature (Ropert-Coudert et al. 2004; Kelsey et al. 2016; Fischer et al. 2018), sea surface temperature (Slater and Byrd 2009; Robert et al. 2012), wind (Teixeira 1987; Bolton 1995; Bolton 2021) and anthropogenic climate change impacts on all of the above (Sydeman et al. 2012; Dias et al. 2019; IPCC 2019a; IPCC 2019b; Orgeret et al. 2022). Trophic drivers include chick provisioning and growth rates (as a proxy for chick quality/food availability; Bolton 1995; Hedd et al. 2002), egg and chick failures, and predation events (at any stage of the breeding period; See Chapter 5, Table 5.1). As discussed in the General Introduction (Chapter 1), the most recent reviews on assessing overall threats to seabird populations conclude that the top three threat categories are: invasive alien species, bycatch from fisheries, and climate change/severe weather events (Croxall et al. 2012; Dias et al. 2019). Of these, alien species and climate are likely to be most relevant to storm-petrels, which seem relatively unaffected by bycatch compared to many larger seabirds (Dias et al. 2019).

Modelling the current and future viability of a population through Population Viability Analysis (PVA) is a common tool for identifying policy changes and conservation action, especially for rare species (Lindenmayer et al. 1993; Morris et al. 1999; Ruiz et al. 2021). Amongst the various options are integrated population models implemented through Bayesian statistics (e.g. Oppel et al. 2022) or modelling systems which include, STELLA (Costanza and Voinov 2001), Seabird mPVA (Ruiz et al. 2021) and VORTEX (Lacy 1993; Morris et al. 1999; Lacy 2000). VORTEX is frequently used in IUCN species assessments. It is an individual-based programme that models the fate of hypothetical individuals (Lacy 1993). These models combine vital rate estimates (e.g. survival, reproduction, dispersal; Table 3.1) and population characteristics (e.g. initial population size, carrying capacity, age distribution) to assess the viability of a specific population (Lacy 2000; Anderson et al. 2018; Lacy and Pollak 2021). VORTEX allows the user to input different scenarios, and has been used to model seabird population changes (Rackete et al. 2021) and the impacts of a variety of threats, including fisheries (Anderson et al. 2018) and predation events (Whelan et al. 2018).

In the Azores Archipelago, Portugal, there is a pair of sibling species of storm-petrels that breed on the same islet (Ilhéu da Praia, off Graciosa) but at different times of year. The Monteiro's storm-petrel (*Hydrobates monteiroi*) is endemic to the Azores and breeds in the summer (April-September), whereas

the band-rumped storm-petrel (*Hydrobates castro*) is more widespread, and, in the Azores, breeds in the winter (September-March; (Monteiro and Furness 1998; Bolton et al. 2008; Bried and Neves 2015). Within the Azores, the two species are well described and studied (Monteiro et al. 1996a; Bolton et al. 2008; Bried et al. 2009; Robert et al. 2012). Previous research has detailed both past and current conservation concerns (Bried et al. 2009; Bried and Neves 2015; Neves et al. 2017), and some annual breeding success data have been reported (Bolton et al. 2004; Bried et al. 2009; Robert et al. 2012; Bried and Neves 2015). However, annual breeding success data were last published in 2012, and so the last eight years of overall breeding success have not yet been published or compared with earlier data from across the last twenty years of data collection. During the 2000-2001 fieldwork season, already published by Bolton et al. (2004), additional fieldwork was conducted to measure chick growth rates and other demographic data. These methods were repeated in the present study (2018-2020), to allow a detailed comparison between these earlier and later years of study.

3.1.1. Aims and hypotheses

The aims of this study were to assess whether there were any changes in selected breeding demographic parameters across two periods of intensive nest monitoring (2000-2001 and 2018-2020), and the intervening, less-intensely monitored years. If changes were identified, environmental parameters were explored to identify possible reasons for the change, and to identify any conservation management implications.

Specifically, these breeding biology demographic parameters included: 1) breeding success (based on number of successful fledges/breeding attempts across the 20 year period and in more detail for the two periods of intensive monitoring), 2) hatching and fledging dates (as a measure of phenological change), 3) chick growth rates, considering both overall growth curves and the three nestling stages typical of storm-petrels, namely (i) the initial growth stage, (ii) the plateau stage of relatively stable body mass, and (iii) the decline in body mass towards fledging (e.g. Allan 1962; Harris 1969; Boersma 1986). Changes in breeding productivity parameters from across the 20 years were explored in relation to wind speed, rainfall and air temperature data, and changes between the two periods of intensive study were explored in relation to (i) chick growth curves and (ii) causes of egg and chick losses. Finally, the data were compiled into a VORTEX analysis to assess future population

projections for each species, based on the past, current and hypothetical future breeding success rates and other demographic parameters.

3.2. Methods

3.2.1. Study site and study period

Fieldwork was conducted on Ilhéu da Praia, Graciosa, Azores, Portugal, a 0.12km^2 islet situated 1.2km off mainland Graciosa (Bolton et al. 2004; Bried et al. 2009; Hereward et al. 2021; Long et al. 2021). Two types of fieldwork occurred across the 20-year period. There were two periods of intensive data collection where nests were checked daily, and chicks weighed daily: Spring 2000 to end of Summer season 2001 (Mid-April 2000 – September 2001, with some significant periods when no data were collected: 6th-14th October 2000, 10th December 2000-16th January 2001, 12th March-12th April 2001; Bolton et al. 2004) and Winter 2018 to end of Summer 2020 (September 2018 – September 2020, with some significant periods where no data were collected: 29th November-7th December 2018, 11th-15th January 2019, 18th February 2019 – 3rd March 2019, 4th March 2019- 22nd March 2019, 23rd March 2019 – 30th April 2019, 20th-25th September 2019, 30th September-5th October 2019, 8th December 2019 – 3rd January 2020, 16th March – 17th June 2020, 10th – 21st August 2020) (Hereward et al. 2021; Long et al. 2021).

In the intervening years (2002-2017), 1-3 visits, which were weather-dependent, were made per breeding season to assess nest histories (number of eggs laid, eggs hatched, chicks fledged). Certain years were removed from the analysed dataset due to bad weather years (i.e. where researchers could not access the Islet at the appropriate times) – these were: the Monteiro's storm-petrel breeding season in 2002; and the band-rumped storm-petrel breeding seasons: 2001-2002, 2003-2004, 2006-2007, 2009-2010, 2010-2011, 2012-2013, 2013-2014, 2014-2015, 2016-2017 (see comments in previously published papers: Bolton et al. 2004; Bried et al. 2009; Bried and Neves 2015). When these data were included in the analyses reported below, the GLM fitted lines were qualitatively similar (not shown) to when they were excluded.

3.2.2. Nest inspections

Nest inspections followed similar protocols to Bolton et al. (2004), to determine the fate of the eggs laid and chicks hatched throughout both

species' breeding seasons (including collecting data on: number of eggs laid, number and dates of eggs hatched, number and dates of chicks fledged, breeding success). These inspections occurred 1-3 times per breeding season in the intervening years, and typically daily during the two periods of intensive data collection. Like all storm-petrels, *H. monteiroi* and *H*. *castro* typically lay one egg per breeding attempt (Warham 1990). Cases of multiple eggs being laid in the same nest did occur in both species' breeding seasons (data from this study) but are most likely to be due to multiple females competing for the same nest site. During nest inspections, the presence of other species in the nest cavity, or on top of the nest, was noted. Also, the losses of eggs and/or chicks were noted, and where possible, the most likely causes of loss were identified. During the two periods of intensive monitoring, chick body mass was measured daily using a pan balance, to monitor their growth rate (Monteiro and Furness 1998). Wing length and tarsus length of chicks were measured whenever the chick was alone in the nest (i.e. with parents absent).

3.2.3. Data analysis

Breeding success data for all years were collated in two separate ways for the early period of intensive study (2000-2001), the "raw" data were collated from the original data (collected by Bolton and Medeiros), and the "published" data were data collated from published papers (these data likely had filtering of nest types, and causes of egg/chick loss, which differ from the definitions used in the present study). These differences were seen where the raw data compared to the published data for Monteiro's storm-petrel in 2000 contained: two fewer eggs laid, one fewer chick fledged; Monteiro's storm-petrel in 2001: four fewer eggs laid, six fewer chicks fledged. Band-rumped storm-petrel in 2000-2001: two more eggs laid, one fewer chick fledged. The data for the intervening years and the latter period of intensive study (2018-2020) remained the same for both analyses.

As a pre-requisite to calculating the chick age in days for chick mass graphs, Julian day for hatch and fledging dates were calculated, where Julian day 1 = 1st January. Chick age was then extracted by comparing the observation date to the Julian hatch date and adding one day. Thus, chick age day 1 is the day the chick emerged from the egg. Chicks for which the hatch date was unknown were not included in associated analyses. Note that hatch dates were only recorded for a few of the band-rumped storm-petrel chicks in artificial

nests in 2000-2001, so consequently only data from the later years were used for the band-rumped storm-petrel chick analysis (2018-2019 and 2019-2020).

3.2.3.1. Nest histories

Across the two decades, the breeding success (i.e. number of chicks successfully fledged/total number of eggs laid) from across all available years (2000-2019/2020 inclusive) was analysed using a GLM to compare both between species and across years, with year (treated as a numerical variable), species and the year x species interaction, and including sample size (i.e. the number of eggs monitored for each species in each year) as a weighting variable. The binomial error family and cauchit link function were used (selected through comparison of model AIC values). This model structure was used twice – once with the "raw" dataset and once with the "published" dataset, as defined above. Analysing the two species together in the same model allowed for direct, between species comparisons. To determine the percentage decline per year, the difference between the earliest and latest predicted values from the individual species models were identified, and then divided by 20 (the duration of the whole study period).

For the two periods of intensive fieldwork, individual GLMMs (using package "lme4" v1.1-29; Bates et al. 2015) were conducted for each species, for hatching success (i.e., number of chicks hatched divided by the number of eggs laid), fledging success (i.e. number of chicks that fledged divided by the number of chicks hatched), and overall breeding success. Each of these models contained two independent variables: year as a fixed factor, and nest ID as a random factor, with binomial error family and log link function. Additional GLMMs were conducted for hatch date, fledge date and chick rear period, again with two variables: year as a fixed factor and nest ID as a random factor, but with Gaussian family and log link function. Julian day was the variable used for measurements of hatch and fledge dates. For band-rumped storm-petrel analysis, these Julian dates were adjusted so that the second half of the season (after December 31st) was +365 days. Note, egg lay dates were not used in this study because the data for this was more patchy or less accurate than the hatch dates. Consequently, hatch dates were used as the primary measure of breeding phenology.

3.2.3.2. Chick growth curves

Chick growth (explained *via* body mass) was analysed separately for each species using a GAM (package "mgcv" v1.8-31; Wood 2003; Wood 2017), with mass in relation to chick age in days (smoothed by year) and year as a factor, using family Gamma as log link function. Individual models were conducted per species for (1) all chicks regardless of fate (survived or died), and then (2) specifically for chicks that later died.

3.2.3.2.1. Segmented (piecewise) regression to describe chick growth

The number of days in the initial and plateau growth stages were extracted using segmented regression models (package "segmented" v5.1-0; Muggeo 2003; Muggeo 2008; Muggeo 2016; Muggeo 2017). Each year was analysed individually, to determine the break points in body mass between the initial growth phase, the plateau phase and the pre-fledging decline in body mass, for each year. This is a two-step analysis where an initial GLM was modelled with mass in relation to chick age, with a Gamma error family and an identity link function. Then the segmented regression was extracted from the GLM with 1-3 suggested turning points as needed per year, depending on the duration of data available (Monteiro's storm-petrel one turning point in 2000, two in 2001, three in 2019 and 2020; band-rumped storm-petrel turning points were only extracted from 2018-2019 data, using three turning points because there was a gap in fieldwork which biases the 2019-2020 turning points).

3.2.3.2.2. Body mass variance during the "plateau stage"

To investigate whether the frequency and/or size of food deliveries differed between species and years, a GAM model was first used to fit a smoothed line through the body mass trajectory of each chick, and then the variance of the residuals around this smoothed fitted line during the plateau stage was used as a measure of variability in body mass. Chicks with less than 10 days of body mass data throughout the whole growth period were removed from this analysis. The plateau stage was identified from the segmented regression analysis described above and was unique to each species and year where the turning points for both sides of the plateau stage could be determined (i.e., Monteiro's 2001, 2019 and 2020, and band-rumped 2018-2019). Two GLM models were then used 1) to compare this body mass variance in later years between species, and 2) to compare body mass variance between the early and later periods for the Monteiro's storm-petrel.

3.2.3.2.3. Peak body mass

For chicks that later fledged, the peak body mass was extracted per individual chick and averaged for each species, across each year of intensive study. A t-test was used to compare the peak mass of the early and later years of the Monteiro's storm-petrel chicks that fledged.

3.2.3.3. Hatch date and fledging success

To test for a relationship between hatch date and fledging success, binomial GAMs were analysed for each species, with chick fledged or died (dependent variable) analysed in relation to hatch date (Julian day, smoothed with the thin plate regression spline method; "tp"), and year (treated as a factor).

3.2.3.4. Chick age at death

To compare the age at which chicks died, chick age of death was compared between years (treating year as a factor), using a GLM with a Gamma error family and a log link function.

3.2.3.5. Associations between weather and storm-petrel breeding success

To assess possible causes of the observed changes in breeding success across the 20-year study period, the associations between weather conditions (air temperature, rainfall and wind speed), and breeding success, were examined using GAMs (package "mgcv" v1.8-31; Wood 2003; Wood 2017). The data for air temperature, rainfall and wind speed data were extracted for all breeding season years between 2000 and 2020, inclusive (see Chapter 2; package v3.1.5; Sparks et al. 2017). The likelihood of breeding success (identified from the raw data – see nest histories section above) was modelled for each species individually, against the yearly averages which were extracted for each weather variable individually (where year was a factor; see Chapter 2). All two-way interactions of these three weather variables were included (Temperature x Wind, Temperature x Rainfall, Wind x Rainfall), using the beta error family and logit link function (selected on the basis of AIC), and weighted by the sample size (number of eggs laid, based on one egg per nest where possible multiple eggs were recorded) for each year.

3.2.3.6. Causes of egg and chick losses

To assess changes in the causes of egg and chick losses during the intensely studied years, chi-squared tests were conducted individually per species and

per stage of breeding (egg or chick stage). Initial analysis included a comparison of the broad causes of egg and chick losses across all years individually. But in further analysis the years were pooled into "early" (2000-2001) and "late" periods (2018-2020) and analysed 1) across broad categories of causes of egg and chick loss (unknown, weather, other species, unviable/remaining, humans) and 2) analysed across known other species cause of egg/chick loss.

3.2.3.7. Future projection modeling

VORTEX 10.3.5.0 (Lacy 1993, 2000; Lacy and Pollak 2021) was used to assess the population viability of both species of storm-petrel breeding on Ilhéu da Praia. Individual models were run for each species and scenario separately. From all of these models, the mean stochastic growth rate, probability of extinction, and mean number of years until extinction, were extracted.

3.2.3.7.1. Baseline analyses

Table 3.1 details the baseline model parameters used, including the five breeding success rates, three for past breeding success rates (2000 for Monteiro's and 2000-2001 and 2002-2003 for the band-rumped storm-petrel) and two for present (2020 for Monteiro's and 2019-2020 for the band-rumped storm-petrel), which were run in separate models. The initial population size used for this main analysis is a pessimistic (small) count of 200 breeding adults for Monteiro's storm-petrel and 400 breeding adults for band-rumped storm-petrel, based on the previously estimated breeding adult population size for Ilhéu da Praia (Monteiro et al. 1999).

3.2.3.7.2. Sensitivity analyses

Sensitivity analyses were conducted on several parameters where the true values were unknown or uncertain, to evaluate the sensitivity of the projections to the value of these specific parameters. Where needed, alternatives to specific parameters are outlined in Table 3.2. Where other parameters are not specified, the baseline parameters were used (already detailed in Table 3.1).

To aid in assessing what level of change is needed in the breeding success rate to maintain a stable population size, and avoid extinction, hypothetical

future breeding success rates at 20%, 35% and 50% using the baseline initial population sizes of 200 and 400 were modelled.

As the true population size for both species in the Azores is unknown, a range of initial population sizes were extrapolated based on the IUCN Red List range (BirdLife International 2018a,b), spanning one and half orders of magnitude (100-1500 individuals). These would hypothetically encompass the whole known Azores populations of both species (not just the populations on Ilhéu da Praia). For these models, both past breeding success values (Monteiro's storm-petrel 2000 = 45.5% and band-rumped storm-petrel 2000-2001 = 54.1%) and currently observed values (Monteiro's storm-petrel 2020 = 23.7% and band-rumped storm-petrel 2019-2020 = 56.3%) were used to provide comparisons with the baseline (Table 3.2).

Due to unpublished reports indicating that the life span and maximum age of reproduction is higher than previously reported (BirdLife International 2018a,b), models were run using the most recent breeding success rates (Monteiro's storm-petrel 2020 = 23.7% and band-rumped storm-petrel 2019-2020 = 56.3%) and baseline initial population estimates (Monteiro's storm-petrel = 200, band-rumped storm-petrel = 400) alongside the baseline life span and maximum age of reproduction as 20 years, as well as increasing this parameter value to 30 years (Table 3.2).

Based on new unpublished data that suggested age of first breeding may be later than in the published literature, models were run using the most recent breeding success rates (Monteiro's storm-petrel 2020 = 23.7% and band-rumped storm-petrel 2019-2020 = 56.3%) and baseline initial population estimates (Monteiro's storm-petrel = 200, band-rumped storm-petrel = 400), alongside the baseline and unpublished data for age of first breeding (Table 3.2).

Table 3.1. Parameters used in VORTEX 10.3.5.0 to produce baseline simulations for the population of Monteiro's storm-petrel (*Hydrobates monteiroi*) and band-rumped storm-petrels (*Hydrobates castro*) on Ilhéu da Praia, Graciosa, Azores, Portugal. The table lists parameters in order of data input in VORTEX v.10.3.5.0.

Parameter name	**Parameter estimate Baseline**	**Source**
Number of iterations	1000 iterations	Selected for this analysis
Number of years (time steps)	100 years (100 time steps)	Selected based on both species' generation times (BirdLife International 2022b,c)
Duration of each year in days	365 days	Robert et al. (2015)
Extinction definition	Only 1 sex remains	Selected for this analysis
Number of populations	1	Selected as analysis was based on Ilhéu da Praia
Inbreeding depression	Not selected (as no evidence)	For Monteiro's storm-petrel Andris et al. (2012); As Monteiro's have a smaller population than band-rumped storm-petrel, this is assumed to be the same
EV (Environmental Variation) correlation between reproduction and survival	0.5	Available setting in version 10.3.5.0 to account for some environmental variation
Reproductive system	Long-term monogamous	Warham (1990); Bried et al. (2003); Robert et al. (2015)
Age of first offspring (reproduction) for females	2 years (rounded)	Data rounded in model. Raw data: 2.3±0.7 years (n= 9); Bried and Bolton (2005)
Age of first offspring (reproduction) for males	2 years (rounded)	Data rounded in model. Raw data: 2.3±0.7years (n= 9); Bried and Bolton (2005)
Maximum age of reproduction (same for both sexes)	20 years	Estimated based on unpublished data
Maximum lifespan	20 years	Estimated based on unpublished data
Maximum number of broods per year	1 brood	Warham (1990); Robert et al. (2015)
Maximum number of progeny per brood	1 individual	Warham (1990); Robert et al. (2015)
Sex ratio at birth	50% males	Robert et al. (2012) found no significant differences in adult survival between sexes for Monteiro's storm-petrel. Assumed the same for band-rumped storm-petrel
Density dependent reproduction	Not selected (unknown)	Unknown
% adult females breeding (SD)	83.5% (5%)	Robert et al. (2012). SD estimated.
Breeding success rate (hatching and fledging combined)	Monteiro's storm-petrel 2000: 45.5% Monteiro's storm-petrel 2020 = 23.7% Band-rumped storm-petrel 2000-2001 = 54.1% Band-rumped storm-petrel 2002-2003 = 64.5%	This PhD's results (Chapter 3; Figure 3.1) NB band-rumped storm-petrel 2002-2003 data included in the analysis to display the range of known breeding success rates

	Band-rumped storm-petrel 2019-2020 = 56.3%	
Offspring distribution per female per brood	Specify exact distribution: 1 offspring = 100%	Warham (1990); Robert et al. (2015)
Mortality rates (ages 0-2+)	0-2 years = 50% ±10 (therefore 29.3%, ± 3.2% per year step) 2+ years = 3% ±0.015	Estimated about half the chicks would die before reproduction, as seen in other procellariiformes species (Croxall et al. 1990; Terauds et al. 2005). SD estimated. Robert et al. (2012, 2015)
Number of type of catastrophes	0 (none modelled)	Not modelled in this preliminary analysis
% adult male in breeding pool (SD)	83.5% (5%)	Robert et al. (2012). SD estimated.
Initial population size	Monteiro's: 200 individuals Band-rumped: 400 individuals	Monteiro et al. (1999) Note for these baseline simulations this is a very conservative population size (based from Ilhéu da Praia only) but see sensitivity analysis results for broader sizes.
Population distribution	Use stable age distribution was selected	Selected for this analysis
Carrying capacity (K) (±SD in K due to EV)	500 individuals ±20	Selected for this analysis. SD estimated. Note for these baseline simulations this is a very conservative (small) population size (based from Ilhéu da Praia only) but see sensitivity analysis results for broader sizes.
Future change in K?	0 (none modelled)	Not modelled in this analysis
Population harvested?	0 (none modelled)	Not modelled in this analysis
Supplementation	0 (none modelled)	Not modelled in this analysis
Genetics	0 (none modelled)	Not modelled in this analysis

Table 3.2. Sensitivity analysis parameters used in VORTEX 10.3.5.0, alongside other parameters already detailed in Table 3.1, to produce sensitivity simulations for the population of Monteiro's storm-petrel (*Hydrobates monteiroi*) and band-rumped storm-petrels (*Hydrobates castro*) on Ilhéu da Praia, Graciosa, Azores, Portugal. Table laid out in order of data input in VORTEX v.10.3.5.0.

Parameter name	**Parameter estimate Baseline**	**Source**
Age of first offspring for females	Monteiro's storm-petrel: 4 years old Band-rumped storm-petrel: 3 years old	Unpublished data (Pers.coms. JB). Data rounded in model. Raw data:Monteiro's storm-petrel: 4.3 ±1.3. Band-rumped storm-petrel: 3.3 ±0.5
Age of first offspring for males	Monteiro's storm-petrel: 5 years old Band-rumped storm-petrel: 3 years old	Unpublished data (Pers.coms. JB) Data rounded in model. Raw data:Monteiro's storm-petrel: 5.1 ±1.8. Band-rumped storm-petrel: 3.3 ±0.5
Maximum age of reproduction (same for both sexes)	30 years	Increased to take into account new, unpublished data
Maximum lifespan	30 years	Increased to take into account new, unpublished data
Initial population size (number of individuals)	Monteiro's storm-petrel: 100, 200, 1000, 1500 Band-rumped storm-petrel: 100, 400, 1000, 1500	Estimates selected for this analysis extrapolated from population counts from BirdLife International (2018a,b)
Carrying capacity (K)	2000 individuals ±20	Selected for this analysis to take into account the larger initial population sizes. SD estimated.

3.3. Results

3.3.1. Nest histories

The breeding success of both species has significantly declined across the two decades of the study period (Figure 3.1; Table 3.3). The rate of decline for the Monteiro's storm-petrel was significantly greater than for the band-rumped storm-petrel (Table 3.3). The percentage decline per year ranged from 1.3 - 1.5% (raw and published data respectively) for the Monteiro's storm-petrel, and 0.2 - 0.3% per year for the band-rumped storm-petrel (raw and published data respectively).

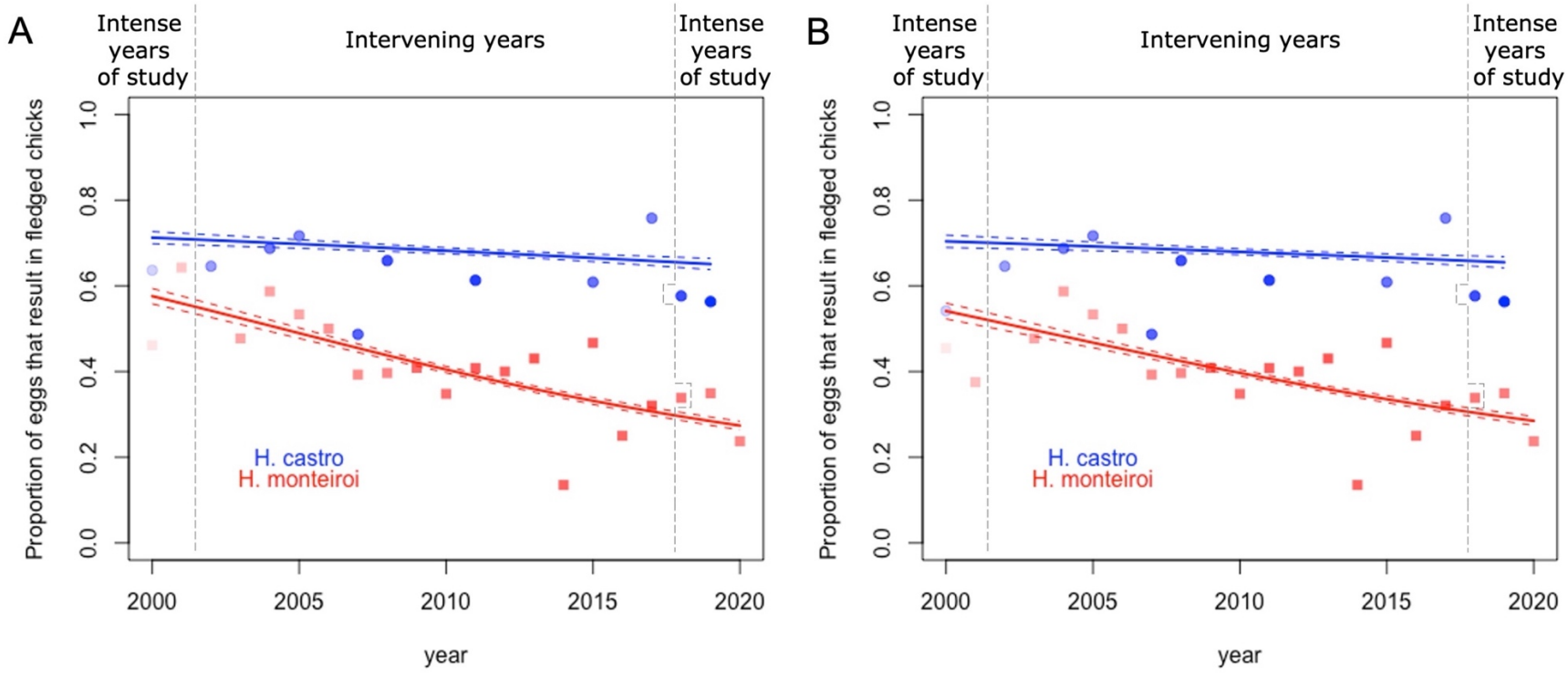


Figure 3.1. Breeding success (chicks fledged/eggs laid) of Monteiro's storm-petrel and band-rumped storm-petrel (from 2000 to 2020, and 2000-2001 to 2019-2020, respectively). Colour intensity is proportional to sample size in each year, and the weighting of sample size for each year is incorporated into this GLM analysis of breeding success. Monteiro's storm-petrel (square red points), band-rumped storm-petrel (circular blue points) A) 2000-2001 Monteiro's and band-rumped storm-petrel data derived from published data, B) 2000-2001 Monteiro's and band-rumped storm-petrel data derived from raw data (as depicted in further figures). Grey vertical dashed lines denote which years for each species fall within the periods of intensive study, and which are intervening years. These data are based on one egg per nest (ignores possible second or third eggs laid in the same nest – seen in intervening years and Monteiro's storm-petrel 2019 and 2020 breeding seasons and band-rumped storm-petrel 2019-2020 breeding season).

Table 3.3. GLM analysis of breeding success (chicks fledged/eggs laid) of Monteiro's storm-petrel and band-rumped storm-petrel (from 2000 to 2020 and 2000-2001 to 2019-2020 respectively). The GLM assesses the breeding success as a proportion, compared to year, species and the interaction between species and year, with the weighting of sample size. GLM family was binomial with cauchit link function. Results are presented for both the published data set and the raw data set (as depicted in further figures).

	Published data set				**Raw data set**			
	Estimate	**Std. Error**	**Z**	**P**	**Estimate**	**Std. Error**	**Z**	**P**
Intercept	29.689	11.424	2.599	0.009 **	23.528	11.302	2.082	0.037 *
year	-0.014	0.006	-2.544	0.011 *	-0.011	0.006	-2.027	0.043 *
Species *Hydrobates monteiroi*	80.892	15.386	5.258	<0.001 ***	69.810	15.155	4.606	<0.001 ***
Year:species *Hydrobates monteiroi*	-0.041	0.008	-5.322	<0.001 ***	-0.035	0.008	-4.673	<0.001 ***

The average breeding success was lower for the Monteiro's storm-petrel in the four intensely studied years (40% success rate or below), compared to the band-rumped storm-petrel, for which the average breeding success remained stable (~ just below 60%; Table 3.4). The trend of an overall decline in breeding success of the Monteiro's storm-petrel was apparent when comparing the years of intensive study (Figure 3.2, Table 3.4), although the decline was not statistically significant across these specific years.

The components of breeding success (hatching success and fledging success) showed differences between species and between the individual years of intensive study. For both species, hatching success (Figure 3.2C&D) remained fairly stable (above 50% success rate for the Monteiro's storm-petrel eggs and between 60% and 80% for band-rumped storm-petrel eggs), although the Monteiro's storm-petrel hatching success was more variable across the four years. By contrast, fledging success was lower in 2020 for the Monteiro's storm-petrel compared to previous years (although not significantly) and across all years was generally lower than in the band-rumped storm-petrel, which had almost 100% fledging success (Figure 3.2E&F).

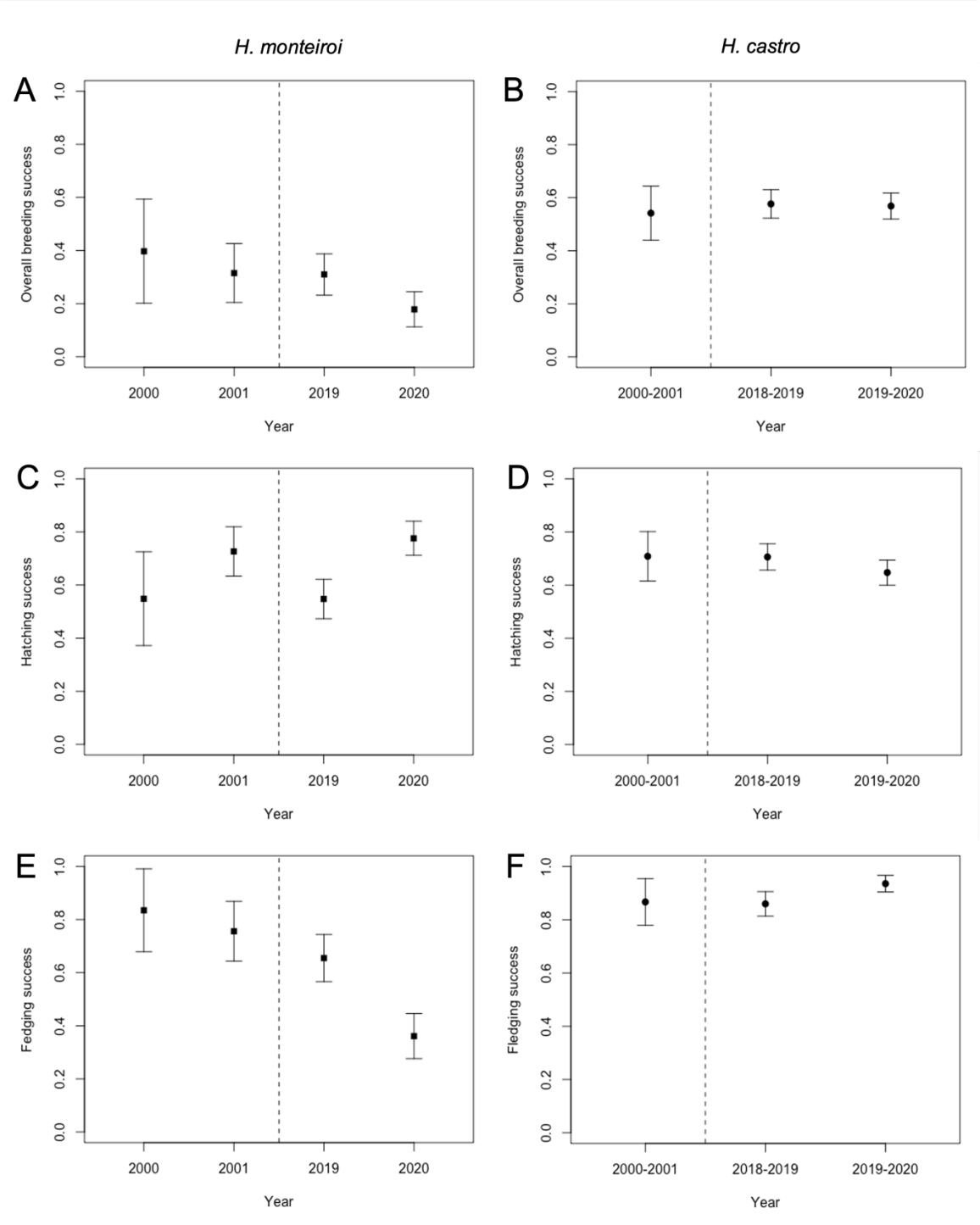


Figure 3.2. Breeding productivity parameters ± SE in years of intensive study for: overall breeding success rates of A) the Monteiro's storm-petrel and B) the band-rumped storm-petrel; hatching success (proportion of eggs that hatched) of C) the Monteiro's storm-petrel and D) the band-rumped storm-petrel; and the fledging success (proportion of newly hatched chicks that subsequently fledged), of E) the Monteiro's storm-petrel and F) the band-rumped storm-petrel. Note that this data analysis excludes chicks remaining at end of the fieldwork season.

Table 3.4. GLMERs to explain overall breeding success, hatching success and fledging success of the two storm-petrel species. Year was treated as a fixed factor, and nest box ID as a random factor, with binomial error family and log link function.

Monteiro's storm-petrel												
	Overall breeding success				Hatching success				Fledging success			
	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P
Intercept	-0.417	0.819	-0.509	0.611	0.195	0.713	0.273	0.785	1.620	1.133	1.431	0.153
Year2001	-0.359	0.912	-0.394	0.694	0.783	0.833	0.940	0.347	-0.490	1.275	-0.384	0.701
Year2019	-0.384	0.870	-0.441	0.659	-0.004	0.767	-0.005	0.996	-0.980	1.194	-0.821	0.412
Year2020	-1.111	0.894	-1.243	0.214	1.048	0.795	1.318	0.188	-2.191	1.194	-1.835	0.067
Band-rumped storm-petrel												
	Overall breeding success				Hatching success				Fledging success			
	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P
Intercept	0.167	0.410	0.408	0.683	0.887	0.449	1.976	0.048 *	1.872	0.760	2.464	0.014 *
Year2018-2019	0.141	0.465	0.304	0.761	-0.012	0.508	-0.023	0.981	-0.059	0.850	-0.070	0.944
Year2019-2020	0.109	0.456	0.240	0.811	-0.281	0.495	-0.569	0.570	0.802	0.919	0.873	0.383

Monteiro's storm-petrel chick hatch dates were significantly earlier (by an average of 10 days) in the later time period (2019-2020) compared to the earlier period (2000-2001; Figure 3.3A; Table 3.5), whereas hatch dates have remained similar for the band-rumped storm-petrel (Figure 3.3B; Table 3.5). In contrast, the fledging dates have stayed similar between the two time periods for the Monteiro's storm-petrel chicks (Figure 3.3C; Table 3.5), compared to the band-rumped storm-petrel chicks which have become significantly earlier (by an average of 20 days, Figure 3.3D; Table 3.5).

Overall, the Monteiro's storm-petrel has a shorter chick-rear period duration, compared to the band-rumped storm-petrel (Figures 3.3E&F; Table 3.5). The duration of the Monteiro's storm-petrel chick-rear period has not changed significantly between the two time periods, although it has tended to increase, given that they are now hatching earlier but fledging around the same date (Figure 3.3E; Table 3.5). This is in contrast to the band-rumped storm-petrel chicks, which are still hatching at around the same date but fledging significantly earlier (this is reflected in the chick-rear period duration graph Figure 3.3F; Table 3.5).

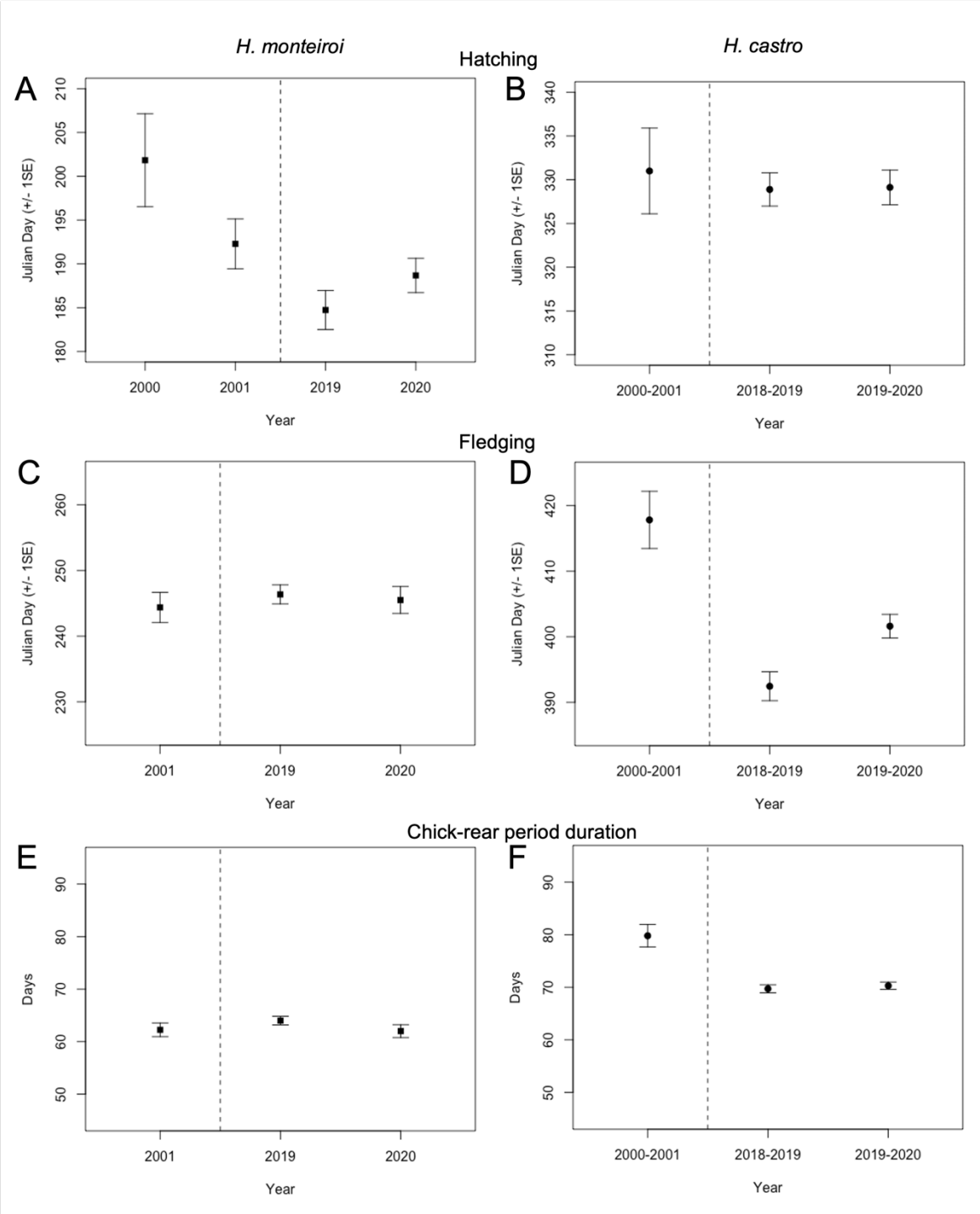


Figure 3.3. Timing of breeding season events for hatching dates (in Julian day) of the A) Monteiro's storm-petrel and B) the band-rumped storm-petrel; fledging dates (in Julian day) of the C) Monteiro's storm-petrel and D) the band-rumped storm-petrel; and the duration of the chick-rear period (i.e. from hatching to fledging) for the E) Monteiro's storm-petrel and F) the band-rumped storm-petrel. NB for C and E there are no data for the 2000 breeding season, due to fledging data not being recorded. The sample size for each measure of breeding phenology depends on the data available from across the whole breeding season in each year, e.g. E, 2001 chick-rear period duration sample size is smaller than for the hatching dates as it does not take into account later hatched chicks (range presented in A for 2001). Data plotted is a model predicted fit ± model predicted SE values extracted from individual GLMMs for each measure of breeding phenology.

Table 3.5. GLMERs to explain hatch date, fledge date and chick-rear period duration for each species, with two independent variables: year as a fixed factor and nest ID as a random factor, with Gaussian family and log link function.

Monteiro's storm-petrel												
	Hatching dates				Fledging dates				Chick-rear period duration			
	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P
Intercept	5.307	0.026	201.675	<0.001 ***	5.499	0.009	586.321	<0.001 ***	4.131	0.021	197.573	<0.001 ***
Year2001	-0.049	0.030	-1.606	0.108	N/A [NB no 2000 data used in these models]							
Year2019	-0.089	0.029	-3.057	0.002 **	0.008	0.011	0.727	0.467	0.028	0.025	1.129	0.259
Year2020	-0.067	0.028	-2.381	0.017 *	0.005	0.012	0.366	0.715	-0.004	0.029	-0.140	0.889
Band-rumped storm-petrel												
	Hatching dates				Fledging dates				Chick-rear period duration			
	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P	Estimate	Std. Error	Z	P
Intercept	5.802	0.015	392.045	<0.001 ***	6.035	0.010	578.854	<0.001 ***	4.380	0.027	163.179	<0.001 ***
Year2018-2019	-0.006	0.016	-0.404	0.686	-0.063	0.012	-5.282	<0.001 ***	-0.135	0.029	-4.657	<0.001 ***
Year2019-2020	-0.006	0.016	-0.355	0.723	-0.040	0.011	-3.481	<0.001 ***	-0.127	0.029	-4.437	<0.001 ***

3.3.2. Chick growth curves

The overall growth curves of both species' chicks were similar across all years, exhibiting the three-part body mass trajectory typical of storm-petrels: (1) an initial growth phase, (ii) a plateau phase and (iii) a period of body mass loss prior to fledging (Figure 3.4 A&B; Table 3.6). The duration of the initial growth phase was shorter for the Monteiro's storm-petrel by 9 days, compared to the band-rumped storm-petrel (Monteiro's storm-petrel ~23 days, band-rumped storm-petrel = 32 days; Figure 3.4 A&B). However, the plateau stage was more similar in the two species; four days shorter for the Monteiro's storm-petrel (~ 25 days) compared to the band-rumped storm-petrel (21 days). Consequently, the mass loss phase began about 5 days later, on average, in the band-rumped storm-petrel (Figure 3.4 A&B).

Chick mass of both species varied between days during the plateau stage, reflecting food deliveries by the parents, interspersed with periods of starvation between feeds (Figure 3.4C). In the most recent time period (2018-2020), band-rumped storm-petrels had a significantly higher variance around the mean fitted GAM line during the plateau stage, compared to the Monteiro's storm-petrel ($F = 7.955$, d.f. = 1,71, $P = 0.00621$). For the Monteiro's storm-petrel, there was no significant difference in the body mass variance within the plateau period between the early and pooled late years ($F = 1.703$, d.f. = 1,68, $P = 0.196$).

The peak mass of chicks that later fledged, was approximately 10g higher for the band-rumped storm-petrel chicks compared to the Monteiro' storm-petrel chicks (average maximum peak ±SE for Monteiro's storm-petrel = 71.1g ± 1.0g, band-rumped storm-petrel = 80.8g ± 0.8g Figure 3.4A&B). When the peak mass of Monteiro's storm-petrel chicks was compared between the early and late years, no significant difference was found ($t = -0.9506$, df = 24.792, $P = 0.351$). However, early year chick peak mass (69.9g ±2.0) was on average 1.8g lower compared to late years (71.7g ±1.0) (Figure 3.4A).

For chicks that died before fledging, the growth curves varied in shape and duration (Figure 3.5A&B; Table 3.7), reflecting the diversity of causes and timing of chick deaths, which occurred throughout each season (Figure 3.5A&B; Table 3.7). The losses occurred more widely throughout the Monteiro's storm-petrel breeding seasons, compared to the band-rumped storm-petrel breeding seasons (Monteiro's chicks were typically lost later in

the season; Figure 3.5C&D; Table 3.8). Furthermore, the age at death of chicks for both species varied considerably (2-61 days and 3-75 days for Monteiro's and band-rumped storm-petrels respectively), although the median age of chick death was within the initial growth phase of the chicks for both species (23 and 18 days for Monteiro's and band-rumped respectively; there was no significant difference between species in the age of chick death; F = 2.001, d.f. = 5,38, P = 0.101; Figure 3.5E; Table 3.9).

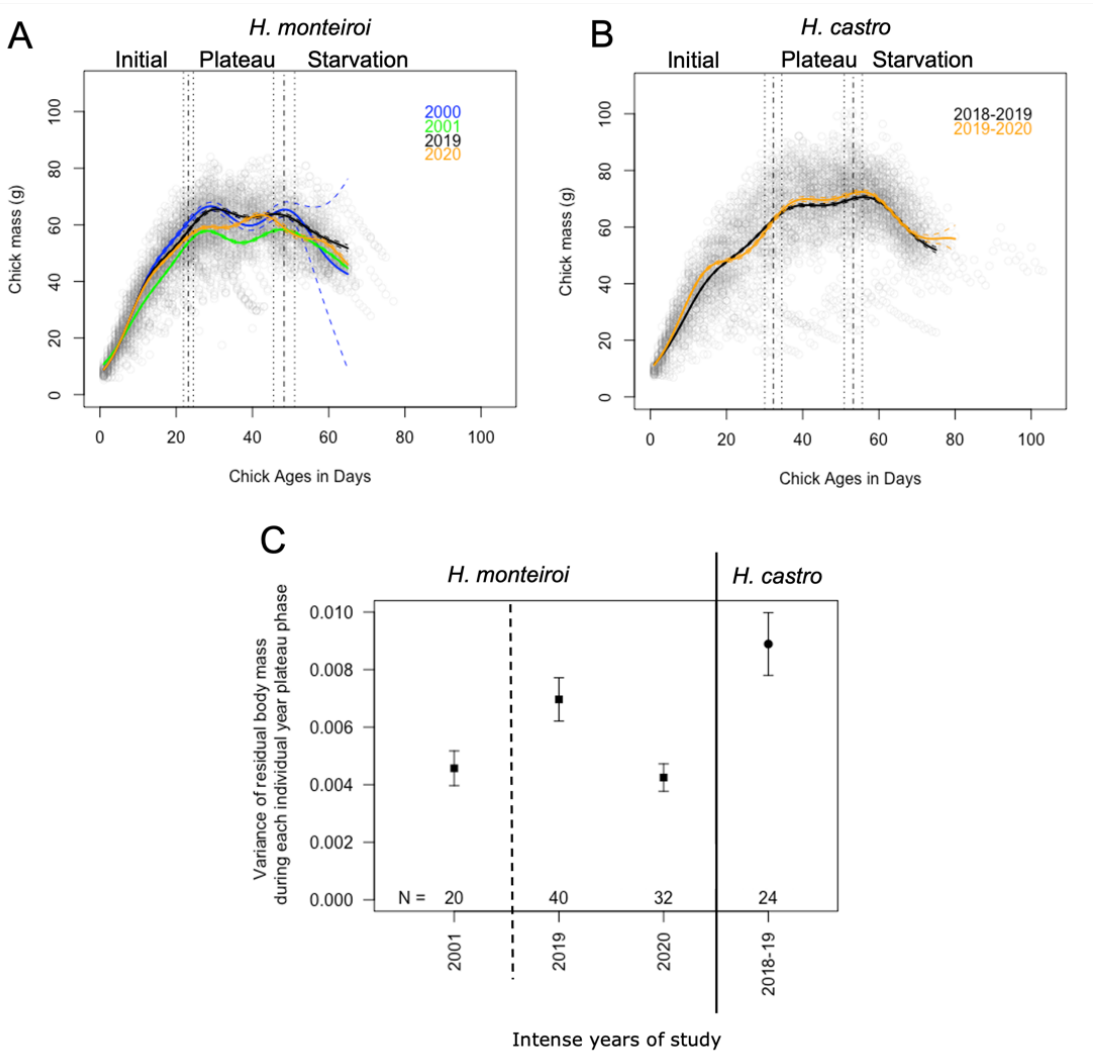


Figure 3.4. Growth curves of all chicks (regardless of fate) for both species in both periods of intensive study for A) the Monteiro's storm-petrel (2000, blue; 2001, green; 2019, black; 2020, orange) and B) the later period of intensive study for the band-rumped storm-petrel (2018-2019, black; 2019-2020, orange). Vertical lines show predicted turning points averaged for each species, extracted from segmented regression models of chick mass ± confidence intervals, with chick age in days as the independent variable. C) Variance in residual body mass during the plateau stage ± model SE, in years where sufficient data were available, for Monteiro's and band-rumped storm-petrels (all chicks included regardless of final fate).

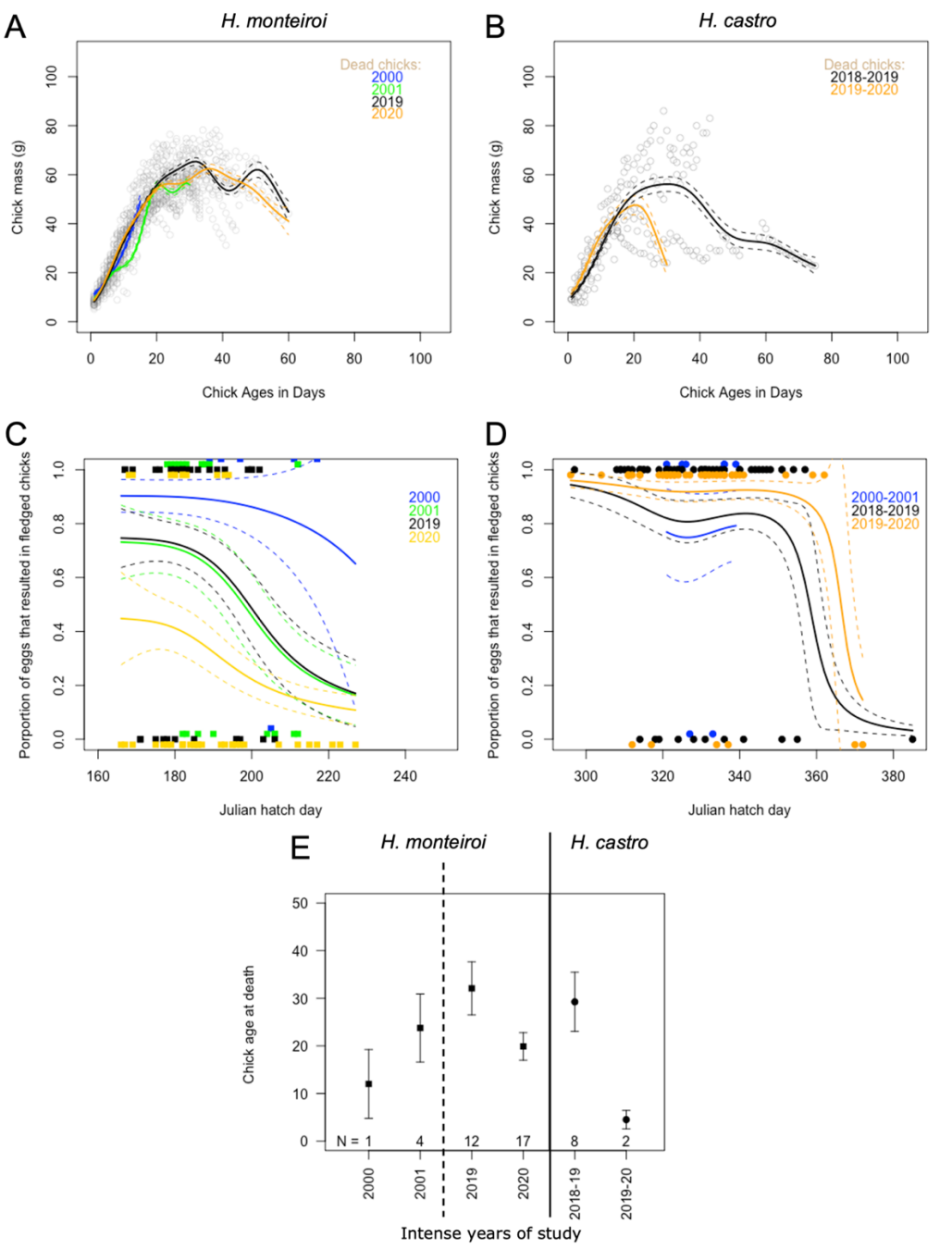


Figure 3.5. Growth curves of chicks that later died for both species in both periods of intense study for A) the Monteiro's storm-petrel (2000, blue; 2001, green; 2019, black; 2020, orange) and B) the later period of intense study for the band-rumped storm-petrel (2018-2019, black; 2019-2020, orange). Seasonal variation in breeding success of C) Monteiro's and D) band-rumped storm-petrels [NB Julian day 1 = 1st January for that year, for band-rumped storm-petrels where they hatched in the following year, 365 was added to the Julian hatch date]. E) Variation in chick age of death for both species in all breeding seasons bar 2000-2001.

Table 3.6. GAM model outputs for chick growth curves for all chicks regardless of fate, for the Monteiro's storm-petrel and the band-rumped storm-petrel chicks. Mass was analysed in relation to chick age in days (smoothed by year), year as a factor, and the two-way interaction between age and year, using the gamma error family and log link function.

All chicks regardless of fate				
Monteiro's storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*t*	P
(Intercept)	3.855	0.056	68.800	<0.001 ***
factor(year)2001	-0.094	0.056	-1.700	0.095
factor(year)2019	0.003	0.056	0.100	0.958
factor(year)2020	-0.036	0.056	-0.600	0.527
Approximate significance of smooth terms				
	edf	Ref.df	F	P
s(AgeDays2): factor(year)2000	6.371	6.771	504.700	<0.001 ***
s(AgeDays2): factor(year)2001	8.015	8.403	844.200	<0.001 ***
s(AgeDays2): factor(year)2019	8.636	8.949	1763.700	<0.001 ***
s(AgeDays2): factor(year)2020	8.873	8.992	1751.700	<0.001 ***
Band-rumped storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*t*	P
(Intercept)	3.930	0.004	1053.300	<0.001 ***
factor(year)2019-2020	0.029	0.007	4.300	<0.001 ***
Approximate significance of smooth terms				
	Edf	Ref.df	F	P
s(AgeDays2): factor(year)2018-2019	8.520	8.895	1184.000	<0.001 ***
s(AgeDays2): factor(year)2019-2020	7.448	7.776	1577.000	<0.001 ***

Table 3.7. GAM model outputs for chick growth curves for chicks that later died, individually for the Monteiro's storm-petrel and the band-rumped storm-petrel chicks. Mass was analysed in relation to chick age in days (smoothed by year), year as a factor, and the two-way interaction between age and year, using the gamma error family and log link function.

Chicks that later died				
Monteiro's storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*t*	P
(Intercept)	4.224	0.093	45.609	<0.001 ***
factor(year)2001	0.066	1.235	0.054	0.957
factor(year)2019	-0.608	0.093	-6.539	<0.001 ***
factor(year)2020	-0.608	0.093	-6.543	<0.001 ***
Approximate significance of smooth terms				
	edf	Ref.df	F	P
s(AgeDays2): factor(year)2000	1.000	1.000	153.700	<0.001 ***
s(AgeDays2): factor(year)2001	6.738	6.943	240.500	<0.001 ***
s(AgeDays2): factor(year)2019	8.139	8.763	514.300	<0.001 ***
s(AgeDays2): factor(year)2020	7.592	8.357	727.900	<0.001 ***
Band-rumped storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*t*	P
(Intercept)	3.555	0.025	143.428	<0.001 ***
factor(year)2001	-0.826	0.814	-1.0150	0.311
Approximate significance of smooth terms				
	edf	Ref.df	F	P
s(AgeDays2): factor(year)2018-2019	6.103	7.239	45.960	<0.001 ***
s(AgeDays2): factor(year)2019-2020	3.600	3.976	30.300	<0.001 ***

Table 3.8. GAM models to explain whether the chick fledged, in relation to hatch date (smoothed with a thin-plate regression spline) and by year.

Monteiro's storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*Z*	P
(Intercept)	2.608	1.973	1.322	0.186
year2001	-2.288	2.018	-1.134	0.257
year2019	-2.200	2.015	-1.092	0.275
year2020	-3.342	2.037	-1.641	0.101
Approximate significance of smooth terms:				
	edf	Ref.df	Chi.sq	P
s(Julian hatch day)	1.598	1.940	5.479	0.082
Band-rumped storm-petrel				
Parametric coefficients:				
	Estimate	SD error	*Z*	P
(Intercept)	1.121	1.109	1.010	0.312
year2018-2019	0.451	1.211	0.373	0.709
year2019-2020	2.799	2.058	1.360	0.174
Approximate significance of smooth terms:				
	edf	Ref.df	Chi.sq	P
s(Julian hatch day)	2.508	2.833	3.813	0.212

Table 3.9. GLM parameter estimates for the age of chick death age (compared to the reference year of 2000), for both species and across all years of intensive study where data was available. The GLM reported here used the gamma error family and log link function.

Coefficients:				
	Estimate	SD error	*t*	P
(Intercept)	2.485	0.602	4.129	<0.001 ***
factor(year)2001	0.683	0.673	1.015	0.317
factor(year)2018-2019	0.891	0.638	1.396	0.171
factor(year)2019	0.983	0.626	1.570	0.125
factor(year)2019-2020	-0.981	0.737	-1.331	0.191
factor(year)2020	0.505	0.619	0.815	0.420

3.3.3. Associations between weather variables and storm-petrel breeding success

Changes in breeding success (Figure 3.1) can be viewed in comparison to the trends in weather (Chapter 2, Figure 2.2). Across the 20-year period, air temperature increased by ~ 0.5 °C, with average breeding season air temperatures being ~ 2 °C higher in the Monteiro's storm-petrel breeding season compared to the band-rumped storm-petrel breeding season. Rainfall decreased slightly across the 20-year period, with generally higher levels of rainfall during the band-rumped storm-petrel breeding season. Wind speed remained very similar across the 20-year period, with marginally higher wind speeds during the band-rumped storm-petrel breeding season, and particularly calm conditions during both species' breeding seasons in 2000. When interactions between weather variables and breeding success were considered, all three of the weather variables were significantly associated with breeding success, either directly, or in two-way interactions with either or both of the other weather variables (Figure 3.6). Specifically for the Monteiro's storm-petrel, higher air temperatures were generally associated with lower breeding success (Figure 3.6A), but not in particularly calm years, when higher air temperatures were associated with higher breeding success (Figure 3.6C). Wind speed had a negative effect on breeding success, while rainfall had a positive effect (Figure 3.6E). For the band-rumped storm-petrels there were more pronounced interactions. Specifically, there was an overall positive association between air temperature and breeding success, except in particularly wet and windy years (Figure 3.6B and 3.6D). Similarly, high rainfall was associated with lower breeding success in windy years, but with higher breeding success in calm years (Figure 3.6F).

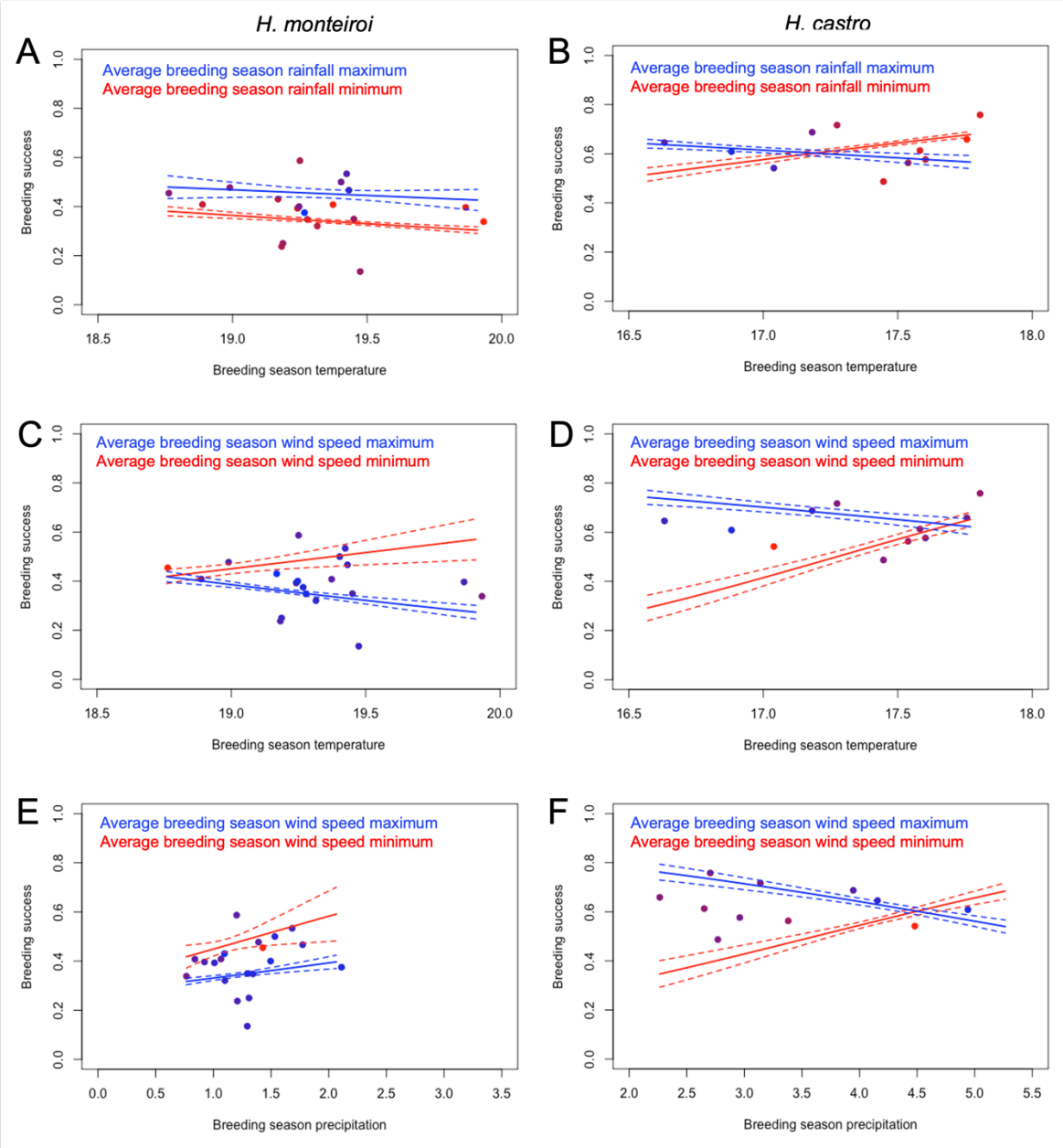


Figure 3.6. Interactive effects of weather variables on the breeding success of both species of storm-petrel breeding on Ilhéu da Praia, Azores, Portugal, combining overall breeding success data from 2000-2020 inclusive, with extracted breeding season weather data (air temperature °C, rainfall (mm s^{-1}) and wind speed (m s^{-1}). Associations between breeding success and average breeding season air temperatures under average breeding season rainfall maximum and minimum (controlling for wind speed) for A) Monteiro's storm-petrel and B) band-rumped storm-petrel. Colour of data points is proportional to rainfall. Association between breeding success and average breeding season air temperatures under average breeding season wind speed maximum and minimum (controlling for rainfall), for C) Monteiro's storm-petrel and D) band-rumped storm-petrel. Colour of data points is proportional to wind speed. Association between breeding success and rainfall under average breeding season wind speed maximum and minimum (controlling for air temperature) for E) Monteiro's storm-petrel and F) band-rumped storm-petrel. Colour of data points is proportional to wind speed. Weather data was extracted at the local level (i.e. Lajes, Terceira Airport, Terceira; 38°45'43.2"N, 27°05'27.6"W) for air temperature and rainfall and at the regional level (i.e. all available Azores islands) for wind speed. NB: x-axes are the same gradations of air temperature or rainfall but different range due to the seasonal differences between the two storm-petrel species.

3.3.4. Causes of egg and chick losses

The proportion of eggs that failed to hatch did not vary significantly across individual years of the intensely studied years, or between the two decades, for either species (Table 3.10, models 1&2). Likewise, the proportion of chicks that failed to fledge was similar for the band-rumped storm-petrel across individual years and between the two decades (Table 3.10, models 4&5). However, for the comparison between individual years of chick loss in Monteiro's storm-petrel, there was significant variation between years in the proportion of chicks that died; specifically, the proportion of chicks that died was significantly higher in 2020 than in the other three years of intensive study (Table 3.10, model 4).

The causes of egg loss have changed significantly across the two decades for both species – more significantly for the Monteiro's storm-petrel egg losses compared with the band-rumped storm-petrel egg losses (Table 3.10, model 3; Figure 3.7A). For egg losses in both species and for the Monteiro's storm-petrel chick failures, the top two most prominent categories of failure in the later decade were unknown causes of egg failure and other species (Figure 3.7A&B).

Further analysis assessing the specific causes of breeding failure due to other species identified that for the Monteiro's storm-petrel, the causes of egg and chick loss by other species significantly changed between the two decades (Table 3.10, model 7&8; Figure 3.8A&B). In addition, although not statistically analysed (due to there not being any noted egg or chick losses due to other species in the early years) the number of other species causing egg and chick failures has increased for the band-rumped storm-petrel too. For the egg losses in the most recent period, for both storm-petrel species, Madeiran wall lizards (*Podarcis dugesii*) were the predominant cause of egg losses (indicated by a round hole in the egg) with the addition of Barolo shearwater (indicated as an egg clearly squashed or a Barolo shearwater found in the nest together with a broken egg; Table 3.10, model 7; Figure 3.8B). For the chick losses in the later period, for the Monteiro's storm-petrel, the predominant causes of chick loss were ants (where ants were found on the chicks, or eyes/feet clearly eaten) and non-parent storm-petrels (i.e. storm-petrels other than the chick's own parents; found during night-time nest monitoring for other data collection, or during the day, often with chick down on their bill). In contrast, for the band-rumped storm-petrel there were only a small number of known

chick losses due to other species all in the later period, and these losses were predominantly caused by yellow-legged gulls (*Larus michahellis atlantis*; 2018-2019; Figure 3.8B).

Table 3.10. Chi-squared results table for analysis of: 1&4) across all years, per species and per egg/chick stage in relation to the overall success or failure of eggs hatching and chicks fledging; 2&5) early (2000-2001) and late years (2018-2020) pooled per species and per egg/chick stage in relation to the overall success or failure of eggs hatching and chicks fledging; 3&6) early and late years pooled per species and per egg/chick stage in relation to broad category of causes of egg/chick loss as (unknown, weather, other species, unviable/remaining, humans); and 7&8) early and late years pooled per species and per egg/chick stage in relation to known other species cause of egg/chick loss.

	Chi-squared	d.f.	P	Variables
1) Eggs – failed vs. succeeded by year				
Monteiro's	7.0611	3	0.0670	Per year, failed vs. succeeded
Band-rumped	2.193	2	0.334	Per year, failed vs. succeeded
2) Eggs – failed vs. succeeded by decade				
Monteiro's	0.173	1	0.677	Per decade, failed vs. succeeded
Band-rumped	0.0976	1	0.755	Per decade, failed vs. succeeded
3) Eggs – broad categories of failure, by decade				
Monteiro's	26.150	3	**<0.001*** **	Weather variable not encountered and so removed for this analysis (Analysis included: unknown combined, other species, non-viable, human)
Band-rumped	13.588	3	**0.004** **	Human variable not encountered and so removed for this analysis (Analysis included: unknown combined, weather, other species, non-viable)
4) Chicks – failed vs. succeeded by year				
Monteiro's	11.608	3	**0.008** **	Per year, failed vs. succeeded
Band-rumped	1.691	2	0.429	Per year, failed vs. succeeded
5) Chicks – failed vs. succeeded by decade				
Monteiro's	1.213	1	0.271	Per decade, failed vs. succeeded
Band-rumped	0.290	1	0.590	Per decade, failed vs. succeeded
6) Chicks – broad categories of failure, by decade				
Monteiro's	10.275	4	**0.036***	Starvation not encountered and so removed for this analysis (Analysis included: unknown, weather, other species, remaining, humans)
Band-rumped	6.082	4	0.193	Human not encountered and so removed for this analysis (Analysis included: unknown, weather, other species, starvation, remaining)

7) Eggs – other species causes of failure, by decade				
Monteiro's	21.000	2	**<0.001*** **	Barolo shearwater and mixed species not encountered and so removed for this analysis (Analysis included: non-parent storm-petrels, lizards and ants)
Band-rumped	NA	NA	NA	Non-parent storm-petrels and ants not encountered and so removed for this analysis: (Analysis included: Barolo shearwater, lizards and mixed species) *Unable to run as no eggs were recorded as lost due to other species in the early decade.
8) Chicks – other species causes of failure, by decade				
Monteiro's	23.000	3	**<0.001*** **	Gulls not encountered and so removed for this analysis (Analysis included: ectoparasites, ants, non-parent storm-petrels, mixed)
Band-rumped	NA	NA	NA	Ectoparasites, ants and non-parent storm petrels not encountered and so removed for this analysis (Analysis included: gulls and mixed) *Unable to run as no eggs were recorded as lost due to other species in the early decade*

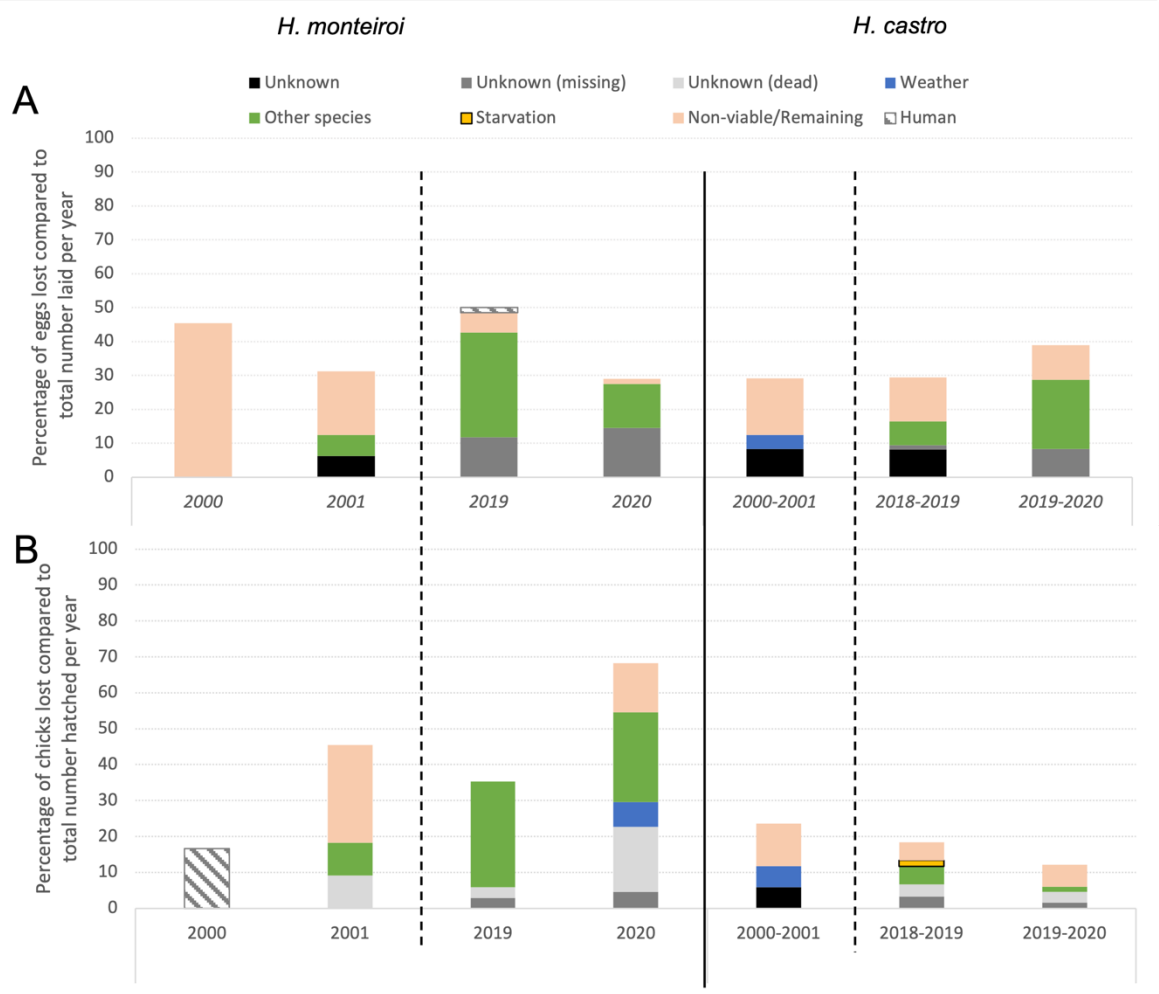


Figure 3.7. Broad categories of causes of A) eggs and B) chicks lost, measured as a percentage of the total number of eggs laid or chicks hatched in each respective year for both species of storm-petrel. NB unknown categories defined as: unknown = notes did not specify the cause of loss, unknown (missing) = notes specified missing but not the cause, unknown (dead) = notes specified chick was dead but not the cause.

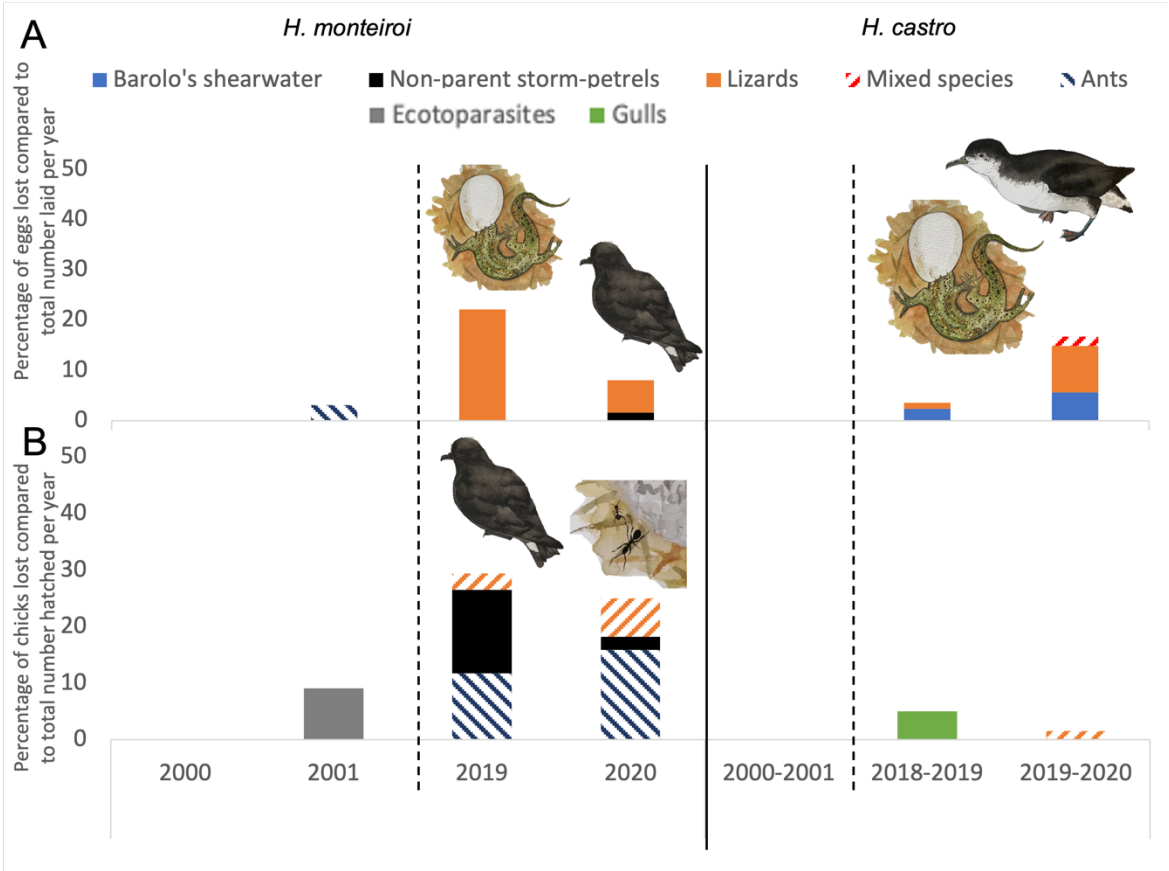


Figure 3.8. Egg and chick loss caused by other species. Proportional loss of A) eggs and B) chicks was calculated relative to the total number of eggs laid or chicks hatched in each respective year for both species of storm-petrel.

3.3.5. Future projections

Preliminary VORTEX population projection models were carried out for each species, using the demographic parameters measured during (i) the early period of intensive study (Monteiro's = 2000, band-rumped = 2000-2001) and (ii) the latter period (Monteiro's = 2020, band-rumped = 2019-2020). Both band-rumped storm-petrel population projections and the early period Monteiro's storm-petrel population projections suggest that they would increase to carrying capacity. However, the later period Monteiro's storm-petrel population projections indicated a decline in population size over the next 100 years, with predicted extinction from Ilhéu da Praia in 82 years (Figure 3.9; Table 3.11).

Sensitivity analyses of these models examined whether these outcomes depended on the specific values of the various demographic parameters (Figure 3.10; Table 3.12). Hypothetical scenarios for breeding success rates, identified that a decline to a breeding success of 20% for an initial population of 200 individuals (as modelled for the baseline Monteiro's storm-petrel analysis) would lead to a projected species extinction on Ilhéu da Praia within

69 years, whereas increasing the breeding success rate to 50% would potentially lead to an increasing population on Ilhéu da Praia, reaching carrying capacity. When the initial population size was 400 individuals (as modelled for the baseline band-rumped storm-petrel analysis), a breeding success of 20% would likely lead to species extinction on Ilhéu da Praia within 81 years, but an increase to 50% would potentially lead to an increasing population on Ilhéu da Praia, reaching carrying capacity. For both initial population sizes, with a 35% breeding success rate, a stable population trend was reached (Figure 3.10A; Table 3.12).

For the Monteiro's storm-petrel, increasing the carrying capacity did not change the trend line for both the early period breeding success projections (where the population was predicted to increase to reach carrying capacity) and the latter period projections (where the population was predicted to decrease to extinction; Figure 3.10B; Table 3.12). These can be compared between Figure 3.9 (Monteiro's storm-petrel 2020 line) and Figure 3.10B (Monteiro's storm-petrel 2020 with an initial population size of 200 individuals). Furthermore, for the latter period breeding success projections for the Monteiro's storm-petrel, the overall declining trend was the same, although the time taken to reach extinction varied from 69.2 years (at 100 initial population size) to 98 years (at 1500 initial population size; Figures 3.10B; Table 3.12). This is in contrast to the band-rumped storm-petrel predictions, where under each scenario the population was projected to increase to reach carrying capacity (Figure 3.10C; Table 3.12), reflecting the same trends as predicted by the baseline models (Figure 3.9).

When the maximum age of reproduction was increased to 30 years, this slowed the declining trend for the Monteiro's storm-petrel (not reaching extinction within 100 years) and led to a stable population for the band-rumped storm-petrel (Figures 3.10D; Table 3.12). Finally, despite differences in the age of first breeding (as per unpublished data, JB) both species showed similar trends (where the Monteiro's storm-petrel declined and the band-rumped storm-petrel increased to carrying capacity; Figures 3.10E; Table 3.12) and was very similar to the baseline results using parameter values from published data (Figure 3.9).

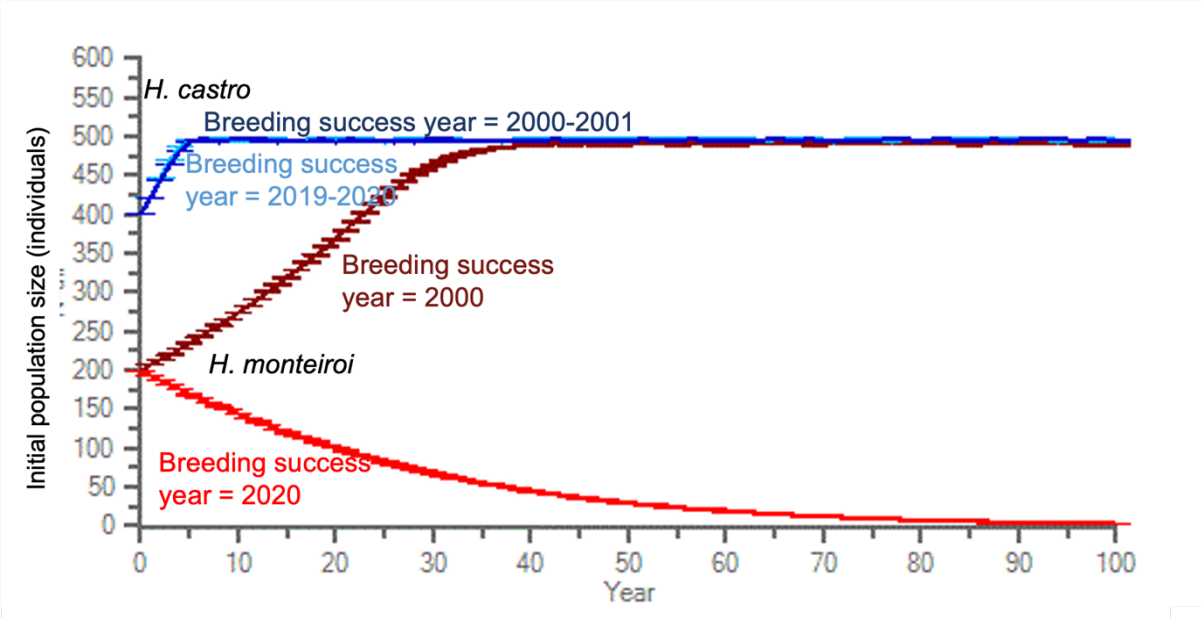


Figure 3.9. Baseline VORTEX model projections starting with initial population sizes of 200 (Monteiro's storm-petrel, red) and 400 (band-rumped storm-petrel, blue). Projections for both species are shown, based on past (2000/2000-2001) and currently observed (2020/2019-2020) breeding success rates (defined as number of chicks fledged divided by the number of eggs laid).

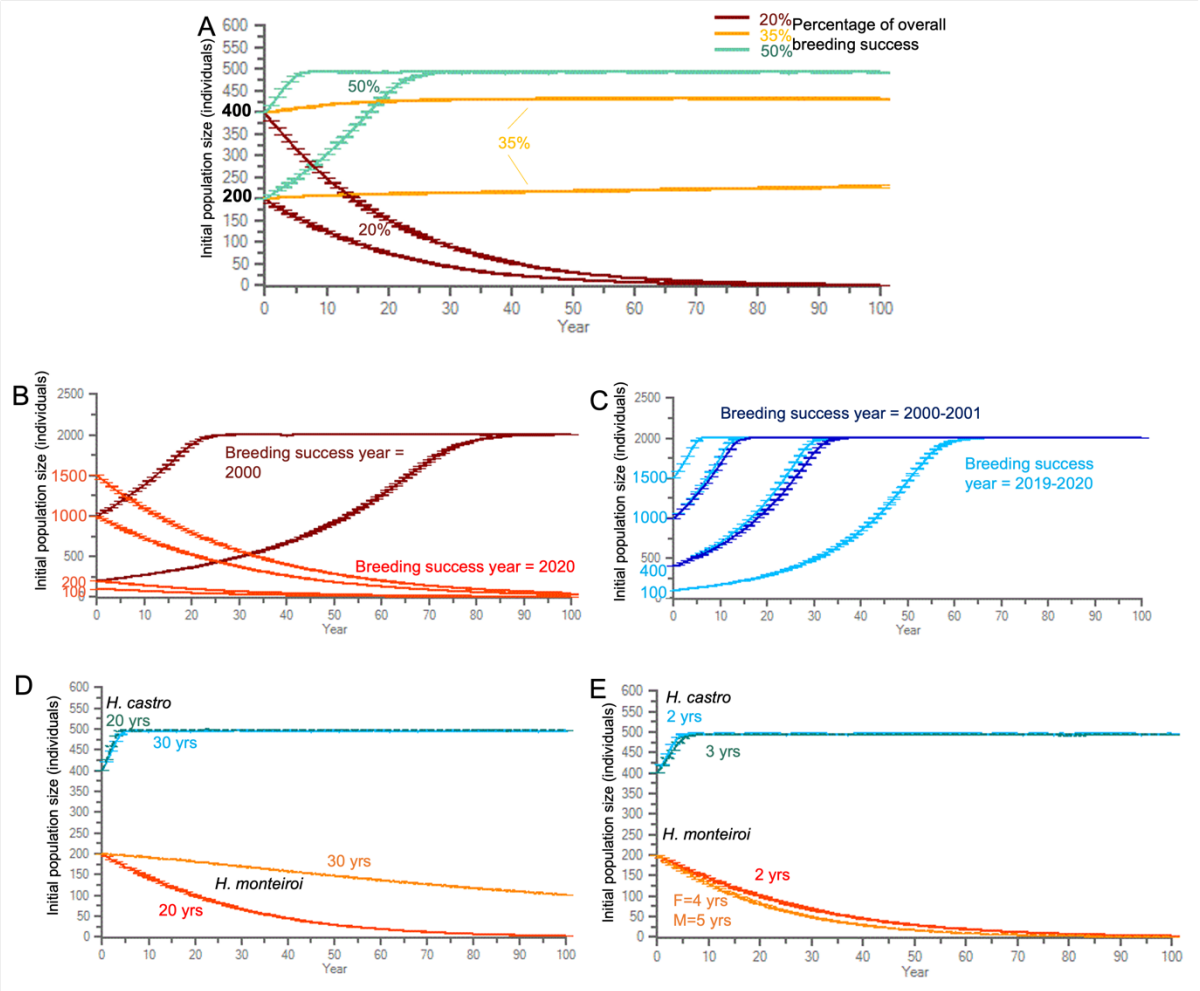


Figure 3.10. Sensitivity analysis VORTEX projections of population change. A) modelling hypothetical breeding success rates of 20% (dark red line), 35% (amber line) and 50% (green line) for both species, using the baseline initial population sizes of 200 (modelled for Monteiro's storm-petrel) and 400 (modelled for band-rumped storm-petrel). These projections are based on past (2000/2000-2001) and currently observed (2020/2019-2020) breeding success rates to model the population change of B) Monteiro's storm-petrel, and a range of hypothetical initial population sizes (across one and half orders of magnitude; 100-1500 individuals) and C) band-rumped storm-petrel, based on a range of hypothetical initial population sizes (across one and half orders of magnitude; 100-1500 individuals). Using the 2020 and 2019-2020 breeding success rates to model population change of D) both species, based on life span and breeding age being 20 or 30 years respectively, and D) both species, based on published (2 years old) and updated but unpublished (3-5 years respectively) data on age at first breeding.

Table 3.11. Baseline VORTEX model predictions for the different overall breeding success, specifying projected population growth rate, probability of extinction over 100 years and mean duration (in years) to extinction for each modelled scenario.

Scenario	Breeding success %	Mean stochastic growth rate	SD of growth rate	Probability of Extinction	Mean duration (years) to extinction ±SE
Monteiro's storm-petrel 2000	45.5	0.030	0.023	**<0.001**	**NA**
Monteiro's storm-petrel 2020	23.7	-0.046	0.090	0.746	82.3 ± 0.4
Band-rumped storm-petrel 2000-2001	54.1	0.049	0.023	**<0.001**	**NA**
Band-rumped storm-petrel 2002-2003	64.6	0.070	0.025	**<0.001**	**NA**
Band-rumped storm-petrel 2019-2020	56.3	0.054	0.024	**<0.001**	**NA**

Table 3.12. Sensitivity analysis results from VORTEX model predictions for hypothetical breeding successes, initial population sizes, maximum age of breeding/lifespan and age of first breeding. Detailing the overall breeding success percentage used and respective results for: mean stochastic growth rate and SD of growth rate, Probability of extinction over 100 years and mean duration (in years) to extinction for each modelled scenario.

Scenario	Breeding success %	Mean stochastic growth rate	SD of growth rate	Probability of Extinction	Mean duration (years) to extinction
Sensitivity analysis for hypothetical breeding success					
Population = 200	20%	-0.060	0.096	0.974	69.0 ± 0.4
Population = 200	35%	0.001	0.029	**<0.001**	**NA**
Population = 200	50%	0.040	0.024	**<0.001**	**NA**
Population = 400	20%	-0.058	0.089	0.893	80.9 ± 0.3
Population = 400	35%	0.003	0.022	**<0.001**	**NA**
Population = 400	50%	0.040	0.023	**<0.001**	**NA**
Sensitivity analysis for initial population					
Monteiro's storm-petrel 2000					
Population = 200 (k=2000)	45.5%	0.031	0.021	**<0.001**	**NA**
Population = 1000 (k=2000)	45.5%	0.032	0.016	**<0.001**	**NA**
Monteiro's storm-petrel 2020					
Population = 100 (k=2000)	23.7%	-0.048	0.102	0.926	69.2 ± 0.5
Population = 200 (k=2000)	23.7%	-0.046	0.089	0.747	82.4 ± 0.4
Population = 1000 (k=2000)	23.7%	-0.038	0.041	0.010	98 ± 0.5
Population = 1500 (k=2000)	23.7%	-0.036	0.032	**<0.001**	**NA**
Band-rumped storm-petrel 2000-2001					
Population = 400 (k=2000)	54.1%	0.0514	0.0185	**<0.001**	**NA**
Population = 1000 (k=2000)	54.1%	0.0516	0.0176	**<0.001**	**NA**
Band-rumped storm-petrel 2002-2003					
Population = 400 (k=2000)	64.6%	0.073	0.020	**<0.001**	**NA**

Population = 1000 (k=2000)	64.6%	0.073	0.019	**<0.001**	**NA**
Band-rumped storm-petrel 2019-2020					
Population = 100 (k=2000)	56.3%	0.055	0.024	**<0.001**	**NA**
Population = 400 (k=2000)	56.3%	0.056	0.019	**<0.001**	**NA**
Population = 1000 (k=2000)	56.3%	0.056	0.018	**<0.001**	**NA**
Population = 1500 (k=2000)	56.3%	0.056	0.018	**<0.001**	**NA**
Sensitivity analysis for maximum breeding age/lifespan					
Monteiro's storm-petrel 2020. Age 30	23.7%	-0.008	0.031	**<0.001**	**NA**
Band-rumped storm-petrel 2019-2020. Age 30	56.3%	0.067	0.023	**<0.001**	**NA**
Sensitivity analysis for age at first breeding					
Monteiro's storm-petrel 2020	23.7%	-0.055	0.096	0.957	73.8 ± 0.4
Band-rumped storm-petrel 2019-2020	56.3%	0.043	0.023	**<0.001**	**NA**

3.4. Discussion

3.4.1. Nest histories

For both species there was a concerning decline in breeding success in the artificial nestboxes over the last two decades. Whilst other studies show that many seabird species undergo large annual variations in breeding success (Chastel et al. 1993; Dunn et al. 2016), the trends in hatching, fledging and overall breeding success seen in this study are of consistent declines over the twenty-year period studied. These declines are especially concerning for the Monteiro's storm-petrel, as it is endemic to the Azores where it has only five known breeding locations, each with only a small breeding population, of which the largest known colony is on Ilhéu da Praia (Monteiro et al. 1999; Bolton et al. 2008; BirdLife International 2018b).

For the two periods of intensive study, a breakdown of the components of breeding success (namely hatching success and fledging success) identified that hatching success did not change between the two periods of intensive study for either species, indicating that hatching success is unlikely to have an impact on the observed decline in overall breeding success. In addition, the band-rumped storm-petrel chick fledging success remained fairly consistent across the 20-year study period, whereas the fledging success rate substantially declined for the Monteiro's storm-petrel. This low fledging success rate (compared to the hatching success rate) has been similarly found among other seabird species (e.g. snow petrels, *Pagodroma nivea* - Chastel et al. 1993; Tristan albatross, *Diomedea dabbenena* - Cuthbert et al. 2014; southern giant petrels, *Macronectes giganteus* - Dunn et al. 2016), although this is in contrast to Bermudian white-tailed tropicbirds (*Phaethon lepturus catesbyi*) breeding in artificial nests, where hatching success was low but fledging success is higher (Mejías et al. 2017).

To investigate potential causes of this decline, further questions were addressed regarding the hatching dates, fledging dates and chick-rear period, and these identified some mechanistic changes of note. Specifically, across the two decades, the Monteiro's storm-petrel retained a fairly consistent chick-rear period duration, in comparison to the band-rumped storm-petrel which has reduced its chick-rear period duration. However, this is unlikely to be a phenological shift in the timing of breeding, as the hatching dates were similar across both periods of intensive study (Keogan et al. 2018). Nevertheless,

across the 20-year period the chick-rear period duration remained longer for the band-rumped storm-petrel compared to the Monteiro's storm-petrel; a difference typical of other sympatric hot and cool season storm-petrel breeding colonies (e.g. Galápagos Islands - Harris 1969). The overall longer breeding period indicates likely weather induced causes, e.g. a slower chick-rear period duration, that are discussed later (Harris 1969; Boersma 1986; Monteiro and Furness 1998). Comparing the hatching dates of the Monteiro's storm-petrel chicks in 2000 to other years suggests possible shifts to earlier hatching dates in later years. However, this 2000 data was not included in the analysis of fledging date and consequently the chick-rear period duration, and so the suggestive hatching date phenological shift is more likely an artifact of not knowing the fledging dates for the year 2000 chicks.

It appears, therefore, that phenological shifts are unlikely to be a contributing cause of the declines in breeding success noted in this study. This is not surprising, however, as Procellariiformes are not known to shift their breeding phenology as they have a strong reliance on photoperiod as a cue (Keogan et al. 2018). However, the other demographic changes noted could be influenced by a variety of variables (see reviews: Croxall et al. 2012; Dias et al. 2019; Rodríguez et al. 2019). In this study three variables, (i) chick quality, (ii) weather effects and (iii) causes of egg and chick loss, are discussed in more detail to determine if all or some could be contributing to the significant decline in breeding success, and particularly in the fledging success decline for the Monteiro's storm-petrel chicks.

3.4.2. Chick growth rates

Changes in chick body mass over time provide a measure of chick quality related to chick provisioning rates. Interestingly, chick growth rates seem to have remained consistent across the early and later periods of intensive study for the Monteiro's storm-petrel, and the overall outline is very similar for both species, except in one year (2001) where there was a marginally lower growth rate for the Monteiro's storm-petrel. This was a warmer and wetter year, indicative of lower breeding success (Boersma et al. 1980; Bolton et al. 2004; Ropert-Coudert et al. 2004; Kelsey et al. 2016; Fischer et al. 2018). This similarity of growth rates of the two species is reflected in previous studies of sympatric hot and cool season storm-petrel breeding systems (Galápagos Islands - Harris 1969). The initial period of intensive study for the band-rumped storm-petrel species was not included in this analysis due to missing

hatching dates, and so possible decadal changes cannot be fully analysed. However, the 2000-2001 chick-rearing period appeared to have been more extended compared to those in the 2018-2019 and 2019-2020 breeding seasons.

The overall three-part growth curve is typical of Procellariiformes (Figures 3.4A&B; e.g. Allan 1962; Harris 1969; Boersma et al. 1980). The comparison between the two species is typical of cool *versus* hot season species, where the cool season species (here the band-rumped storm-petrel) grew to a higher mass, had a longer initial growth stage and overall longer chick-rear period duration, compared to the hot season (here the Monteiro's storm-petrel), likely related to weather and oceanic conditions e.g. Harris (1969), who comments that the slower growth rate in the winter species could be attributed to depletion of food supplies as more individuals breed in the winter.

For the chicks that later fledged, the growth curves followed a three-part growth curve (e.g. Allan 1962; Harris 1969; Boersma et al. 1980). The overall variance in mass during the plateau phase was smaller in the warmer Monteiro's storm-petrel breeding season, compared to the cooler band-rumped storm-petrel season, indicating smaller but more frequent feeds in the Monteiro's storm-petrel, consistent with other studies of sympatric hot and cool breeding season populations (Galápagos Islands - Harris 1969).

For the chicks that died before fledging, the growth curves varied substantially. There was a large variety of reasons for the chick deaths (see other species causes of egg and chick loss section below), so it is hard to distinguish anything consistent from these growth curves. However, band-rumped storm-petrel chicks hatching at the very end of the season were more likely to fail, whereas in the Monteiro's storm-petrel breeding seasons this failure started to occur in chicks hatching from mid-season onwards (Figure 3.5; typical of other hot breeding season storm-petrels; Harris, 1969). This could partly be explained by chicks not attaining optimum peak weights before the end of the season (Boersma et al. 1980). However, in this study system it is more likely to be linked to the causes of losses due to other species for the Monteiro's storm-petrel (see below). Finally, although there was a large range of ages of chick death for both species, these occurred typically more often in

the early stage of chick development, similar to chicks that died in other studies (Boersma et al. 1980; Mínguez and Oro 2003; Mejías et al. 2017).

The lack of change between the early and late periods of intensive study in overall growth curves, and in variance in the plateau stages, implies that chick provisioning rates and consequent chick growth rates are unlikely to be a cause of the observed declines in overall breeding success for either species. However, the differences between hot and cool season species are likely to be related to weather (see discussions below; see also e.g. Harris 1969). In addition, as already mentioned, the reasons for chick losses (especially in the later years for the Monteiro's storm-petrel chicks) are likely due to other species (see discussions below).

3.4.3. Weather effects

Effects of weather during the respective breeding seasons were identified on the overall breeding success of both species of storm-petrel over the twenty-year study period. These effects on the overall breeding success appear to be less severe for the Monteiro's storm-petrel compared to the band-rumped storm-petrel. For the summer-breeding Monteiro's storm-petrel, higher air temperatures and lower rainfall led to lower breeding success, while for the winter-breeding band-rumped storm-petrel higher air temperatures and higher rainfall led to lower breeding success. This is important because the climate predictions for the Azores in the summer are predicted to decrease in rainfall and increase in air temperature and in the winter, both rainfall and air temperature are likely to increase (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018), thus for both species the projected changes in seasonal weather conditions are likely to further impair breeding success.

Higher winter air temperatures may aid the band-rumped storm-petrel chicks in avoiding hypothermia and strategic "torpor" (Boersma 1986; Monteiro and Furness 1998), but overall for both species, the chicks are more likely to overheat (become hyperthermic) unless the artificial nests are well-ventilated or insulated (as seen for other species artifical boxes: Kelsey et al. 2016; Fischer et al. 2018). For the Monteiro's storm-petrel, the combined effect of higher ambient air temperatures and low rainfall possibly exacerbates the high air temperature issue as there would be fewer cooler wet days (Kelsey et al. 2016; Fischer et al. 2018). Higher winter rainfall could also possibly increase flooding risk to nests and consequently chick survival, as seen previously in

this study system (Bolton et al. 2004), and in other species (Boersma et al. 1980).

The Azores climate change projections (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018) do not mention wind as a factor, but the present study indicates that low windspeeds seem to have positive impacts on breeding success when paired with higher air temperatures and higher rainfall. However, higher windspeeds have negative impacts on breeding success. This is likely to reflect the foraging ability of adults at sea, where the higher the windspeed, the more vulnerable they are to being storm-driven (Teixeira 1987; Bolton 2021). However, Bolton (1995) found that the food delivery to the chick by European storm-petrels (*Hydrobates pelagicus*) was not influenced by wind speed.

Finally, an increase in occurrence of extreme events (e.g. winter storms; Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018) could also influence the breeding success of the storm-petrels (Sydeman et al. 2012; Dias et al. 2019; Orgeret et al. 2022). Extreme events could impact both species at sea (as mentioned above), but also at the nest due to increased erosion of natural nesting habitat, or negatively impact the external structure of the artificial nest boxes, alongside other causes already mentioned (Kelsey et al. 2016; Fischer et al. 2018).

For the present study, the impact of sea surface temperature was not assessed due to its strong positive correlation with air temperature. Nevertheless, previous studies have shown the importance of sea surface temperature as a proxy for breeding success and food availability (Slater and Byrd 2009; Robert et al. 2012). In the present study, however, chick provisioning does not appear to influence the declines in overall breeding success. Nevertheless, sea surface temperature would still be a useful additional variable to analyse in future studies, alongside the other variables already analysed in this study (namely air temperature, rainfall and wind speed).

It is important to note that the possible climate impacts identified here are tentative results due to the relatively low number of years for which data are available. Nevertheless, given the size and direction of the apparent weather impacts, the continued collection of breeding success data and ongoing

analysis of the extended datasets will clearly be important for informing conservation actions for both species of storm-petrel in the Azores.

3.4.4. Causes of egg and chick losses

The number of eggs that did not hatch was similar across both species and across years, and is typical of previous storm-petrel studies (16-30% failed = Boersma et al. (1980), 40% failed = Harris (1969) 17-62% failed = Chastel et al. (1993)), although this is higher than the average egg failure rate for birds generally (Koenig 1982; Savage et al. 2021). However, the causes of egg loss changed across the study period, with substantially more being lost due to other species in the later years compared to the earlier years. Likewise, for the chicks that did not fledge, the average failure rate is similar to previous species (Harris 1969; Boersma et al. 1980; Chastel et al. 1993), except for the Monteiro's storm-petrels in later years (especially in 2020, which had a much higher failure rate compared to early years). Interestingly, the proportion of band-rumped storm-petrel chicks that did not fledge has not changed markedly. Alongside this, as with egg loss, the causes of both species' chick losses have changed, with substantially more being lost to other species compared to earlier years. Previous studies of other storm-petrel species and populations identified a range of causes of egg and chick loss, including weather (e.g. snow melt for the fork-tailed storm-petrel, *Hydrobates furcatus*, Boersma et al. 1980), egg abandonment, starvation, and other species (Harris 1969; Chastel et al. 1993).

3.4.4.1. Loss of eggs

When the other species category is looked at in more detail, the majority of Monteiro's storm-petrel egg losses in the later seasons were attributed to Madeiran wall lizards, while for the band-rumped storm-petrel it was a mix of Madeiran wall lizards and Barolo shearwaters. The ejection or damage of storm-petrel eggs by Barolo shearwaters is typical of such inter-species interactions in other systems (Harris 1969; Boersma et al. 1980). However, the increase over the study period in losses of eggs to Madeiran wall lizards is interesting. Lizards or skinks in other systems are either seen as opportunistic scavengers on abandoned eggs and dead chicks (Madeiros 2005; Turner et al. 2021), or they de-predate eggs but at a low level unlikely to be the major cause of population regulation (Walls 1978; Markwell 1998; Carey 2010; Corkery et al. 2014,2015). Therefore, further work is needed to assess the

impacts of Madeiran wall lizards on Ilhéu da Praia, but so far the increase in egg losses identified due to the lizards in the later period is of concern (Matias et al. 2009; Bried and Neves 2015; Neves et al. 2017). There is little information available on the population change of this species over the last 20 years (or before). They were known to be present in the Azores from the 1900s (Malkmus 1995; CABI Data Mining 2011; Seebens et al. 2017). However, on Ilhéu da Praia, from the nest check data in 2000-2002 there are only occasional notes of lizards in the nests. However, a more recent paper indicates that their presence has been increasingly noticed from 2010 onwards (Neves et al. 2017). This is exemplified in the increased numbers of lizards noted in nests in the later period of intensive study (HFRH *pers. obs*.). In its native islands (Madeira) these lizards are found across all habitats, although favouring places to sun themselves – which includes rocks and trees (Malkmus 1995; Brehm et al. 2001). Over the last 20 years on Ilhéu da Praia the habitat has shifted from overgrazed and eroded soil to a variety of native and non-native shrubs and grasses (Bried et al. 2009; Long et al. 2021). Although, the causes of this lizards population boom are unknown, it is possible that the substantial change in vegetation cover over the study period has provided increased opportunities for the lizard to thrive, and this could mean there are now more individuals taking opportunistic meals from the available eggs, as is seen in other systems (Walls 1978; Markwell 1998; Carey 2010; Corkery et al. 2014,2015). Artificial nest boxes potentially provide extra habitat for the lizards, and they could be using these as shelter from extreme air temperatures, as with the Tuatara (*Sphenodon punctatus*) in New Zealand (Markwell 1998; Corkery et al. 2014; Fischer et al. 2019), though as lizards were also present in some of the natural nests monitored, the nest boxes are not necessarily excessively contributing to contact between lizards and breeding storm-petrels.

On Ilhéu da Praia, Barolo shearwaters have been increasingly using the storm-petrel artificial nests, especially where the entrance tunnel is no longer attached or eroded and so the nest entrance is large enough for them to enter (HFRH *pers. obs*.). However, the original design of the nests on Ilhéu da Praia included a tunnel (Bolton et al. 2004). Some degradation of the nestboxes has occurred over the last 20 years due to weather impacts (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018) and so during both winter seasons in 2018-2019 and 2019-2020 fieldwork, some nests were refurbished and in 2019-2020, new entrance tubes fitted (HFRH *pers. obs*.). Barolo

shearwaters have been recorded as breeding in the Azores since the 1950s (Monteiro et al. 1996a; Monteiro et al. 1999) and have a decreasing population trend (BirdLife International 2018c) and so despite their apparent impacts on breeding storm-petrels a balance will be needed in order to best manage and conserve this species alongside the two storm-petrel species.

3.4.4.2. Loss of chicks

For the Monteiro's storm-petrel chicks, ants and non-parent storm-petrels were the predominant cause of chick loss, and for the band-rumped storm-petrel chicks it was mainly gulls. All three taxa have previously been observed to be causes of chick loss in other systems (ants - Plentovich et al. 2009; DeFisher and Bonter 2013; Flores et al. 2017; Mejías et al. 2017; Halpin et al. 2021; non-parent storm-petrels - Allan 1962; Harris 1969; and gulls - Sanz-Aguilar et al. 2009).

Previous research on ants in other seabird systems identified mixed impacts of ants on chick survival (Plentovich et al. 2009; DeFisher and Bonter 2013; Flores et al. 2017; Mejías et al. 2017; Halpin et al. 2021). In some cases, even within the same system, chicks of one species were killed and chicks of another were not (Plentovich et al. 2009; Halpin et al. 2021). As with the Madeiran wall lizard, there are few previous data on ant abundance on Ilhéu da Praia (but see Neves et al. [in prep].). However, there are various possible contributing factors to the apparent impacts of ants in the present study. 1) Although ants are typically opportunistic foragers (Hölldobler and Wilson 1990), one of the ants found, the thief ant *Solenopsis* sp. is part of the fire ant family, and the specific genus is also known as the "thief ant" because they are known to pilfer food or broods from other ant nests – this could potentially be extended to detritovorous or even carnivorous behaviours towards other species, possibly including storm-petrel chicks (Wetterer et al. 2004; Pacheco and Mackay 2013). 2) Habitat change – the other two ant species found on the islet (*Monomorium carbonarium* and *Lasius grandis*) are found across all habitats. By contrast, *Solenopsis* sp. are typically found in disturbed soils so the change in habitat on Ilhéu da Praia (Bried et al. 2009; Long et al. 2021), could have provided extended habitat for this species to thrive (Wetterer et al. 2004; Pacheco and Mackay 2013; Seifert 2020). 3) Ants may use the artificial nest boxes due to their internal microclimate and the heat given off from the storm-petrel nests (Maziarz et al. 2020). Alternatively, the ants could be

scavenging nest parasites as seen in songbird nests (Maziarz et al. 2020) and other nest box users (Salido et al. 2021) or, as in other bird species, there could be a mutual beneficial interaction involving "anting" behaviour, where birds purposefully allow ants onto their feathers to aid in removing ectoparasites (Clayton and Vernon 1993). 4) Ants are known to increase the amount of protein in their diet as spring/summer progresses (Hölldobler and Wilson 1990), and storm-petrel chicks represent a potential source of such protein.

The decrease in Monteiro's storm-petrel breeding success later in the season appears, at least in part, to be influenced by interference from returning winter-breeding band-rumped storm-petrels. Furthermore, the overlap of the end of the Monteiro's breeding season and the beginning of the band-rumped storm-petrel breeding season seems to have become more prevalent in later years (Figure 3.3). Although the successful sharing of nests of hot and cool season species has previously been recorded on Ilhéu da Praia (Bolton et al. 2008), negative interactions have been detailed in other sympatric hot and cool season storm-petrel colonies where some chicks were described as "mohawks", with little head plumage left or even with head scars and often had damp heads, all caused by pecking from adults of the other species (Allan 1962; Harris 1969). In the present study system, not all non-parent storm-petrels physically attacked the Monteiro's chick (*pers. obs*. from camera footage; see Chapter 5). However, nest monitoring provided evidence of some chick heads and/or eyes being pecked, as described by Allan (1962).

The causes of this overlap between the breeding seasons of the two species are uncertain. Whilst in some seabirds a shift in the start of the breeding season has been seen, it is not common in Procellariiformes (Keogan et al. 2018). This is exemplified in the present study for the band-rumped storm-petrels which had similar hatch dates between the two periods of intensive study. Across the last 20 years of data collection band-rumped storm-petrels have been found in the nest boxes during the day from late July/early August onwards (unpublished data). It is possible that this overlap is inadvertent, due to the asynchronous nature of the breeding timings of the two species (Warham 1990). An additional possibility is that competition for nests has increased – possibly due to an increased number of breeders, with overlap in preferences for the same nest and/or more nest boxes needing refurbishing (Ramos et al. 1997; Bolton et al. 2004).

Although fewer chicks were lost in the band-rumped storm-petrel breeding season, the few that were lost were predominately taken by gulls. Reinstating entrance tunnels and entrance coverings would help to reduce the accessibility for larger seabirds including yellow-legged gulls and Cory's shearwaters (Sanz-Aguilar et al. 2009; Libois et al. 2012).

3.4.5. Future projections

The population viability models based on the current breeding success for both species of storm-petrel in this study produced concerning results in terms of the speed of projected extinctions on Ilhéu da Praia (and hypothetically across the Azores) for the Monteiro's storm-petrel being within 82 years under current breeding success rates. This is in contrast to projections using the early period breeding success rates for the Monteiro's storm-petrel and both periods for the band-rumped storm-petrel, where the populations were projected to increase to carrying capacity.

Following the approach of Whelan et al. (2018), the additional projection models run (with breeding success of 20%, 35% and 50%) suggested that a 35% breeding success could be needed for both species to retain a long-term stable population, and an increase to 50% breeding success could be needed for both species to reach carrying capacity, on Ilhéu da Praia. These rates are within the scope of breeding success seen in other seabird species (Simons 1981; Chastel et al. 1993), and have previously been recorded for the Azores species (see 2000/2000-2001 rates). For the Monteiro's storm-petrel to reach a 35% or 50% breeding success, the breeding success would need to increase by an additional ~ 11% (for a stable population size) or ~ 26% (for an increasing population size) per season (based on the 2020, 23.7% breeding success). This could be achieved by reducing the number of eggs and chicks lost due to other species. For eggs, this would equate to a ~ 15% increase in breeding success and for chicks this would equate to a ~ 16% increase. Combined, these are greater than both the required increases suggested above (~ 11% or ~ 26%), and would equate to increasing the number of birds successfully fledging by ~ 7-16 individuals per breeding season. Although the band-rumped storm-petrel population trend is already projected to be increasing regardless of egg and/or chick specific losses, their breeding success could be increased further by reducing egg and chick losses (currently

due to other species). These results, and possible conservation interventions, are further discussed in the General Discussion.

As identified in the sensitivity analysis conducted on various parameters, the pessimistic (small) initial population estimates used in the main analysis (of 200 individuals for Monteiro's storm-petrel and 400 for band-rumped storm-petrel) produced similar results to the other models run with varied initial population sizes, showing that the conservative estimates are a robust estimate for these preliminary models, given the current uncertainties surrounding the true population size of both species. There was also little difference in the projections when the age of first breeding was increased. However, from these additional analyses, I suggest that research into the current total population size of both species in the Azores and their maximum age of reproduction will be imperative for furthering the conservation of both species, but especially the Monteiro's storm-petrel, and to aid in potential reassessment of the Monteiro's storm-petrel IUCN classification status (IUCN 2012; BirdLife International 2018a,b). Data compiled from this study, and the results of suggested further research, could be further modelled using VORTEX or alternative systems. For example, the populations could alternatively be modelled using STELLA (Costanza and Voinov 2001) or by updating the parameters for the Seabird mPVA database for both species (nhydra.shinyapps.io/mPVA1/; Ruiz et al. 2021), or as an integrated population model implemented through Bayesian statistics (e.g. Oppel et al. 2022).

3.4.5. Conclusion

Here, I have shown that there is a concerning decline in breeding success in the two sibling-species of storm-petrels breeding in the Azores, across the 20-year study period. This decline is especially marked for the Monteiro's storm-petrel and is primarily due to an increase in chick mortality. Of the possible factors discussed, there appears to be little change in the growth rate or variance in mass of the Monteiro's storm-petrel between the earlier and later years. This implies that changes in chick provisioning rates are unlikely to be a cause of the overall decline in breeding success. However, the fledging success of the Monteiro's storm-petrel chicks across the two periods of intensive study showed stronger declines in survival in the latter part of the breeding seasons compared to the band-rumped storm-petrel. Weather appears to have some impact on the overall breeding success (although care in interpretations is needed given the limited number of years with sufficient data available for analysis). The broader conclusions that can be made from the analysis of weather effects are that with the projected trends of warmer and drier summers, and warmer and wetter winters, the breeding success of both species is likely to continue to decline. These weather impacts will therefore need to be taken into account when considering future conservation action. Finally, the numbers of eggs lost for both species, and the numbers of chicks lost for the Monteiro's storm-petrel, that were caused by other species increased substantially in the later years of the study. When looked at in more detail the Madeiran wall lizards and Barolo shearwaters cause egg losses, and ants, non-parent storm-petrels and gulls cause chick losses. These combined causes of breeding success decline produce concerning population trend projections in the form of declines based on current breeding success rates for the Monteiro's storm-petrel.

The coming data chapters will detail the use of novel technology to aid in describing in-nest and at-sea behaviours to help broaden the understanding of this potentially bleak outlook, especially for the Monteiro's storm-petrel, and aid in identifying conservation actions.

Chapter 4.

Raspberry Pi Nest Cameras: An Affordable Tool for Remote Behavioural and Conservation Monitoring of Bird Nests

This chapter has already been published under the same name in Ecology and Evolution.

Photographs: top left (Jodie Henderson and Hannah Hereward setting up Raspberry Pi based cameras; Ben Porter), top right (bespoke nest camera deployed on artificial nest; Hannah Hereward), bottom left (blooper still from camera deployments; Hannah Hereward), bottom right (a video still of an adult and chick in the nest; Hannah Hereward)

Summary

Bespoke Raspberry Pi cameras are increasingly popular research tools in the fields of behavioural ecology and conservation, due to their comparative flexibility in programmable settings, ability to be paired with other sensors, and because they are typically cheaper than commercially built models.

Here we describe a bespoke Raspberry Pi-based, portable, weather-resistant camera, paired with a Passive Infrared (PIR) sensor, to create a movement-triggered camera capable of recording videos over a 24-hour period. We describe an example deployment involving "retro-fitting" these cameras into artificial nest-boxes on Praia Islet, Azores Archipelago, Portugal, to monitor the behaviours and interspecific interactions of two sympatric species of breeding storm-petrel (Monteiro's storm-petrel *Hydrobates monteiroi* and Madeiran storm-petrel *Hydrobates castro*) during their chick-rearing periods. We provide suggestions for initial video analysis of diel behavioural patterns (analysing one 30s video per hour, spaced one hour apart, termed "hourly analysis") when faced with overwhelming numbers of videos/images from frequently-triggered motion-detection cameras.

Of the 138 deployments, 91% of Monteiro's and 76% of Madeiran storm-petrel deployments were considered usable. The bespoke cameras proved to be easily transportable and reasonably weatherproof, and we make further suggestions to mitigate some weather-related technical failures.

The camera-build methods and scripts detailed here could be easily applied to many different species that also utilise cavities, burrows and artificial nests, and can potentially be adapted for other wildlife monitoring situations. Hourly analysis across 24-hour periods can provide novel insights into species-specific diel behaviours and interspecies interactions.

4.1. Introduction

The use of photography and video systems to remotely monitor wildlife has become increasingly popular (see reviews: Cutler and Swann, 1999; Swann et al. 2004; Trolliet et al. 2014; Edney and Wood, 2020; Hereward et al, [in prep. to resubmit] see Appendix 2). This is because remote-monitoring cameras can greatly reduce the time and effort required to collect observational field data and are typically less invasive than direct observation by researchers in the field (Cutler and Swann 1999; Trolliet et al. 2014). However, designing, implementing, and maintaining camera systems can require technical expertise, the presence of the camera can potentially affect an animal's behaviour, and the type of data collected can be limited (Cutler and Swann 1999; Reif and Tornberg 2006; Trolliet et al. 2014; Caravaggi et al. 2020). Nevertheless, infrared-sensitive, movement-triggered video cameras now enable greater flexibility than earlier designs in remote surveillance of wildlife (Scheibe et al. 2008), and video monitoring has been increasingly used to aid population monitoring and to examine behavioural and ecological interactions (Meek et al. 2014; Trolliet et al. 2014).

There are a wide range of camera systems available (see reviews: Cutler and Swann, 1999; Swann et al. 2004; Trolliet et al. 2014; Edney and Wood, 2020; Hereward et al, [in prep. to resubmit] see Appendix 2), but these can be split broadly into (i) commercially (vendor) built systems (e.g. Meek and Pittet, 2014; Trolliet et al. 2014) or (ii) bespoke (user-built) microcomputer systems (Greenville and Emery 2016; Johnston and Cox 2017; Allan et al. 2018).

Commercially built systems are typically easier to use, with little setup time or knowledge of the system required (Cox et al. 2012; Meek and Pittet, 2012; Hereward et al. [in prep. to resubmit] see Appendix 2). However, their deployment settings are typically less flexible, specifically in the length of time cameras can be left during deployments due to limited battery life and image/footage storage capabilities, and due to the limited programable settings available (Reif & Tornberg, 2006; Cox et al. 2012; Prinz et al. 2016). By contrast, simple programmable computers, or circuit boards, such as Raspberry Pi (www.raspberrypi.org) or Arduino (www.arduino.cc), have been increasingly used by researchers (Hereward et al. [in prep. to resubmit] see Appendix 2). These technologies have allowed greater scope for development of purpose-built cameras and for addressing specific research questions

(Greenville and Emery 2016; Johnston and Cox 2017; Allan et al. 2018; Jolles 2021). The increasing popularity of these bespoke units is not only driven by their comparative flexibility in programable settings, but also by the reduced costs and by the cameras being combined with other sensors; for example, temperature loggers (McBride & Courter, 2019). Do-it-yourself, self-assembly cameras can be produced more cheaply than commercially available models; for example, Cox et al. (2012) calculated that their bespoke system ("System One") cost ~33% less than a comparable pre-built unit. However, it is important to note that these bespoke cameras require additional expertise and time to design, set-up and trouble shoot (Cox et al. 2012; Hereward et al. [in prep. resubmit]).

Raspberry Pi has been used as the foundation to develop bespoke units to study a variety of taxa (see recent reviews: Jolles, 2021; Hereward et al. [in prep. to resubmit] see Appendix 2), including: video monitoring of free living fish (Mouy et al. 2020); laboratory studies of fish behaviours (Jolles et al, 2018); in-situ lemming (*Lemmus* spp. and *Dicrostonyx* spp.) subnival behaviours (Kalhor et al. 2019); behaviour, surface body temperature and respiration rate of hibernating meadow jumping mice (*Zapus hudsonius*) (Kallmyer et al. 2019); behaviours of captive song birds (Alarcón-Nieto et al. 2018); behaviours of birds at baited traps (Nazir et al. 2017a); behavioural dynamics and inter-individual / inter-specific interactions at bird feeders (McBride and Courter 2019; Youngblood 2020) and breeding behaviours of cavity nesting birds (Prinz et al. 2016).

Some of these papers specifically describe the building methods of the camera setup, where the costs ranged from ~$85 USD (Youngblood 2020) to ~1000€ (Zárybnická et al. 2016). A range of different power sources was used; (i) Mains power or large batteries (60Ah 12 V battery), occasionally attached to solar panels, providing power lasting 6.5–7 days (Prinz et al. 2016; Zárybnická et al. 2016; Nazir et al. 2017a). Or (ii) Smaller powerpacks of 10,000–20,000mAh often attached to solar panels lasting four to seven days (McBride and Courter 2019; Youngblood 2020). Or (iii) D-cell batteries in series, creating 70,000mAh, which lasted at least 14 days (Mouy et al. 2020). For storing the recorded image/video files, various designs coded the Raspberry Pi to upload the files from the SD card to "the cloud", thus avoiding the need to remove the SD card periodically and reducing the likelihood of the SD card becoming full (Prinz et al. 2016; Zárybnická et al. 2016; Alarcón-Nieto et al.

2018; McBride & Courter, 2019; Youngblood, 2020). However, Mouy et al. (2020) were not able to connect their system to a network during deployment, and so found that their SD card capacity (200GB) became the limiting factor for storage over the 8–14 days that their devices were deployed, recording a maximum of 212 hours. During trials, Mouy et al. (2020) found that using USB storage rather than SD storage used more energy, therefore reducing battery life. Furthermore, they also found USB storage was less reliable, due to having a more fragile connection e.g. vibrations from the boat disrupting the connection prior to deployment (Mouy et al. 2020). Nevertheless, by comparison, Kallmyer et al. (2019) successfully used a 32GB USB for data storage. Regarding cameras, only Youngblood (2020) did not use a camera, but instead paired passive integrated transponders on the birds, with a radio-frequency identification reader at the feeders. The rest of these studies used a variety of different camera types including Pi NoIR (Prinz et al. 2016; Nazir et al. 2017a; Kallmyer et al. 2019) or Raspberry Pi camera module v2 (Alarcón-Nieto et al. 2018; Mouy et al. 2020), often combined with some form of passive infra-red (PIR) detection system (Prinz et al. 2016; Zárybnická et al. 2016; Nazir et al. 2017a), or using changes in pixel intensity to indicate movement (Prinz et al. 2016).

There are a few published papers that detail the build of cameras to monitor cavity nesting species, using Raspberry Pi (Prinz et al. 2016; Kalhor et al. 2019; Kallmyer et al. 2019) or using a Linux FTP server control board (Zárybnická et al. 2016), including specifically for birds (Prinz et al. 2016; Zárybnická et al. 2016). All of these are designed so that the camera(s) (and additional modules) are embedded within -and become a part of- the nest box design. This is useful because the same nest box can be monitored over a long period. However, this is also restrictive in cases where the focal animals do not end up using the specific nest box, as happened for Prinz et al. (2016) due to changes in group composition. It also reduces the number of different nests monitored, compared to having the possibility of moving a camera system between nest boxes, which would allow greater insight into a wider number of nests/individuals across each breeding season.

Deploying cameras in extreme environments is technologically challenging due to the impact these conditions have on the performance and degradation of the equipment being used (O'Connell et al. 2011). However, several of the published camera systems have implemented waterproofing of the equipment.

These deployments have included cold locations and therefore frosty conditions (Kalhor et al. 2019), as well as underwater (including marine) locations where not only does the case need to be watertight but also needs to cope with salt water and high water pressure (Phillips et al. 2019; Greene et al. 2020; Mouy et al. 2020).

For terrestrial systems, some camera systems would be completely exposed to rain, humidity, and salt spray (if near the coast), and so mitigation has typically taken the form of water-resistant/water-proof casings -for example using a Peli Case (peliproducts.co.uk) (Youngblood 2020) or similar casing (e.g. Camacho et al. 2017; McBride & Courter, 2019), or a double box with drainage holes in the outer box (Nazir et al. 2017b). However, other systems have been partially enclosed (e.g. a waterproof junction box; Prinz et al. 2016) due to being within a cavity/box and so less mitigation was deemed necessary, or not encased due to being fully enclosed within the nest box (e.g. Zárybnická et al. 2016; Kalhor et al. 2019). Nevertheless, despite the weather proofing of these terrestrial systems, humidity leading to condensation or frost on the camera lens still occurred with little additional mitigation suggested, other than removing or replacing the equipment (Camacho et al. 2017; Kalhor et al. 2019; Kallmyer et al. 2019), and including silica gel packets within the weatherproof casing during deployment (Youngblood 2020).

Here I describe a novel camera system that is fully portable and yet weatherproof, which was developed to study the behaviour of two sibling-species of sympatric, nocturnal, cavity-nesting storm-petrels (Hydrobatidae) that breed on Ilhéu da Praia, an isolated, uninhabited, volcanic islet (~12 ha) in the Azores Archipelago, Portugal (Bolton et al. 2004; Long et al. 2021). While there are now various bespoke camera models described in the scientific literature, few combine mitigation strategies for both salt spray and humidity alongside the need for easy access and full portability between nests throughout a single breeding season. Consequently, these unique circumstances presented by our study system required the development of a novel method of deployment. This included a bespoke camera and housing design to be fully portable between the 160 previously deployed artificial nest boxes on Ilhéu da Praia. These nest boxes were initially deployed in 2000, to provide additional breeding sites for two storm-petrel species: the Monteiro's storm-petrel *Hydrobates monteiroi* breeding in the "hot" season (April–September), and the band-rumped storm-petrel (here after referred to in this

chapter as "Madeiran storm-petrel") as *Hydrobates castro* breeding in the "cool" season (September–March) (Bolton et al. 2004, 2008; Bried et al. 2009). The camera system was required to record behaviours and interspecific interactions in these artificial nests over successive 24-hr periods, on an isolated islet with no mains power supply, where it is difficult to bring in bulky equipment, and where the equipment would frequently be exposed to conditions of salt-laden spray and high humidity. Here, we detail how this system can be deployed effectively in these circumstances (see appendices materials for full build details).

4.2. Materials and methods

We used a Raspberry Pi Zero circuit board, programmed using Python 3.5.3, paired with a fisheye camera with infrared LED attachments to create a bespoke camera small enough to fit on top of a storm-petrel artificial nest box (see Bolton et al. 2004 for nest box design; Figure 4.1, Figure 4.2) and programmed to record when triggered by a change in infrared levels (detected using a passive infra-red [PIR] sensor). After triggering, recording lasted for 30 s with a 10 s break between each recording. The resulting video files were stored on a USB flash dive (cf. McBride and Courter 2019; Mouy et al. 2020). The camera housing was designed to be weather resistant through the use of plastic Tupperware containers, and silicon sealant was used around holes drilled for the wiring (Figure 4.2). Each camera cost a total of ~£86 GBP (~$115 USD) to build, with additional costs of ~£23 GBP (~$31 USD) per camera housing and ~£100 GBP (~$133 USD) needed for equipment to allow the construction of multiple cameras prior to deployment (Figure 4.1 and 4.2; see full part details and build methods in the Chapter 4 Supplementary Materials, with costs detailed in S4. Table 1).

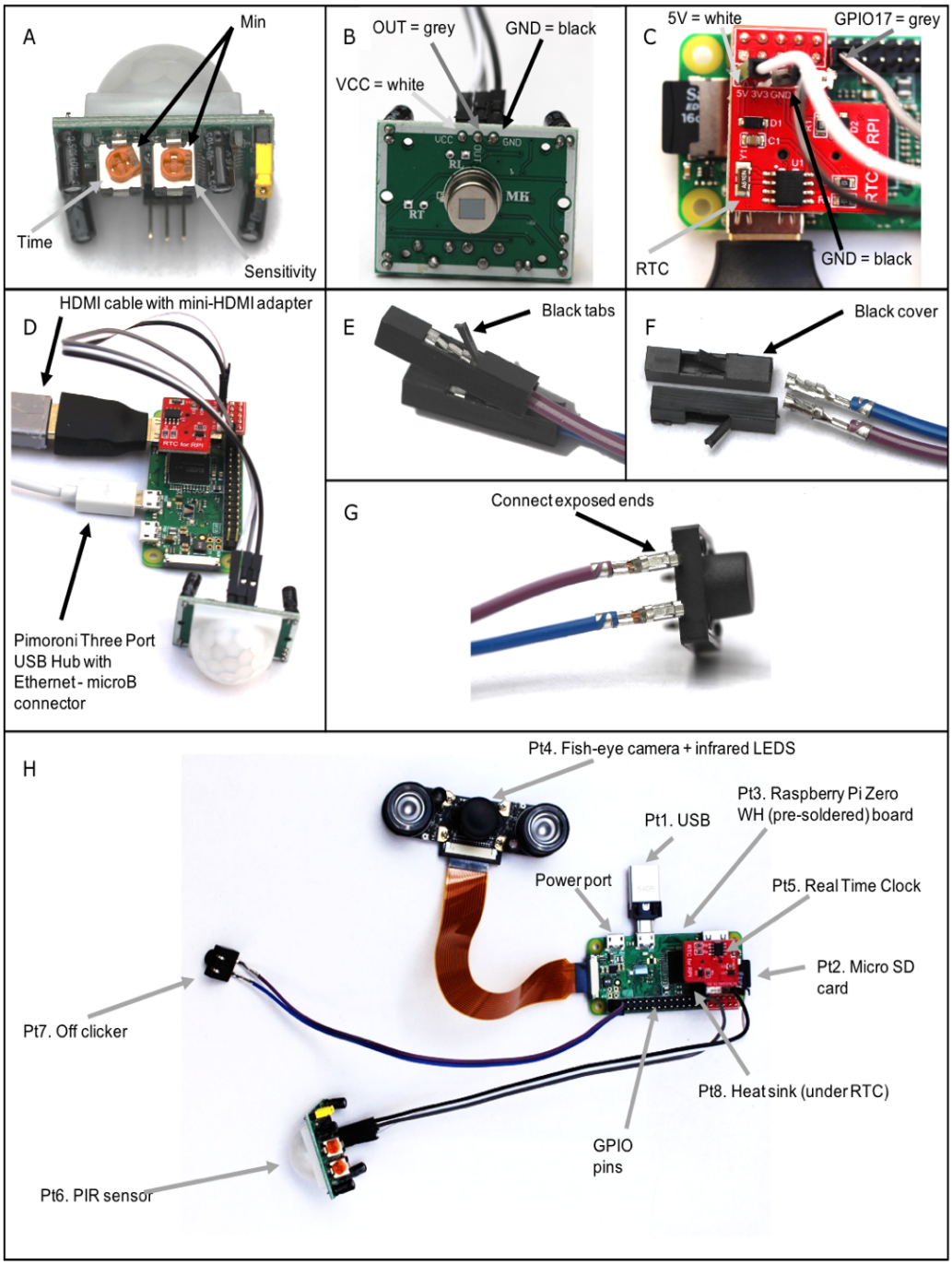


Figure 4.1. Pictures illustrating the building of the Raspberry Pi camera described in this study. A) Passive infra-red (PIR) sensor, showing the suggested positions of the sensor settings (sensors labelled with grey arrows, minimum ("min") labelled with black arrows), the left setting = time (set at "min") and the right setting = sensitivity (set at 90º to min), B) PIR sensor without the sensor cover, showing the pin connections: white cable = VCC, grey = OUT, black = GND (labelled with respective arrows), C) Real Time Clock (RTC) (red board, labelled with grey arrow) already connected to the Raspberry Pi board (GPIO pins 1-10), PIR sensor cables connecting onto the Real Time Clock 5V = white cable and GND = black and on the Raspberry Pi zero board, GPIO17 (pin 11) = grey (labelled with respective arrows), D) completely connected Real Time Clock and PIR sensor, labelling the HDMI and USB connector ports, E, F and G) to connect the switch to the Raspberry Pi board using two female-female cables, first remove the black covers on the switch end of the female-female cables by lifting the black tabs (E), then remove the black covers (F), finally attach to the switch by connecting the exposed ends of the female-female cable to two of the switch ends (G), and H) final built camera ready to be deployed, labelled with each part.

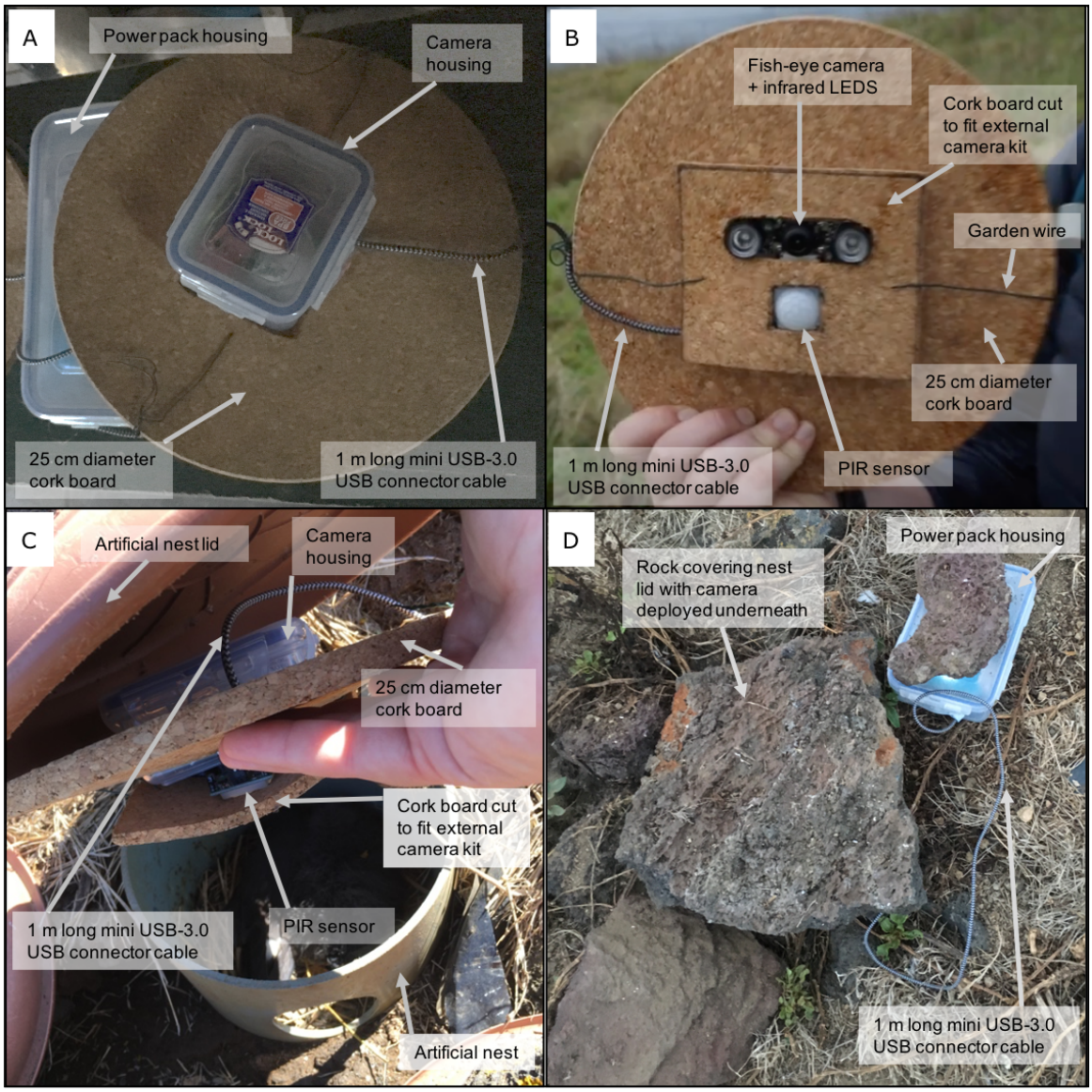


Figure 4.2. Photographs of the camera in various stages of deployment labelled with the different parts visible. A) the top of the housing showing the camera housing, main cork board that sits on top of the nest box rim, powerpack housing and the USB cord, B) the underside of the housing with the main cork board again, this time showing the camera and PIR sensor which are held with the additional square of cork, C) showing where the camera sits – on top of the nest box rim, below the nest box lid - and showing the different parts of the camera and D) the camera deployed and hidden underneath a rock covering the artificial nest box, with powerpack + housing to the side with a rock on top to weigh the housing down. Deployed on Ilhéu da Praia, Graciosa, Azores.

4.2.1. Field deployment example

Fieldwork took place across the breeding seasons of both storm-petrel species breeding on Praia Islet, Azores: Monteiro's storm-petrel (*Hydrobates monteiroi*; May–September 2019) and band-rumped storm-petrel (*Hydrobates castro*; early breeding season: September–early-December 2019 and late breeding season: mid-January–March 2020). Of the 150 artificial nest boxes available, nests were selected for video-monitoring based upon (i) whether the nest box was occupied, (ii) accessibility of the nest box and (iii) whether the lid of the box was at an appropriate height above the nest (so that the footage captured would be in focus at a vertical distance of ≥ 15 cm). One camera per nest was deployed opportunistically across the subset of appropriate nests (n = 54) for 24 hrs at a time, across the successive breeding seasons. During each 24-hr deployment, at least two cameras were deployed in different nests. Each camera was removed after the 24-hr period, the footage downloaded and then each camera was opportunistically re-deployed at another nest of suitable breeding stage. The frequency of re-deployments was dependent on the available (solar) power to charge the powerpacks.

In this paper we present the technical outcomes, using a table of definitions, to define whether each of the deployments was a Failure, Partial failure (non-usable), Partial failure (usable), or a Success (S4 Table 2), and we detail causes of -and solutions to- any failures. Alongside these technical outcomes, we were able to successfully record and classify behaviours on the nest during the chick-rearing period, alongside interspecific interactions, where it was possible to identify other species entering the nest cavity. Details of these behaviours and interspecific interaction observations will be available elsewhere (Hereward et al. [in prep].; Chapter 5).

4.3. Results

Across the two breeding seasons, there were 138 camera deployments in 54 different nests, which created a total of 109,183 videos (each 30 s long) (S4 Table 3 and 4). Of these 138 deployments across both species, 70% of all deployments (n = 97) were deemed to be Successful, which equated to 86% of the individual 30 s videos (94,526; 30 s videos). A further 14% of all deployments (n = 20) were deemed to be Partial (usable), which added an additional 13% of usable 30 s videos (14,595; 30 s videos) (S4 Table 3 and 4). Combining both Successful and Partial (usable) deployments and videos together, this equated to a total of 84% usable deployments (n = 117) and 99% useable 30 s videos (109,121; 30 s videos) (S4 Table 3 and 4). Partial (usable or non-usable) or total Failures accounted for 30% of deployments and were categorised into trouble-shooting and biological issues (Table 4.1). Solutions to Failures and Partial failures are detailed in Table 4.2.

Table 4.1. Counts of deployment causes of Failure, Partial failure (non-usable) and Partial failure (usable) from all deployments on Ilhéu da Praia, Graciosa, Azores. Categorised into species (Monteiro's storm-petrel *Hydrobates monteiroi* and band-rumped storm-petrel *Hydrobates castro*) and technical trouble-shooting and biological issues.

	Issues identified	Failure	Partial (non-useable)	Partial (useable)	Total
Monteiro's storm-petrel					
Trouble-shooting issues					
	Battery.	2	0	2	4
	Humidity, overheating, dislodged connection.	4	0	3	7
	Unknown issue causing break in footage.	0	0	9	9
	Camera placing.	0	0	1	1
Biological issues					
	Limited movement (adult incubating egg).	0	0	1	1
	Limited movement (egg alone).	0	1	1	2
Madeiran storm-petrel					
Trouble-shooting issues					
	Humidity, overheating, dislodged connection.	9	1	1	11
	Rain or nest empty.	0	1	0	1
	PIR sensor connection.	0	0	1	1
	Camera placing.	0	0	1	1
Biological issues					
	Nest empty.	2	1	0	3
Total		**17**	**4**	**20**	**41**

Table 4.2. Causes of the Failure and Partial failure deployments during the breeding seasons of both storm-petrel species, and solutions to address these causes. The causes are separated into technical trouble-shooting issues and biological issues.

Broad causes of Failure/Partial failure	Specific causes	Solutions
Trouble-shooting issues		
Rain, Humidity, overheating, dislodged connection, PIR sensor connection, Break in footage.	Isolated islet, where sea spray and rain are frequent throughout the year.	Restrict entry/exit holes to camera/powerpack boxes using blue tac/glue at the holes to make it more waterproof. Use silica gel sachets in the camera/powerpack boxes to mitigate humidity in the boxes. Take the in-nest camera apart every 6-10 deployments to spend 24-48hrs in a sealed container with silica gel to reduce humidity around the components
	Lifting the camera once deployed sometimes caused connection dislodgement.	Avoid moving cameras during deployment. Replace cables/kit when worn.
Battery	Running out of battery led to no or few recordings.	Ensure the battery is fully charged before deployment, if it continues to be a problem consider replacing the battery or upgrading to a larger capacity battery and/or solar panels.
Camera placing	Nest dimensions, including depth, varied.	Adjust the camera housing accordingly.
Biological issues		
Nest empty	No or limited movement in the nest led to no or few recordings.	Absence of recordings indicate that the box is not (yet) being used.

4.4. Discussion

Here I have described and demonstrated the successful building and deployment of a bespoke camera that is small, portable, weatherproof, battery-run and with PIR motion-trigger capabilities. This bespoke camera, based on a Raspberry-Pi microcomputer, is cheaper or similarly priced to other bespoke cameras of similar build (Prinz et al. 2016; Zárybnická et al. 2016). The poweradd Pilot X7 20,000 mAh powerpack proved to have enough capacity for a 24-48 hr deployment if needed (Youngblood 2020). This deployment duration could be further improved to last for longer per deployment, or to allow for more deployments, for example by employing the use of camera-specific solar panels to extend battery life (Prinz et al. 2016; Nazir et al. 2017a; McBride and Courter 2019).

In comparison to previous nest box/cavity system designs (e.g. Prinz et al. 2016; Zárybnická et al. 2016; Kalhor et al. 2019; Kallmyer et al. 2019), our camera housing was independent of the nest box design and so completely portable, allowing easy transfer between nests throughout the breeding season, thus allowing us to gain insight into a wider number of individual nesting behaviours as well as avoiding missing out on recordings because individuals did not use an initially targeted nest box (as has occurred previously, e.g. Prinz et al. 2016; Zárybnická et al. 2016).

Despite the increased portability and easy access to download the data, the need to frequently open-up the camera housing increased the system's vulnerability to salt spray and humidity, and left parts vulnerable to dislodgement and degradation due to these environmental conditions. Nevertheless, the weatherproofing of the camera housing was generally successful or partially successful (combining "Successful" and "Partial Failure [usable]" footage; 84% usable deployments and 99% of videos usable) which is similar to some previous studies (e.g. 96% of photos usable, McBride & Courter, 2019) and substantially more successful than others (e.g. in Camacho et al. 2017, after one month of deployments, 80% of the cameras had ceased to function due to humidity and vandalism; and Kalhor et al. 2019, recorded a 100% deployment success rate but only 32% of videos were considered of high enough quality to be retained for future analysis). In the present study, ~14% of deployments had trouble-shooting issues specifically due to the weather/humidity, particularly in the winter (band-rumped storm-

petrel) breeding season, which was typically cooler and wetter than the summer (Monteiro's storm-petrel) breeding season (Monteiro and Furness 1998; Chapter 2 Figure 2.2). This is despite mitigation efforts already employed from previously published papers, including housing as much of the equipment as possible within waterproof casings (Prinz et al. 2016; McBride and Courter 2019; Youngblood 2020) and including silica gel packets to reduce humidity within the equipment casing during deployments (Youngblood 2020). Consequently, some additional waterproofing is suggested alongside the further housing adjustments summarised in Table 2, to aid in reducing these specific failures in the future. These mitigations include placing the camera in a box of silica gel between deployments, to reduce the humidity around the components, prior to re-deployment. The calculated percentage success rates based on the Successful, Partial (usable), Partial (non-usable) and Failure definitions could be used by researchers to estimate how many total successful deployments will be needed to achieve a target sample size.

4.4.1. Conclusion

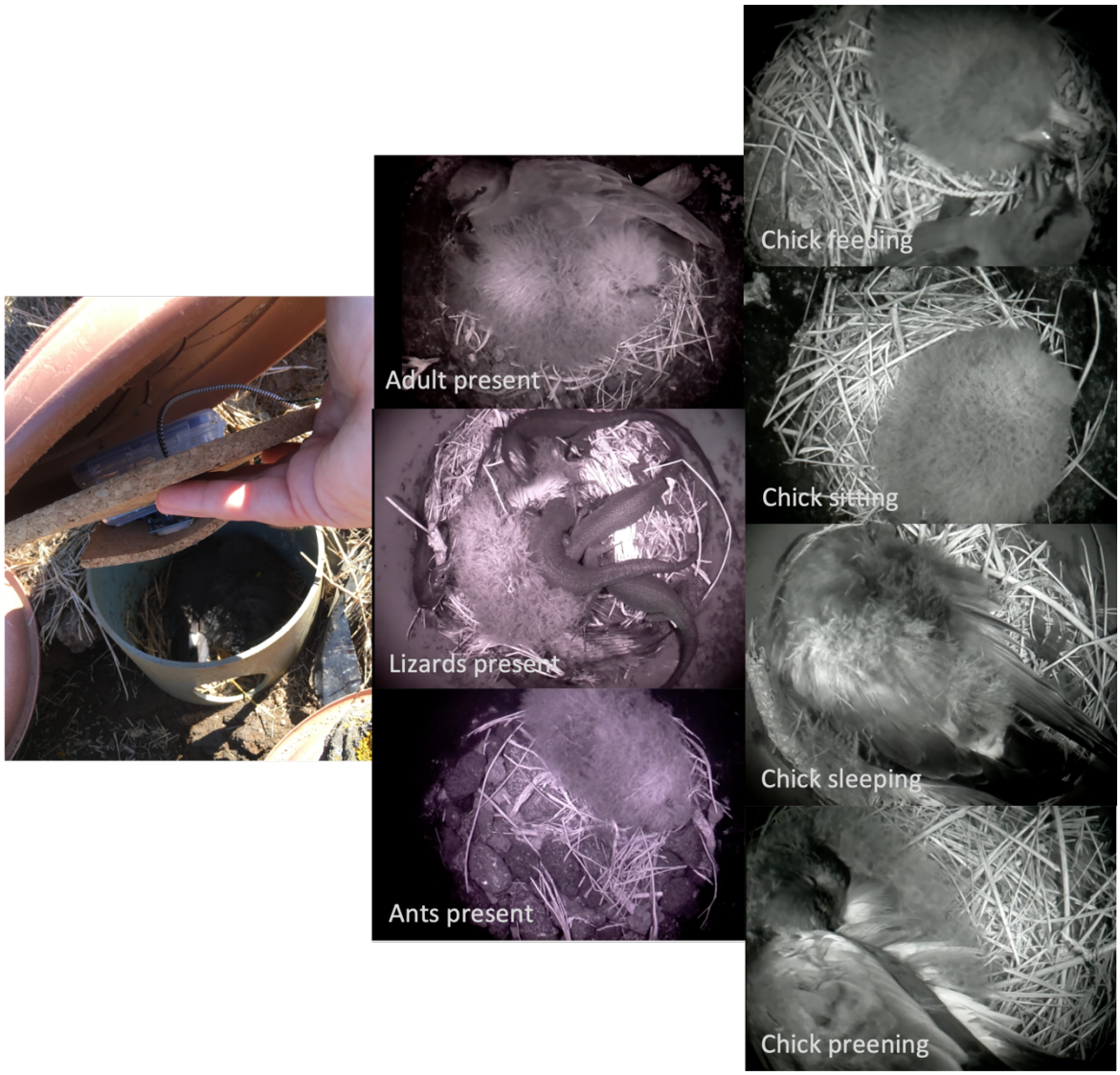
The present study provides a template for building and programming a bespoke, portable camera paired with a PIR sensor, particularly suitable for use in remote study locations with burrow- or cavity-breeding species, where camera size needs to be minimised and limited power is a constraining factor. Due to its portability and mitigation against salt-spray and humidity, this template could be applied to a wide range of different species that utilise cavities, burrows, and artificial nests, or potentially adapted for other wildlife surveillance situations, to monitor behaviours and interspecific interactions, as demonstrated in this study. To further extend the data-gathering capabilities of these cameras, future additions to this template design could include a microphone to record vocalisations, and temperature and humidity modules to record changes in nest-specific environmental conditions -for example to monitor daily, seasonal and between-year variations in these variables, or as a comparison between natural and artificial cavities.

The final chapters will detail the results of the successful camera deployments (Chapter 5) and detail a case-study combined methods approach (Chapter 6) and discuss the results in light of conservation implications (Chapter 7).

Chapter 5.

Video Monitoring of Two Sympatric Species of Burrow-Nesting Storm-Petrels Reveals Temporal Differences in Behaviours and Potential Threats

This chapter is in prep. and near submission for publication.



Photographs: left (bespoke nest camera deployed on artificial nest; Hannah Hereward), remaining photos (screen shots of videos showing different behaviours and potential threats in the nests with Monteiro's storm-petrel or band-rumped storm-petrel chicks and adults; Hannah Hereward)

Summary

Studies of breeding seabirds have traditionally monitored nests manually, but movement-triggered cameras have become more commonly used to monitor wildlife behaviour and predator or threat interactions. Little research, using cameras for monitoring burrow-nesting seabirds, has so far been published describing the range and temporal patterns of nesting behaviours and potential threats.

In this study I monitored, during their respective chick-rearing periods, two storm-petrel species that breed sympatrically but allochronically in the Azores, Portugal (summer breeding species - Monteiro's storm-petrel, *Hydrobates monteiroi* and the closely-related winter breeding species - band-rumped storm-petrel, *H. castro*). I combined analysis of videos extracted from 24-hour camera deployments in artificial nest boxes, with more traditional nest monitoring, to describe temporal changes over the nestling period in 1) behaviours of adults and chicks, and 2) potential threats present in the nest. Video analysis was conducted using an ethogram to analyse one 30 s video per hour. These results were used to determine whether breeding success can be explained by the number and type of interactions with other species within the nest cavity.

The video analysis revealed novel insights into the circadian patterns of adult and chick behaviours, with chick sitting, preening and sleeping being the predominant behaviours. Three categories of organisms (ants, Madeiran wall lizards and other seabirds) were identified as present or interacting with the resident chick and/or adult, and these most frequently occurred during the Monteiro's storm-petrel breeding season. Survival rates for the Monteiro's storm-petrel chicks were not directly associated with the presence of these identified potential threats, but decreased with later hatch dates.

Seasonal differences in ambient temperature, and the stage of chick growth, were likely to have the greatest influences on the frequency of different behaviours observed in the two species, and on the occurrence of potential threats (particularly lizard and ant activity) during their breeding seasons. The workflow, methods and analysis conducted here could readily be applied to other seabird species where camera monitoring is already used, or could be implemented, to improve knowledge of different behaviours and to measure potential threats. These together inform our understanding of the mechanisms by which eggs and chicks may die, and hence aid in the conservation of the species.

5.1 Introduction

Traditionally, biological studies of breeding seabirds have monitored nests manually at regular intervals, collecting data such as egg laying dates, chick growth and provisioning, and adult nest attendance. Such observations may also reveal the presence and impact of invasive alien species (Warham 1990; Schreiber and Burger 2001; Brooke 2004; Lucas and Simmons 2005; Scheibe et al. 2008; Neves et al. 2017). Nevertheless, continual manual monitoring is not often possible, meaning information gets missed (Cutler and Swann 1999; Trolliet et al. 2014). In addition, frequent manual monitoring of nests increases the human disturbance to the birds, potentially affecting the behaviours exhibited or threats present (Cutler and Swann 1999; Trolliet et al. 2014). Consequently, the use of cameras to monitor nests has become more common, allowing continual monitoring without continual human presence, to monitor behaviour and predation or threat patterns (see examples below and in Table 5.1; Cutler and Swann 1999; Reif and Tornberg 2006; Cox et al. 2012; Edney and Wood 2021; Hereward et al. 2021; Bird et al. 2022).

The manual monitoring of nests has been widely used to measure both adult attendance rates (Allan 1962; Harris 1969; Boersma et al. 1980; Boersma 1986; Monteiro and Furness 1998; Mauck and Ricklefs 2005) and chick provisioning rates (Masello et al. 2001; Gladbach et al. 2009a,b; Sugishita et al. 2017). However, more recently, manual nest monitoring has been combined with the monitoring of nests using cameras to better understand chick provisioning of Wilson's storm-petrels (*Oceanites oceanicus*) (Gladbach et al. 2009a,b; Masello et al. 2001) and the Atlantic puffin (*Fratercula arctica*) (Fayet et al. 2021), and as a way of assessing occupancy and breeding behaviours of grey petrels (*Procellaria cinerea*) and blue petrels (*Halobaena caerulea*) at the nest (Bird et al. 2022). This has been further extended to also include other automated devices, for example, the use of automated weighing scales under nests of Northern royal albatross (*Diomedea sanfordi*), alongside GPS tracking of the parent birds to monitor their behaviours at sea (Sugishita et al. 2017).

In addition to these behavioural studies, a plethora of possible threats to the nesting adult seabirds, their eggs and/or chick stages have also been identified. Such threats include mammals, other birds, reptiles, and arthropods (Table 5.1). The use of camera traps has helped to shed light on some of

these threats, identifying species causing mortality of adults, eggs or nestlings, alongside more subtle, sub-lethal or indirect impacts (Table 5.1). This has included determining that although predators such as rats *Rattus* spp. can often severely reduce breeding success (Amaral et al. 2010; Ratcliffe et al. 2010; Mejías et al. 2017), such impacts may not necessarily be direct. For example, Flores et al. (2017) identified possible sub-lethal impacts of rats potentially increase disease transmission between seabird nests (Thiébot et al. 2014) and cats (*Felis catus*) causing nest abandonment. Nevertheless, in some circumstances the presence of various mammals (including rats) has not been found to impact breeding success (Thiébot et al. 2014; Stolpmann et al. 2019). In addition to these impacts of mammals, camera trap studies have also identified other taxa, such as ants, directly predating chicks (e.g. Flores et al. 2017). Furthermore, camera traps have also aided in determining that the structure of underground burrows is important in deterring egg depredation by corvids (Ekanayake et al. 2015).

Here, we present a workflow and case study, focusing on two closely related species of storm-petrels that breed sympatrically but allochronically in the Azores, Portugal; namely the Monteiro's storm-petrel (*Hydrobates monteiroi*) which breeds in the summer (April-September) and the band-rumped storm-petrel (*H. castro*) which breeds in the winter (September-March). Both species are of conservation concern – the Monteiro's storm-petrel is an Azores-endemic, listed as Vulnerable on the IUCN Red List and has a small breeding population (< 400 pairs; BirdLife International 2018b). By contrast, the band-rumped storm-petrel is categorised as Least Concern and is more widespread, breeding across the Pacific and Atlantic Oceans, but has a decreasing population trend (BirdLife International 2018a). We use evidence from hourly samples of video footage within the nest cavity, during the chick-rearing period of the two species, to describe the temporal changes (across the daily cycle and chick-rearing period) in 1) behaviours of adults and chicks, and 2) potential threats present in the nest. The potential threats identified in different nests are compared to the overall breeding success of the chicks monitored, to assess whether breeding success can be explained by 1) the quantity of other taxa observed per nest and 2) the frequency of occurrences of these other taxa.

Table 5.1. Threats to seabird breeding success identified from previously published articles.

Group	Threat	Species under threat	Life-stage of species at threat	Direct impact on breeding success?	Camera used to monitor nests?	Citation
Mammals						
	Small Indian mongoose (*Herpestes auropunctatus*)	Red-tailed tropicbird (*Phaethon rubricauda*)	Eggs and chicks	Yes	No	Vanderwerf and Young (2014)
	Rabbits (*Oryctolagus cuniculus*)	Grey-faced petrel (*Pterodroma gouldi*)	No predation events noted	No. No significant impact on incubating phase or chick hatch success noted.	Yes	Stolpmann et al. (2019)
	Rats (*Rattus* spp.)	White-tailed tropicbird (*Phaethon lepturus catesbyi*)	Eggs and chicks	Yes	No	Mejías et al. (2017)
		Amsterdam albatross (*Diomedea amsterdamensis*)	No predation events noted	No. Possible sublethal or indirect impacts due to disease transmission.	Yes	Thiébot et al. (2014)
		Grey-faced petrel (*Pterodroma gouldi*)	No predation events noted	No. No significant impact on incubating phase or chick hatch success noted.	Yes	Stolpmann et al. (2019)
		Red-tailed tropicbird (*Phaethon rubricauda*)	No predation events noted	No. None noted.	Yes	Flores et al. (2017)
	Black rat (*Rattus rattus*)	White-chinned petrel (*Procellaria aequinoctialis*)	Eggs and chicks	Yes	No	Jouventin et al. (2003)
		Roseate tern (*Sterna dougallii*)	Eggs	Yes	No	Amaral et al. (2010)
		Ascension Island seabirds	Eggs and chicks	Yes	No	Ratcliffe et al. (2010)
	Cats (*Felis catus*)	Red-tailed tropicbird (*Phaethon rubricauda*)	No predation events noted	No. Possible indirect impacts due to disturbance.	Yes	Flores et al. (2017)

		Common tern (*Sterna hirundo*)	Chicks and adults	Yes	Yes	Lamelas-López et al. (2021)
	Dogs (*Canis familiaris*)	Red-tailed tropicbird (*Phaethon rubricauda*)	Fledgling chicks	Yes	Yes	Flores et al. (2017)
		Common tern (*Sterna hirundo*)	Eggs	Yes. Nest abandonment.	Yes	Lamelas-López et al. (2021)
Birds						
	Common starlings (*Sturnus vulgaris*) and ruddy turnstone (*Arenaria interpres*)	Common tern (*Sterna hirundo*) and Roseate Tern (*Sterna dougallii*)	Eggs	Yes	No	Neves et al. (2011)
	Chimango caracara (*Phalcoboenus chimango*)	Red-tailed tropicbird (*Phaethon rubricauda*)	Eggs and chicks	Yes	Yes	Flores et al. (2017)
	American crow (*Corvus brachyrhynchos*)	White-tailed tropicbird (*Phaethon lepturus catesbyi*)	Eggs and chicks	Yes	No	Mejías et al. (2017)
	Little raven (*Corvus mellori*)	Little penguin (*Eudyptula minor*)	Eggs and chicks	Yes	Yes	Ekanayake et al. (2015)
	Northern long-eared owl (*Asio otus*)	Monteiro's storm-petrel (*Hydrobates monteiroi*) and band-rumped storm-petrel (*Hydrobates castro*)	Adults	Yes	No	Monteiro et al. (1996); Bolton et al. (2008)
	Short-eared owl (Galápagos; *Asio flammeus galapagoensis*)	Galápagos storm-petrel; band-rumped storm-petrel (*Hydrobates castro*) and wedge-rumped storm-petrel (*Hydrobates tethys*)	Chicks and adults	Yes	No	Harris (1969)
	Short-eared Owl (*Asio flammeus*)	Band-rumped storm-petrel (*Hydrobates castro*)	Adults	Yes	No	Bried (2003)
	Yellow-legged gull (*Larus michahellis*)	European storm-petrel (*Hydrobates pelagicus*)	Chicks and adults	Yes	No	Sanz-Aguilar et al. (2009)

	Great blue heron (*Ardea herodias*)	Galápagos storm-petrel; band-rumped storm-petrel (*Hydrobates castro*) and wedge-rumped storm-petrel (*Hydrobates tethys*)	Chicks	Yes	No	Harris (1969)
Reptiles						
	Tuatara (*Sphenodon punctatus*)	Fairy prion (*Pachyptila turtur*)	Eggs and chicks	Yes. But not likely to be the major cause of population regulation.	No	Walls (1978); Markwell (1998); Corkery et al. (2014,2015)
	Stewart Island green skink (*Oligosoma aff. Chloronoton*) and southern grass skink (*Oligosoma aff. olychrome*)	Whenua Hou diving petrel (*Pelecanoides whenuahouensis*)	No predation events noted	No. Stewart Island green skinks use the burrows, but no predation event recorded.	No	Fischer et al. (2019)
	Bermuda skink (*Plestiodon longirostris*)	Bermuda petrel (*Pterodroma cahow*) and white-tailed tropicbird (*Phaethon lepturus catesbyi*)	Eggs and chicks	Possibly. Skinks seen to scavenge including dead chicks, abandoned eggs, but no direct predation events noted.	No	Madeiros (2005); Turner et al. (2021)
	Madeiran wall lizard (*Podarcis dugesii*)	Cory's Shearwater (*Calonectris borealis*), Bulwer's petrel (*Bulweria bulwerii*), band-rumped storm-petrel, (*Hydrobates castro*), white-faced storm-petrel (*Pelagodroma marina*)	Chicks	Yes	No	Matias et al. (2009)
		Monteiro's storm-petrel (*Hydrobates monteiroi*)	Eggs and chicks	Yes	No	Bried and Neves (2015); Neves et al. (2017)
	Galápagos iguana (*Conlophus* spp.)	Galápagos storm-petrel; Band-rumped storm-petrel (*Hydrobates castro*) and wedge-rumped storm-petrel (*Hydrobates tethys*)	Eggs	Yes	No	Harris (1969)

	Seychelles giant tortoise (*Aldabrachelys gigantea*)	Lesser noddy (*Anous tenuirostris*)	Chicks	Yes. But not likely to be the major cause of population regulation.	No	Zora and Gerlach (2021)
Arthropods						
	Red rock crab (*Grapsus grapsus*)	Galápagos storm-petrel; Band-rumped storm-petrel (*Hydrobates castro*) and wedge-rumped storm-petrel (*Hydrobates tethys*)	Chicks	Yes	No	Harris (1969)
	Big-headed ant (*Pheidole megacephala*) and tropical fire ant (*Solenopsis geminata*)	Wedge-tailed shearwater (*Ardenna pacifica*)	Big-headed ant = no predation events noted.	Big-headed ant = no.	No	Plentovich et al. (2009)
			Tropical fire ant = chicks.	Tropical fire ant = yes.		
	European fire ants (*Myrmica rubra*)	European herring gull (*Larus argentatus*)	Chicks	Yes	No	DeFisher and Bonter (2013)
	Argentine ant (*Linepithema humile*)	White-Tailed tropicbird (*Phaethon lepturus catesbyi*)	Chicks	Yes	No	Mejías et al. (2017)
		Red-tailed tropicbird (*Phaethon rubricauda*)	Chicks and adults	Yes	Yes	Flores et al. (2017)
	Phillip Island centipede (*Cormocephalus coynei*)	Black-winged petrel (*Pterodroma nigripennis*)	Chicks	Black-winged petrel = yes.	No	Halpin et al. (2021)
		White-necked petrel (*Pterodroma cervicalis*)		White-necked petrel = no.		

5.2. Materials and methods

5.2.1. Study site

The study was conducted on Ilhéu da Praia, a 0.12 km^2 islet, situated 1.2 km to the east of Graciosa, Azores, Portugal (39°03'N, 27°57'W). From 2000 to 2001, 150 artificial nest boxes were installed on the islet (nest box design detailed in Bolton et al. 2004) and in 2015 an additional 14 nests were installed on the islet (Veronica Neves personal communication) to provide suitable nesting sites for the two sibling species of storm-petrels that breed on the islet and often in the same nest boxes, but at different times of year.

5.2.2. Camera design and field deployment

To record the storm-petrels' behaviours at the nest, and the potential threats in the artificial nest boxes, a bespoke camera system based on Raspberry Pi microcomputer technology (www.raspberrypi.org) was developed (camera design detailed in Hereward et al. 2021 and in Chapter 4). These cameras included a fisheye lens and a passive infrared sensor, and were programmed to record 30 s videos whenever a change in infrared detection occurred.

Here we present the results from camera deployments during the chick-rearing period of the Monteiro's storm-petrel 2019 breeding season (28/06/2019-18/08/2019; 52 camera deployments on 19 different nests; chick age in days ranged from 1 to 74) and the band-rumped storm-petrel 2019-2020 breeding season (20/01/2020-04/03/2020; 33 camera deployments on nine different nests; chick age in days ranged from 37 to 78). One camera per nest box was deployed opportunistically across a sub-set of appropriate nests for 24-hours at a time, with, typically, two individual cameras being deployed on two different nests per 24-hour period. Repeat deployments on the same nest were used where possible, to capture events on a range of dates. However, these were not typically on consecutive days but rather at intervals throughout each breeding season.

After a 24-hour deployment, the camera was typically collected during the daily nest check (~10am-12noon, see below) and any videos recorded were downloaded onto an external hard drive. Cameras were then re-deployed - often on a different nest, in order to measure as much variation in chick age as possible, within the logistical constraints of these deployments. Either a different camera was deployed during the same daily nest check, or the same

camera was re-deployed later in the afternoon, after any necessary camera maintenance or repairs had been performed. The frequency of re-deployments was dependent on the availability of solar power for recharging the powerpacks. Full details of the camera build, programming, calibration, piloting and the deployment success rates can be found in Hereward et al. (2021), and in Chapter 4.

5.2.3. Daily nest monitoring

As part of ongoing fieldwork on breeding parameters (spanning April 2019 – March 2020), nest checks were conducted daily to record the body mass and fledging success of the chicks. The body mass growth curve of any chick that was remaining at the end of the study season was assessed, and if the chick was clearly close to fledging with regard to body condition, then it was included in the group of fledged chicks (n=1 chick per season). Where adult storm-petrels other than the chick's own parents were present in the nest, the ring number was read, and the species clarified.

5.2.4. Video analysis

To investigate diel variation in behaviours and potential threats, I analysed one 30 s video per 1-hour period. 30 s videos allowed me long enough to obtain an instantaneous view of events in the nest. The videos closest to each 1-hour interval, across each camera deployment, were selected and analysed using an ethogram to categorise behaviour (Table 5.2). This followed a binary coding (1 = occurred, 0 = did not occur, noting that more than one behaviour could be recorded as occurring during a single 30 s observation, e.g. sitting and preening). Where possible, additional videos were also analysed at 30 min intervals; where available these were retained in the analysis because they add to the temporal resolution of the data. The presence or absence of possible threats was also noted (both direct interactions with the nest occupant(s), and indirect where other species were just present in the nest box), these included: Madeiran wall lizards (*Podarcis dugesii*); ants (several species pooled together; Neves et al. [in prep.]); Cory's shearwater (*Calonectris borealis*); and/or known or suspected non-parent adult storm-petrels (Monteiro's storm-petrels, *Hydrobates monteiroi* or band-rumped storm-petrels, *H. castro*). The exception to this binary coding system was the abundance of Madeiran wall lizards, which was recorded as a count of the number of individuals present. The video times were aligned to UTC (where in the Azores: 31st March 2019 – 27th October 2019 = UTC+0hr i.e. Monteiro's

storm-petrel breeding season and 28th October 2019 – 28th March 2020 = UTC-1hr i.e. band-rumped storm-petrel breeding season). If a chick death occurred during a camera deployment, all videos recorded during the deployment were watched to determine the cause of death.

Table 5.2. Ethogram table with definitions of the different behaviours identified across both storm-petrel species (*Hydrobates monteiroi* and *H. castro*) from the chick-rearing part of their breeding seasons (summer 2019 and winter 2019-2020 respectively) on Ilhéu da Praia, Graciosa, Azores.

Behaviours	**Definitions**
Chick sitting while awake	Bird sitting calmly still with head visible, not tucked under wing, with no other active behaviours occurring.
Chick preening	Using bill to nibble or clean feathers, often interspersed with shaking and ruffling of feathers.
Chick sleeping	Head tucked under wing or into chest, bird does not move.
Chick feeding	Adult and chick heads are close together, chick bill is in adult's bill while adult transfers food to the chick.
Adult nest attendance	Adult present in nest.
Adult sitting while awake	Bird sitting still with head visible, not tucked under wing. Can include birds brooding young chick.
Adult preening self	Using bill to nibble or clean feathers, often interspersed with shaking and ruffling of feathers.
Adult preening chick	Adult using bill to nibble or clean chick feathers.
Adult feeding chick	Adult and chick heads are close together, chick bill is in adult's bill while adult transfers food to the chick.
Adult sleeping	Head tucked under wing or into chest, bird does not move.
Adult nest building/ maintenance	Using bill to move nest materials around
Adult incubating/ brooding	Adult specifically seen sitting on top of chick, or standing/walking on top of chick. (This is the same behaviour as "adult sitting" but only when specifically on the chick)
Adult being vigilant	Actively looking around, not sitting or sleeping or being still.

5.2.5. Statistical analysis

The statistical analyses were carried out using *R* 4.0.2 (R Core Team 2020) and implemented in *RStudio* version 1.3.1093 (RStudio Team 2020). For each video, the chick age in days was recorded in relation to the hatch date (day 1 = the day that the chick emerged from the egg). For each species of storm-petrel, Generalised Additive Models (GAM) were conducted to analyse diel and seasonal variation in each behaviour and each possible threat, using a binomial error family and "cauchit" link function (or Poisson error family and "logit" link for lizard counts), implemented with the *mgcv* package (v1.8-31; Wood 2003; Wood 2017). Each GAM included two smoothed variables: Hour, and chick age in days. Hour was smoothed (to examine non-linear changes across the 24-hour cycle) using the cubic cyclic spline method (due to the circular nature of the 24-hour clock). Chick age in days was included in the model as a smoothed independent variable (using the default thin plate regression spline method), to examine non-linear changes across the nestling period and to control for chick age when examining other effects. The degree of non-linearity was selected parsimoniously using the cross-validation method.

Finally, a Generalised Additive Mixed Model (GAMM) was conducted to assess the survival of the Monteiro's storm-petrel chicks in relation to the presence of potential threats, with lizard and ant presences as fixed independent variables and nest number as a random factor, using a binomial error family and "logit" link function, implemented with the *mgcv* package (v1.8-31; Wood 2003; Wood 2017). Hatch date was smoothed (to examine non-linear changes in survival across the range of hatch dates) using the default thin plate regression spline method. All of the band-rumped storm-petrel chicks monitored from the videos in this chapter fledged successfully, and so the association between fledging success and lizard and ant activity or hatch date could not be statistically analysed for this species.

5.3. Results

Across the chick-rearing periods of the two species, 1,105 hourly video recordings (corresponding to 9.2 hours) were analysed for the Monteiro's storm-petrel breeding season and 482 (corresponding to 4.0 hours) were analysed for the band-rumped storm-petrel breeding season (S5 Figure 1). Thirteen different behaviours were identified across adults and chicks of both species in this study (Figure 5.1; S5 Table 1). Figure 5.1, and S5 Table 1, detail the number of videos analysed and percentages of behaviours / occurrences of other species. Figures 5.2 & 5.3, and S5 Table 2, show GAM analyses of a subset of the behaviours (adult nest attendance, chick feeding, chick sitting, chick sleeping, chick preening, lizards present, ants present) and other species observed in the storm-petrel nests. Finally, Figure 5.4, and S5 Table 3, show the survival rates of the Monteiro's storm-petrel chicks from nests monitored using in-nest cameras to examine the relationship between the outcome of the breeding attempt, hatch date, and the presence in the nest box of potential threats.

5.3.1. Adult presences and feeding events

More detections of adults attending the nest were made in the Monteiro's storm-petrel breeding season videos compared to the band-rumped storm-petrel breeding season (Monteiro's = 8% of videos, band-rumped = 3%; Figure 5.1A; S5 Table 1), this is discussed below. However, some of the adults present during the Monteiro's storm-petrel chick rearing season (2% of videos) were either known to be, or suspected to be, non-parent adult Monteiro's storm-petrels, or band-rumped storm-petrels that were investigating nests currently occupied by Monteiro's storm-petrels.

For both species, across the 24-hour cycle there was a period when adults were never observed to be present, ~5am-10am, whereas adults were detected after ~10am during daylight hours in the Monteiro's storm-petrel chick nests (Figure 5.2A&C); this anomaly is discussed below.

Across the chick age range there were periods in which there was a low probability of detecting adults visiting the nest (during these periods, chicks were still gaining weight and were therefore still being fed; see Chapter 3). The final seasonal peak in the probability of detecting Monteiro's storm-petrel

adult attendance was earlier (~40 days) than that of the band-rumped storm-petrel parents (~60 days, Figure 5.2B).

There were very few "adult feeding chick" events recorded (Figure 5.1B) and these all occurred at night for both species, even when the adults remained in the nest during the day (Figure 5.2D&F). However, the chicks were fed across the nestling period, with the age of the last recorded chick feeding event being very similar for the two species, at day 49 (band-rumped) or day 50 (Monteiro's) (Figure 5.2E&F).

5.3.2. Chick behaviours

Sitting was the most common behaviour for the chicks of both species (49% of Monteiro's storm-petrel videos, 48% of band-rumped storm-petrel videos; Figure 5.1B & 5.2G-I; S5 Table 1&2), with both species exhibiting a clear peak in sitting at night, and a decline in sitting towards dawn (from midnight to 5am). After dawn, the Monteiro's storm-petrel chicks were more likely to be sitting between ~ 10h and 14h, whereas the peak sitting period for the band-rumped storm-petrel chicks was in the afternoon and towards evening. Across chick age, there was a general decline in sitting, but with various peaks and troughs (Figure 5.2H). The two troughs for sitting in Monteiro's storm-petrel chicks match the increased peaks in sleeping, but both species were less likely to be observed sitting in the last 5-10 days before fledging.

Band-rumped storm-petrel chicks were more frequently recorded sleeping overall, than Monteiro's storm-petrel chicks (27% of band-rumped storm-petrel videos, 20% of Monteiro's storm-petrel videos; Figure 5.1B; S5 Table 1), with the diel peak in band-rumped storm-petrel chick sleeping being late morning, compared to the Monteiro's storm-petrel chicks, in which sleeping peaked in the afternoon (Figure 5.2J&L). Sleeping generally increased over the first 30 days after hatching for the Monteiro's storm-petrel chicks, but dipped around day 40; the inverse pattern was seen for sitting (see above above). In the band-rumped storm-petrel chicks, sleeping peaked between ~ days 40 and 60 and ~ day 80, just before fledging (Fig 2K&L).

Similarly, band-rumped storm-petrel chicks typically preened more often than Monteiro's storm-petrel chicks (43% of band-rumped storm-petrel videos, 34% of Monteiro's storm-petrel videos; Figure 5.1B&O; S5 Table 1). Band-rumped storm-petrel preening peaked before dawn (i.e. before their sleeping

peak), whereas preening by Monteiro's storm-petrel chicks peaked at ~ 8am (before their sitting peak, Figure 5.2M&O). Preening activities often occurred together with sitting within the same 30 s video. Across chick ages, preening occurred most often in young chicks (~10-30 days for Monteiro's storm-petrel) and older chicks (~55-65 days for both species) (Figure 5.2N).

5.3.3. Occurrence of non-parent storm-petrels, and other taxa

Three categories of organisms were identified as being present with the resident chick and/or adult. These included: ants (several species pooled together; Neves et al. [in prep.]); Madeiran wall lizards and other species of seabirds, namely Cory's shearwater and non-parent adult storm-petrels. All three of these categories of other species presences occurred during the Monteiro's storm-petrel breeding season (Figure 5.1C; S5 Table 1) and only two occurred during the band-rumped storm-petrel breeding season - these were: 1. ants and 2. Madeiran wall lizards. All non-parent storm-petrel or other taxa occurrences were more frequently observed during the Monteiro's storm-petrel breeding season, where ants (observed in 17% of videos), non-parent/band-rumped storm-petrels (2%), and Madeiran wall lizards (2%) were most frequently observed.

Lizards were recorded only twice during the band-rumped storm-petrel breeding season (both instances were when the chick was absent from the nest, having just fledged). Consequently, the great majority of lizard observations were recorded during the Monteiro's storm-petrel breeding season, though it should be noted that this difference was amplified in our dataset because this includes a dead Monteiro's storm-petrel chick being eaten by lizards (Fig5.3A-C). When the model was re-run excluding the data collected during this incident, neither the daily nor seasonal variation in lizard activity was statistically significant (not shown). Whilst the hourly and seasonal terms in the models of lizard behaviour were not significant, the raw data in the hour of the day graph depicts a diurnal pattern, where presences only occurred between ~ 10am and 8pm (Figure 5.3A). Lizards were present in the Monteiro's storm-petrel nests throughout the chick rearing period (Figure 5.3B).

By contrast, ants were present across the 24-hour cycle during the Monteiro's storm-petrel breeding season and were more common than during the band-rumped storm-petrel breeding season (although found across the 24-hour

cycle in both breeding seasons; Figure 5.3D-F). Across the nestling period of both storm-petrel species there were various peaks and troughs in the likelihood of ants being present in the nest (Figure 5.3D). A newly-hatched late-season Monteiro's storm-petrel chick could have caused the initial peak in ant activity across chick age, as the ants were observed eating egg remains in this nest. This was only observed in videos recorded from this one chick, but ants feeding on egg remains were noted *ad hoc* in other nests during nest checks. Finally, there was a similar peak in ant activity for both storm-petrel species when the chicks were near to fledging (Figure 5.3E).

5.3.4. Chick survival rates

Of the 19 nests monitored using nest cameras during the chick-rearing period of the Monteiro's storm-petrel breeding season (2019), five chicks died (26% of nests monitored with cameras; chick age at death ranged from 21 to 61 days old) and in videos analysed at least one different predator/threat taxon was seen to occur in these nests whilst still alive (Figure 5.4A&B). However, only one of these mortality events was caught on camera (and not in the hourly analysis videos). This chick was 42 days old at death. Videos recorded before, during and after the death of this chick revealed that the cause of death was seemingly of "natural causes" (i.e. no other taxa were visible in the videos at the time of death). Nevertheless, two adults known to be band-rumped storm-petrels had been occupying the nest with the Monteiro's storm-petrel chick the night before its death and notes from the nest check the day after stated that some of the chick's neck and wing covert feathers were missing, which would indicate likely pecking from the band-rumped storm-petrels. Furthermore, lizards appeared within minutes once the chick had died.

The causes of the remaining four chick deaths were inferred, based upon the nest check observations. One was attributed to ants because when found, many ants were eating the chick (this chick was 21 days old at death), and three were attributed to non-parent storm-petrel adults entering the nest. This caused the chicks to move out of the nest, consequently they were no longer being fed by their parents, and lost weight (these chicks were 42, 47 and 61 days old at death). One of these three chicks was also the chick that was picked up by a Cory's shearwater, and ants were in the nest on hatching (chick was 47 days old at death). The remaining 14 Monteiro's storm-petrel chicks (74% of those monitored with in-nest cameras) fledged successfully (one was remaining at the end of the season – but was very near fledging

weight and was therefore assumed to fledge; Figure 5.4A). In contrast to the Monteiro's storm-petrel chicks, all nine of the band-rumped storm-petrel chicks monitored with in-nest cameras fledged successfully (again, one was remaining at the end of the season – but was very near fledging weight and was therefore assumed to fledge; Figure 5.4A).

The GAMM analysis showed that the Monteiro's storm-petrel chick survival was not significantly affected by lizard or ant presences. However, there was a significant effect of hatch date on survival whereby the later hatched chicks were less likely to fledge (Figure 5.4C; S5 Table 3).

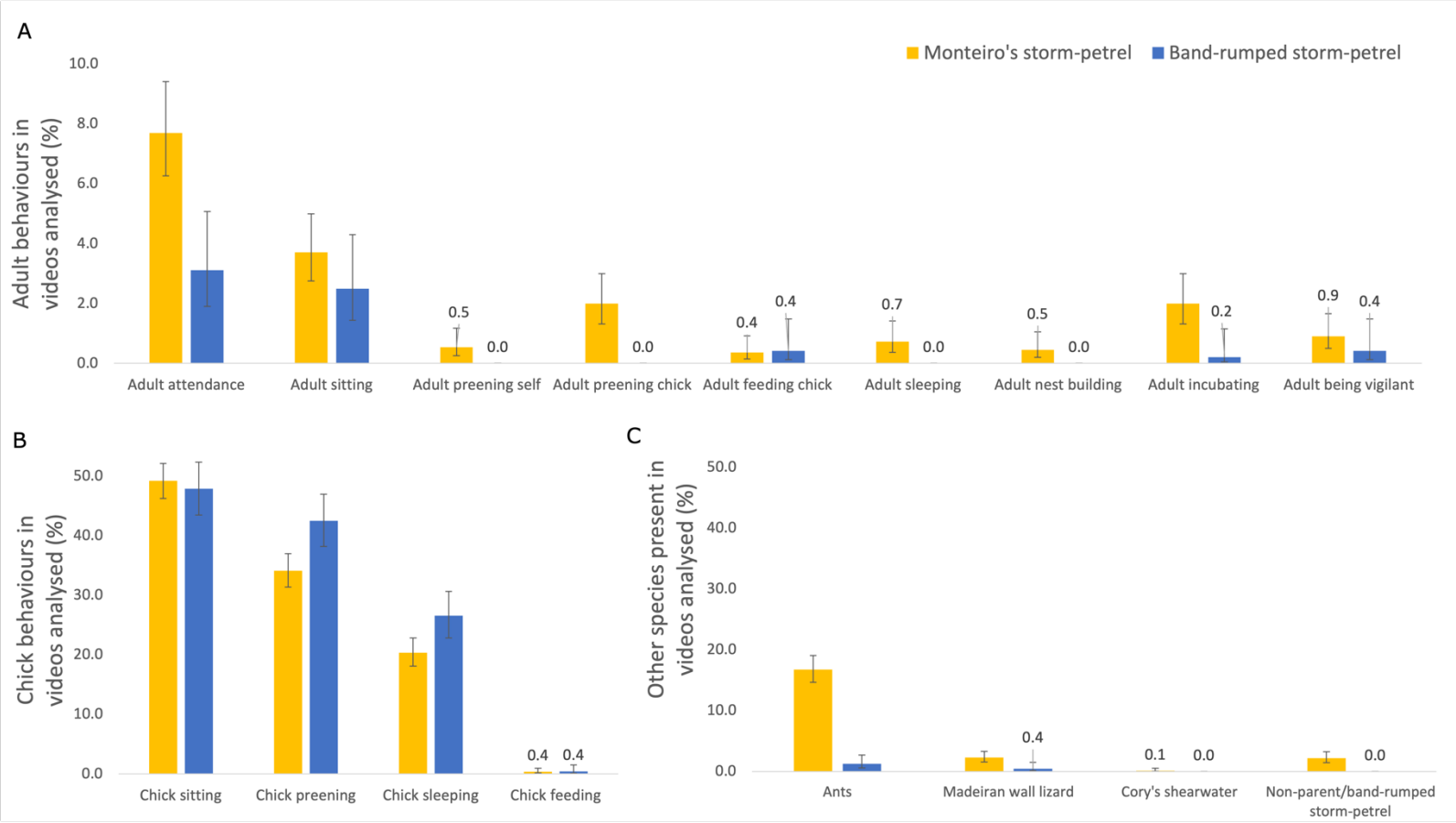


Figure 5.1. Percentage (± 95% central confidence interval) of A) adult behaviours (y-axis at 10%), B) chick behaviours (y-axis at 50%) and C) between-species interactions (y-axis at 50%), across all hourly videos analysed for both species: Monteiro's storm-petrel (*Hydrobates monteiroi*; yellow) and band-rumped storm-petrel (*Hydrobates castro*; blue), across the chick-rearing period of their breeding seasons (summer 2019 and winter 2019-2020 respectively) from Ilhéu da Praia, Graciosa, Azores. NB: any percentages below 1% are labelled above the relevant bar on the graph. Binomial error bars were computed using the online Bayesian calculator at: www.causascientia.org/math_stat/ProportionCI.html.

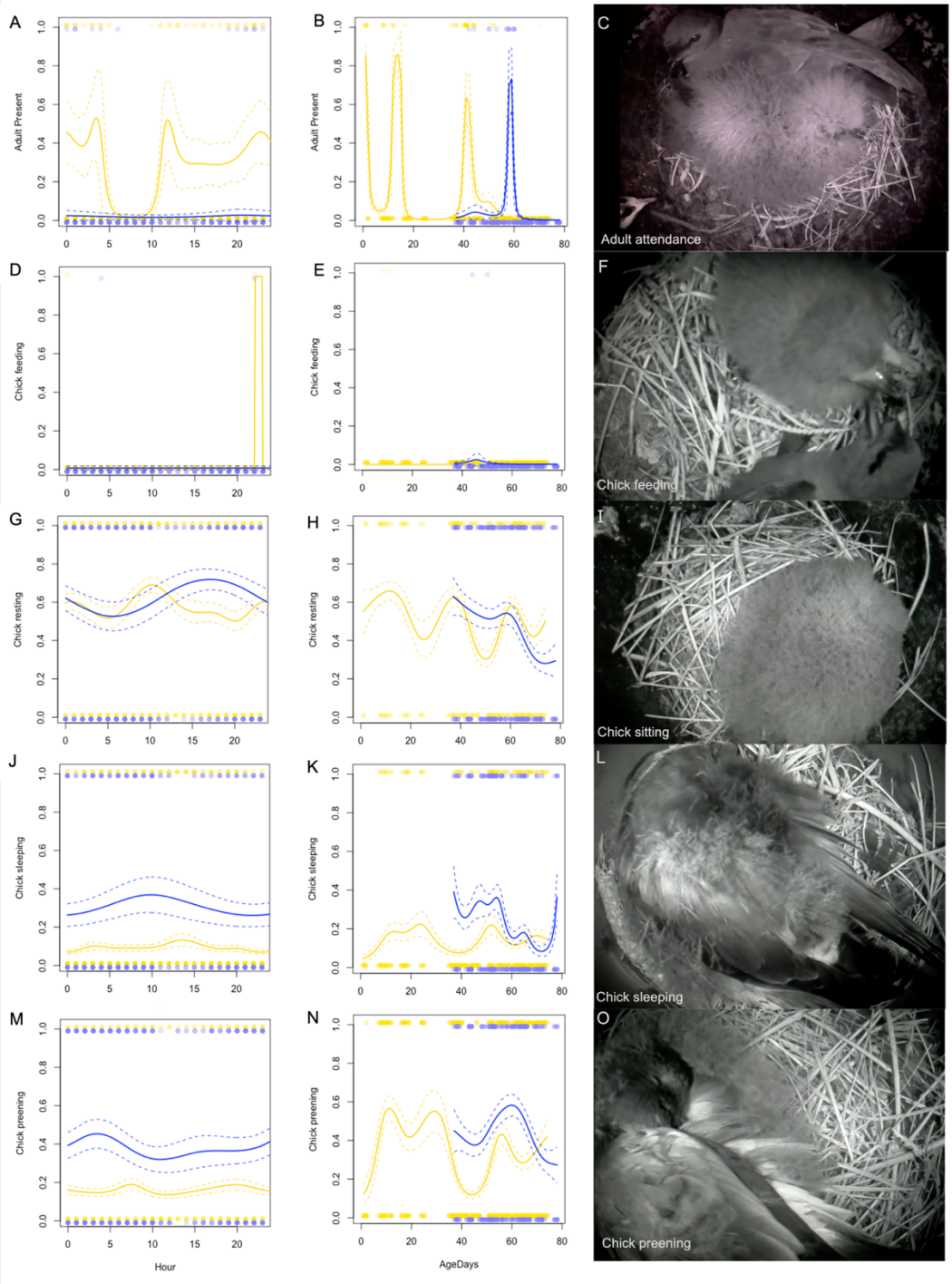


Figure 5.2. Daily and seasonal patterns of variation in behaviours and species occurrences in the nests of Monteiro's storm petrel (*Hydrobates monteiroi*; yellow) and band-rumped storm-petrel (*H. castro*; blue) across the 24-hour cycle and across the nestling period, with photos illustrating each type of event: A-C) adult present, D-F) chick feeding, G-I) chick sitting, J-L) chick sleeping, and M-O) chick preening. Fitted lines show the predictions from the GAM analyses of behaviour and species occurrences. The daily patterns detail the non-linear changes across 24-hours using chick age = 40 days and predictor lines for seasonal patterns detail the non-linear changes across the chick age at hour = 24. Dotted lines indicate standard errors. Hour of the day recorded as UTC. N = 19 Monteiro's storm-petrel chicks, N = 9 band-rumped storm-petrel nests.

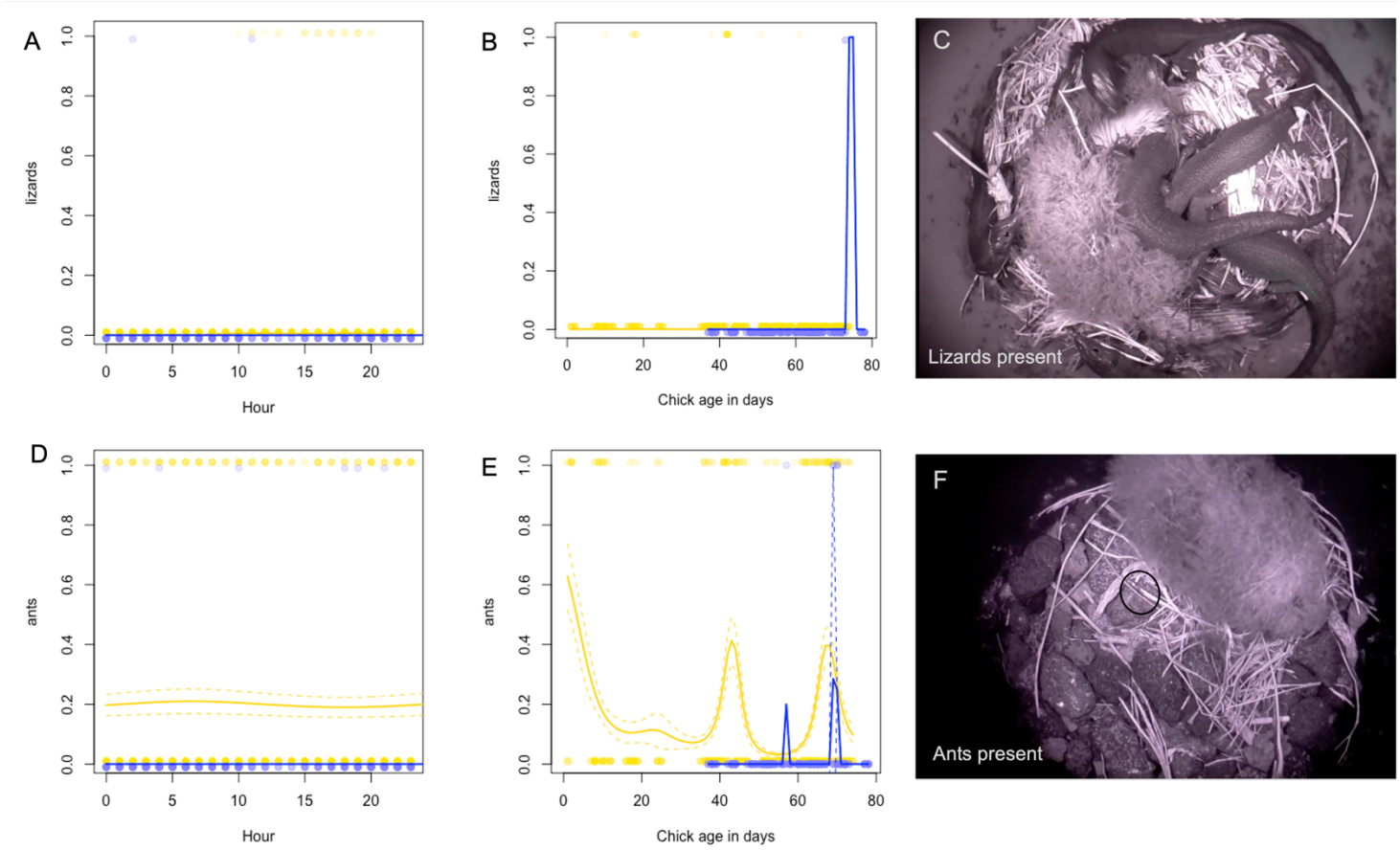


Figure 5.3. Daily and seasonal patterns of variation in species occurrences in the nests of Monteiro's storm petrel (*Hydrobates monteiroi*; yellow) and Band-rumped storm-petrel (*H. castro*; blue) across the 24-hour cycle and across the nestling period, with photos illustrating each type of event: A-C) lizards present, and D-F) ants present (note black circle in F denoting examples of where ants were). Fitted lines show the predictions from the GAM analyses of behaviour and species occurrences. The daily patterns detail the non-linear changes across 24-hours using chick age = 40 days and predictor lines for seasonal patterns detail the non-linear changes across the chick age at hour = 24. Dotted lines indicate standard errors. Hour of the day recorded as UTC. N = 19 Monteiro's storm-petrel chicks, N = 9 band-rumped storm-petrel nests.

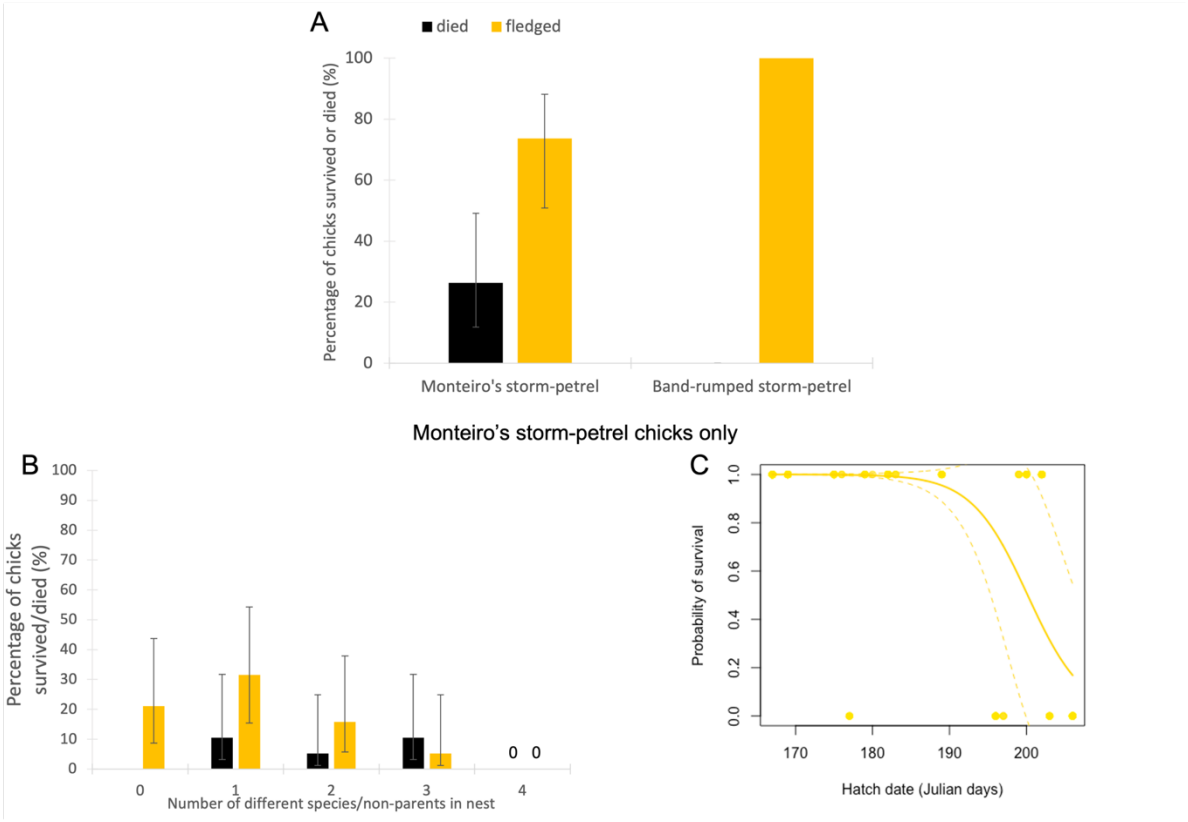


Figure 5.4. To aid in describing links between chick survival rates and "other taxa" present in the nest A) overall percentage of chicks monitored using in-nest cameras that survived or died from the Monteiro's storm-petrel 2019 and band-rumped storm-petrel 2019-2020 breeding seasons, B) percentage of different Monteiro's storm-petrel only, 2019 nests which had 0, 1, 2, 3 or 4 different species/taxa recorded in the nest via in-nest cameras deployed throughout the chick-rearing period. Error bars are Binomial error bars, computed using the online Bayesian calculator at: www.causascientia.org/math_stat/ProportionCI.html, C) Generalised Additive Mixed Model to explain the probability of Monteiro's storm-petrel chick only, survival in relation to hatch date (in Julian days, Julian Day 1 = 01 January 2019), each individual dot is a separate chick (n=19), and the predictor lines detail the non-linear changes in the probability of survival of Monteiro's storm-petrel chicks in relation to hatch date. Dotted lines indicate standard errors.

5.4. Discussion

For the first time we detail the circadian and seasonal patterns in adult nest attendance, chick behaviours and occurrences of other species in the nest cavity, during the chick-rearing period of two sympatric but allochronic storm-petrel species (Monteiro's storm-petrel and band-rumped storm-petrel) breeding in artificial nest boxes.

5.4.1. Adult nest attendance and feeding events

The adult nest attendance and chick feeding events identified give a snapshot view of some adult-chick behaviour interactions, although they were not commonly observed. This is unsurprising as during the chick-rearing period the parents are at sea during the day foraging, returning only briefly to feed their chick at night (Harris 1969; Warham 1990; Bolton et al. 2004; Brooke 2004) and so would frequently be missed on the hourly videos analysed. Monteiro's storm-petrel adults were more commonly observed in the nests compared to band-rumped storm-petrel adults. This is likely because, as detailed, only the latter half of the band-rumped storm-petrel breeding season (~ chick age 40+ days) was monitored in the present study, when there are likely to be fewer parent visitations but providing larger feeds, compared to earlier in the nestling period when the adults are brooding their chick and/or staying longer with their chick to provide more frequent but smaller feeds (Allan 1962; Hedd et al. 2002; Mauck and Ricklefs 2005).

In addition, the few adult nest attendances identified in our analysis indicate that the final observed peak in the seasonal pattern of adult attendance is earlier in the Monteiro's storm-petrel breeding season compared to that of the band-rumped storm-petrel. This could be attributed to a slower growth rate of the band-rumped storm-petrel chicks, as similarly seen by Harris (1969), where the winter season chicks took significantly longer to grow and consequently longer to fledge. Furthermore, in the present study the adults of both species left their nest before dawn and band-rumped storm-petrel adults arrived after dusk, typical of other storm-petrels (Harris 1969; Boersma et al. 1980; see further details and analysis on adult nest attendance in Chapter 6). However, it is harder to extract the arrival times for Monteiro's storm-petrel adults from this video analysis graph (Figure 5.2A) because they sometimes remained in the nest during the day to brood their chick. Whilst the lack of Monteiro's storm-petrel adults from 5am and then presence in the nest from

10am could at first sight indicate day-time arrivals, it is more likely due to an artifact caused by the nature and timing of the camera removals and re-deployments. These i) occurred, typically, 10am-12noon, and ii) were opportunistic across the sub-set of available nests and so they could be removed from a nest where the chick was alone, and re-deployed onto a different nest which had an adult in it, thus causing this artifact in the data. This artifact would occur regardless of camera deployment time, because it would often be the case that the cameras were moved between nests with or without an adult present at the time. The daytime adult presences all occurred during the Monteiro's storm-petrel camera deployments; one was during chick-brooding, when the adults typically remain in the nest during the day (Allan, 1962; Harris, 1969). However, the remaining two occurrences were for chicks aged 40 and 43 days. The 40-day old chick rapidly lost weight (within three days prior to death), this is when the parent stayed with the chick during the day (this is the chick death that was captured on video, and described in the results as seemingly natural, although pecking by a band-rumped storm-petrel was also suspected). In contrast, for the 43-day old chick, the adult present was known to be a band-rumped storm-petrel. This phenomenon of band-rumped storm-petrels inspecting nest sites at the end of the Monteiro's breeding season, has previously been observed, although not frequently (Bolton et al. 2008).

For these hourly videos analysed, chick feeding events were not commonly observed for either species. However, as expected those observed always occurred at night and the last observed chick feeding event was around the same chick age for both species (49 and 50 days old), despite the slightly longer chick rearing season for band-rumped storm-petrels (Monteiro and Furness 1998). The longer chick rearing season for the band-rumped storm-petrels is likely due to the slower growth of the typically larger band-rumped storm-petrel chicks, which may be an adaptation to cope with the cooler temperatures of the winter breeding season (Harris 1969). The lag between these last observed chick feeds and their fledging is similarly found in Leach's storm-petrel (*H. leucorhous;* Mauck and Ricklefs, 2005) and band-rumped storm-petrels breeding in the Pacific (Galápagos; Harris 1969) where, near to fledging, the adults no longer - or less frequently - feed their chick, causing the chick to use up its stored fat reserves in order to become light enough to fledge.

These results indicate that viewing 30 s videos recorded every hour is an effective way to analyse video data to identify diel routines of behaviour. Further continuous-time analysis (e.g. examining continuous footage in fast-forward mode) would be needed to gain a more detailed picture of adult arrival and departure times and chick feeding event occurrences and durations (Hereward et al. [in prep].; Chapter 6). The number of feeds per night and duration of feeds could then be compared to chick mass growth rates and fledging success.

5.4.2. Chick behaviours

Due to there being few adult nest attendance events in the videos analysed, the majority of the behaviours exhibited were consequently behaviours performed by the chick alone. The higher likelihood of band-rumped storm-petrel chicks to sleep compared to the Monteiro's storm-petrel chicks may be due to average temperatures being ~5-10 °C lower during the band-rumped storm-petrel breeding season compared to the Monteiro's storm-petrel breeding season and thus band-rumped storm-petrels may sleep more to conserve energy (Figure 5.2J-L; Chapter 2, Figure 2.2; Monteiro and Furness 1998). In some circumstances this could lead to the chicks going into "torpor" to conserve energy (cf. Boersma 1986; Watson 2013; Kuepper et al. 2018). Furthermore, the ambient temperature is also likely to influence the 24-hour temporal variations in behaviour (Boersma 1986; Monteiro and Furness 1998). This is especially likely for the Monteiro's storm-petrel chicks, which primarily rested in the middle of the day, when the ambient temperature outside the nest box could reach up to 25°C (Chapter 2, Figure 2.2). The increase in sleeping was also seen with increasing chick age, showing (possible) increases in sleeping and preening compared to sitting, prior to fledging, possibly as a response to physiological shifts prior to fledging as seen in Leach's storm-petrel (Mauck and Ricklefs 2005), alongside increased preening prior to fledging (Boersma et al. 1980). Another impact on these different behaviours is the feather growth from chick down to adult plumage (Allan 1962). This feather growth happens in stages and is likely to increase the likelihood of sleeping (to allow energy to be converted into feather building) and preening (as the feathers grow, they are likely to be uncomfortable, and preening will help remove down and remove the waxy sheaths of maturing feathers; Boersma et al. 1980).

A further impact on the preening behaviour could be the presence of ants. Occasionally ants were noted to be on the chick (when preening behaviour occurred) as well as passing through the nest (see below). The presence of ants could potentially increase the level of preening by the chick (Plentovich et al. 2009; Flores et al. 2017), although this was hard to detect in the videos due to the small size of the ants, and is unlikely to be the case for the band-rumped storm-petrel breeding season, where preening behaviour was more frequently observed but ant occurrences were lower.

5.4.3. Occurrence of non-parent storm-petrels and other taxa

5.4.3.1. Behaviours

The analysis of temporal changes across 24-hours and across the nestling period are useful as they can inform us about indirect and/or sub-lethal impacts of potential threats (Thiébot et al. 2014; Flores et al. 2017; Stolpmann et al. 2019). There were various non-parent storm-petrels or other taxa occurrences in the nests. In some instances, they were recorded as directly interacting with the adult/chick (Cory's shearwaters, non-parent storm-petrels, Madeiran wall lizards, ants) and in other instances they just occurred in the nest at the same time as the storm-petrel adult/chick without appearing to interact (Madeiran wall lizards, ants). These were all more prevalent during the summer Monteiro's storm-petrel breeding season, compared to the winter band-rumped storm-petrel breeding season. This is likely to be due partly to there being more species and individuals available to interact during the Summer (and warmer), Monteiro's storm-petrel breeding season compared to the cooler band-rumped storm-petrel breeding season, and so more interspecies interactions were observed (Chapter 2, Figure 2.2; Harris 1969; Monteiro and Furness 1998; Fischer et al. 2019). Barolo shearwaters (*Puffinus baroli*) are present during the band-rumped storm-petrel breeding season and at the beginning of the Monteiro's storm-petrel breeding season, but no Barolo shearwaters were observed in the videos analysed for this Chapter.

The Cory's shearwater direct interaction was between a newly hatched Monteiro's storm-petrel chick and a Cory's shearwater adult. The Cory's shearwater was observed putting its head into the nest and picking up the Monteiro's storm-petrel chick in its bill; this is unusual behaviour, and Ramos et al. (1997) describe such storm-petrel – Cory's shearwater incidents as

"accidental". The Monteiro's storm-petrel chick was freshly hatched, and the parent storm-petrel was chased out of the nest during the incident. It is possible that the chick calling, or the smell of a freshly hatched chick, attracted the attention of this Cory's shearwater.

The videos showing Madeiran wall lizard presence revealed no direct interactions with storm-petrel adults, or with live chicks, across both storm-petrel species. It is possible that the Madeiran wall lizards on Ilhéu da Praia typically use the artificial storm-petrel burrows in a similar way to the tuatara (*Sphenodon punctatus*) in New Zealand - by using the burrows as shelter from extreme temperatures (Markwell 1998; Corkery et al. 2014; Fischer et al. 2019). However, an event was recorded of a Monteiro's chick dying (seemingly) from natural causes, and subsequently being eaten by lizards, demonstrating that the lizards are opportunistic scavengers on dead storm-petrels, and also aid in keeping the nest burrows clean. This interaction has been suggested to occur for the Bermuda skink (*Plestiodon longirostris*) in the nests of Bermuda petrel (*Pterodroma cahow*; Madeiros 2005; Turner et al. 2021) and has been similarly suggested for tuatara in the nests of fairy prions (*Pachyptila turtur*; Walls 1978; Fischer et al. 2019). Nevertheless, the lack of direct interactions between lizards and live storm-petrels on Ilhéu da Praia observed in the videos analysed was surprising, as other authors (Matias et al. 2009; Neves et al. 2017) have observed Madeiran wall lizards dragging storm-petrel chicks out of nests. Due to this difference, additional videos to those described in this Chapter, were watched to clarify these interactions. While no direct lizard-chick interactions were observed, during the incubation period an incubating adult Monteiro's storm-petrel chased a lizard out of the nest. Furthermore, there were instances of lizards breaking and eating Monteiro's storm-petrel eggs (HFRH personal observations).

Observations of the various ant species known to be present on Ilhéu da Praia were pooled together into an ant presence-absence variable. The peak in ant presence in the nests prior to (and just after) chick fledging events could imply that they aid in nest sanitation by consuming nest ectoparasites, as has previously been observed in songbird nests (Maziarz et al. 2020). A similar potentially beneficial interaction with ants involves "anting" behaviour, where birds purposefully allow ants onto their feathers to aid in removing ectoparasites (Clayton and Vernon 1993). Furthermore, previous studies have described associations between bird nests and ants, due to the ambient heat

given off from nests (Maziarz et al. 2020). While the videos analysed did not confirm chick deaths directly caused by ants; one chick death was directly attributed to ant depredation (based on the nest check notes as described in the results section), and so it is important to view these results in the context of previous seabird studies which have reported both positive and negative impacts of ants on chick survival and overall breeding success (Plentovich et al. 2009; DeFisher and Bonter 2013; Flores et al. 2017; Mejías et al. 2017).

A further factor to consider for interpreting the impacts of both the Madeiran wall lizards and the ants is the seasonal temperature variation, as lizards and ants were more commonly observed in the nests during the Monteiro's storm-petrel breeding season compared to the band-rumped storm-petrel breeding season. This is likely due to these heterothermic (lizards) and ectothermic taxa (ants) being more active with increased temperature, i.e. during the hot season when Monteiro's storm-petrels breed (Chapter 2, Figure 2.2; Markwell 1998; Corkery et al. 2014; Fischer et al. 2019; Maziarz et al. 2020).

Finally, although not separated in the adult nest attendance and behaviour analysis in this Chapter, some of the adult presences during the Monteiro's storm-petrel breeding season could be attributed to non-parent Monteiro's storm-petrels, or early-arriving band-rumped storm-petrel adults inspecting nests. This was known from reading adult ring numbers at the time of camera deployment, retrieval and/or night-time nest inspections as part of other aspects of fieldwork. This interspecific interaction was previously described as the "sharing" of nests during the day by Bolton et al. (2008), and has been occasionally noted in other species that have hot and cool season breeding populations that use the same nests at different times of year (Galápagos; Harris 1969). While no direct pecking of Monteiro's storm-petrel chicks by adult band-rumped storm-petrels was recorded on video, there were two adult-chick behaviours described from additional video analysis that were more exaggerated than the usual interactions between known parent storm-petrels and their chicks (these were adult-preening-chick and adult-brooding-chick behaviours, where it appeared that the adult was stamping on the chick). Further video recordings and analysis of known Monteiro's storm-petrel chick – adult band-rumped storm-petrel interactions would be needed to clarify these anecdotal observations. These remote video observations, paired with *ad hoc* direct observations during day- and night-time fieldwork indicated that the head wounds on some of the chicks and chick down feathers observed

on adults, were likely to have been connected to adults pecking the chicks. Chicks with these head wounds in other storm-petrel breeding colonies have previously been described as "mohawks" and suspected to be the victims of interactions with other bird species (Allan 1962; Harris 1969). However, further video analysis and *in situ* nest monitoring will be needed, to assess more comprehensively the impact of these interactions on the Monteiro's storm-petrel chicks.

5.4.3.2. Conservation implications

The chances of observing an actual depredation or mortality when viewing one 30 s video per hour are low, due to the short sampling time. Despite this, one chick death was caught on camera, which was a seemingly natural death, and consequently the cause of death remains unclear (although suggestions are made in this Chapter's results section). However, there are many factors influencing the likelihood of breeding success and/or chick survival – including parental incubation and provisioning effort, food availability and nest site characteristics, as well as threats from predators and parasites (General Introduction, Table 1.1; Michielsen et al. 2019). Predator impacts include direct predation and indirect effects (Table 5.1; Thiébot et al. 2014; Flores et al. 2017). Such impacts were most frequent in the present study for the Monteiro's storm-petrel, where chick deaths often occurred in nests where one or more predator/threat taxon was observed to be present, whereas no deaths occurred in nests where no such threats were recorded (Figure 5.4B). However, there was no detectable effect of lizard and ant presence on survival rate for this relatively small sub-set of nests, and so we recommend a broader analysis of these species presences across all nests studied, to assess these possible impacts at the population level (See Chapter 3 and Hereward et al. in prep.; Neves et al. [in prep.]). Further analysis of the geographical distribution of the different threats could be conducted to identify possible threat "hot spots" on the islet, through using the daily nest check species occurrence data (HFRH unpublished data). Nevertheless, the chick survival probability for the Monteiro's storm-petrel chicks significantly decreased with later hatch dates. While this is likely due to the variety of factors influencing breeding success rates (Michielsen et al. 2019), one of these is the arrival of the prospecting band-rumped storm-petrel adults, as already discussed (Harris 1969; Bolton et al. 2008). The relationship between hatch date and fledging success

(regardless of camera deployments) across all chicks has been further discussed in Chapter 3.

These survival results and insights into the causal mechanisms have implications for the design of conservation strategies to maximise the long-term breeding success and survival of the Monteiro's storm-petrel, given that it already has a restricted and small breeding population (BirdLife International 2018b). I suggest further analysis encompassing all of the nests where breeding attempts occurred, alongside more detailed surveys to assess the full impact of the non-parent storm-petrels and other taxa on breeding success (Chapter 3 and Hereward et al. [in prep].). It is likely that further conservation management of the breeding area will need to be considered to potentially reduce these lethal and non-lethal but harmful interactions, as has previously been done for other seabird colonies (Amaral et al. 2010; Ratcliffe et al. 2010; Libois et al. 2012; Binny et al. 2021) and previously on Ilhéu da Praia by the eradication of rabbits and the deployment of artificial nest boxes (Chapter 7, General Discussion; Bried et al. 2009; Bried and Neves 2015).

5.4.4. Conclusion

Here we present a workflow and case study for describing temporal patterns in the chick-rearing behaviours and potential threats to two sympatric, allochronic storm-petrel species. Behaviours and threats varied diurnally and seasonally, and video monitoring is an effective way of quantifying that variation. These data describe variations that likely influence chick provisioning and growth. The implications of interactions with non-parent storm-petrels and other taxa, and the association between later hatch dates and reduced chick survival, shed light on possible causes of breeding failure at the egg and nestling stages, which informs conservation management, especially for the endemic Monteiro's storm-petrel (Oliveira 2016; BirdLife International 2022c; Chapter 7, General Discussion). The workflow analysis conducted here could easily be extrapolated to other species where camera monitoring is already used, or could be implemented, in order to further the knowledge of different behaviours and shed light on possible threats which could aid the conservation of the species.

Chapter 6.

Assessing Chick Growth and Parental Provisioning Strategies of two Sympatric Burrow Nesting Seabirds, Through Traditional and Novel Monitoring Techniques - A Proof-of-Concept Study

This chapter is in prep. for submission for publication.

Photographs: top left (chick being weighed; Ben Porter), top right), (a video still of an adult and chick in the nest; Hannah Hereward), bottom left (alternative picture of bespoke nest camera deployed on artificial nest; Hannah Hereward), bottom right (Hannah Hereward holding a successfully retrieved GPS tag and band-rumped storm-petrel; Ben Porter).

Summary

Technological innovations are being increasingly combined with traditional methodologies to identify conservation problems and aid in finding solutions. Here I present a case study to combine traditional nest monitoring techniques with novel techniques for studying two sibling species of storm-petrels of current conservation concern in the Azores, Portugal.

This study follows two example nests per species (band-rumped storm-petrel, *Hydrobates castro*, 2019-2020 breeding season and the endemic Monteiro's storm-petrel *H*. *monteiroi*, 2020 breeding season). Specific methods included daily nest checks and chick weighing, cameras inside and outside nest cavities, and GPS tracking of adults. Chick growth curves were compiled and mass change was examined for dates on which the technology deployments provided behavioural information. Within-nest videos were watched in fast-forward mode until footage of returning adults was identified. Then, all footage of adult-chick interactions was watched at real-time speed. GPS tracks were analysed individually using Expectation-Maximisation Binary Clustering to classify different behavioural states, and the percentage of fixes classified as foraging was estimated and their locations mapped.

The chick growth curves followed the three-stage pattern typical of storm-petrels (initial growth, plateau and mass loss stages). Cameras inside/outside nest cavities were deployed successfully 27 times across all four nests monitored, and attendance events were recorded which included feeding events. Daily mass change of the chicks identified that body mass increased after nights with all-bar-short feeding events, but decreased after nights without feeds (either due to the adults not returning, or not feeding the chick). For the first time I record an adult band-rumped storm-petrel feeding a Monteiro's storm-petrel chick.

This chapter provides a proof-of-concept case-study of how the combination of multiple monitoring approaches can further the knowledge of behaviours on land and at sea, and provide important information relevant to the conservation of these sibling species of storm-petrel in the Azores, with wide application to other systems.

6.1. Introduction

Traditional ecological methods can be combined with technological innovations, to identify conservation problems and aid in finding solutions (Marvin et al. 2016). Technology can both aid in automating data collection for long-term monitoring of species and habitats, alongside collecting novel types of data to expand the current knowledge of ecological systems (Pimm et al. 2015; Allan et al. 2018). This has meant that research questions can be expanded from isolated recordings of an individual's location or a behavioural snapshot, to remotely detailing species movements and monitoring behaviours (e.g. Gladbach et al. 2009a; Sugishita et al. 2015; Garriga et al. 2016; Rotger et al. 2020; Bolton 2021; Hereward et al. 2021; Chapters 4 and 5). Such approaches can aid in identifying habitat usage, potential threats, and factors influencing breeding productivity (Marvin et al. 2016). The results of these studies can contribute to biodiversity conservation efforts, e.g. to mitigate the impacts of climate change and habitat loss on the long-term survival and breeding success of the focal species (Pimm et al. 2015; Allan et al. 2018).

Avian breeding success and longevity are influenced by a variety of climatic and trophic factors, including threats from predators and parasites, parental incubation and provisioning effort, food availability and nest site characteristics (Chapter 1, Table 1.1; Michielsen et al. 2019). For seabirds (which are considered to be one of the most threatened avian groups globally, the top three threats to their survival are invasive alien species, fisheries by-catch and climate change/severe weather events (Croxall et al. 2012; Dias et al. 2019). Seabirds are also known to be "ecosystem sentinels", whereby a change to a seabird population can indicate unseen changes in the environment, e.g. pollution events (Mallory et al. 2010; Sydeman et al. 2021) and consequently are a useful group to study for monitoring the overall state of marine ecosystems. Traditionally, seabird breeding success is monitored through manual nest monitoring, to determine chick growth rates. This is usually done by recording mass changes of individual chicks by taking frequent measurements throughout their time in the nest (Ricklefs et al. 1985; Granadeiro et al. 1999; Gladbach et al. 2009b). These mass changes can be used to infer adult provisioning rates (Williams and DeLeon 2020). Manual nest monitoring also contributes to determining hatching success and fledging success, which together comprise overall breeding success (Allan 1962; Harris 1969; Gladbach et al. 2009a). However, by only using these traditional nest

monitoring techniques many of the variables identified above as impacting breeding success and survival, are left un-measured. Therefore, in order to fully understand the impacts of these factors influencing seabird breeding success, survival and population change, traditional techniques are being increasingly combined with novel technologies (e.g. Gladbach et al. 2009a,b; Sugishita et al. 2015,2017; Fayet et al. 2021).

Novel technologies, such as the use of automatic weighing balances inside nests, enhance traditional monitoring of chick growth by manual nest checks, as they give more frequent readings and generally require less time in the field to install and download (e.g. Phillips and Hamer 2000; Hedd et al. 2002; Sugishita et al. 2017). Likewise, cameras inside and outside nest cavities are increasingly being used to monitor nest attendance and other behaviours, as they reduce the amount of human presence/interference during nest monitoring, whilst providing more detailed levels of data (Cutler and Swann 1999; Sugishita et al. 2017). Specifically, cameras provide opportunities to (i) detail adult nest attendance rates (Sugishita et al. 2017) (sometimes used as a proxy for provisioning rates; Williams and DeLeon 2020), (ii) describe behaviours at the nest, e.g. adult-chick interactions, and chick behaviours when alone in the nest (Hereward et al. [in prep.]; Chapter 5), (iii) monitor potential threats and their impacts on eggs and chicks (Stolpmann et al. 2019; Hereward et al. 2021), and (iv) identify sex specific feeding rates/parental investment (e.g. Gladbach et al. 2009a). Finally, GPS tracking has been used on its own (Guilford et al. 2008; Afán et al. 2014; Rotger et al. 2020; Bolton 2021) and in tandem with these other technologies (Sugishita et al. 2015; Fayet et al. 2021) to assess the overlap of foraging ranges with fisheries, impacts of severe storms, at-sea habitat preferences, foraging techniques and habitat quality, and to compare these to the quantity of food delivered (via automatic weighing scales and/or nest cameras).

Here I present a case study to combine traditional nest monitoring techniques with novel techniques, through comparing the sympatric but allochronic breeding species of storm-petrel of the Azores - the endemic Monteiro's storm-petrel (*Hydrobates monteiroi*) and its more widespread sibling species, the band-rumped storm-petrel (*Hydrobates castro*). I assess the behaviour at sea and the behaviours in and near the nest related to chick growth, discuss the effectiveness of this combined approach through examples for future adaptations and address conservation implications which will be further developed and discussed in the General Discussion Chapter (Chapter 7).

Specifically, I combined: 1) Traditional nest monitoring techniques to monitor chick mass change between chick feeding events, and across the nestling period. 2) Cameras inside the nest cavity, to identify adult-chick interactions (including numbers and duration of feeding bouts). 3) Cameras outside the nest cavity to determine the timing of fledging and associated behaviours. 4) GPS tracking of parent birds, to identify the timing, duration and location of foraging at sea, through mapping of GPS fixes and analysis of flight speed and turning angle between location fixes (Figure 6.1).

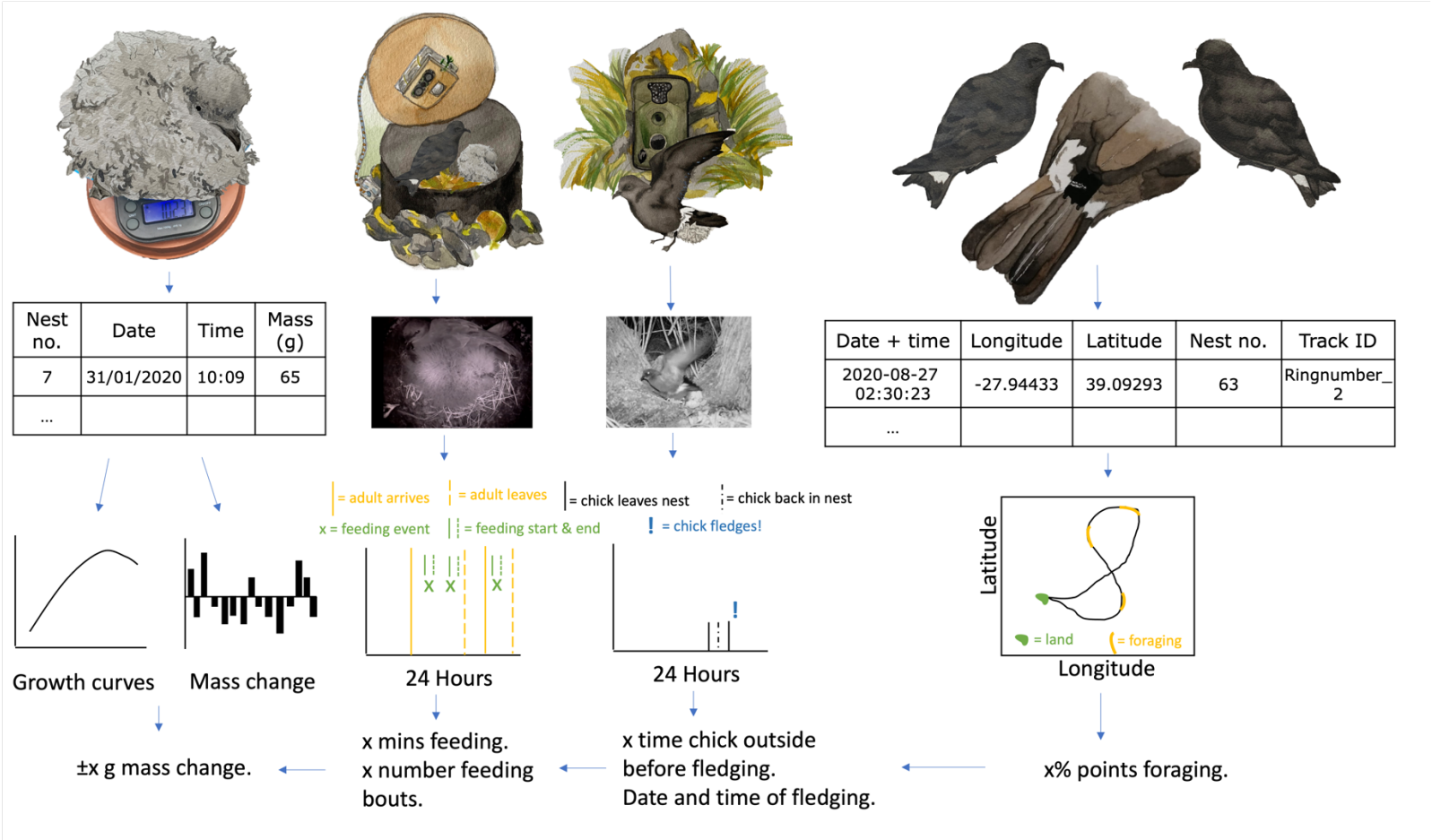


Figure 6.1. Schematic detailing the combinations of traditional and technological monitoring techniques for breeding storm-petrels. A) Mass change through daily weight measurements; B) in-nest cameras to identify feeding bouts and duration and C) near-nest cameras to identify time spent outside the nest by the chick and fledging events; D) GPS tracking of parent adults recording departure and arrival times and at-sea behaviours. Artwork: Sarah Long, Seafarer Sarah Artwork.

6.2. Methods

6.2.1. Study site and overview of methods

The two sibling species of storm-petrels were studied in artificial nest boxes, which were originally deployed in the early 2000s (Bolton et al. 2004), on Ilhéu da Praia, a 12 ha islet, off Graciosa, Azores, Portugal (Bolton et al. 2004; Bried et al. 2009; Hereward et al. 2021; Long et al. 2021). Fieldwork was conducted over one breeding season each, for the Monteiro's storm-petrels (June-September 2020) and for the band-rumped storm-petrels (August 2019-March 2020). See General Methods (Chapter 2) for full details.

6.2.2. Fieldwork

6.2.2.1. Daily nest checks

Daily nest checks were conducted throughout each of the breeding seasons to monitor the nesting activity/stage (see Chapter 2 for details), following similar protocols to Bolton et al. (2004) and Monteiro and Furness (1998). Once an egg hatched, the chick body mass was measured daily when fieldwork conditions allowed (typically mid-morning) using a pan balance ("AccuWeight" scale, accurate to 0.1g; www.accuweigh.co.uk).

6.2.2.2. GPS tracking

Following similar protocol to Bolton (2021), GPS tracking of the parent storm-petrels was conducted opportunistically during the chick-rearing period. Individuals were selected to be tracked based upon the breeding biology information gathered from the daily nest checks (e.g. egg laid/chick hatched dates and matched with video-monitoring of nests; tracking methods specific to the Azores are detailed in Neves et al. [in prep.]). Pathtrack GPS tags (www.pathtrack.co.uk) were set to record the bird's location every 30 minutes (except Nest 7, Female = 1 hr intervals). They were deployed on a staggered basis, to ensure that all birds were re-trapped within an appropriate amount of time to ensure tag retrieval (i.e. ~ 5-7 days following deployment during chick rearing). Following Bolton (2021), one tag per individual was attached to the central tail feathers using Tesa-tape (www.tesa.com/en-gb). During the chick-rearing period the adults only return to their nests at night, and so the adults were caught in the nest using a one-way trap-door mechanism at the nest entrance. The trap-door retained the adult(s) that had returned to feed the chick during the night, until they were extracted from the nest. The GPS tag was deployed on appropriate adults captured using this method, and retrieved

during subsequent nightly vigils, where the focal nests were checked every 20-30 mins throughout the night. Before and after tag deployment, the adult's body mass was recorded.

6.2.2.3. Camera deployments

Bespoke Raspberry Pi based cameras (Hereward et al. 2021; Chapter 4) were deployed inside nest cavities, alongside commercially-built trail cameras (Acorn Ltl 5210A), deployed outside the nest. Deployment decisions were based upon which nests cameras could be safely installed at, as well as the breeding stage and concurrent GPS tag deployments. This allowed for footage of the GPS tagged adult departures/arrivals to be recorded on camera, as well as chick fledging events. Camera build methods are detailed in Hereward et al. (2021) and in Chapter 4, and initial camera deployment results are detailed in Hereward et al. [in prep.] (Chapter 5).

6.2.3. Video analysis

As described in Chapter 5, all videos were analysed using ethograms designed for in-nest or near-nest footage. Following on from this video analysis (i.e. one 30 s video every hour), in-nest videos were watched in fast-forward mode, until footage of returning adults was identified. Then, all adult-chick footage was watched at real-time speed, to determine (i) adult arrival and departure times, and (ii) the number and duration of feeding bouts. Footage from outside the nest was analysed to identify (i) chick pre-fledging behaviours and (ii) chick fledging events/timings.

6.2.4. Statistical analyses

All statistical analyses were carried out using the statistical software R 4.0.2 (R Core Team 2020) and implemented in *RStudio* version 1.3.1093 (RStudio Team 2020). All times and dates were corrected to UTC time (where in the Azores: 28th October 2019 – 28th March 2020 = UTC-1hr i.e. Band-rumped storm-petrel breeding season, and 29th March – 25th October 2020 = UTC+0hr i.e. Monteiro's storm-petrel breeding season).

6.2.4.1. Chick growth curves

For each nest, chick age in days was calculated in relation to the hatch date (chick age day 1 = day chick emerges from the egg; Chapter 2). The chick mass data were analysed using Generalised Additive Models (GAMs), using a

gamma error family and "log" function, implemented with the "mgcv" package (v1.8-31; Wood 2003; Wood 2017). Chick age in days was smoothed using the default "thin plate regression spline" method. A separate GAM model was used for each chick, to calculate the individual's growth curve. Where possible, daily mass change was also calculated, by finding the difference between the mass readings obtained at 24-hour intervals.

6.2.4.2. Video analysis

From the in-nest footage, adult attendance events were analysed to record the timing and duration of feeding bouts. These camera deployments, adult attendance (including GPS-tracked adults), feeding behaviours and fledging events were plotted onto the growth curve graphs to aid visual interpretation.

6.2.4.3. GPS tracks

The GPS tracks were analysed track-by-track, using Expectation-Maximisation Binary Clustering (EMbC; Garriga et al. 2016; Garriga and Bartumeus 2019), to identify the location and number of fixes classified as foraging-type movement patterns. Foraging locations were defined as any points classified as (i) Low speed and high turning angle = LH = "intensive search", or (ii) high speed, and high turning angle = HH, "extensive search" (following De Pascalis et al. 2020). No post-processing smoothing was conducted (post-processing smoothing picks out single points that have different behavioural states to their neighbours and assesses if the currently labelled behaviour state is deemed temporally appropriate), as the interval between the fixes is much longer than storm-petrel transitions of behaviours observed at sea (many observed transitions between behaviours over a 15min period, e.g. Lee 1984; Haney 1985).

6.3. Results

6.3.1. Technical results

Due to fieldwork constraints, mass change was not always possible to calculate, but, for the nests where GPS tags and cameras were combined with body mass measurements, only one mass change is missing (Nest 7, on 2/2/2020). Of the 28 camera deployments, only one deployment failed (Hereward et al. 2021; Chapter 4), the remaining 27 were successful (see descriptions in Hereward et al. 2021 and Chapter 4). All of the five GPS tags deployed were successfully recovered. However, the added technicalities of aligning camera deployments with GPS-tracked parent storm-petrels was harder, especially at the end of the band-rumped storm-petrel breeding season, where the GPS tags did not always successfully record downloadable tracks. Consequently, the band-rumped storm-petrel at-sea behaviours identified from the GPS data are harder to directly compare with the behaviours at the nest and chick mass change than is the case for the Monteiro's storm-petrels. New GPS tags were used in the subsequent 2020 Monteiro's storm-petrel season, which avoided this issue and returned complete tracks.

6.3.2. Biological results

The chick growth curves presented here follow the typical three-stage shape described in Chapter 3, comprising an initial increase in mass (chick age: ~ days 0-20), before a plateau stage of relatively stable body mass (chick age: ~ days 20-60) and then a decrease in mass ahead of fledging (chick age: ~ days 60-70) (Figure 6.2; for overall season graphs see Chapter 3; Hereward et al. [in prep.]). The two Monteiro's storm-petrel growth curves do not depict this final stage of mass loss, due to fieldwork constraints (Covid-19 evacuation from the islet) curtailing the monitoring period.

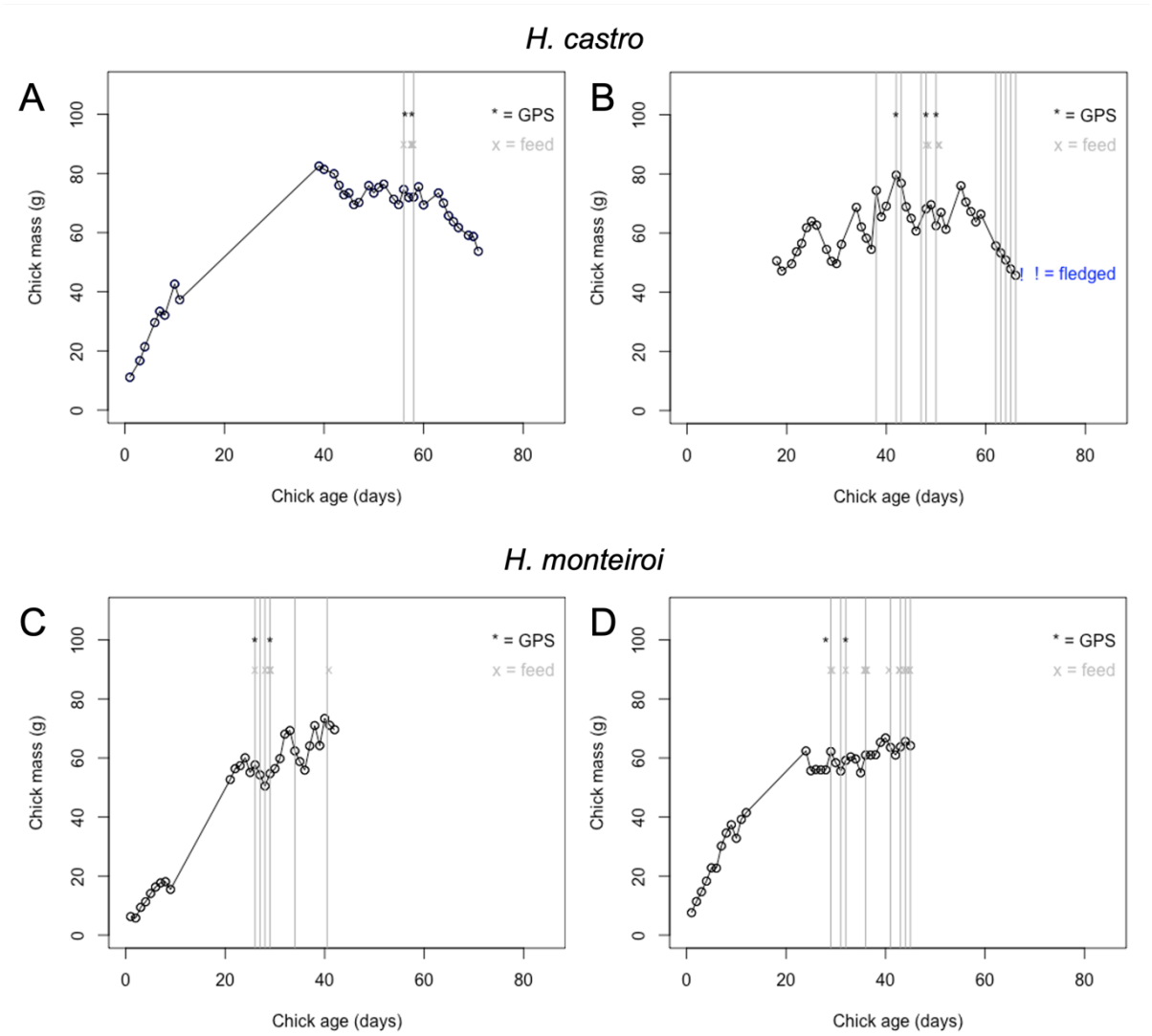


Figure 6.2. Growth curves of all four chicks. band-rumped storm-petrels 2019-2020, A) Nest 4 (Estimated hatch date: 27/11/2019), B) Nest 7 (Hatch date range: 7/12/2019-4/1/2020 but estimated from average growth curves to be: 18/12/2019) and Monteiro's storm-petrels 2020, C) Nest 63 (Estimated hatch date: 02/08/2020) and D) Nest 89 (Estimated hatch date: 30/07/2020). Vertical grey lines denote a camera deployment. * = GPS adult in nest. x = feeding bout event, ! = fledging event.

Cameras inside/outside nest cavities were deployed successfully 27 times (13 times in band-rumped storm-petrel nests: two = Nest 4, 11 = Nest 7; and 14 times in Monteiro's storm-petrel nests: six = Nest 63, eight = Nest 89; see vertical grey lines in Figure 6.2; Hereward et al. 2021).

For the two band-rumped storm-petrel nests, a total of six adult attendance events occurred, across both deployments in Nest 4, and in four of the deployments for Nest 7. The mean length of time (hours:minutes:seconds) that an adult storm-petrel stayed in the nest was 00:41:05 (min = 00:14:07, max = 06:23:40). During these six visits, on only one occasion was no feeding event captured on video (duration of this visit with no feeding was 01:23:55). During the remaining five visits, between one and four bouts of chick-feeding occurred per visitation (n=9, average = 00:03:00, min = 00:00:31, max = 00:07:26). These chicks were of a similar age; in Nest 4 the chick was 56-58 days old and in Nest 7 the chick was 42-66 days old.

By contrast, for the two Monteiro's storm-petrel nests, a total of six attendance events were recorded for Nest 63 across three of the camera deployments, and a total of 47 attendance events were recorded for Nest 89 across all eight camera deployments. However, whilst it is clear from the videos that one or more adults attended the chicks on most nights (where cameras were deployed inside the nest cavity) these include suspected non-parent and/or known band-rumped storm-petrel adults, as well as the parent Monteiro's storm-petrels themselves. The average length of time that a known/suspected parent remained with the chick was 00:52:48 (min = 00:02:15, max = 02:38:00; note this time in the nest is likely extended due to the trap door). In comparison, the average time that a non-parent/known band-rumped storm-petrel remained in the nest was 01:25:29 (min = 00:03:17, max = 14:45:44). During these visits, on only one occasion was there no observed feeding event. Consequently, during the remaining 10 deployments a total of 22 feeding bouts were observed, with a maximum of two feeding bouts per visitation but typically only one. I documented non-parent adults feeding chicks (where feeding behaviour was observed between a known band-rumped storm-petrel adult identified via ring number and the resident Monteiro's storm-petrel chick in the nest), but the average feeding duration was similar for both parent and non-parent adults (parent: average = 00:02:32, min = 00:00:41, max = 00:08:37. non-parent: average = 00:02:10, min = 00:00:40, max = 00:06:36). The monitored Monteiro's

storm-petrel chicks were a similar age to each other, but slightly younger than the monitored band-rumped storm-petrel chicks. In Nest 63 the chick was 26-41 days old and for Nest 89, 28-45 days old.

For four of the band-rumped storm-petrel feeding events, a daily change in mass could be calculated, and all four had positive increases in mass the day after feeding event(s) (average = 2.8g, min = 0.1g, max = 5.1g). On deployment nights where there were no adult visits/feeding events, the mass decreased by the following day (average = -4.5g, min = -2.2g, max = -8.9g). For the Monteiro's storm-petrel feeding events, a daily change in mass could be calculated for all 10 feeding visits. For Monteiro's storm-petrel parent-chick feeds there was a mean increase of 2.9g (min = -2.3g, max = 6.2g), although one night there was only one short feeding event (00:00:41) leading to a decrease in mass the following day. For non-parent feeds, there was a mean increase of 1.2g, however on two occasions where only short feeding events occurred (00:00:43 and 00:00:45 + 00:00:40), this led to decreases in mass the following day (of -3.2g and -1.4g). Furthermore, during deployments where no feeds occurred but non-parent adults were present, a decrease in mass was also recorded the next day (-3.1g). Similarly, where no adults visited the nest, decreases in mass were recorded the following day (average = -4.7g, min = -3.4g, max = -6.9g).

External trail cameras were deployed on seven occasions (three during the band-rumped storm-petrel season near Nest 7, and four during the Monteiro's storm-petrel season, twice near both nests). For Nest 7, the behaviours recorded included wing exercising which increasingly occurred in the last few days before the chick fledged. This camera also aided in identifying the exact date and time that the chick fledged from the nest (Nest 7 chick, fledged at 20:42 UTC on 21st February 2020). Of the four external camera deployments during the Monteiro's storm-petrel season, only one camera was triggered once, where it matched with the internal cameras - recording a non-parent adult going in and out of the nest (the ring number was checked during a night-time nest check).

Across the four nests followed in this case study, nine camera deployments captured the presence of the GPS-tracked parents. Five of these included GPS-tracked adults returning from a foraging trip and the subsequent feeding events (three = band-rumped, two = Monteiro's). However, due to incomplete

GPS tracks returned from the band-rumped storm-petrel deployments, the tracks do not overlap with the camera deployment and GPS tag retrieval (despite the successful camera deployments). Nevertheless, an estimated amount of foraging can still be calculated for the tracks available: Nest 4 female parent adult spent a total of 29 fixes, 21.48% of the total trip, foraging (12 fixes, 8.89% of the total trip intensive searching, LH; 17 fixes, 12.59% of the total trip extensive searching, HH), Nest 7 male parent adult spent 17 fixes, 19.77% of the total trip foraging (6 fixes, 6.98% of the total trip intensive searching, LH; 11 fixes; 12.79% of the total trip extensive searching, HH), Nest 7 female parent adult spent 31, 34.83% of the total trip foraging (17 fixes, 19.10% of the total trip intensive searching, LH; 14 fixes, 15.73% of the total trip extensive searching, HH).

The two GPS deployments for the Monteiro's storm-petrel parent adults were successful. Nest 63 parent female spent a total of 33 fixes, 23.57% of the trip foraging (15 fixes, 10.71% of the total trip = intensive searching, LH and 18 fixes, 12.86% of the total trip = extensive searching, HH) and Nest 89 parent female spent 25 fixes, 17.01% of the total trip foraging (20 fixes, 13.61% of the total trip intensive searching, LH; 5 fixes, 3.40% of the total trip extensive searching, HH). For the Monteiro's storm-petrel tracks, the GPS track fixes (at 30min or 1hr intervals) showed that they were in the general vicinity of the islet (either at sea nearby or on the islet already) from: 00:00:35 UTC on 30th August 2020 (Nest 63) and 03:46:38 UTC on 30th August 2020 (Nest 89). However, the cameras identified adult arrival into the nest times as 23:53:32 UTC on 29th August 2020 (for Nest 63) and 03:45:12 UTC on 30th August 2020 (for Nest 89). For the band-rumped storm-petrel parents, upon return to the nest from these trips in any one night the adults spent 00:01:56 (1 feeding bout), 00:05:27 (4 feeding bouts) or 00:07:57 (2 feeding bouts) feeding their respective chick, which equated to 1.4g, 0.1g or 4.5g mass increase the following day (respectively). This is compared to the Monteiro's storm-petrel adults, where the parent adult(s) spent a total of 00:03:23 (1 feeding bout) or 00:14:49 (00:12:26 was the GPS adult; two feeding bouts per adult) feeding their chick. This equated to a 4.2g or 3.6g mass increase the following day respectively (Figure 6.3).

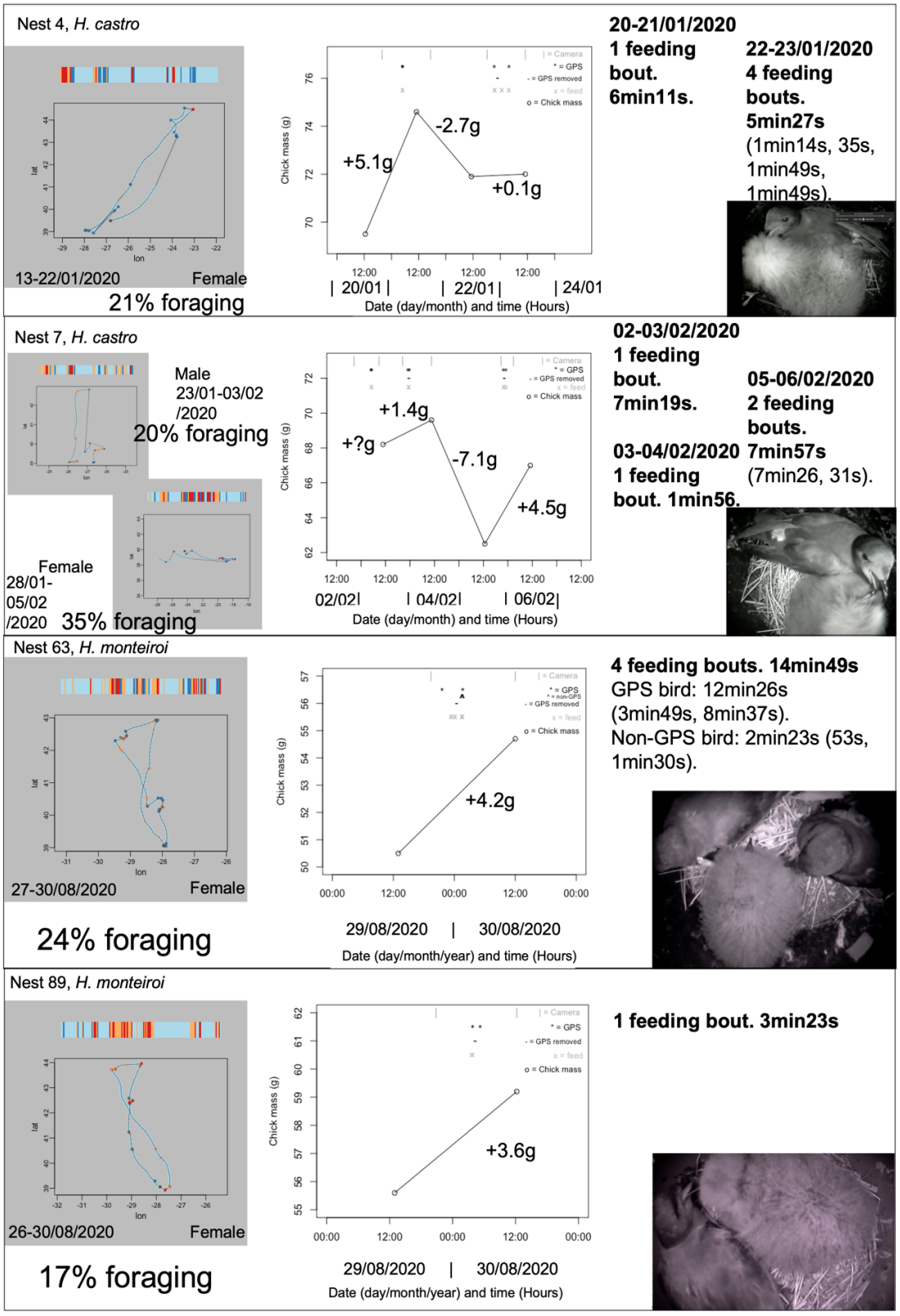


Figure 6.3. By nest and species graphics of: GPS tracks of parent adults (the four different colours are different states of movement with two being associated with foraging: "intensive search", Low speed, High turning angle, LH, red; "extensive search", High speed, High turning angle, HH, dark blue; one associated with "floating", Low speed, Low turning angle, LL, orange; and one associated with "relocation", High speed, Low turning angle, HL, light blue); chick growth curves by time and date for the GPS-tagged parent return nights annotated with mass change (top to bottom: | = camera deployments: * = GPS adult in nest, ^ = non-GPS adult, - = GPS tag removed, x = feeding bout event, o = chick mass) and details of the feeding event bouts and duration.

6.4. Discussion

Here I present a combination of traditional and more modern technological monitoring techniques, representing a proof-of-concept case-study of how such combinations of methods can further the knowledge of seabird behaviours at the nest site and at sea. This case-study provides information of great relevance to the conservation of the two sibling species of storm-petrel in the Azores, discussed below, but has wide application to other study systems.

I utilised traditional chick weighing techniques, as suitably miniaturised technology could not be developed in time to combine previously described remote-weighing methods (e.g. Phillips and Hamer 2000; Hedd et al. 2002; Sugishita et al. 2017) into this study's pre-established artificial nest boxes. However, this method has been long used with other larger Procellariiformes (e.g. Phillips and Hamer 2000; Hedd et al. 2002; Sugishita et al. 2017), as well as with other taxa (e.g. red squirrels, *Sciurus vulgaris*; Bosch et al. 2015). Therefore, it would be possible to adapt this technology for future projects involving artificial nest box studies interested in recording chick provisioning and chick growth. Nevertheless, where this is still not possible for technical or species size reasons, previous studies have already shown that once daily or twice-daily weighing can be sufficient to describe the overall pattern of chick growth (Allan 1962; Ricklefs 1968; Harris 1969; Ricklefs and White 1975; Benson et al. 2003, see also Chapter 3). The growth curves detailed in the present study were typical of other storm-petrels, and the seasonal differences between the larger band-rumped storm-petrel and the smaller Monteiro's storm-petrel were similar to other seasonally segregated species-pairs (e.g. among storm-petrels breeding in the hot and cool seasons in the Galápagos Archipelago; Harris 1969). These seasonal differences have already been discussed further in Chapter 3.

Nest cameras are being increasingly used within behavioural and conservation research fields (see reviews: Cutler and Swann, 1999; Swann et al. 2004; Trolliet et al. 2014; Edney and Wood, 2020; Hereward et al. [in prep. to resubmit] see Appendix 2). This is because they increase the knowledge of behaviours inside and outside the nest, when humans are not directly present, as well as aiding in identifying previously unobserved threats and quantifying known threats (Cutler and Swann 1999; Trolliet et al. 2014; Hereward et al.

[in prep.]; Chapter 5). The present study shows the value of these remote monitoring techniques (nest cameras to address knowledge gaps in and monitor adult attendance rates and feeding bouts/duration), alongside traditional techniques (to monitor the growth rates identified from daily chick weights, where automated weigh balances are not yet available). The feeding frequency, duration and mass gain identified in this study are similar to those of other storm-petrel species, for example, the Wilson's storm-petrel (*Oceanites oceanicus*; Gladbach et al. 2009a,b), although adults of both species in the Azores tended to spend less time, on average, in the nest with their chick than is the case for Wilson's storm-petrels (Gladbach et al. 2009a,b). Where use of integrated weigh balances is already possible, they provide more detailed mass change information, and have been paired with cameras to record videos of the feeding bouts *etc*., for example in the Northern royal albatross (*Diomedea sanfordi*; Sugishita et al. 2017). In addition, the external nest cameras in this study also aided in identifying behaviours near the nest, in the form of wing exercising and also the exact fledging date and time - which typically happened shortly after dusk, similar to other nocturnal Procellariiformes (e.g. Johnston et al. 2003). Finally, this method aided in discovering the visitations of non-parent adult conspecifics and other species (band-rumped storm-petrels) to nests containing Monteiro's storm-petrel chicks (as seen for the Monteiro's storm-petrel 2020 season, in nest 87). Some of these non-parent adult visitations included known ringed band-rumped storm-petrel adults and these adults were recorded feeding the resident chick. To our knowledge this is the first time this inter-species feeding has been recorded in this species pair, although intra-species cooperative breeding has been recorded in another procellariform species, the Balearic shearwater (*Puffinus mauretanicus*; Genovart et al. 2008). The chicks being fed in this Chapter, ranged in age from 35-44 days old (where day of hatching equals day 1). These non-parent feeding events occurred at various nests during the Monteiro's storm-petrel breeding seasons in 2019 and 2020 (personal observations, HFRH), but was only noted to occur at the juncture between the end of Monteiro's storm-petrel breeding season and the beginning of the band-rumped storm-petrel breeding season (Hereward et al. [in prep.]; Chapter 5). The conservation implications of these visitations are discussed below (but also see the General Discussion Chapter).

GPS tracking is also being increasingly used to assess at-sea behaviours of procellariform species (Afán et al. 2014; Rotger et al. 2020; Bolton 2021;

Ramos and Pereira 2022; Neves et al. [in prep.]), whilst also being combined with camera monitoring of behaviour within the nest cavity, and measuring changes in chick body mass (Sugishita et al. 2015; Fayet et al. 2021). This means that the researcher can assess the quality of habitat used for foraging (identified through analysing at-sea behaviours) based on the mass change of the chick and the consequent chick growth or mass loss (Sugishita et al. 2015; Sugishita et al. 2017). The results of my proof of concept study show that both species of storm-petrel species in the Azores are typical of other Procellariform species which spend ~ 20% of a single trip foraging (e.g. Afán et al. 2014). Neves et al. [in prep.] details more on both species of storm-petrel from the Azores (band-rumped storm-petrel and Monteiro's storm-petrel), incorporating a larger data set of GPS tracks for both species.

The combination of novel technologies presented in this study, could be further enhanced by incorporating additional modular technologies within the local environment as stand-alone data loggers or as part of a micro-computer board set-up (e.g. environmental sensor modules; temperature, humidity, etc; e.g. McBride and Courter 2019, Hereward et al. [in prep. to resubmit] see Appendix 2). These would aid in monitoring the nest microclimate – shown to be important for chick growth and development in other species (Michielsen et al. 2019; Facey et al. 2020; Sauve et al. 2021). This is especially important in light of climate change impacts e.g. heat waves or severe storms (Michielsen et al. 2019), and specifically for this study, given the climate change projections for the Azores (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018). Furthermore, an acoustic module could be used in tandem with cameras, to assess the surround soundscape - for example through deploying AudioMoth recorders (Hill et al. 2019). These could be easily integrated into the flexible Raspberry Pi bespoke camera system detailed in Chapter 4 (Hereward et al. 2021) and the wider applications of additional module options are discussed in more detail and with example case studies in Hereward et al. [in prep. to resubmit] (see Appendix 2).

Through the combination of traditional and modern technological monitoring techniques, various conservation implications have been identified in this proof-of-concept case-study. These include, chick provisioning, at-sea human-storm-petrel interactions/Marine Protected Areas (MPAs) and in-nest inter-species interactions.

Daily or remote chick weighing and cameras in the nest cavity aid in identifying chick provisioning rates (Gladbach et al. 2009a; Sugishita et al. 2017; Williams and DeLeon 2020; Fayet et al. 2021). As already discussed in Chapter 3, chick provisioning rates in this study do not seem to be a dominant cause of the breeding success declines seen in both species of storm-petrel. However, this combined technological approach could be applied to other systems and species to help detect changes in chick provisioning (Gaglio et al. 2017; RSPB 2020; Fayet et al. 2021). These combined methods are especially effective for species that carry large prey in their bill, making it possible to identify prey via camera footage, and to identify whether the prey species changes over time – as seen for Atlantic puffins (*Fratercula arctica*) in the UK (RSPB 2020; Fayet et al. 2021) and greater crested terns (*Thalasseus bergii*) in South Africa (Gaglio et al. 2017).

Another aspect of the study with conservation implications is the use of GPS tracking data to examine at-sea behaviour and interactions with human activities; this would be applicable to other seabirds too (e.g. Guilford et al. 2008; Bengsen et al. 2011; Afán et al. 2014; Rotger et al. 2020; Bernard et al. 2021; Bolton 2021). Specifically, this could include assessing whether foraging areas overlap with fisheries (Sugishita et al. 2015; Anderson et al. 2018) or if there are interactions with other man-made objects at sea (e.g. offshore oil/gas platforms with associated burn-off flares and other light pollution (e.g. Wiese et al. 2001; Rodríguez et al. 2015; Rotger et al. 2020). The identification of overlaps of the birds' foraging areas with fisheries or platforms could inform the design of Marine Protected Areas, as have already been suggested for other storm-petrel species off Scotland, UK (European storm-petrel; Bolton 2021). Finally, there is mixed reporting of the impact of interactions in the nest between band-rumped storm-petrel adults and Monteiro's storm-petrel chicks. Previously this behaviour has been described as "sharing of burrow" interactions and have been previously documented among storm-petrel species in the Azores (Bolton et al. 2008), and in other locations where there are hot and cool season breeding species (Galápagos;

Harris 1969). However, Allan (1962) describes some chicks as "mohawks" due feather loss on their heads (by being pecked by those sharing the burrow; Allan 1962; Harris 1969). Such interactions between the two species breeding on the Azores will be important to monitor further (using in-person and remote monitoring methods), to determine further negative interactions which so far have included pecking of the chicks and in extreme cases, evictions of the Monteiro's storm-petrel chicks from the nest cavity, leading to their demise (HFRH personal observations; further discussed in the General Discussion Chapter).

Of these three factors outlined in this chapter, and taking into account the top three threats to seabird survival globally (Croxall et al. 2012; Dias et al. 2019), for the sibling species of storm-petrel in the Azores, I suggest that the inter-species and conspecific interactions between the adult storm-petrels and the Monteiro's storm-petrel chicks are of highest concern, and so on-land conservation actions would be important to consider and potentially implement. Such actions could include the renovation and additional deployment of appropriately designed artificial next boxes to reduce competition for the current boxes (Bolton et al. 2004; Hart et al. 2016; Kelsey et al. 2016), taking into account climate change predictions for the Azores and other inter-species interactions described in other chapters (see discussions in previous Chapters 1-5 and in General Discussion Chapter to follow).

6.4.1. Conclusion

Here I demonstrate the effectiveness of combining traditional and technological methods and the benefits that these combinations could have for advancing knowledge of how storm-petrel behaviour on land and at sea contributes to breeding success or failure. These combinations of methods provide valuable insights for designing conservation actions and potential solutions for these two species of storm-petrel in the Azores, with wider applications to similarly monitored seabirds.

Chapter 7. General Discussion

Photographs: top left (Ilhéu da Praia; Ben Porter), top right (Monteiro's storm-petrel adult; Hannah Hereward), second from the top right (band-rumped storm-petrel; Ben Porter), bottom left (chick being weighed; Ben Porter), bottom right (sunset from the islet; Hannah Hereward).

7.1. Summary of key findings

The research presented in this thesis shows, for the first time, that the breeding success of both of the storm-petrel species breeding in the Azores has declined (most substantially in the Monteiro's storm-petrel) over the 20 years of this study. Of the potential causes, both weather conditions and other species appear to have become increasingly important in reducing breeding success. Remote video cameras inside the nest cavity proved to be a useful aid in describing key chick behaviours and interspecies interactions (identifying both direct and indirect effects of other species). GPS tracking provided information about the location and timing of the species' at-sea behaviours between visits to the colony. Furthermore, the approach of integrating GPS tracking with in-nest cameras and traditional chick-weighing methods has provided important data for understanding chick growth and quality, and their death or survival, in relation to the behaviours of chicks and their parents, and potential threats. The combined results from these chapters have shed light on various conservation concerns and these will now be discussed in relation to potential conservation actions.

The severe decline in the endemic Monteiro's storm-petrel is particularly concerning, making conservation action for this species considerably more urgent than previously anticipated. Here I further discuss the impacts of weather/climate change, other species at the breeding colony and in foraging areas at sea. The potential conservation management options are then discussed, based upon these current findings and I then suggest future research to address important remaining knowledge gaps.

7.2. Current impacts of weather, and future climate change

Differences in weather between summer and winter in the Azores appear to influence the two storm-petrel species in terms of overall chick growth (slower chick growth in the winter-breeding band-rumped storm-petrels) and behaviour patterns, as well as overall breeding success. Chicks of the winter-breeding band-rumped storm-petrel also grew to a larger peak body mass and spent more time sitting/sleeping compared to the summer-breeding Monteiro's storm-petrel. The larger peak body mass is consistent with Bergmann's rule (Bergmann 1847; who identified that species living at cooler temperatures tend to have a larger body size; specifically seen in birds - e.g. review in Olson

et al. 2009). In the Azores context, the larger body mass of chicks in the winter breeding species is possibly an adaptation to conserve energy by reducing the surface area to body mass ratio (Monteiro and Furness 1998), as is also the case in other species or populations of storm-petrels (e.g. band-rumped storm-petrels in the Galápagos, Harris 1969). In addition, air temperature is also likely to influence the 24-hour temporal variations in behaviour (Boersma 1986; Monteiro and Furness 1998), for example in the Monteiro's storm-petrel chicks, which primarily rested in the middle of the day, when the ambient temperature outside the nest boxes could reach up to 25 °C (Chapter 2, Figure 2.2).

Based on the available climate change models for the Azores, climate change predictions are an increasing concern for both species, due to their respective breeding success being lower in years with weather conditions matching the predicted future climate of the Azores. These are, for the summer, a decrease in rainfall and increase in temperature, and for the winter an increase in both rainfall and temperature (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018). Higher winter temperatures may aid the band-rumped storm-petrel chicks in avoiding hypothermia and strategic "torpor" (Boersma 1986; Monteiro and Furness 1998), but overall for both species, the chicks are more likely to overheat (become hyperthermic) unless the artificial nests are well-ventilated and/or insulated (as seen for artifical box designs for other species; Kelsey et al. 2016; Fischer et al. 2018). For the Monteiro's storm-petrel, the combined effect of higher temperatures and low rainfall could possibly exacerbate the negative effect of high temperature, as there would be fewer cooler, wet days (Kelsey et al. 2016; Fischer et al. 2018). Higher winter rainfall could also possibly increase flooding risk to nests and consequently chick survival, as seen previously in this study system (Bolton et al. 2004), and in other species (Boersma et al. 1980).

Weather was also associated with activity of other species present in the nest boxes. Specifically, in the summer, ants and Madeiran wall lizards were more commonly seen in videos recorded by the nest box cameras (Chapter 5). This is likely due to these heterothermic (lizards) and ectothermic taxa (ants) being more active with increased temperature (Chapter 2, Figure 2.2; Markwell 1998; Corkery et al. 2014; Fischer et al. 2019; Maziarz et al. 2020). In addition, the Madeiran wall lizards could be using the artificial nests as a shelter from extreme temperatures, as observed in other species (e.g. Tuatara

Sphenodon punctatus in New Zealand; Markwell 1998; Corkery et al. 2014; Fischer et al. 2019).

7.3. Impacts of other species

In the past on Ilhéu da Praia, various species were already identified as threats to the breeding storm-petrels. This stems back to the rabbits (*Oryctolagus cuniculus*; eradicated in 1997; Bried et al. 2009), northern long-eared and short-eared owls (*Asio otus* and *A. flammeus* respectively; which have caused the death of numerous storm-petrels; Monteiro et al. 1996b; Bried 2003; Bolton et al. 2008) and more recently the Madeiran wall lizard (Matias et al. 2009; Neves et al. 2017). Various management options were successfully undertaken to protect the islet and the seabird species using it, including the rabbit eradication programme combined with the restoration and reintroduction of native plants on the islet (Bried et al. 2009; Long et al. 2021). However, the results from the present study show there are other species posing potential and actual threats to the eggs/chicks/adults and these are discussed in more detail here.

7.3.1. Other storm-petrel individuals

In late summer, the decrease in Monteiro's storm-petrel breeding success appears, at least in part, to be influenced by the return of the winter-breeding band-rumped storm-petrels (in this context, more generally categorised as a "non-parent storm-petrel" as not all individuals were identified to species level). Furthermore, the overlap of the end of the Monteiro's breeding season and the beginning of the band-rumped storm-petrel breeding season seems to have become longer in duration in later years. Concurrent occupancy of nests of hot and cool season species has previously been recorded on Ilhéu da Praia (recorded as "nest sharing"; Bolton et al. 2008), and in other hot and cool season storm-petrel colonies (Allan 1962; Harris 1969). In some studies, the chick victims of interspecific interactions were described as "mohawks", with little head plumage left, or even with head scars and damp heads due to pecking. In this study system, not all non-parent storm-petrels physically attacked the Monteiro's chick (*pers. obs*. from camera footage), however from nest monitoring there was evidence of some chicks receiving pecks to their heads and eyes, as described by Allan (1962). The in-nest camera footage revealed that extreme preening/brooding behaviours were also seen (where

the non-parent storm-petrel aggressively preened and stamped on the Monteiro's storm-petrel chick).

The causes of this overlap in the timing of breeding of the two species are uncertain. Whilst in some seabirds a shift in the start of the breeding season has been seen in association with recent climate change, such shifts appear to be uncommon in Procellariiformes (Keogan et al. 2018), this is exemplified in the present study by the band-rumped storm-petrels, which had similar hatch dates between the two periods of intensive study. Indeed, across the last 20 years of data collection band-rumped storm-petrels have been found in the nest boxes during the daytime, from late July/early August onwards (unpublished data from this study). It is possible that this overlap is inadvertent, simply due to the asynchronous nature of the timing of breeding of the two species (Warham 1990). However, an additional possibility is that competition for nest sites has increased – possibly due to increased numbers of breeding birds, the preference of individuals for the same nest, and/or a reduction of "usable" nests (i.e. more nests needing refurbishing; Ramos et al. 1997; Bolton et al. 2004).

7.3.2. Barolo shearwater

On Ilhéu da Praia, Barolo shearwaters have been increasingly using the storm-petrel artificial nests (Bried and Neves 2015), especially where the entrance tunnel is no longer attached, or has become eroded, and so the nest entrance is large enough for them to enter (*pers. obs*.). The original design of all of the nest boxes on Ilhéu da Praia included a tunnel (Bolton et al. 2004), but erosion has occurred over the last 20 years due to weather impacts (Santos et al. 2004; Jones and Phillips 2009; Calado et al. 2018) as well as some nests being excavated by Cory's shearwaters, and so during the fieldwork winters of 2018-2019 and 2019-2020, some nests were refurbished and in 2019-2020, some new entrance tubes fitted (*pers. obs*.). Nevertheless, Barolo shearwaters have been recorded as breeders in the Azores since the 1950s (Monteiro et al. 1996a,1999) and have a decreasing population trend (BirdLife International 2018c) and so a balance will be needed in order to best manage and conserve this species alongside the two storm-petrel species.

7.3.3. Cory's shearwater

Cory's shearwaters have appeared in storm-petrel nest-site videos (both as described in this study - Chapters 3 & 5, and as unpublished data from other

cameras deployed near the nest entrances), directly interacting with the Monteiro's storm-petrels through attempting to (and sometimes succeeding in) putting their heads into the storm-petrel artificial nest boxes. Previous research has described incidents between Cory's shearwater and band-rumped storm-petrel as "accidental", where there was competition for natural nest sites (Ramos et al. 1997). However, there is no direct competition between the storm-petrels using the artificial nest boxes and the Cory's shearwaters using natural nest sites, so consequently the direct interactions seen in this study are surprising. One of the previous successful solutions to reduce competition for nest sites (and therefore potentially aiding in reducing interspecies interactions) was to deploy artificial nest boxes in the early 2000s (Bolton et al. 2004; Bried et al. 2009). Similarly to the recommendations for mitigating the Barolo shearwater issues described above, reinstating tunnels and entrance coverings would aid in reducing these interactions between storm-petrels and Cory's shearwaters (Bolton et al. 2004; Libois et al. 2012).

7.3.4. Yellow-legged gulls

Although fewer chicks were lost in the band-rumped storm-petrel breeding season, the few that were lost were predominately taken by gulls. The artificial nest boxes were originally designed with entrance tunnels (Bolton et al. 2004) and so similarly to the suggested action to mitigate the actions of Barolo and Cory's shearwaters, reinstating tunnels and entrance coverings would help to reduce the ability of larger seabirds, including yellow-legged gulls, to access the nests and disturbing (or predating) any eggs, chicks or adults within (Sanz-Aguilar et al. 2009; Libois et al. 2012).

7.3.5. Madeiran wall lizards

The non-native Madeiran wall lizards have been of increasing concern in the Azores / Ilhéu da Praia (Matias et al. 2009; Bried and Neves 2015; Neves et al. 2017). However, there is still little information available on the population change of this species over the last 20 years (or before). They were known to be present in the Azores from the 1900s (Malkmus 1995; CABI Data Mining 2011; Seebens et al. 2017). However, on Ilhéu da Praia, from the nest monitoring data in 2000-2002 there are only occasional notes of lizards in storm-petrel nests. This contrasts with the much more frequent observations in the later period of intensive study (*pers. obs*.). In its native islands (Madeira and surrounding islets) these lizards are found across all habitats, although often favouring places where they can bask in the sun – which includes rocks

and trees (Malkmus 1995; Brehm et al. 2001). Over the last 20 years on Ilhéu da Praia, the habitat has shifted from overgrazed and eroded soil to a variety of native and non-native shrubs and grasslands (Bried et al. 2009; Long et al. 2021). Although it is unclear as to the cause of Madeiran wall lizard abundance increase, one possible contributing factor could be that this shift in vegetation has provided increased possibilities for the lizard to thrive (as seen for the black-cheeked lizard, *Calotes nigrilabris,* in Sri Lanka; Somaweera et al. 2012), and this could mean that there are now more individuals taking opportunistic meals from the available storm-petrel eggs/chicks, as is seen in other systems (Walls 1978; Markwell 1998; Carey 2010; Corkery et al. 2014, 2015). As mentioned above, artificial nest boxes provide extra habitat for the lizards, and they could be using these to shelter from extreme temperatures as with the Tuatara (*Sphenodon punctatus*) in New Zealand (Markwell 1998; Corkery et al. 2014; Fischer et al. 2019), but as lizards were also present in some natural nests monitored, the nest boxes may not be excessively contributing to their presence.

7.3.6. Ants

Previous research on the impacts of ants in other seabird breeding colonies identified mixed impacts of ants on chick survival (Wedge-tailed Shearwater, *Ardenna pacifica*, Plentovich et al. 2009; European Herring Gull, *Larus argentatus*, DeFisher and Bonter 2013; red-tailed tropicbirds, *Phaethon rubricauda*, Flores et al. 2017; white-tailed tropicbirds, *Phaethon lepturus catesbyi* and Mejías et al. 2017; See Chapter 5, Table 5.1 for full details). Even within the same breeding colony, one species of ant killed a species of shearwater chick, and another ant species did not (Plentovich et al. 2009). As with the Madeiran wall lizard, there are few previous data on ant abundance on Ilhéu da Praia (but see Neves et al. [in prep.]). However, compared to other studies there are various factors that may contribute to the impacts of ants on the storm-petrels of Ilhéu da Praia.

1) Thief ant behaviour – although ants are typically opportunistic foragers (Hölldobler and Wilson 1990), the thief ant, *Solenopsis* sp. (one of the ants found on Ilhéu da Praia) is part of the fire ant family, and the specific genus is also known as the "thief ant" because they are known to pilfer food or broods from other ant nests. This could potentially be extended to detritivorous or even carnivorous behaviours towards other species possibly including chicks (Wetterer et al. 2004; Pacheco and Mackay 2013).

2) Habitat change – the other two ant species found on the islet (*Monomorium carbonarium* and *Lasius grandis*) can be found across all habitats whereas, *Solenopsis* sp. are typically found in disturbed soils, so as with the Madeiran wall lizard population, the change in habitat on Ilhéu da Praia (Bried et al. 2009; Long et al. 2021), could have increased the available habitat for these ant species to thrive (Wetterer et al. 2004; Pacheco and Mackay 2013; Seifert 2020) alongside the disturbed soils within seabird burrows.

3) Artificial nest boxes – the ants may be attracted to the artificial nest boxes due to ambient heat given off from nests (Maziarz et al. 2020). Alternatively, the ants could be feeding on nest parasites, as seen in songbird nests (Maziarz et al. 2020) and other nest box users (Salido et al. 2021). There could also be a mutual beneficial interaction involving "anting" behaviour, as observed in other bird species, where birds purposefully allow ants onto their feathers, in order to aid in removing ectoparasites (Clayton and Vernon 1993).

4) Searching for protein – ants are known to increase the amount of protein in their diet as spring and summer progress (Hölldobler and Wilson 1990), which could coincide with their increased presence in the summer months.

7.4. Conservation management recommendations

As already discussed in Chapter 3, the preliminary VORTEX Population Viability Analysis models indicated that increasing the breeding success of the Monteiro's storm-petrel would aid the species in attaining a stable or increasing population trend (requiring a 35% or 50% breeding success rate, respectively). Based on their 2020 breeding success rates (62 attempts, 23.7% breeding success rate), this would require an estimated increase in breeding success equivalent to an additional 7-16 successfully fledged chicks per season (as discussed in Chapter 3). Drawing together the current information presented in this thesis, several conservation management recommendations can be made to potentially aid in achieving this.

The first is careful repair and refurbishment of current artificial nest boxes, and design of future nest boxes, in light of the known threats (egg and chick depredation) and climate change predictions for the Azores. Refurbishing the nests following the original Ilhéu da Praia nest box design will be important

(Bolton et al. 2004). However, additional design improvements could be made to reduce the threats to nesting storm-petrels, as described in this thesis. These include: (i) ensuring that there is a distinct "step" between the entrance tunnel and the nest cavity, to prevent eggs from being rolled out the nest; (ii) using smoother stones or sand as the top layer of the nest surface to reduce the risk of eggs being cracked in the nest, (iii) ensuring entrance tunnels (6 cm in diameter) are deployed on all nest entrances that are currently exposed, to avoid egg/chick loss due to Barolo shearwaters, Cory's shearwaters and/or yellow-legged gulls being able to access the nest cavity, and (iv) using heat reflective material to reduce the temperature inside the nest cavity, and a fully waterproof lid to avoid flooding (see examples: Kelsey et al. 2016; Fischer et al. 2018). Assuming that the suggested nest refurbishment/ redesigns are effective, and taking into account the projected number of additional successfully fledged chicks needed, this could equate to targeted improvements to 30-40 nests (which takes into account a 50% or less breeding success rate).

Another conservation management option, which has been successful against various vertebrate species on various islands previously, is non-native species removal programmes (e.g. Buxton et al. 2016; Jones et al. 2016; see Chapter 1, Table 1.1 for a more substantial list). However, lizard eradication programmes are less common, and of those that exist, few programmes have successfully eradicated non-native lizards. Two exceptions are Italian wall lizard (*Podarcis siculus*) eradications in the UK and Greece (Hodgkins et al. 2012; Adamopoulou and Pafilis 2019). These two programmes show that lizard eradication is possible in small, isolated areas. However, both of these successful non-native lizard eradications were undertaken early, soon after their introductions. Early eradications are important because reptile populations are hard to eradicate once fully established (Kraus 2009; Adamopoulou and Pafilis 2019). In terms of non-native species removal programmes in seabird colonies, Buxton et al. (2016) provides a decision-making tool for invasive vertebrates – and suggests that active management techniques are used when seabird populations are declining (as the preliminary models predict is the case for the Monteiro's storm-petrels on Ilhéu da Praia). However, if species eradication methods were again undertaken on Ilhéu da Praia, it would be important to consider the possible knock-on effects to the other established species (Zavaleta et al. 2001). For example, if the Madeiran wall lizards were removed, there is concern about

the potential for trophic cascades resulting, especially in relation to the ants (which may boom, as lizards are likely to be, to an extent, a biological control for the ants). This could have negative knock-on effects on the eggs, chicks and adults given the already concerning impact of ants to the storm-petrel species (as discussed in Chapters 3 & 5). To avoid this possibly disastrous trophic cascade situation, I suggest that initial conservation management for the storm-petrels should focus on repairs and modifications to the artificial nest box design, as described above (see examples: Kelsey et al. 2016; Fischer et al. 2018). If these nest box modifications are unsuccessful then biological control of both lizards and ants could be the next management option to be carefully considered and cautiously trialled (e.g. in some but not all parts of Ilhéu da Praia).

7.5. Further research

Although some management suggestions have been made above, these focus on the threats encountered at the nest sites, but not those encountered at sea, which could inform the design of Marine Protected Areas (as discussed below). Nevertheless, in both terrestrial and marine contexts there are still important knowledge gaps that remain to be addressed, in order to better understand various aspects of the breeding performance of each species and therefore their ultimate fates.

In terms of climate change concerns – I recommend survey work using temperature loggers inside the nest cavity, to examine the relationship between nest box temperature and breeding success, and to assess whether the current artificial nest boxes are significantly warmer than successful or unsuccessful natural nest sites (as has been done in other places using loggers inside artifical eggs, or iButton loggers in the nest itself, e.g. as used with Cassin's auklet *Ptychoramphus aleuticus* - Kelsey et al. 2016; and South Georgian diving petrel *Pelecanoides georgicus* - Fischer et al. 2018).

For concerns relating to other species – I suggest utilising nest box monitoring data from 2000-2001 and 2019-2020, to map where ants/lizards/other species are most active in the artificial nest boxes, to assess whether there are particular areas of the islet/nests that are particularly vulnerable to other species impacts (unpublished data; Mark Bolton and HFRH). These could then help to target management options as already described above. In addition, I

suggest continued monitoring of breeding productivity and causes of egg/chick failure – this could be through in-person monitoring and/or the use of remote technologies including the camera system deployed in the present study (Chapter 4; Hereward et al. 2021).

This study has focused on breeding success, but another important variable for understanding population change is the overall population size itself, both on Ilhéu da Praia and across the Azores Archipelago. This is important for assessing any population change in the two species, and therefore their conservation status as defined by the IUCN Red List (IUCN 2012). As far as I am aware a full population census across the Azores Archipelago for Monteiro's storm-petrel or band-rumped storm-petrel has not been conducted/published (Oliveira 2016) and so the baseline population estimates presented were based on the breeding population estimates from Ilhéu da Praia identified by Monteiro et al. (1996a; 1999) and updated by Oliveira (2016). As discussed in Long et al. (2021), the habitat on Ilhéu da Praia has changed substantially in the last 20 years and so the population is likely to have expanded to use various other suitable nesting habitats (tree cavities, *Festuca petraea* tussocks, rock crevices and earth burrows, as well as the artificial nest boxes themselves). However, this possible increase in population size will be dependent on the overall breeding success which, as described in Chapter 3, is declining in both species. Therefore, I suggest an updated population census for both species will be an essential next step in assessing both species conservation status and further management. For this, incorporating population surveys in natural habitat locations, as well as the ongoing nest box monitoring, would be beneficial to gain a whole-islet population estimate for Ilhéu da Praia, and equivalent surveys of other islets will be necessary to obtain an Azores-wide population estimate (Long et al. 2021). Furthermore, there is a great amount of currently unpublished ringing data which could all be incorporated into a capture-recapture integrated analysis model, to include and combine both nest check pair data (Bried unpublished data, and this study) and mist-netting data (Bolton unpublished data, SPEA unpublished data, and this study).

Finally, as discussed in Chapter 6, further assessment of a larger number of GPS tracks (see Neves et al. [in prep.]) would aid in determining interactions at sea between storm-petrel and human activities, that potentially need mitigating (e.g. overlap with fisheries; Sugishita et al. 2015; Anderson et al.

2018 or off shore oil/gas platforms with associated burn-off flares and other light pollution; e.g. Wiese et al. 2001; Rodríguez et al. 2015; Rotger et al. 2020), which could inform the design of Marine Protected Areas, as have already been suggested for other storm-petrel species off Scotland, UK (European storm-petrel, *Hydrobates pelagicus*; Bolton 2021).

These additional results would aid in improving the Population Viability Analysis models, presented in Chapter 3, to provide a more accurate future population projection for both species, which could feed into an updated assessment of the IUCN listings for both species (IUCN 2012; BirdLife International 2018a,b). Currently, the Monteiro's storm-petrel is categorised as Vulnerable due to its small population size and restricted occupancy (categories D1+2; BirdLife International 2022c) and the band-rumped storm-petrel is currently categorised as Least Concern, but with a decreasing population trend (BirdLife International 2018a; BirdLife International 2022b). From the preliminary VORTEX Population Viability Analysis (as detailed in Chapter 3), the predicted time to extinction for Monteiro's storm-petrel using the most pessimistic (smallest) population estimates (100 or 200 individuals), would be 69 or 82 years, respectively. This is a shorter timescale to extinction than the IUCN Red List criteria required for classification as an Endangered species for category E (Table 7.1; IUCN 2012). Similarly, with higher initial population sizes (1000 and 1500 individuals) the models still predicted a long-term decline towards extinction. Therefore, given this combination of already known criteria (of small population size and restricted occupancy) and the newly presented data in this PhD thesis (declining breeding success, due to combined impacts of climate change and other species), I strongly recommend an urgent re-evaluation of the Monteiro's storm-petrel IUCN Red List classification (including further Population Viability Analysis). In addition, the wider geographical distribution of the band-rumped storm-petrel makes this species harder to determine possible extinction rates. However, for the Azores population (as already outlined in this PhD; Chapters 3 & 5), interference of breeding attempts caused by other species appears to be an increasing problem for both species of storm-petrel breeding on Ilhéu da Praia, and so I suggest that an IUCN Red List classification reassessment for the band-rumped storm-petrel should also be considered. Nevertheless, any reclassification would be made much more accurate by new research into the current total population size of both species in the Azores, and their maximum age of reproduction. These up-to-date population projections and demographic

data will be imperative for the reassessment of both species' IUCN classification status (IUCN 2012; BirdLife International 2018a,b), to ensure that both species are appropriately designated, thus furthering the conservation of both species (as discussed above).

7.6. Conclusion

This thesis has shown that breeding success in both species is declining, and if this continues, the overall population is likely to decline. Based on current breeding success, the Monteiro's storm-petrel is projected to become extirpated on Ilhéu da Praia in the next ~60-90 years. Nevertheless, there are feasible management actions that could aid in preventing this outcome. So, the time to act is NOW!

Table 7.1. IUCN classification information for Monteiro's storm-petrel. Monteiro's storm-petrel is categorised as Vulnerable due to its small population size and restricted occupancy (categories D1+2; BirdLife International 2022c) Re-classification criteria required for Endangered: Quantitative analysis showing the probability of extinction in the wild is at least 20% within 20 years or five generations (whichever is longer, up to 100 years), and Critically Endangered: Quantitative analysis showing the probability of extinction in the wild is at least 50% within 10 years or three generations (whichever is longer, up to 100 years).

Classification information	**Monteiro's storm-petrel**
Current classification and codes	Vulnerable. D1+2 (small population size and restricted occupancy)
Generation time (years; based on the BirdLife species fact sheet)	16.5 years
Current breeding success (results from this study)	2020 = 23.7%
Quantitative analysis results of probability of extinction (from this study's VORTEX models, initial population size 100, 200 or 1000 individuals)	100% probability of extinction in 69, 82 or 98 years
Re-classification assessment based on category E. Generation time based on classification criteria:	
Endangered (generation time x five generations). Critically Endangered (generation time x three generations).	Endangered. E. (Five generations = 16.5x5 = 82.5 years). Critically Endangered. E. (Three generations = 16.5x3 = 49.5 years)
Suggested updated classification for the Azores (based on the quantitative analysis results and generation calculations for category E)	Endangered-Critically Endangered (as at least with the smaller initial population sizes the species is projected to become extinct within 82 years, i.e. five generations). NB, based on the estimated population size, the classification would still sit best within Vulnerable for category D1+2 (and not any higher classification)

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Supplementary Materials

Chapter 4 Supplementary Materials

Detailed part list, programme scripts and extended build instructions

Part list

Single-buy kit for set-up

Setting up the camera requires the following single-purchase kit: a Pimoroni Three Port USB Hub with Ethernet - microB connector, a USB keyboard, a USB mouse, a computer screen (for fieldwork deployments we recommend a small bespoke screen; the Elecrow 5 Inch Touch Screen HDMI Monitor Small HD 800x480 TFT LCD Display for Raspberry Pi), an HDMI cable with mini-HDMI adapter, either two micro-USB cable chargers (for mains power), or two micro-USB cables with USB-compatible rechargeable powerpacks (if mains power is not available). Where possible, we recommend setting up cameras using mains power prior to deployment in a remote location, to minimise battery usage in the field. This equipment costs ~£100 GBP (~$133 USD) to allow the construction of multiple cameras prior to deployment.

List of parts required to build each camera

The following parts are required to build each camera. Each camera cost a total of ~£86 GBP (~$115 USD) to build. Each numbered part is referred to within the build instructions below:

- Part 1: Dual USB flash drive, Mini USB to USB 3.0. We used a SANDISK Ultra (64 GB) which has a mini-USB connector on one end of the USB and a USB 3.0 connector on the other end. This is where the recorded video files were stored. In this study we used a USB to store video files and found this to be

highly successful and aided in smooth transfers of files from cameras after each deployment. This reduced the SD space limitations mentioned in previous papers (Prinz et al. 2016; McBride & Courter, 2019; Mouy et al. 2020; Youngblood, 2020) and, for our deployments, allowed storage of the 3-5 GB of video files created per 24-48 hr deployment. However, for those setting up cameras in extreme conditions, the preliminary trials from Mouy et al. (2020) using a USB are important to take into account, as they found the USB-USB port connection to be fragile and consequently disrupted by vibrations during transport by boat prior to deployment. We suggest labelling each USB flash drive to ensure that each USB drive stays with the same Pi Zero board and to avoid confusion if multiple cameras are being set up and deployed.

- Part 2: MicroSD card. This SD card acts as the Raspberry Pi computer's hard drive and holds a copy of the Python command scripts. A 16 GB microSD card provided sufficient storage space (we specifically used a NOOBS 16 GB microSD card (version 2.8) as the Raspberry Pi Operating System is preinstalled). For future users working in remote locations, we would recommend setting up the cameras and cloning the SD cards before the start of fieldwork. This consequently reduces setup time in the field and is especially useful when there is limited or unreliable access to electrical power.
- Part 3: Raspberry Pi Zero WH (pre-soldered) board. The small size of this circuit board allows the camera to be as compact as possible to fit within the nest box. This circuit board does not require soldering (a version without the GPIO header pins attached is cheaper, but requires soldering). In the Python script, the GPIO pins were set to "GPIO layout" (see "nestcam.py").
- Part 4: Fisheye camera + infrared LED attachments. In order to capture the widest possible field of view, and to allow for day and night footage of nests to be recorded, we used a night vision camera module for Raspberry Pi,

incorporating a 160º fisheye lens with a standard focus distance of ~15 cm, combined with infrared LED attachments (shop.pimoroni.com).

- Part 5: Real Time Clock. To provide an accurate date and time stamp on video recordings, we used a DS1307 RTC Real Time Clock Module Board with additional GPIO pins, powered separately with a LiCB CR1220 3V Lithium Battery Button Cell Battery. Occasionally we found video files returned with the wrong date and/or time. This was likely due to an insecure connection to the Real Time Clock, or because the separate button battery was running low, causing the Real Time Clock date and time to reset itself. This is easily fixed between deployments, by replacing the button battery (or the whole component), and then repeating the Real Time Clock setup as described below. For buffering against such technical failures, we recommend taking several sets of spare components into the field to allow for smooth and quick fixes if changes are needed.
- Part 6: Passive Infra-Red (PIR) sensor + 3 female-female cables. To enable the camera to record after detection of motion, a pre-assembled PIR sensor was used (Figure 4.2A-D). This method assumed that a change in infrared detection would indicate that motion of an animal had occurred within the field of view.
- Part 7: Off clicker + 2 female-female cables. To allow for correct shutting down of the Pi Zero board in the field, a "shutdown" script was written (see "shutdown.py"). On the switch end of the female-female cables, the black covers were removed for easier attachment of the switch (Figure 4.1E-G).
- Part 8: Heat sink. One heat sink was added to each Raspberry Pi Zero board, to reduce the risk of over-heating.
- Part 9: Mini USB 3.0 USB connector cable + powerpack. To power the Pi Zero board, a 1 m long mini-USB 3.0 USB connector cable was connected to a

Poweradd Pilot X7 20,000 mAh portable powerpack (these powerpacks typically powered the camera setup for 24-48 hrs).

Equipment housing

For our study system, the design of the equipment housing was an important consideration, given the high relative humidity and salt spray, and the pre-existing artificial nest box dimensions. As a result, we used two sizes of plastic container to house the equipment: a smaller one for the camera (Lock & Lock HPL805 Stackable Airtight Container Rectangular 180 ml, Plastic, Clear, 11 x 8.9 x 4.9 cm) and a larger one for the powerpack (Lock & Lock 800ml Food Container Rectangular Lunch Box HPL816, 13.7 x 5.3 x 20.8 cm). Holes to accommodate the camera wiring were drilled into appropriate places. Blue tac (Bostik, Leicester, UK) and glue (such as PVC pipe adhesive), were used to seal the gaps in the drilled holes where necessary, reducing the likelihood of water entry, and at least one 1 g silica gel sachet was also placed inside each of the sealed boxes to help reduce humidity around the equipment.

Camera mounts

To mount the cameras on top of the nest rim, but underneath the lid, we cut a hole from the centre of a round cork board (25 cm diameter, 1 cm thick) into which the waterproof camera box base slotted. We then attached (using thin garden wire) an additional thinner cork board square (cut from a 22 cm diameter, 0.6 cm thick cork board) with camera, IR LED and PIR sensor holes to support these (Figure 4.2A-D). The equipment housing and camera mounts cost an additional ~£23 GBP (~$31 USD) per camera.

Programme scripts and associated files

Five python files can be found in the archived data repository. Two are python scripts that were used to run the camera and shutdown option ("nestcam.py"

and “shutdown.py”). The other three files are details of the command lines to be used in the Raspberry Pi “terminal”, which assist in the camera set up described below (“script for RaspPi terminal_RTC.py”, “script for RaspPi terminal_runonboot.py”, “script for RaspPi terminal_usb.py”).

Step-by-step instructions for building the camera

Using the parts described above, and each of the scripts provided, we suggest setting up the camera in this order:

1. Before beginning to build the camera, plug the uniquely labelled USB (Part 1) into a computer and copy the five python files (see archived data repository) onto the USB. Note that in any future connections of the USB to the computer it will suggest “fixing a bug problem” - do not select this option as it will reformat the USB.
2. Install onto the microSD card (Part 2) the Raspberry Pi Operating System, which is downloadable (with installation instructions) from: www.raspberrypi.org/downloads/raspbian/ (if you have bought a NOOBS microSD then the system is pre-installed so you can skip this step).
3. Insert the microSD card (Part 2) into the Pi Zero board (Part 3) and connect the Pimoroni Three Port USB Hub to the Pi-Zero “USB” port. Connected to this three-port hub should be the USB (Part 1), keyboard and mouse. Then connect the screen using the HDMI cable with mini-HDMI adapter.
4. Once the above items have been connected, only then connect the power source for the screen and Pi Zero board, using USB cables to mains power or USB cables to powerpacks.
5. Configure the SD card by following these dropdown menus: pi → Preferences → Rasp.pi configuration – interfaces – enable…. Enable: “camera”, “SSH” and “I2C”.

6. In the folder window, find the Pi folder (home → Pi) and create two folders, “scripts” and “usb” (this creates folders on the microSD card – note the use of all lowercase letters in folder names).
7. From the USB, copy over the scripts into the new “scripts” folder.
8. At this point the USB is recognised in the folder: home → media → USB but the next step is to “mount” the USB so that the USB is always given the same name/location and so that the data can be written to this location (each USB has a unique code hence the importance of labelling each USB so it remains with the same Pi Zero board after “mounting” it). Here we set the new USB folder in: home → Pi → usb - this is the folder where the USB will then always open. To do this, follow the step-by-step guide in the "script for RaspPi terminal_usb.py".
9. Once these steps are completed, the rest of the camera can be built up on the Raspberry Pi board following these steps:

a. Turn off the board (Pi → shutdown).
b. Add the camera (Part 4) to the Camera Serial Interface port on the Raspberry Pi board.
c. The Real Time Clock (RTC; Part 5) is then placed on the GPIO pins 1-10 (GPIO pins are numbered starting from pin 1 at the SD card end).
d. The pre-assembled PIR sensor (Part 6) is then added to the additional pins on the Real Time Clock using three female-female cables. The PIR sensor “VCC” pin is connected to the Real Time Clock “5V” pin and then the two “GND” pins are connected together. Finally, “OUT” on the PIR sensor is connected to GPIO17 (pin 11) on the Pi-Zero board (Figure 4.1A-D). The sensor settings (time and sensitivity) are then altered using the settings; Time = min, sensitivity = 90º to min (Figure 4.1A).
e. The “Off” switch (Part 7) is added to pins 39 (GND) & 40 (GPIO 21) (i.e. the end GPIO pins) using two female-female cables (Figure 4.1E-G).

f. Add the Heat sink (Part 8); remove the peel-off-sticker and place onto the chip on the Raspberry Pi board (Part 3).

g. Then reconnect the power via the USB connector cable.

10. Next, configure the Real Time Clock to run on the correct time and date. To do this, follow the step-by-step guide in the "script for RaspPi terminal_RTC.py".

11. Before configuring the terminal so that the scripts run on boot (i.e. run automatically when power is connected), it is useful to check that the camera script is working. Open Pi → Programming → Python 3 (IDLE) → file → open → scripts → "nestcam.py" and press F5 to run the script. Pressing "shift and F6" stops the script running. You will notice that the "nestcam.py" is scripted to print the word "idle" when the camera is off and "recording" when the camera is recording. This is displayed on the python shell output screen, and aids in testing the camera before deployment.

12. Once you have checked that the camera is working correctly, add the "nestcam.py" and "shutdown.py" scripts to the "bootup" so that they will run when it is connected to power; see the step-by-step guide in the "script for RaspPi terminal_runonboot.py".

13. When all of the components are assembled (Figure 4.1H) and configured, the camera is ready to deploy in the field. Disconnect the HDMI cable + mini-HDMI adapter, Pimoroni Three Port USB Hub (with keyboard and mouse) and connect the USB (Part 1) directly to the "USB" port on the Raspberry Pi board (Part 3).

14. Prior to deployment the camera needs to be fitted into the weatherproof housing as described above.

15. Finally, when ready to turn the camera on, connect a Mini USB-3.0 USB connector cable (Part 9) to the "power in" port on the Raspberry Pi board (Part 3) and the powerpack (Part 9).

S4 Table 1. Cost break-down by component, for the single-purchase kit requirements, camera, and housing used in this study (costing as of July 2020). Prices given in GBP £.

Equipment	Quantity	Single-purchase kit	Per camera	Per housing
Elecrow 5 Inch Touch Screen for Raspberry Pi	1	£32.99		
HDMI cord	1	£3.50		
Mini HDMI converter	1	£2.96		
Micro USB cable + charger (e.g. Raspberry Pi 3 Power adapter UK/EU 5V 2.5A OR using micro USB - USB cable + powerpack already acquired to run the boards)	2	£16.99		
Wired USB keyboard + USB mouse	1	£28.98		
Pimoroni Three Port USB Hub with Ethernet - microB connector	1	£9.90		
Spare Lock & Lock 800ml Food Container Rectangle Container Lunch Box HPL816	1	£4.00		
Silica gel (20g packet)	5	£10.00		
Total for single kit requirements		**£109.32**		
Raspberry Pi Zero WH (pre-soldered) board	1		£13.02	
Real Time Clock (RTC)	1		£9.99	
PIR sensor (connected using Female-Female jump leads)	1		£3.50	
160° fisheye lens with infrared attachments (+ zero lead)	1		£20.00	
NOOBS SD card (with micro SD card)	1		£9.00	
Mini USB to USB 3.0 USB	1		£11.99	
Off switch/clicker	1		£0.03	
Poweradd Pilot X7 20000mAh portable powerpack	1		£15.99	
Mini USB-3.0 USB connector cable	1		£2.30	
Heat sink	1		£0.50	
Female-female jump leads x 3 (for motion sensor), x 2 (for switch) (0.075p per lead)	5		£0.38	
Total for camera			**£86.70**	

Lock & Lock HPL805 Stackable Airtight Container Rectangular 180ml	1	£3.50
Lock & Lock 800ml Food Container Rectangle Container Lunch Box HPL816	1	£4.00
Cork board - 25 cm diameter round, 1 cm thick	1	£7.00
Cork board - 22 cm diameter round, 0.6 cm thick	1	£2.00
Garden wire diameter ~1.2 mm (small amount needed from large reel)	1	£6.00
Silica gel (1g packet)	1	£0.08
Total for housing		**£22.58**

Total for the camera + housing	**£109.27**	
Overall total	**£218.59**	

S4 Table 2. Description of the Success, Partial failure or Failure of each in-nest camera deployment

Type of deployment success/failure	Description
Failure	Where only 0-2 videos recorded.
Partial failure (non-usable)	When more than two videos were recorded but in total less than 1 hour was recorded.
Partial failure (usable)	When there was an unexpected interruption in the footage but there was more than 1 hour of footage recorded (e.g., caused by loss of battery power, technical faults, or a break in footage despite movement still occurring in the nest due to an adult or chick being present).
Success	Continuous footage with no known interruptions (allowing for anticipated breaks between footage when no movement was detected).

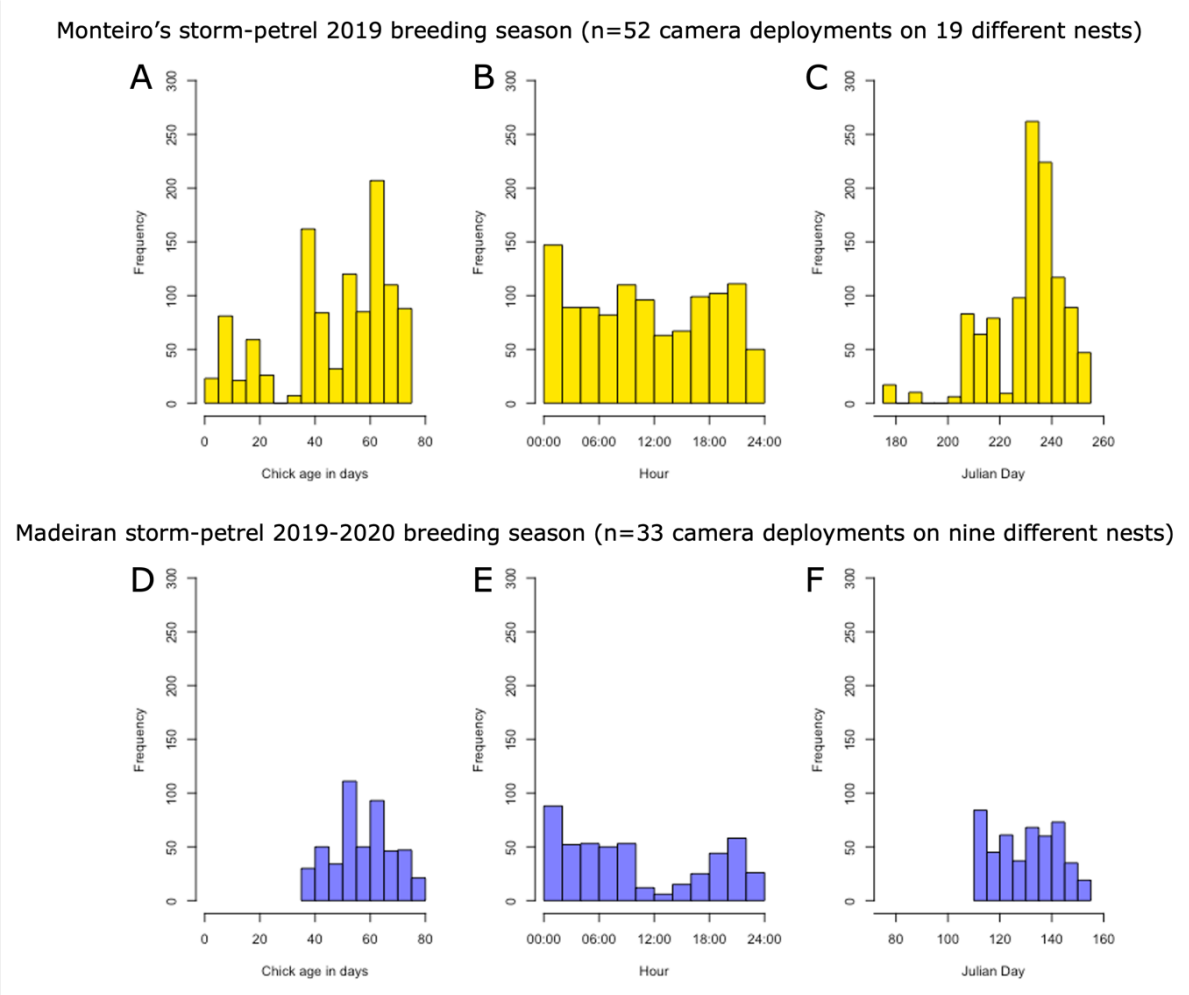
S4 Table 3. Number of deployments, number of 30 s videos created per deployment, sum, maximum, mean and standard error of the hours of footage recorded. Categorised into if the deployment was a Failure, Partial failure (non-usable), Partial failure (usable) or Success both species: Monteiro's storm-petrel Hydrobates monteiroi and Madeiran storm-petrel Hydrobates castro, from the chick-rearing breeding seasons (summer 2019 and winter 2019-2020 respectively) on Praia islet, Graciosa, Azores.

	Deployment outcome	No. deployments	No. videos	Hours of footage recorded			
				Sum	Max	Mean	SE
Monteiro's storm-petrel	Failure	6	3	0.0	0.0	0.0	0.0
	Partial (non-useable)	1	6	0.1	0.1	0.1	0.0
	Partial (useable)	17	14,086	117.4	22.0	6.9	1.4
	Success	56	52,118	434.3	14.9	7.8	0.5
Subtotal		**80**	**66,213**	**551.8**	**37.0**	**14.7**	
Madeiran storm-petrel	Failure	11	10	0.1	0.0	0.0	0.0
	Partial (non-useable)	3	43	0.4	0.2	0.1	0.0
	Partial (useable)	3	509	10.7	6.5	3.6	1.5
	Success	41	42,408	353.4	17.5	8.6	0.5
Subtotal		**58**	**42,970**	**364.5**	**24.2**	**12.3**	
Total		**138**	**109,183**	**916.3**	**22.0**	**6.6**	**0.4**

S4 Table 4. Number of Successful and Partial failures (usable) deployments categorised by the duration of the footage obtained based on start and end times of the footage (1hr-12hr, 12-24hr, 24+ hours) for both species: Monteiro's storm-petrel *Hydrobates monteiroi* and Madeiran storm-petrel *Hydrobates castro* from the chick-rearing breeding seasons (summer 2019 and winter 2019-2020 respectively) on Praia islet, Graciosa, Azores.

Deployment outcome	**Storm-petrel species**	**Duration of footage**			
		1hr-12hr	**12-24hr**	**24hr+**	**Total**
Successful	Monteiro's	7	30	19	56
	Madeiran	0	37	4	41
	Subtotal	**7**	**67**	**23**	**97**
Partial (useable)	Monteiro's	7	2	8	17
	Madeiran	1	0	2	3
	Subtotal	**8**	**2**	**10**	**20**
Total		**15**	**69**	**33**	**117**

Chapter 5 Supplementary Materials



S5 Figure 1. Frequency of videos from all chick-rearing videos analysed for the Monteiro's storm-petrel 2019 breeding season (n=52 camera deployments on 19 different nests; A-C), and band-rumped storm-petrel 2019-2020 breeding season (n=33 camera deployments on nine different nests; D-F), for: A&D) different chick age days (where day of emerging from egg = day 1); B&E) across the 24-hour period (time aligned to UTC - where in the Azores: 31st March 2019 – 27th October 2019 = UTC+0hr i.e. Monteiro's storm-petrel breeding season and 28th October 2019 – 28th March 2020 = UTC-1hr i.e. band-rumped storm-petrel breeding season), and C&F) across Julian days (where Julian day one = 1st January 2019 for the Monteiro's storm-petrel season and 1st October 2019 for the band-rumped storm-petrel breeding season, graphs edited to show 85 Julian days per season).

1

S5 Table 1. Percentage of occurrence of different behaviours and inter-specific interactions across both species' (*Hydrobates monteiroi* and *H. castro*) chick-rearing periods, with definitions of behaviours, from the chick-rearing breeding seasons (summer 2019 and winter 2019-2020 respectively) on Ilhéu da Praia, Graciosa, Azores.

	Definitions	Monteiro's storm-petrel	Band-rumped storm-petrel
Total no. of hourly videos analysed		1,105	482
Percentage no. videos			
Behaviours			
Chick sitting while awake	Bird sitting calmly still with head visible, not tucked under wing, with no other active behaviours occurring.	49.23	47.93
Chick preening	Using bill to nibble or clean feathers, often interspersed with shaking and ruffling of feathers.	34.12	42.53
Chick sleeping	Head tucked under wing or into chest, bird does not move.	20.36	26.56
Chick feeding	Adult and chick heads are close together, chick bill is in adult's bill while adult transfers food to the chick.	0.36	0.41
Adult nest attendance	Adult present in nest.	7.69	3.11
Adult sitting while awake	Bird sitting still with head visible, not tucked under wing. Can include birds brooding young chick.	3.71	2.49
Adult preening self	Using bill to nibble or clean feathers, often interspersed with shaking and ruffling of feathers.	0.54	0.00
Adult preening chick	Adult using bill to nibble or clean chick feathers.	1.99	0.00
		0.36	0.41
Adult feeding chick	Adult and chick heads are close together, chick bill is in adult's	0.72	0.00

	bill while adult transfers food to the chick.		
Adult sleeping	Head tucked under wing or into chest, bird does not move.	0.45	0.00
Adult nest building/ maintenance	Using bill to move nest materials around	1.99	0.21
Adult incubating/ brooding	Adult specifically seen sitting on top of chick, or standing/walking on top of chick. (This is the same behaviour as "adult sitting" but only when specifically on the chick)	0.90	0.41
Other species present			
Ants		16.74	1.24
Lizards		2.26	0.41
Cory's shearwater		0.09	0.00
Known or suspected non-parent adult storm-petrel		2.17	0.00

S5 Table 2. Generalised Additive Models (GAMs) of daily and seasonal patterns of variation in behaviours and species occurrences in the nests of Monteiro's storm petrel (*Hydrobates monteiroi*) and band-rumped storm-petrel (*Hydrobates castro*) across the 24-hour cycle and across the nestling period with a binomial error family and *cauchit* link function, on each binomial behaviour of interest and each binomial interspecies interaction from the hourly video footage using the *mgcv* package. * = statistically significant to P = 0.05 or below.

	Hour				Chick age in days			
Models for *H. monteiroi*:	edf	Ref.df	Chi squared	P	edf	Ref.df	Chi squared	P
Adult present	7.75	8.00	4.85	0.755	7.66	8.24	32.06	<0.001*
Chick feeding	1.76	8.00	<0.01	1.000	1.91	2.40	1.46	0.578
Chick sitting	5.44	8.00	15.80	0.006*	8.28	8.86	37.56	<0.001*
Chick sleeping	6.98	8.00	28.17	<0.001*	8.20	8.79	34.13	<0.001*
Chick preening	5.58	8.00	13.99	0.015*	8.53	8.94	47.59	<0.001*
Lizards	6.02	8.00	3.72	0.718	7.97	8.27	5.81	0.726
Ants	0.73	8.00	1.01	0.239	8.75	8.98	52.97	<0.001*
Models for *H. castro*:	edf	Ref.df	Chi.sq	p-value	edf	Ref.df	Chi.sq	p-value
Adult present	2.50	8.00	5.78	0.056	4.60	5.50	9.88	0.101
Chick feeding	<0.01	8.00	<0.01	0.663	1.84	2.39	1.00	0.690
Chick sitting	2.11	8.00	10.54	0.002*	4.24	5.21	16.87	0.006*
Chick sleeping	1.32	8.00	4.57	0.021*	7.59	8.38	17.53	0.029*
Chick preening	2.75	8.00	4.63	0.146	4.28	5.28	13.37	0.026*
Lizards	0.94	8.00	<0.01	1.000	1.65	1.00	<0.01	0.995
Ants	<0.01	8.00	<0.01	0.544	4.05	1.00	<0.01	0.990

S5 Table 3. Generalised Additive Mixed Model (GAMM) was conducted to assess the survival of the Monteiro's storm-petrel chicks only, with lizard and ant presences as fixed factors and nest number as a random factor, using a binomial error family and "logit" function, implement with the *mgcv* package. Hatch date was smoothed (to examine non-linear changes across hatch date) using the default thin plate regression spline method. * = statistically significant to P = 0.05 or below.

Model for *H. monteiroi*:				
Parametric coefficients	Estimated Std.	Error	T value	P
Lizards	-0.59	3.91	-0.15	0.880
Ants	-0.76	2.34	-0.32	0.746
Approximate significance of smooth terms	edf	Ref.df	F	p-value
Hatch date (Julian day)	1	1	4.09	0.043*

Appendices: Other Papers Arising from Work Completed Alongside this Project

Appendix 1

Habitat Categorisation and Mapping of a Seabird Reserve: Ilhéu da Praia, Azores

Already published under the same name in Seabird.

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ABSTRACT

The removal of invasive species and mitigating habitat loss are vital conservation tools for species such as seabirds. We surveyed habitats across the entirety of a small seabird islet reserve in the Azores, two decades on from mammalian eradication and floral restoration. Here, we present an in-depth map, to a 12 metre resolution, representing the first full habitat survey of this islet. Following restoration efforts in the 1990's, the islet's dominant habitats are meadow, grassland dominated by *Festuca petraea,* or a combination of the two. We also report a novel observation of both Madeiran (*Hydrobates castro*) and Monteiro's (*Hydrobates monteiroi*) Storm Petrels breeding in the invasive *Tamarix africana* tree cavities.

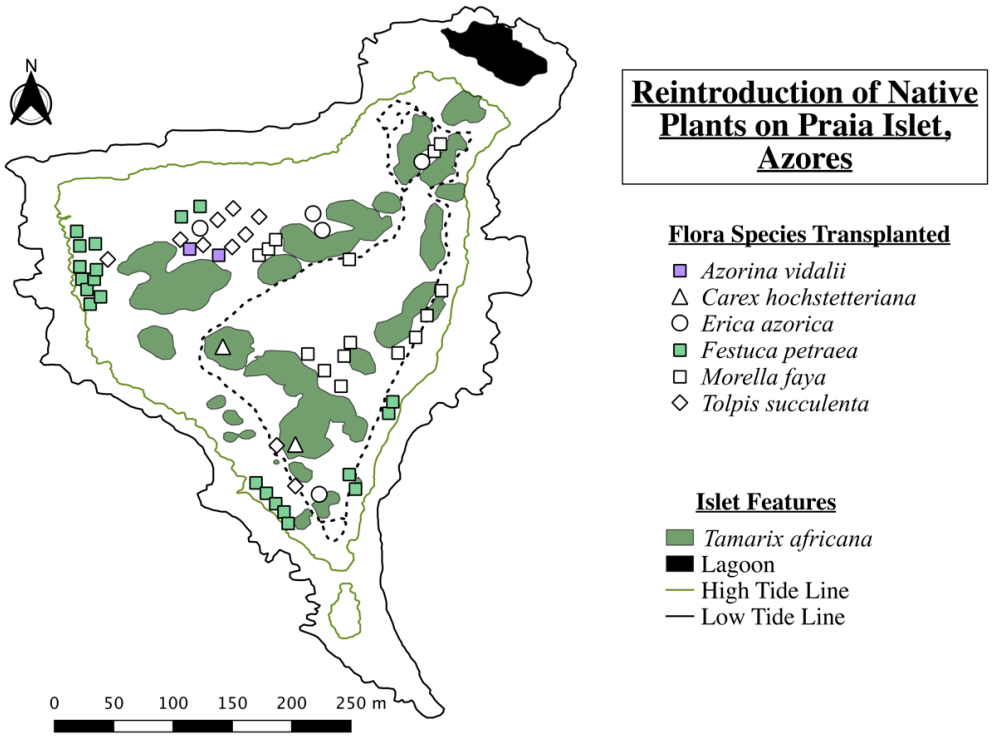
INTRODUCTION

Islands provide a crucial resource for rare and endangered taxa. While all nine islands of the Azores have been deeply transformed by almost six centuries of

continued human presence, it is still possible to find many endemic species (>70 species of vascular plants, >260 species of arthropods, and two species of birds (Borges *et al.* 2010; Rodrigues *et al.* 2010; Silva *et al.* 2010)). It is the islets (smaller islands) of the Azores, however, which are particularly important, as their remote nature has enabled them to host unique ecosystems, particularly due to the absence of herbivorous grazers, which deplete and erode the vegetation and soil that many species depend on for food or shelter (Boersma *et al.* 2002). Such species include seabirds, which require undisturbed land for nesting and have historically used islands as refuges, with fewer predators, competitors, and anthropogenic activities compared to mainland sites (Bellingham *et al.* 2010). In the Anthropocene, however, colonies of seabirds on islands have become increasingly threatened, primarily driven by invasive species, e.g. mammals, particularly rodents (Harper *et al.* 2015; Brooke *et al.* 2017; Jones *et al.* 2019), and habitat loss, e.g. erosion and overgrazing (Monteiro *et al.* 1996; Cadiou *et al.* 2009; Gizicki *et al.* 2018; Dias *et al.* 2019). Ground- and burrow-nesting seabirds that use such islands are highly vulnerable to invasive species and habitat degradation, which is amplified by their low fecundity (Ratcliffe *et al.* 2009). Additional anthropogenic threats have also emerged for pelagic species such as seabirds: mainly climate change, overexploitation of fishing resources, entanglement in discarded fishing gear, and plastic ingestion (Bertrand *et al.* 2012; Grémillet *et al.* 2016; Savoca *et al.* 2016; Donnelly-Greenan *et al.* 2019). Procellariiformes are one of the most threatened groups of seabirds, their decline driven by many of these threats (Dias *et al.* 2019; Solothurnmann, 2019). The removal of invasive species and habitat restoration at crucial breeding sites are valuable conservation tools for seabirds, leading to increased nesting success and enhanced adult survival (Cadiou *et al.* 2009; Brooke *et al.* 2017). One such example of this active conservation is Ilhéu da Praia (in English: Praia Islet; hereafter, Praia), a volcanic islet located 1 km east of Graciosa Island, in the Azores Archipelago, classified in 2007 as a Biosphere Reserve, due to its importance as a breeding site for seabird species such as the endemic Monteiro's Storm Petrel (*Hydrobates monteiroi*) (UNESCO, 2007).

Historically, Praia was used by local farming communities of Graciosa as pasture for grazing goats (*Capra argagrus hircus)*, until the late 20th century. Praia was also used as a recreational area by Graciosa residents, mostly during the summer months. Consequently, the disturbance level was too high for many seabirds to breed, particularly terns. Grazing by mammals, including European

Rabbits (*Oryctolagus cuniculus)* (introduced pre-1830's (Andrade, 1831)), contributed to continued habitat loss and soil erosion. By 1995, the vegetation over most of Praia was highly degraded, primarily through overgrazing and trampling by domesticated animals and humans, leading to soil compaction and vegetation suppression (Boersma *et al.* 2002; Bried *et al.* 2009). However, due to its proximity to rich Atlantic feeding grounds, absence of mammalian predators, and holding breeding colonies of several red-listed seabirds, Praia is arguably an internationally important site for seabird conservation (Monteiro *et al.* 1996; BirdLife International, 2018). Recognising the existing damage, and ongoing threats to this important seabird nesting community, access was restricted and significant restoration work was carried out on Praia between 1996 and 2004: European Rabbits were successfully eradicated, soil erosion mitigation measures implemented, much non-native flora removed, and native flora reintroduced (Appendix 1. Figure 1) (Bried *et al.* 2009). Invasive Hottentot Fig (*Carpobrotus edulis*), which is native to South Africa and forms vast "mats" to the exclusion of all other plants, was removed, along with Wild Sage (*Lantana camara*), which chemically prevents other plants growing adjacent (Taylor *et al.* 2012; Smyth *et al.* 2013). Between 2000 and 2003, various native plants were transplanted onto Praia. These included: four *Azorina vidalii*, 450 *Festuca petraea*, 165 *Carex hochstetteriana,* 120 *Tolpis succulenta,* 42 *Erica azorica,* and 32 *Morella faya* (Bried *et al.* 2009). In addition, Graciosa Natural Park frequently control the non-native tree, *Tamarix africana*.



Appendix 1. Figure 1. Native plants reintroduced to Praia between 1998 and 2004. Modified from Bried *et al.* (2009), with permission from authors. First published in ECOLOGICAL RESTORATION 27.1 27-36 © 2009 by the Board of Regents of the University of Wisconsin System. Reprinted by courtesy of the University of Wisconsin Press. Produced using QGIS version 3.10 (QGIS Development Team, 2019).

Alongside the vegetation restoration work, 50 artificial nest boxes were also installed in 1996 to increase suitable breeding areas for terns along the western coast of Praia, the area most deprived of vegetation (Bried *et al.* 2009). The terns on Praia are not observed to use these boxes, unlike in the UK (Morrison and Gurney, 2004). In 2000-2001, 150 plastic cavity nesting boxes were installed for storm petrels, mostly along the eastern and northern coasts, which have been successfully used (Bolton *et al.* 2004).

Through these conservation approaches of both habitat restoration and nest box installation, there was a rapid increase in breeding seabird numbers, and diversity, which now total at least six species. Common (*Sterna hirundo*) and Roseate Tern (*Sterna dougallii*) populations increased by 200 and 570 breeding pairs respectively by 2015 (Bried et al. 2009; Neves et al. 2016). In 2013, Madeiran Storm Petrel *(Hydrobates castro)* active nests totalled 101, signifying a four-fold increase in breeding attempts from 2000. Similarly, 95 active nests of the endemic Monteiro's Storm Petrel *(Hydrobates monteiroi)* represented a six-fold increase in breeding attempts over the same period. For both storm petrel species, recorded successful breeding attempts in natural nests were in

natural crevices in bare rock, and burrows in the ground (Bolton *et al.* 2004). Barolo Shearwaters (*Puffinus lherminieri baroli)* now breed on Praia, with over nine attempts in 2013 (Bried and Neves, 2015). Cory's Shearwater *(Calonectris borealis)* breeding pairs number between 120 and 150, although breeding success has not been monitored closely (Bried and Neves, 2015). Other birds have been recorded breeding in a variety of the reintroduced flora: Roseate Terns breed in the shelter of the larger *Azorina vidalii* plants, with chicks observed sheltering under *Festuca petraea* (Bried and Neves, 2015).

Following the conservation measures described above, the flora of Praia has now had approximately 20 years to establish and recover from anthropogenic pressures (Appendix 1. Figure 2).

Appendix 1. Figure 2**.** comparison between the vegetation levels on Praia in 1997 from the south, before rabbit eradication (left) (photo: Elizabeth Bell / Wildlife Management International Ltd.), and in 2020 (right) (photo: Ben Porter).

In this study, we surveyed the entire islet and characterised vegetation complexes in 12 x 12 m resolution cells to create the most complete, accurate, and up-to-date vegetation map of Praia. We discuss the conservation implications of these modifications in floral communities, particularly for the recovering seabird communities present. Finally, we present potential uses for this resource as a conservation tool.

MATERIALS AND METHODS

Study Site

Praia (39°03’23.0” N 27°57’20.0 W) is a small islet of 0.1 km² in size, with an elevation summit of 52 m. Praia hosts a relatively stable climate, with a year-round average temperature range of 13 °C to 22 °C, and with substantially more rainfall in the winter months (October - February). The annual mean rainfall is 1076 mm (Climate-data.en, 2020).

Habitat Categorisation

Habitat categorisations were generally assigned based on the dominant plant species/substrate type present, with the exception of the “Meadow” habitat, in which three species were found to be present in varying proportions without any being particularly dominant (Appendix 1. Table 1). There are 197 flora species that are considered native to the Azores, of which at least 15 are found on Praia (Schaefer, 2005; Silva *et al.* 2010). Identification of plants and habitat complexes was achieved using visual identification and subsequently identified to species level using multiple sources (Schaefer, 2005, CABI, 2020; Kew Science, 2020, and Sociedade Portuguesa de Botânica, 2020).

Appendix 1. Table 1. Dominant habitat types present on Praia. Asterisk (*) denotes native flora species; (**) denotes endemic Azorean species.

Habitat Type	Status
*Azorina vidalii***	Four plants reintroduced 1998 (Bried *et al.* 2009).
Artificial	The structure (now a small research base) was built pre-1900’s.
Bare Volcanic Rock	Naturally occurring. Susceptible to erosion.
Bare Soil	Naturally occurring. Susceptible to erosion.
Volcanic Boulders	Naturally occurring. Susceptible to erosion.
*Festuca petraea***	450 plants reintroduced 2000-2003 (Bried *et al.* 2009).
	Mixed species habitat, composed primarily of:

Meadow Complex	*Daucus carota* subsp*. azoricus***, *Plantago coronopus, Plantago lanceolata**
Tamarix africana (Deciduous tree)	Estimated arrival date to the Azores in the 15th century (Costa *et al.* 2013). Possible arrival date to Praia in the early 20th century.

Other flora species found in low densities on Praia, but not at densities high enough to constitute or exclusively apply to a specific habitat type, included: *Anagallis arvensis** (Primulaceae)*, Apium graveolens** (Apiaceae)*, Asplenium marinum** (Aspleniaceae), *Atriplex prostrata** (Amaranthaceae), *Carex hochstetteriana*** (Cyperaceae), *Cyperus esculentus* (Cyperaceae), *Erica azorica*** (Ericaceae), *Euphorbia azorica*** (Euphorbiaceae), *Morella faya** (Myricaceae), *Picris echioides,* (Asteraceae), *Solidago azorica***(Asteraceae)*, Spergularia azorica*** (Caryophyllaceae), *Tolpis succulenta** (Asteraceae). In line with Table 1, asterisk (*) denotes native species, whereas (**) denotes species endemic to the Azores. Unmarked species are non-native or considered naturalised.

Habitat Survey

We surveyed the habitat of Praia between October and December 2019. Using a handheld Garmin eTrex 20x GPS, habitat category was documented every 0.5 arc seconds (approximately 12 metres, or 1/3600 of a degree) after allowing sufficient time for the GPS to stabilise. At each point, the dominant habitat category (>50 % of habitat) in a 2.5 m radius from the central point was defined and recorded. Where two habitats were present and neither dominant, both habitat types were logged as a mixed habitat e.g. Bare Rock/Meadow. All accessible points were assessed in this manner, whilst non-accessible points, such as hazardous/tidal and thickly vegetated areas (i.e. centre of Tamarisk trees), were assessed by sight (either by eye or with binoculars) from the nearest accessible point. To minimise observer error (see review by Morrison, 2016), all data points were made by the same primary surveyor, accompanied by at least one field assistant. Specific plant identifications were discussed by multiple people to minimise overlooking and misidentification errors.

Digitisation of Mapping Data

Data were transferred into QGIS version 3.10 (QGIS Development Team, 2019) from a .csv file. The Geometry Definition section in QGIS included DMS coordinates, and the Geometry CRS was EPSG:4326 - WGS 84. Our sampling points were created at 5 x 5 metres and assigned a unique colour scheme and pattern, according to their habitat categorisation. Around our 5 x 5 metre sampling points, a regular grid of 12 x 12 metre cells (i.e. approximately 0.5 arc seconds) was overlaid so that the sampling points were in the centre of the cells. This grid was then joined to the sampling points and their habitat categorisations, and filled with the central survey points' colour scheme at 50 % opacity, in order to aid visual interpretation of the map itself. An outline of the approximate low tide line of Praia was also added, as a separate layer.

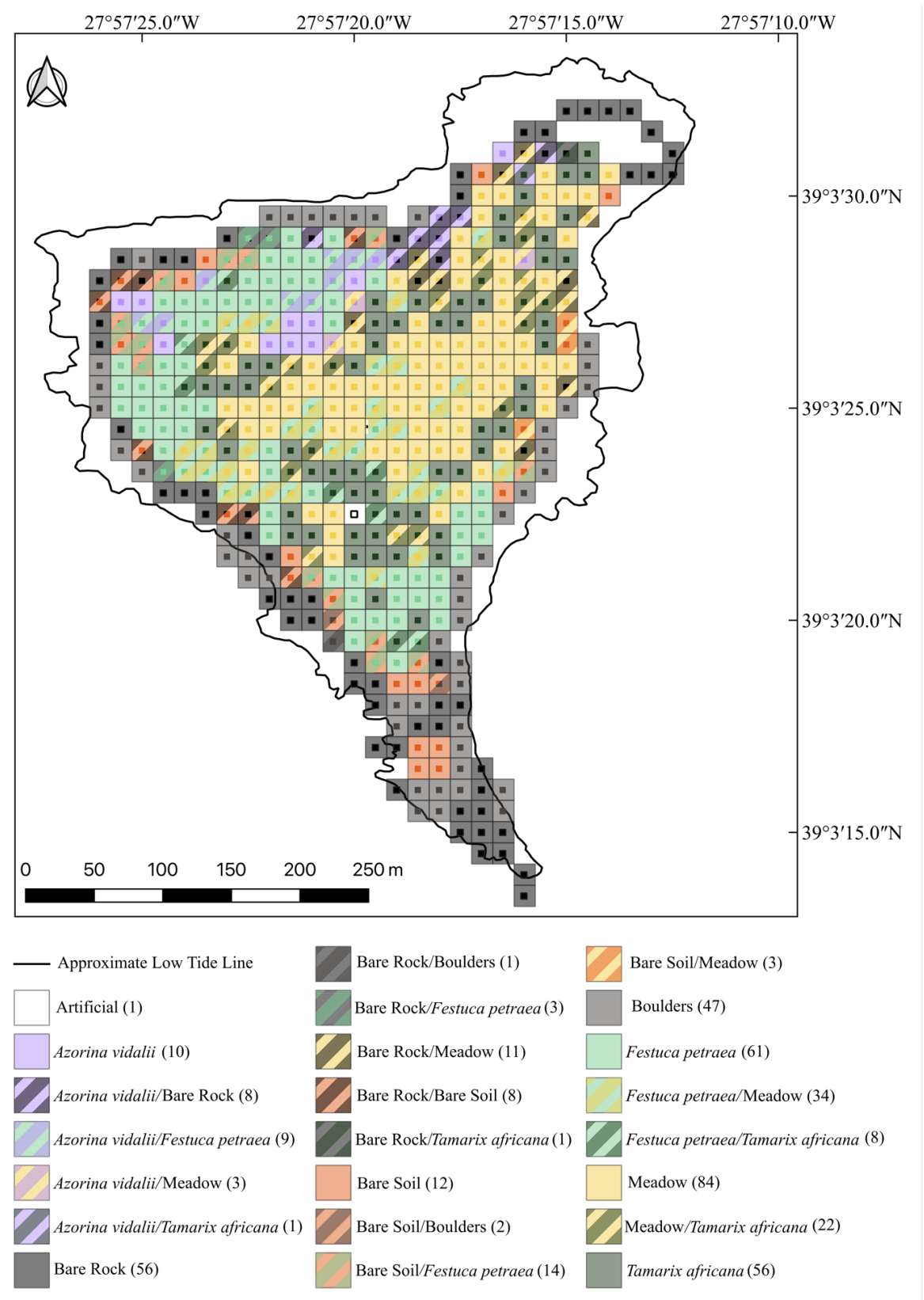
Seabird Observations

Ad. hoc observations of habitat use by breeding storm petrels took place between October – December 2019, and were made in conjunction with a larger project (spanning March 2019 – March 2020), which included breeding population monitoring of the two species of storm petrel in both artificial and natural nests.

RESULTS

Habitat Survey

We defined eight distinct habitat categories and 15 mixed habitat categories across the 455 cells surveyed (Appendix 1. Figure 3). Of these, five habitats dominated the islet landscape: Meadow (n = 84; 18.5 %), *Festuca petraea* (n = 62; 13.6 %), Bare Rock (n = 56; 12.3 %), *Tamarix africana* (n = 56; 12.3 %), and Boulders (n = 47; 10.3 %) (Appendix 1. Figure 3). The "Meadow" habitat was mainly found in the central and eastern regions of Praia, whereas *Festuca petraea* was distributed in the western and southern extents of Praia, mainly at lower altitudes. *Tamarix africana* was mainly found alongside the meadow habitat, with Bare Rock and Boulder habitats found around the periphery of Praia (Appendix 1. Figure 3).



Appendix 1. Figure 3. Habitat map of Praia Islet, Azores. Habitat type was defined at 5 x 5 metres, which formed the central square of each 12 x 12 metre cell. The abundances for each habitat type are listed in brackets after the category, representing the number of 5x5 metre sampling points each was recorded in (Total number of instances = 455). Produced using QGIS version 3.10 (QGIS Development Team, 2019).

The most numerous mixed habitat was *Festuca petraea*/Meadow (n = 34; 7.5 %), followed by Meadow/*Tamarix africana* (n = 22; 4.8 %), Bare Soil/*Festuca petraea* (n = 14; 3.1 %), Bare Rock/Meadow (n = 11; 2.4 %), and *Azorina vidalii*/*Festuca petraea* (n = 9; 2 %). The least numerous distinct habitat type was Artificial (n = 1; 0.2 %).

Over the last 20 years since the native plants were reintroduced (Appendix 1. Figure 1), *Azorina vidalii* has expanded over much of the northwestern area of Praia and is now the dominant or co-dominant habitat type in 7 % of the grid cells surveyed (Appendix 1. Figures 1 & 3). Praia's meadow of *A. vidalii* is now one of the largest fields of the monospecific genus Azorina in the Azores. Similarly, *Festuca petraea* has now established over much of the lower altitudinal areas of Praia (Appendix 1. Figures 2 & 3), on land that was previously overgrazed (Appendix 1. Figures 1 & 2). *Festuca* is now the dominant vegetation type in 13.6 % of the grid cells surveyed and is co-dominant in a further 15 % of cells, often forming a mixed habitat with bare soil. Conversely, reintroductions of *Carex hochstetteriana, Tolpis succulenta, Erica azorica,* and *Morella faya* (Bried *et al.* 2009) have been less successful, and were not observed in great enough numbers in this study to constitute a distinct habitat type. Finally, *Tamarix africana*, a non-native tree species on Praia, appears to have spread, despite control efforts by the Graciosa Natural Park.

Seabird Observations

We observed Cory's Shearwaters, as well as Madeiran and Monteiro's Storm Petrels, successfully breeding in *Festuca petraea*, Bare Rock, and Meadow habitats. In addition, Barolo Shearwaters successfully bred in *Festuca petraea.* Interestingly, these species nesting within *Festuca petraea* have been observed nesting in cavities within the plant communities themselves, without excavating a burrow, contrasting their behaviour in other habitat types. Additionally, Cory's Shearwaters successfully breed underneath the non-native *Tamarix africana*. Barolo Shearwaters have also been observed excavating nests around the *Tamarix* trees, but the breeding success was unknown. Furthermore, Madeiran Storm Petrels were also observed to successfully breed within the *Tamarix* trees, using cavities and natural holes at the base of the trunks. Monteiro's Storm Petrels were also seen prospecting these holes but were not observed breeding.

DISCUSSION

This study presents the first complete, high-resolution habitat map of Praia Islet. It demonstrates how the multi-faceted conservation efforts in the 1990s and early 2000s have transformed the habitat structure and landscape of this important seabird nesting site.

In this work, we surveyed vegetation complexes across the whole of Praia to a resolution of 12 metre cells. Following conservation and habitat restoration work conducted 20 years ago, we have mapped the spread and status of some of the reintroduced, and non-native, flora species. However, a more in-depth assessment to determine the range expansion or contraction of these reintroduced species would be beneficial. Specifically, the *Tolpis succulenta* plants growing on Praia, and found in low numbers in the Azores, may be a new species or subspecies, endemic to the Azores or even to Graciosa (Kerbs *et al.* 2019; Crawford *et al.* 2020). The plants found on Praia may be of considerable conservation importance, due to the threats of anthropogenic habitat degradation and competing exotic plants on inhabited Azorean islands, particularly on Graciosa (Borges Silva *et al.* 2015). A population estimate (i.e. the number of individual plants) on Praia would investigate their success on this protected islet.

Comparing our updated vegetation map with previous work by Bried *et al.* (2009) (Appendix 1. Figure 1), it is evident that the habitat restoration on Praia has been highly successful. Whilst differing sampling methodologies prevent direct comparisons between present-day habitat composition and two decades earlier (i.e. Bried *et al.* 2009), several conclusions can be drawn. Most evident is the spread of *Festuca petraea,* which has spread from 450 plants to being present in almost 30 % of the islet's surface (Appendix 1. Figure 3). This has positive implications for Praia's seabirds, as they were previously constricted to Bare Rock habitat, with limited nest burrows in earth banks (Bolton *et al.* 2004; Bried *et al.* 2009). This study has also identified that procellariiformes now breed successfully throughout four of the five most prevalent habitat categories (Meadow, *Festuca petraea,* Bare Rock, *Tamarix africana,* Boulders). Specifically, *Festuca* is used as a nesting habitat by both Cory's and Barolo Shearwaters as well as Madeiran and Monteiro's Storm Petrels, similar to the behaviour of other procellariiformes (Gillham, 1963). For the first time, we describe the nesting of Madeiran Storm Petrels in the base of the non-native tree, *Tamarix africana*, and the use of this tree cover by Cory's and Barolo Shearwaters. This use of

trees as nest sites is similar to observations of nesting Leach's and Fork-Tailed Storm Petrels (Chilelli, 1999; Vermeer *et al.* 1988). These trees are still prevalent on Praia despite the control efforts by Graciosa Natural Park. Such control efforts prevent formal comparison between the distribution of *Tamarix africana* in 2009 and present day. This nesting observation, however, presents difficult conservation decisions between avoiding removing nesting habitat and controlling the spread of the *Tamarix africana* tree cover, which, if allowed to spread, could cause a challenge to seabirds landing and taking off from Praia, particularly newly fledged individuals. The effects of these non-native trees on the breeding success of procellariiformes on Praia could potentially be investigated in future studies.

This study contributes to a growing body of evidence documenting the effectiveness of invasive species eradication and subsequent habitat restoration as conservation tools for island-nesting seabirds (e.g. Cadiou *et al.* 2009; Brooke *et al.* 2017; Bell *et al.* 2019). Rabbits are known to be detrimental to the breeding of nesting seabirds, and previous studies have shown the removal of rabbits to increase breeding success in procellariiformes (Zino *et al.* 2008). Additionally, anthropogenic activities cause disturbance to seabird colonies and lower breeding success (Anderson *et al.* 1980). Having almost fully removed all these pressures to seabird breeding on Praia 20 years ago, seabird population recovery is ongoing. As Praia hosts 40-50 % of the world's population of Monteiro's Storm Petrel (Oliveira, 2016), classed as "Vulnerable" by the IUCN (BirdLife International, 2018), it is essential that habitat restoration is maintained to support this endemic Azorean species. Whilst other seabird species that breed on this islet are all classified as Least Concern (BirdLife International, 2018), protecting the colonies on this site creates an extra buffer to the global populations, increasing resilience against continued climate change and direct anthropogenic activities, e.g. overfishing (Dias *et al.* 2019).

The habitat map (Appendix 1. Figure 3) produced within this study shows the increase in available breeding areas for seabirds on Praia, which, along with reduction in disturbance, is key to their breeding success. To fully investigate the impacts of habitat restoration, we suggest that a full-islet seabird census needs to occur, to determine the habitat usage of each species, including both terns and procellariiformes, and quantify the relative importance of each habitat for breeding. Data on breeding bird populations, and their proportional habitat use, does not yet exist. In order to solve this, an infra-red/thermal imaging

camera study during the breeding seasons of each species would provide a non-invasive option that would minimise sampling effort and disturbance to any breeding seabirds, whilst enabling specific habitat use to be quantified (Perkins *et al.* 2018). This could then guide further decision-making on habitat management of Praia. The continued monitoring of accessible natural, and all artificial, nests will allow average egg and chick survival rates to be extrapolated across the islet to allow for predictions of breeding success. Our mapping of non-floral habitats, such as Bare Soil, and Bare Rock, create a baseline to allow for future mapping of erosion, a factor of habitat loss for seabirds in the Azores (Monteiro *et al.* 1996). Finally, as plant communities and habitat composition on Praia are continually changing, our habitat map and categorisation scheme will also act as a baseline from which future changes can be monitored.

ACKNOWLEDGEMENTS

We thank Direção Regional do Ambiente, Região Autónoma dos Açores for granting access to Praia Islet (HFRH licence number: SAI-DRA/2019/1821 Proc. 116.14.03/43) and Graciosa Natural Park for helping us access and stay on Praia Islet. Thank you to Dr. Verónica Neves for providing contacts and information, and to Dr. Joël Bried for kind permission for use of his data. Figure 1 was reprinted by courtesy of University of Winconsin Press. Figure 2 featured a photograph courtesy of Elizabeth Bell/Wildlife Management International Ltd. Thanks to Dr Robert Thomas and Dr Renata Medeiros-Mirra for their initiation of this paper. This work was conducted in conjunction with HFRH's PhD who is supervised by: Dr. Robert Thomas, Dr. Frank Hailer, Dr. Renata Medeiros-Mirra, Dr. Sean Rands and Dr. Verónica Neves, and advised by Dr Mark Bolton and Dr. Joël Bried. HFRH is supported by a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council [NE/L002434/1] and is thankful for the support and additional funding from CASE partner, Eco-explore Community Interest Company and Cardiff University. Finally, we thank our two anonymous reviewers, whose constructive comments greatly improved the quality of this paper.

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Appendix 2

Single-board, modular computers as low-cost, bespoke camera trap systems for ecological and conservation research - a systematic review

Paper rejected but with offer to resubmit under the same name in Remote Sensing in Ecology and Conservation

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Abstract

Video and still-frame remote-sensing cameras are versatile and effective tools for studying wildlife ecology and addressing conservation issues. More recently, cameras based on self-build microcomputer systems, such as Raspberry Pi or Arduino, have become increasingly popular. These modular systems offer the potential for users to combine cameras with multiple additional sensors, thus yielding more comprehensive and useful information about the camera's location and environment, as well as the study system or species. In this systematic review, we used online literature searches focussed on the Raspberry Pi and Arduino systems to explore their use as wildlife cameras and the development of their functionality over time in terms of additional sensor modules. A total of 125 publications, 23% of which were

peer-reviewed, were identified as specifically focused on camera build methods. We show that the use of additional sensor modules, in addition to a camera, has increased over time. We also examined emerging and future questions in ecology and conservation to identify a series of key questions which could be addressed, at least in part, using self-build microcomputer systems. We showcase some of these questions through example case studies for monitoring (i) breeding success and habitat range usage of breeding birds; (ii) threats and impacts of hunting within national parks / wildlife reserves; (iii) stressors on marine systems due to climate change; and (iv) insect-plant interactions on agricultural crops in light of climate change impacts.

Introduction

Cameras have been increasingly used in wildlife ecology and conservation (Cutler and Swann 1999) to address a wide range of questions, from the individual to population level (e.g. McCarthy *et al.* (2019) and Gardner *et al.* (2010), respectively) and on local- to landscape-scales (e.g. Martin *et al.* (2015) and Jachowski *et al.* (2015), respectively). Camera trap technology dates back to the late-nineteenth century, when a shutter-release and magnesium flash system was triggered via trip wire (O'Connell et al. 2011). Subsequent developments saw camera trap systems become increasingly portable and practical, supported by technological advances such as the use of beams of visible light in place of trip wires (e.g. Dodge and Snyder (1960)) and, later, the development of infrared sensors (Carthew and Slater, 1991). Modern camera traps embrace digital technology (though some professional photographers continue to use 35 mm film in bespoke systems) and the units are typically commercially-built (Meek and Pittet 2012; Pimm et al. 2015; Edney and Wood 2021). More recently, single-board microcomputers such as Raspberry Pi (www.raspberrypi.org) and Arduino (www.arduino.cc) have been

used to develop user-built (or bespoke) camera traps (Greenville and Emery 2016; Johnston and Cox 2017; Allan et al. 2018).

Commercially-built camera traps are simple to use, and the researcher does not need knowledge of how to build the camera, or how to repair it if it malfunctions (Cox et al. 2012; Meek and Pittet 2012). However, commercial units are restricted to pre-determined designs, with little possibility for adaptation for specific purposes (Cox et al. 2012). Costs for commercial units vary (e.g. £36 GBP, Victure HC100 – £659 GBP, Reconyx HP2XC), though those at the very low-end of the price range are seldom used in wildlife research. By contrast, bespoke wildlife cameras are typically cheaper than commercial builds (Cox et al. 2012), and the potential to include a variety of sensor modules, such as temperature and humidity loggers (McBride and Courter, 2019), allows much greater flexibility in camera designs and hence the range of research questions that they can be used to address (Greenville and Emery 2016). There are a number of such systems available, though Raspberry Pi and Arduino are the most commonly used for wildlife conservation and ecological studies (Greenville and Emery 2016). It must be noted, however, that bespoke cameras require more technical skills (e.g. programming, soldering) and time to design, deploy and trouble shoot (Cox et al. 2012). Furthermore, the quality of additional modules often lags behind those found in commercial builds (e.g. Cox *et al.* 2012; McBride and Courter, 2019).

Here, we systematically review the peer-reviewed and grey literature to identify bespoke cameras that use Raspberry Pi or Arduino systems for wildlife monitoring. We identify the additional modules used and discuss the

applications of these to bespoke camera systems suitable for addressing current and projected questions in ecology and conservation.

Materials and Methods

Five different searches were undertaken to review the current peer-reviewed and grey literature on the use of Raspberry Pi or Arduino as microcontroller boards for wildlife cameras (Appendix 2. Table 1). The records returned were screened and summarised using the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method (Moher et al. 2009).

Results

A summary of the systematic literature search is outlined in the PRISMA flow diagram (Moher et al. 2009) (Appendix 1. Figure 1). Of the records rejected because they were not wildlife camera papers, 11 (peer-reviewed literature) and 18 (grey literature) described other non-camera-based wildlife monitoring systems e.g. acoustic remote monitoring systems (Browning et al. 2017), the use of radio-frequency identification (RFID) tag readers at bird feeding stations (Youngblood 2020), and temperature and humidity sensors (Neville 2017).

Of the remaining 244 articles (the full data set is available at Hereward et al. 2021), 125 described camera build methods, 21 described image analysis methods, 15 presented results obtained from bespoke cameras, and 17 reviewed various aspects of bespoke cameras (Appendix 2. Figure S1A). Other articles were found, including Unmanned Aerial Vehicle (UAV), underwater UAVs and robot platforms (Appendix 2. Figure S1B-D), as well as other articles including methods for carrying out automated image analysis (Appendix 2. Figure S1E).

Of the 125 camera build method articles, the number of articles found in grey literature (77%, n = 96), was substantially higher than in the peer-reviewed literature (23%, n = 29). The grey literature was defined as: blogs, books, conference proceedings, forums, magazine articles, online store, reports, theses, and videos. The number of articles per year has steadily increased for both grey and peer-reviewed literature, with the number of peer-reviewed literature articles lagging behind the grey literature articles (Appendix 2. Figure S2A).

Over half of the 125 camera method papers used a means of movement detection (62%, n = 78) and this use has generally increased over time. The most common form of movement detection across the literature was a passive infra-red (PIR) sensor (58% of articles with a form of detection, n = 45). Alternative motion detection methods used included alternative sensors (e.g., ultrasonic or RFID tags or *in situ* pixel change software: e.g. "Motion") or a combination of methods (Appendix 2. Figure S2B).

Similarly, the use of at least one additional sensor module attached to the camera has generally increased over time across the literature and was used in 42% of all the 125 articles (n = 52) (Appendix 2. Figure S1C). Here we define additional modules as those other than a detection method (i.e. a standard camera includes a camera + a detection method). One grey literature article (conference proceedings) described the combination of six different modules. These additional sensor modules included: temperature, humidity, soil moisture, ultrasound, air quality, UV sensor. Furthermore, the use of Wi-Fi/radio/phone network connection to remotely connect and transfer images/alerts has similarly increased over time, although they were only used in 10 of the 125 articles (Appendix 2. Figure S1D). By comparison, the use of

solar panels to supplement and extend battery power in remote locations has remained similar across the years, only being used in six of the 125 articles (Figure S2E).

Discussion

Here we have demonstrated that the use of Raspberry Pi and Arduino boards to build wildlife cameras is becoming more common, in both the peer-reviewed literature as well as in the grey literature. This proliferation of the use of cameras in wildlife monitoring provides researchers with valuable tools to address key research questions (Appendix 2. Table S1), as well as opportunities to engage citizen scientists in answering these questions (e.g. Gaver *et al.* 2019; Phillips *et al.* 2020).

We have shown that PIR sensors are still the predominant method for movement detection in bespoke cameras. However other methods already exist, including *in situ* automated methods – which could also aid in automating image/video analysis (Pimm et al. 2015; Prinz et al. 2016). Further work is needed in fine-tuning the models used to apply machine learning to specific study systems (but see e.g. Carl *et al.* 2020 for a successful example).

The use of Wi-Fi/radio/phone networks to transmit/upload data from cameras, and the use of solar panels to extend battery life (especially valuable in remote locations) is currently minimal. However, with the increase in machine learning capabilities it is possible that the use of Wi-Fi/radio to transmit data will increase as it decreases the amount of in-field retrieval and redeployments from remote locations, although concerns of data security may need to be considered (Cleveland 2006). An alternative to this is the use of UAVs/drones to retrieve this data instead (see e.g. Qin *et al.* 2019). Similarly, for the use of

solar panels, it is likely to increase as the solar panel adaptations become more user friendly, allowing for easier remote deployments (see Laut *et al.* 2014 for example deployment).

We have also identified that versatile combinations of cameras with additional modules and detection methods, potentially have a wider application within ecology and conservation than just recording images/videos of wildlife. However, there seems to be little uptake on the use of additional modules, which seems surprising given the benefits of using of them to collect additional data (e.g. McBride and Courter, 2019). We therefore suggest that the versatility of Raspberry Pi and Arduino is yet to be fully exploited in ecology and conservation applications, indicating that this is an important area for further development. Indeed, many of the emerging questions in ecology and conservation, identified as global priorities (e.g. Sutherland *et al.* 2009; Lepczyk *et al.* 2017; Dey *et al.* 2020), could be at least partially answered using bespoke camera technologies in combination with additional sensors (e.g. Appendix 2. Table S1).

Here we take some of these global questions from Appendix 2. Table S1, to provide four case study examples. These are not exhaustive, but aim to provide suggestions and ideas for future development of self-build microcomputer camera systems.

The monitoring of breeding birds at their nests aids in answering questions about the optimal design of protected areas, and of habitat "corridors" or "stepping stones" linking protected areas. This can be advanced using cameras in combination with other remote-monitoring technologies, to determine adult return rates, with tracking technologies, to determine habitat usage and

foraging locations (e.g. *via* pairing in and/or near-nest cameras with GPS tracking - Guilford *et al.* 2008; Bolton, 2021). Alternatively, RFID-equipped birdfeeders and nest boxes could be used in a similar manner to track the movement and behaviour of birds around their territories and pair with cameras to monitor delivery of food to their nests (e.g. Zárybnická *et al.* 2016; McBride and Courter, 2019; Youngblood, 2020). Likewise, questions regarding the impacts of changing local weather patterns on nest microclimate, chick provisioning, growth and breeding success (Facey et al. 2020; Sauve et al. 2021) could be answered by combining previously-used methods that describe the build and use of a camera (such as Prinz *et al.* (2016) or Hereward *et al*. [In Press]), with additional modules such as RFID tags on the adults with readers at bird feeders and the nest box, to determine habitat use by individual parents before returning to feed the chick (e.g. Youngblood, 2020). Remote weighing scales could be used to determine the mass of food delivered to chicks, and chick mass change (c.f. Bosch *et al.* 2015), alongside *in situ* wind and temperature sensors (e.g. McBride and Courter, 2019) or in-nest body surface temperature of the birds (c.f. Kallmyer *et al.* 2019).

Self-build microcomputer systems could also be used to assess threats and stressors of hunting impacts within protected land and reserves. Several papers have already demonstrated this use, identifying poacher presences using detection of pixel change (Trehan and Singh, 2016) or thermal and infrared detection modules (Tan et al. 2016) combined with GPS and phone networks (e.g. Mah, 2018) to send a message alert and location. This could be further applied to other reserves where there are specific problems of illegal persecution of wildlife, for example, hen harriers (*Circus cyaneus*) which nest on grouse moorlands (Fernández-Bellon et al. 2017; Murgatroyd et al. 2019;

Newton 2021). Camera technology would aid in monitoring and being alerted to hunting events (The Royal Society for the Protection of Birds [RSPB] 2019), alongside non-invasive/minimal disturbance monitoring of the biology and behaviours of the target species (Reif and Tornberg 2006). Developing the use of Wi-Fi/phone networks/GPS would be incredibly useful in furthering the scope of hunting monitoring as well as for citizen science projects (e.g. Jones *et al.* 2018; Glover-Kapfer, Soto-Navarro and Wearn, 2019; Edney and Wood, 2020), especially where the deployment sites are hard to access, and where remote transfer of the images/videos would aid in reducing disturbance on the wildlife being monitored. Citizen science projects targeted at examining footage or image analysis are becoming more common, because they enable the processing of otherwise insurmountable amounts of data sets (Jones et al. 2018). Therefore, through developing ways of directly uploading data to an online platform, this would provide easier access for the citizen scientists (e.g. Laut *et al.* 2014; Jones *et al.* 2018).

In addition, questions relating to marine system threats and stressors could combine cameras, to monitor the biodiversity of key marine ecosystems, alongside a variety of modules, to monitor the changing environment. Variables measured could include: temperature, pH, lux, dissolved oxygen and depth (e.g. Laut *et al.* 2014). For example, the degradation of coral reefs through bleaching is influenced by increased sea temperatures and changes in pH (Berkelmans and Willis 1999; Pratchett et al. 2008; Hughes et al. 2017), and this could be monitored by combining systems such as the CoralCam (Greene et al. 2020) with some of these additional modules (e.g. Laut *et al.* 2014; Swetha *et al.* 2020) in order to both monitor the growth of coral plates and the in-situ environmental changes, which are integral to the coral's growth and survival (Pratchett et al. 2008; Hughes et al. 2017). This could

increase local accuracy of the data, compared to that of remotely-sensed sea surface temperature data, which has previously been used for coral reef assessments (e.g. De *et al.* 2021). Similar systems could also be set up to monitor kelp forest habitats which are important ecologically and economically (Beaumont et al. 2008) but their growth rate, species distributions and long term survival are also impacted by climate-driven changes, through extreme heat waves and increases in sea temperature and turbidity (Harley et al. 2012; Smale et al. 2019; Hereward et al. 2020). This could also incorporate citizen science projects, for example creating a similarly compact system to that of CoralCam (Greene et al. 2020) with additional sensors, to be attached to surf boards, which would build on a recent successful trial of deploying temperature loggers on surf boards (Brewin et al. 2020).

Finally, questions regarding insect-plant interactions, with reference to agriculture crops (Barlow and O'Neill 2020) and in light of climate change impacts on plant assemblages (e.g. alpine Ohler, Lechleitner and Junker, 2020), could utilise already published advanced technologies of these self-build microcomputer systems (e.g. Droissart *et al.* 2021 and see table in Barlow and O'Neill, 2020) with additional modules, to monitor the interaction between insects and plants and the associated microclimates. For example, this could be done by combining the plant-insect interactions camera trap (PICT) system developed by (Droissart et al. 2021) with additional modules, such as air and soil humidity and temperature modules, to better understand and consequently manage pests on crops such as coffee plants (*Coffea* spp.), as these abiotic factors have been shown to influence the level of pest impact (Ijala et al. 2021). This could also be applied to other agricultural crops as well as for climate change or community-scale monitoring on disturbed land (e.g. Sánchez-Reyes *et al.* 2019).

Conclusion

The use of bespoke, single-board camera systems is a rapidly developing area across the ecology and conservation literature. However, it is clear that the true potential of such systems is yet to be fully utilised. There is considerable untapped potential to combine additional modules with camera systems to better monitor wildlife and/or ecosystems and address more complex ecological questions. We encourage bi-directional engagement and collaboration between scientists and system developers, so that key needs can be identified with the goal of supporting knowledge acquisition, and conservation and management processes.

Acknowledgements

Many thanks to Nigel Morgan for assistance with systematic searches and search string methods. This work was conducted in conjunction with HFRH's PhD that is supervised by: Dr. Robert Thomas, Dr. Frank Hailer, Dr. Renata Medeiros-Mirra, Dr. Sean Rands and Dr. Verónica Neves, and advised by Dr Mark Bolton and Dr. Joël Bried. HFRH is supported by a NERC GW4+ Doctoral Training Partnership studentship from the Natural Environment Research Council [NE/L002434/1]. We are grateful for the support from Cardiff University and additional funding from the project CASE partner, Eco-explore Community Interest Company.

Data Accessibility

Raw data and associated reference list are archived with Figshare: Hereward, Hannah F. R.; Facey, Richard J.; Caravaggi, Anthony; Rands, Sean; Thomas, Robert J. (2021): Raw data for review paper submitted to Remote Sensing in Ecology and Conservation. Hereward et al. Single-board, modular computers as low-cost, bespoke camera trap systems for ecological and

conservation research. figshare.

https://doi.org/10.6084/m9.figshare.16577930

Supplementary Information

Appendix 2 Figures S1 and S2 and Table S1 are available in the supplementary information.

Conflict of Interest

We declare we have no conflict of interests.

Author contributions

The concept was concieved by HFRH, RJF and RJT. All co-authors contribued to follow-up discussion about paper direction, content and systimatic review terms (HFRH, AC, RJF, SAR and RJT). SAR contributed to the systimatic reviewing methods. HFRH conducted the systimatic review, screened and summarised all the results. All contributed to finding relevant ecological questions which HFRH then complied into four case studies, with discussion from all other co-authors. Finally, all co-authors had opportunity to provide edits and have aproved the final version of the manuscript prior to submission and agree to be accountable to each aspect that they contributed to.

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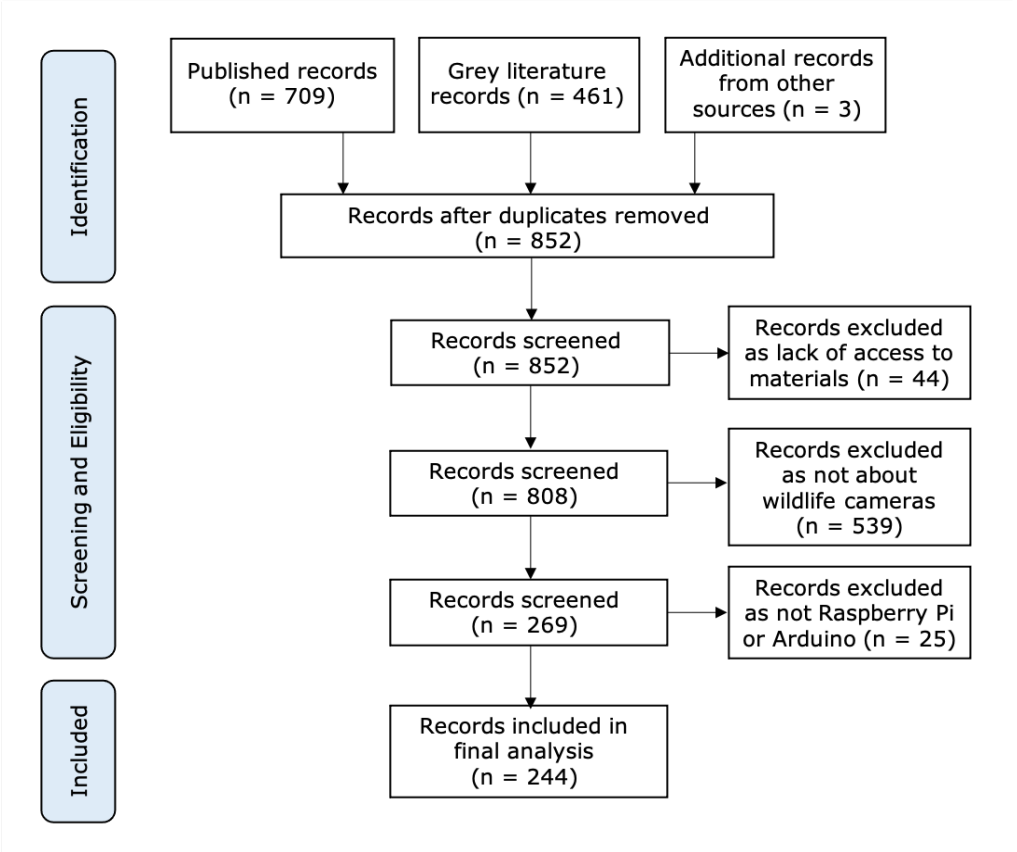
Figure



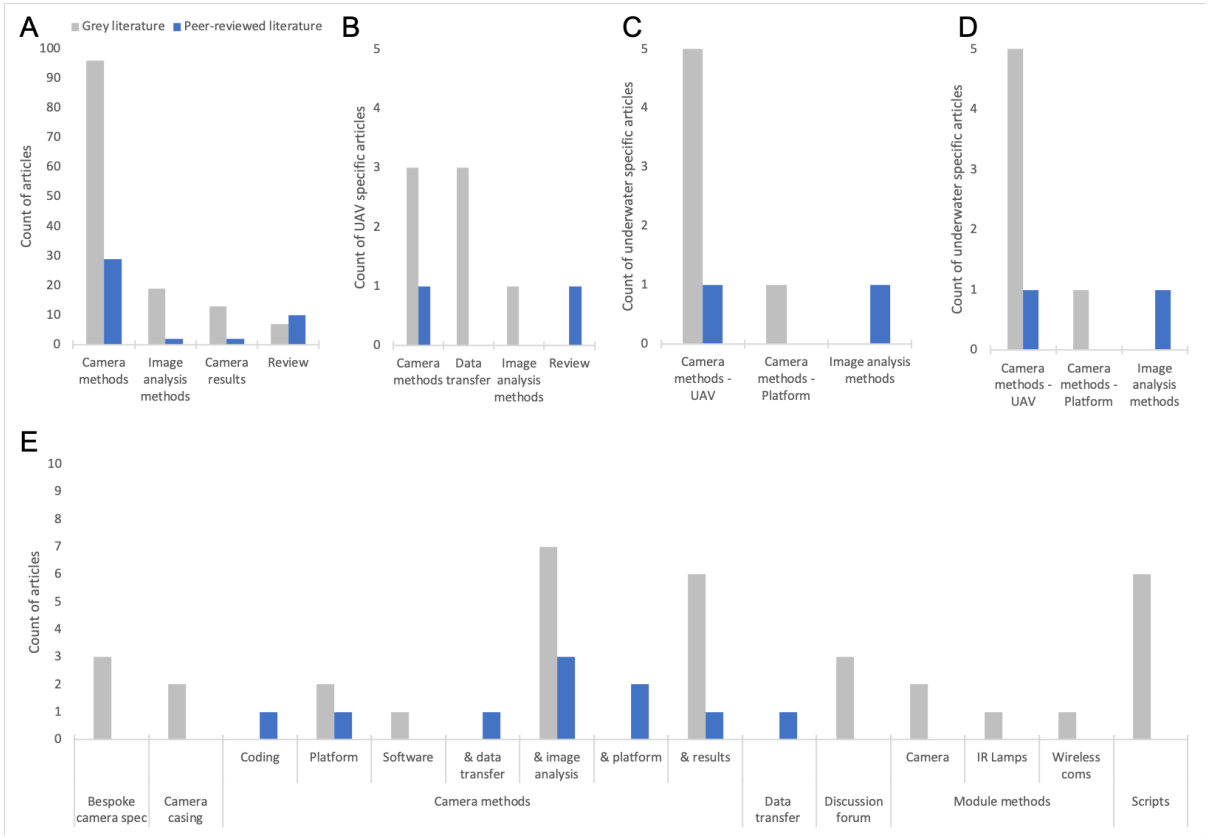
Appendix 2. Figure 1. Summary of the systematic review of published and grey literature for Raspberry Pi or Arduino based camera systems to study wildlife (Moher et al. 2009).

Table

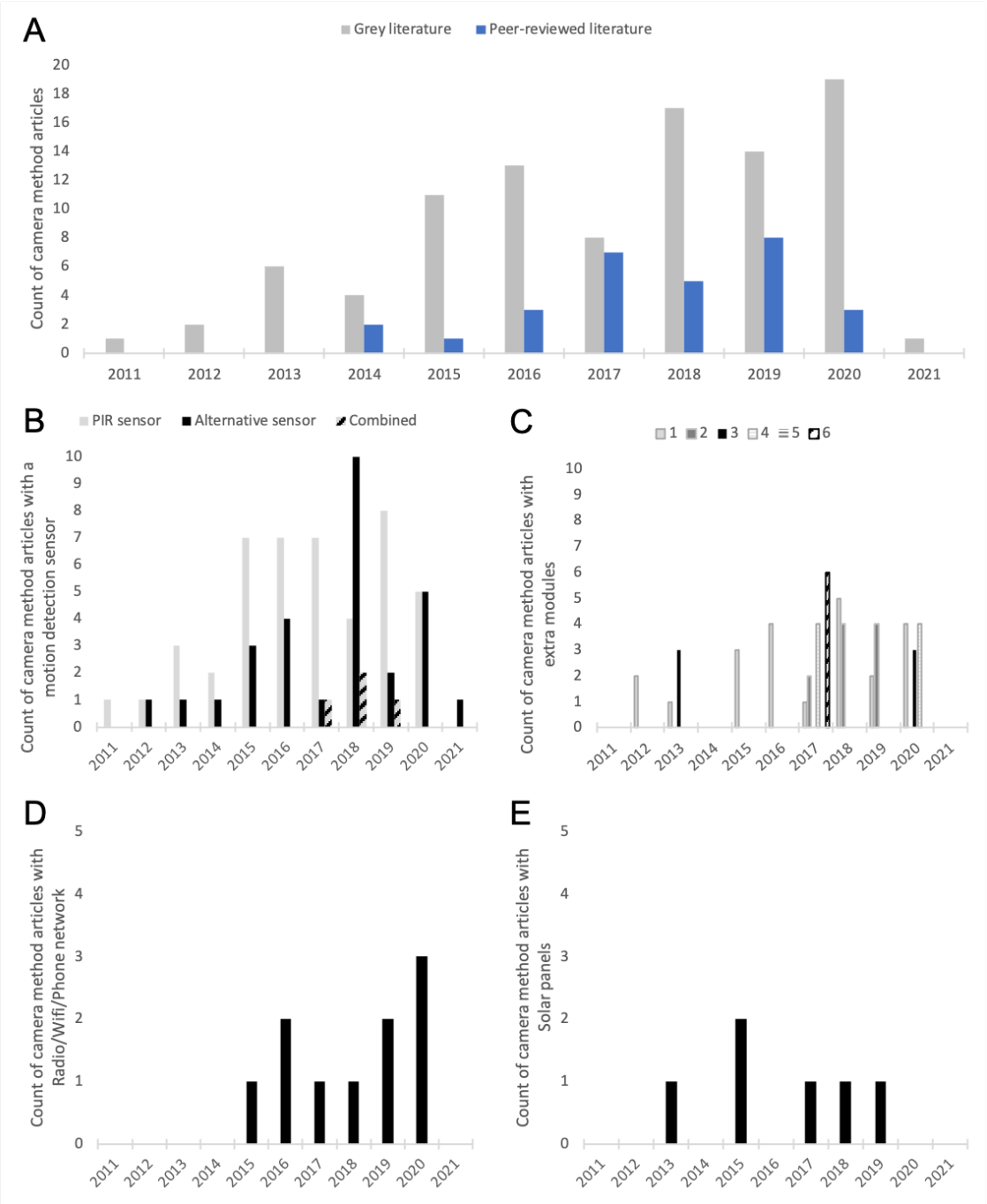
Appendix 2. Table 1. Systematic search engines used in the systematic review of wildlife cameras based on Raspberry Pi and Arduino technology, and searches conducted per search engine.

Search terms	Associated search engines	Date of search	Total articles returned	Total articles retained
Peer-reviewed literature				
"Raspberry Pi" AND "Camera trap", "Raspberry Pi" AND "trail cam*", "Arduino" AND "Camera trap", "Arduino" AND "trail cam*"	Google Scholar, Web of Science	20th January 2021	205	88
(("raspberry pi*" OR arduino) AND ("camera*" OR "cam" OR "cams") AND (wild* OR animal* OR bird* OR mammal* OR fish OR invertebrate* OR nest*)).	String searches in: Web of Science (core collection and BIOSIS; topic search), Scopus (title, abstract and key words), IEEEXplore (full text and metadata)	8th February 2021	164	42
"raspberry pi" AND "wildlife" AND "cam" and "arduino" AND "wildlife" AND "cam"	Google Scholar	24th February 2021	340	26
Grey literature (i.e. non-peer-reviewed)				
raspberry pi wildlife camera, arduino wildlife camera	Duckduckgo (https://duckduckgo.com)	23rd February 2021	461	85

Appendix 2 Supplementary Materials



Appendix 2. Figure S1. Count of articles in grey literature (colour = grey) or peer-reviewed literature (colour = blue) that were A) camera methods, image analysis, camera results or review, B) Unmanned Aerial Vehicle (UAV) articles (camera methods, data transfer, image analysis or review), C) underwater camera articles (camera methods, platform software or image analysis), D) robot camera articles (camera methods, or camera results) and E) remaining other articles identified.



Appendix 2. Figure S2. Count of camera methods article per year: A) across the grey literature (colour = grey) and peer-reviewed literature (colour = blue), and per year and across all literature: B) that included a PIR sensor, an alternative motion detection, or a combination of both, C) that included at least one extra modules (number of modules ranged from 1-6), D) with Radio, Wifi or phone network capabilities and F) across all literature with solar panels.

Appendix 2. Table S1. Global ecological and/or biodiversity conservation-based questions that could be answer by or in part through combining a Raspberry Pi or Arduino camera with other environmental or wildlife monitoring modules.

Broad category	**Question identified**	**Paper**	**Example environmental monitoring modules**	**Example wildlife monitoring modules**
Agricultural practices	Agricultural practices	Top 8. (Dey et al., 2020)	Air humidity, Soil pH, CO2, Soil moisture, Rain fall, UV or lux	Camera
Renewable energy	Technological change: How do the type, location and associated mitigation measures of renewable energy technologies affect biodiversity?	Q24. (Sutherland et al., 2009)		Camera, sound recorder
Habitat corridors/ stepping stones	Urban green spaces: How connected should green spaces be to support biodiversity	Q4. (Lepczyk et al., 2017)		Camera (with facial recognition software), sound recorder, , GPS/GLS/RFID
Protected areas/ nature reserves/ green space/ reintroductions	Protected areas: How effective are different types of protected areas (e.g. strict nature reserves, hunting reserves, and national parks) at conserving biodiversity and providing ecosystem services?	Q27. (Sutherland et al., 2009)		
	Terrestrial ecosystems: What are the contributions of urban nature reserves and other green amenity spaces, such as golf courses, to biodiversity conservation, and how can these be enhanced?	Q45. (Sutherland et al., 2009)		
	Urban green space: How large must an urban green space be for biodiversity conservation	Q1. (Lepczyk et al., 2017)		
	Urban green space: How are animal population sizes limited by green spaces during their life cycle?	Q2. (Lepczyk et al., 2017)		
	Urban green space: How does heterogeneity within and across green spaces affect plant and animal assemblages?	Q3. (Lepczyk et al., 2017)		

	Protected areas	Top 3. (Dey et al., 2020)		
Threats/ stressors	Climate change	Top 1. (Dey et al., 2020)	Air humidity, Soil pH, CO2, Soil moisture, Rain fall, UV or lux	Camera
	Ocean acidification	Top 7. (Dey et al., 2020)	Ocean pH	
	Marine Ecosystems: How will multiple stressors, especially fishing, pollution, sea temperature fluctuations, acidification, and diseases, interact to affect marine ecosystems?	Q52. (Sutherland et al., 2009)	Ocean temperature, ocean pH, depth gauge	Camera, sound recorder
	Invasive species	Top 4. (Dey et al., 2020)		

"…God, brilliant Lord,
your name echoes around the world."
(Psalm 8:9, The Message)