Constraints to migratory shorebird populations at a tropical non-breeding site in northern Australia

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Abstract

The populations of many species of shorebird that migrate within the East Asian-Australasian Flyway have declined rapidly. The responsibility for management of these migratory species is shared among the managers of the network of sites used by the birds in many political jurisdictions. This study aims to improve knowledge of the habitat requirements of the shorebirds at a site in northern Australia, Darwin Harbour, which is a terminus for some migrants and a staging post for others. To place the local population in a global context, I first examined annual trends in structural size and body mass over time across multiple sites in Australia. I found that both have been declining as the climate has warmed but that individuals from the Darwin study site, in particular, were smaller and lighter than their equivalents elsewhere. The decline in size has been occurring at the same time as my analysis of local numbers of shorebird populations demonstrates that they have been increasing in Darwin, often in contrast to trends nationally and globally. While smaller size may have reduced metabolic demand of shorebirds, allowing them to stay in less productive tropical habitats than they would normally do, another more likely reason for the increase in numbers is the creation of an industrial site that the shorebirds use as an additional safe roost close to feeding grounds. My two companion studies of the relationship between roosting and feeding sites and the availability of food showed that both roosting and feeding sites are part of a network, of which varies not only daily in line with the tidal cycle but also seasonally as food availability changes. My research therefore suggests that Darwin Harbour needs to be managed as a network of related sub-sites. While the addition of an extra roosting site appears to have increased harbour usage by the migratory shorebirds, a failure to manage the full network of feeding sites could reverse this trend.

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying online via the University's Open Access repository eSpace.

Amanda Lilleyman

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This work was approved from the Charles Darwin University Animal Ethics Committee under approval A13014 and approved by the Northern Territory Parks and Wildlife Commission under approval 48170 and was approved by the Australian Bird and Bat Banding Scheme.

Publications included in this thesis

Lilleyman, A. 2016. Records of waterbirds and other water-associated birds from the 2014/15 migratory season in the Darwin region. *Northern Territory Naturalist*, 27, 54.

A Lilleyman conducted the fieldwork and prepared the manuscript. Included as an appendix.

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A Lilleyman conceived the idea, MJ Lawes assisted with statistical analysis, and all contributed to the manuscript. Included as an appendix.

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A Lilleyman conceived the idea and performed the statistical analysis. DI Rogers, ST Garnett, RA Fuller and MV Jackson contributed to refining the results. All involved in preparing the manuscript. Included as Chapter 3.

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All conducted the fieldwork and contributed to the manuscript. Included as an appendix.

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Reflections

In 2012 while finishing my honours project on shorebirds I met with Stephen Garnett to discuss further work on shorebirds in Darwin. He took me along to a meeting with business representatives from the Northern Territory Government. It was my first meeting in an official setting, and I was nervous. I did not get a PhD scholarship in the first round of offers so for months I was left in limbo, knowing I so badly wanted to do a PhD but did not know if it would happen. Somebody had declined their offer and so I was granted a scholarship. It was the beginning of a long journey.

I had the support of the Northern Territory Government and my supervisors. I was then able to design my fieldwork schedule and research questions around the contractual obligations. I was granted freedom to be creative and to manage my own budget. I was thrown into a world that I knew almost nothing about, but I was eager, and I wanted to earn my place.

I had never wanted anything so much as this PhD. It gave my energy, I was motivated to work on it and to contribute to the field of shorebird science. I was overly enthusiastic with all other opportunities too, as I spent time volunteering and working on casual contract jobs over the many years. I had developed the condition that so many academics live with – the inability to say no. I was soon organising the Australasian Shorebird Conference in Darwin in 2014, all the while collecting data in the field. And then in 2015 I saw the end of the official fieldwork season. The page had turned, and I was into the next phase of the PhD. I was no longer the motivated PhD student that spent all their spare time working on the topic. I became detached from the PhD and the topic. I was exhausted. The thing that I had loved and wanted so badly had become a drain of energy. It took some time to move through the phases of the PhD and just when things had started picking up I was sent into a world of complete unknown with some horrible news that shook my career and my life.

It was during the lowest moments that I realised the PhD was mine, and that no matter what happened, I always had my PhD. It became the constant. I had earned my place and I was ready to conquer the PhD. I was going in an upwards trajectory and things had never been better. I had regained the love and passion for my PhD and the topic. I knew where I was going, and I wanted that PhD like never before.

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I am forever grateful to my primary supervisor Stephen Garnett. Stephen saw my passion and enthusiasm for shorebirds and the region early on and created the opportunities that I've been so lucky to experience. He has been caring, yet critical, and understanding at the hardest times. He provided a safe workspace and allowed me to work independently. I so appreciate the trust he has in my ability as it's given me confidence in myself as a researcher. Stephen provides critical thought to my work, he sees the world through a different lens – that allows him to assess ideas through evolutionary timeframes. He is not short-sighted and that has provided me with hope at times when I have not been able to see the forest for the trees. Stephen has taught me how to navigate the business world and I now can work between the demands of academia and with industry stakeholders – an incredibly important skill in conservation science. But all the while, he does not take life or himself too seriously and that is rare, particularly in academia. It's refreshing and also emblematic of the attitude of Darwin. I am grateful to Danny Rogers, my secondary supervisor, who was the original examiner of my honours thesis. I still remember meeting Danny in the Broome Bird Observatory shade house all those years ago before approaching Danny to formally be involved in my PhD. I am incredibly grateful that he agreed, as Danny has been an invaluable source of expertise. Danny has always provided me with answers to my bird questions, my identification queries when I have been interested in ageing shorebirds or when I've thought that I've found something rare! Danny has helped me understand the importance of being curious and to thoroughly think through the question being asked and what possible explanations there might be. Danny has provided me with a source of inspiration as he is fascinated by anything and everything to do with shorebirds, and his passion is infectious.

I'm so grateful to be friends with Gavin and Meg O'Brien; they are like family to me. I am indebted to Gavin for his tireless efforts over the years, his enthusiasm and care for shorebirds, his energy for counting birds and for catching at all hours of the day/night (even at 3 am). Gavin has provided a wealth of knowledge, expertise and contribution to my PhD through collecting data, time spent in the field and discussions over tea and almonds at his and Meg's house. Gavin has also shared his beautiful artworks with me and I am so proud to include them in this thesis. Thank you, Meg, for always sharing your love

for shorebirds, your enthusiasm in whatever projects I am involved with and your care for the local environment and advocacy work.

To Bas and Jantine Hensen, more friends that turned into birding family. I first met Bas while I was driving through the uni and he was looking up at the Osprey nesting on the communications tower. We have spent many hours watching shorebirds on Lee Point beach and ventured further afield to find other Top End specialities. Bas and Jantine have supported and encouraged me in my career over the years. Thank you.

Thanks to the friends I've made along the way, Jennifer Macdonald, Stewart Pittard, Miguel Bedoya-Perez, Veronica Toral-Granda, Gabi Arcoverde, Sam Walker, Sarah Bonney, Jill Verus (Segura), Alea Rose, Tiffanie Pearse, Leigh Woolley, Hayley Geyle (my office mate for the last few years), Elvey, Dave Fry, Amelie Corriveau, Brien Roberts, Billy Ross, Matt Northwood, Lindsay Hutley and many more that provided support throughout the long journey. Most notably, Jen, (Bubba) for always being there for whatever came up, particularly during the worst times. Thank you for always asking questions and being interested, for helping me with timelines, for encouraging your mum (Ms Honey) to help with any bird fieldwork, and for providing the love and support that you have given me over many years. Thanks to my original Darwin girls Kaz Gregory, Christine Power, Kiya Gill. I thank Micha Jackson, who I've worked closely with over the last few years. I love that we have been able to support each other during our journeys and provide sanity when the process has challenged us. Thank you to Simon Moss who started off as a mentor and turned into a friend. I so appreciate the conversations we've had over the years, the laughs, the advice, the free counselling, the stories, and support when I've questioned the process. To Grace Maglio who I've known since the beginning of the journey. She has been a steady rock for me, always available to chat, discuss ideas, laugh at me and provide advice when I've needed it. A close friend and colleague, I love our collaborations and hope for more in the future. Love and thanks to my friends from back home Rebecca Doenau, Lexi Burrell, the Gossip Girls that kept me sane and provided daily entertainment, Rickielea Tucker and Kim Paget.

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Thesis layout

Chapter 2

Trends and variation in the structural size and body mass of multiple migratory shorebird species across the Australian non-breeding grounds

- Structural size and body mass of multiple species has changed in the last three decades.
- Great Knot body mass and size has decreased over time.
- Great Knot weights are lower in Darwin than in the rest of Australia.

Link

Site fidelity results in adaptation to local environmental conditions which affects the morphology of individuals

Chapter 4

Site fidelity and international movements of an endangered migratory shorebird in the East Asian-Australasian Flyway

- Great Knot were highly site faithful between years and within years to the Darwin Harbour region.
- Birds move within a network of sites.
- Some birds make greater movements during the pre-migratory months.
- Juvenile birds make greater movements away from optimal sites.

Constraints to migratory shorebird populations at a tropical non-breeding site in northern Australia

Chapter 3

An artificial site provides valuable additional habitat to migratory shorebirds in a tropical harbour

- Overall increases in shorebird population numbers at artificial and natural sites in Darwin Harbour.
- Multiple species numbers increasing over 9-year period.

Link

Understanding site fidelity is needed to inform the protection of coastal environments and protect species

Link

Biomass variation drives local movements within the landscape and through time.

Chapter 5

Reliability of prey influences foraging site selection, but temporal variability influences site exploration in a migratory shorebird on the tropical non-breeding grounds

- Great Knot selected foraging sites that were close to roost sites throughout the non-breeding season.
- Some individuals commuted to foraging sites that were further away from the main roost site during times when biomass at those sites was higher.

Link

Biomass is lower in the Northern Territory than in north-Western Australia which may be reflected in lower body weights in Great Knots.

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Chapter 1. Introduction

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One of the more extraordinary natural phenomena in the world is the migration of birds between hemispheres. The physiological and navigational adaptations that enable often very small birds to fly thousands of kilometres without stopping – and to then make the return journey – has amazed people for as long as they have known about it. After this there was a realisation that migratory species are a form of common property, the responsibility for which lies with multiple sites, peoples and countries so that depletion or loss in one country affects places all along the migratory pathway. As early as 1918, at the end of the First World War, the US passed the Migratory Bird Treaty Act and the Convention on the Conservation of Migratory Species of Wild Animal (the Bonn Convention) was, in 1979, one of the earliest multinational environmental agreements to be negotiated and signed.

To be able to protect migratory and other animals, one needs to be able to understand their ecological requirements. For migratory species this requires detailed study at each place they use so that conservation is an aggregation of multiple knowledges along their movement pathways, each a stand-alone study but each formulated in a manner that it can be joined with other studies so that conservation resources can be applied most efficiently. This thesis is one such study, set in the non-breeding habitat of migratory shorebirds in northern Australia, a place that acts both as a terminus and a staging post for birds that nest from northern China to the high Arctic. In the thesis, I explore the trends and ecology of a suite of species that participate in one of the world's flyways that has been most heavily affected by human development along its route. Ultimately the research aims to make sure that the birds that visit northern Australia are provided with the environment that gives them the greatest chance of completing their migrations and returning, as they have done for many millennia.

Migratory shorebird ecology

What are shorebirds?

Migratory shorebirds belong to the avian order Charadriiformes which is characterised by species which live in open landscapes, predominantly near water – whether it be coastal, marine or freshwater. Most

would think of shorebirds as smallish, leggy birds that forage in shallow water or mud (hence the alternate name 'waders') and typically occur in big flocks. Across the world, the 214 species of shorebird make up approximately 2% of all bird species in the world (Hollands and Minton 2012). Shorebirds are diverse, cosmopolitan and adaptable, both behaviourally and physiologically. At least 80 species of shorebird have been recorded in Australia. These species can be divided into categories based on their general ecology (Hollands and Minton 2012). In Australia 9 are true residents, 9 species are nomads that are opportunistic wanderers when conditions are good, 37 are regular migrants of which 36 nest in the northern hemisphere and 24 species are vagrants, Palaearctic breeding species that normally migrate along other flyways (Hollands and Minton 2012).

The association of shorebirds with open plains and shallow water means that body shape tends to be fairly similar among the different shorebird species. Differences in size and bill shape then allow them to exploit different foods and feeding substrates (Geering 2007), known as resource partitioning (Walter, 1991). The largest two families recognised as shorebirds are the Scolopacidae (sandpipers and allies), and the Charadriidae (plovers and lapwings). Plovers and some scolocapids are primarily visual foragers, taking food from the surface, many sandpipers are tactile foragers that find their food by probing their bills into mud or sand (Hollands and Minton 2012). Differences in feeding mode, size and the shape of their bills (Figure 1) allows many shorebird species to coexist in the same environment.
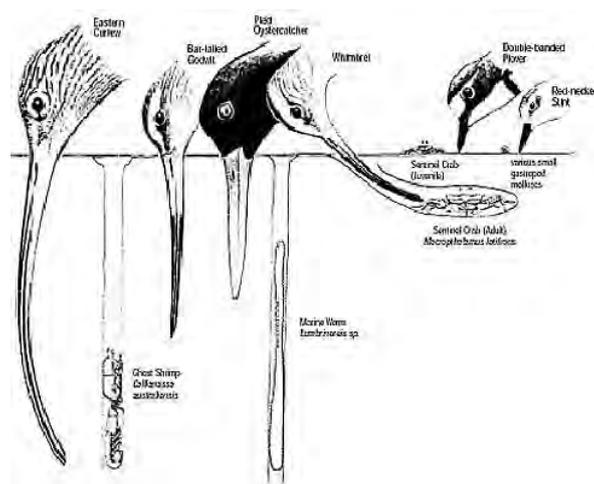
Figure 1. Shorebird bill length and access to invertebrate prey. Image credit: Jeff Davies in Dann (1987).

Many shorebird species are long-distance migrants, breeding at high latitudes in the northern hemisphere, and then migrating to non-breeding grounds to lower latitudes of the northern hemisphere and in the tropics or southern hemisphere to take advantage of the world's seasonality (Piersma et al. 2005), a movement pattern that has evolved over many thousands of years (Piersma and Lindström 2004). These intercontinental migrations of thousands of kilometres are undertaken annually: studies of marked individuals have found that many individuals live for more than 20 years, returning to the same non-breeding sites year after year (Goede 1993; Minton et al. 2017).

The focus of this thesis is the migratory shorebirds that visit Australia, particularly the region around Darwin on Australia's north coast.

Migration flyways

Populations of shorebirds that migrate through many countries are considered as belonging to a flyway. A flyway is the entire range of a group of species of migratory birds, which move on an annual basis from breeding grounds to non-breeding grounds and use similar sites to rest and refuel (Boere and Stroud 2006). There are eight main trans-hemispheric flyways for shorebirds across the world (Boere and Stroud 2006) (Figure 2a); Australia is part of the East Asian-Australasian Flyway (EAAF) (Figure 2b). Environmental conditions along a flyway influence the timing of breeding for shorebirds; as conditions in the Arctic become too severe, birds migrate south for thousands of kilometres to take advantage of the progressive peaks in productivity of food resources (Battley and Rogers 2007).
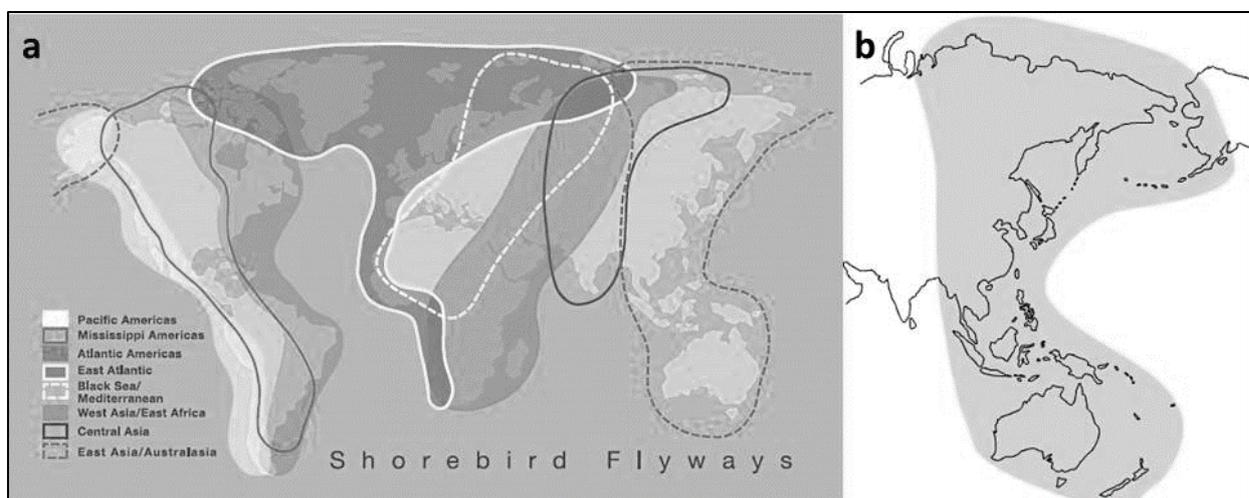
Figure 2. a) The eight trans-hemispheric flyways for migratory shorebirds across the world (Boere and Stroud 2006); b) the East Asian-Australasian Flyway (Australasian Wader Studies Group 2008).

Threats to shorebirds and conservation management

Maintaining an adequate set of sites along a flyway is critical for conserving migratory shorebird species (Runge et al. 2014). Changes to coastal habitat of migratory shorebirds, however, are causing loss and degradation of staging areas that are crucial stepping stones for migrating shorebirds (Murray et al. 2014). As a result of coastal development, migratory shorebirds are declining in all trans-equatorial flyways, but the fastest declines are in the EAAF. This is largely because important stopover and staging sites for shorebirds in the EAAF happen to be in some of the most densely-populated parts of the planet. In some parts of the flyway, such as the Yellow Sea region, 65% of tidal flats used by shorebirds have been lost in the last 50 years (Murray et al. 2014) with rapid land use change restricting many shorebirds and waterbirds to the fringes of highly urbanised environments (Ma et al. 2004). This contraction in available habitat has been linked to the flyway-wide collapse of shorebird populations in the EAAF (Amano et al. 2010, Piersma et al. 2016, Studds et al. 2017). Within Australia, where shorebird population declines have been recorded for over 40 years (Hansen 2011), the greatest declines have been noted at the migration endpoint for many species in southern Australia (Hansen et al. 2015, Clemens et al. 2016). Much less is known about trends in shorebirds that spend the non-breeding season in northern Australia. While there have been declines recorded in the very large populations in north-western Australia (Rogers et al. 2019), local-scale increases have been reported in the Northern Territory (Clemens et al. 2016, Lilleyman et al. 2016).

Coastal development and migratory shorebird habitat use

Coastal wetlands are highly productive ecosystems under such intense human pressure that there has been at least a 33% loss across the globe due to land use change (Hu et al. 2017). Land use changes have caused degradation in many aspects of wetland quality, including increases in heavy metals and pollutants, spread of weeds, increased human disturbance and competition between birds for roosting space and food resources (Studds et al. 2017).

The loss of natural wetlands has impacted many migratory shorebird species and has severely eroded the ecological integrity of flyways, the world over (Donglai et al. 2013). Loss of habitat is a significant threatening process for migratory shorebirds, with extensive reduction of breeding and staging sites within the EAAF (Barter 2002, International Wader Studies Group 2003, Clemens et al. 2010). Although the most catastrophic declines in shorebird species in the EAAF have been reported from the Yellow Sea and Bohai Sea region (Moores et al. 2008, Battley et al. 2010), the sudden loss of smaller sites on non-breeding grounds can impact individual fitness in some shorebirds (Burton et al. 2006). Because shorebirds use different sites during their migration, particularly as they refuel for the rest of the journey, there is a need to protect all sites of variable sizes used by shorebirds along the EAAF (MacKinnon et al. 2012).

Among the habitats used by shorebirds are many that have been created for a variety of human uses. Although their importance to shorebirds is species-specific (Jackson et al. *in press*), artificial habitats can be a valuable tool for managing migratory shorebirds (Rogers et al. 2007, Donglai et al. 2013). For example some species can breed on artificial habitat such as dredge islands (Scarton et al. 2013), artificial wetlands such as sewage ponds (Rogers et al. 2007, Rogers et al. 2013), shrimp farms (Navedo and Fernandez 2019), fish ponds can be used for foraging, and many species roost in artificial habitat (Jackson et al. 2020).

Overall, while the conservation management of migratory shorebirds requires the alignment of policies at an international scale, because their distribution spans many geopolitical borders, appropriate management practices need to be undertaken at a local scale to ensure that a network of sites is protected. Knowing what habitat (whether natural or artificial) to protect and manage is key to ensuring that shorebird populations are sustained into the future. Understanding the ecological requirements of shorebirds can inform best practice for protecting shorebird habitat and can also guide environmentally sensitive planning and development, particularly in urban settings.

Non-breeding ecology of migratory shorebirds in Australia

Most migratory shorebirds in Australia breed in Siberia, Alaska or China, and visit Australian shores in the austral summer. Their annual migration is determined by the phenology of food availability and reproduction.

On arrival in Australia, coastal shorebirds spend the duration of the austral summer seeking out their main prey – intertidal invertebrates. Tidal cycles dictate foraging and roosting times for most coastal shorebirds that feed on exposed mudflats during low tide. At high tide, when the foraging grounds are submerged, shorebirds retreat to roosts on open ground above the high tide mark, including sandy beaches, claypans and rocky reefs. The maximum foraging time available for shorebirds therefore depends on the duration of exposure of those parts of the tidal mudflats from which they obtain their prey (van de Kam et al. 2004) although, in some settings, some individuals forage on supra-tidal near-coastal wetlands at high tide (Masero and Perez-Hurtado 2001). The use of several feeding sites helps ensure that there is always one site available at which the birds can forage, although this means the birds have to monitor conditions at these sites to be able to decide where to forage.

Migratory shorebirds typically choose feeding and roosting habitats that are close to one another to maintain positive daily energy budgets, but their habitat choice is also influenced by safety from predators and their ability to reduce thermal stress (Rogers et al. 2006b) and find high-quality food resources. The distribution of feeding habitat in large part determines the distribution of shorebird populations (Kraan et al. 2009). However, without suitable roosting habitat nearby, even rich feeding sites may become too costly for shorebirds to exploit. To identify and manage appropriate shorebird habitat, the availability of feeding grounds must be paired with suitable roosting grounds nearby (Rogers et al. 2006b). A network of safe and high-quality roosting habitat is needed to ensure the ongoing survival of shorebird species in the EAAF (Aharon-Rotman et al. 2016).

Constraints on migratory shorebirds on the non-breeding grounds

Resources, competing species, predators and parasites can constrain population size in birds (Newton 1998), and these external limitations influence the decisions that birds make to maximise their fitness. Individuals that fail to balance the costs and benefits of their activities will be selected against. To maximise fitness, it is assumed that shorebirds must optimise their time and energy when moving between roosting and feeding sites so their average energy intake is maximised, at minimal cost to body condition. To do this, shorebirds must know what roost sites are available at different tidal conditions, different times of the day and in different seasons (Rogers et al. 2006a). In some places, shorebirds commute 60 to 100 km per day on a daily basis between roosting and feeding sites (Rogers et al. 2006b). Roost site requirements can be as exacting as those required for feeding with shorebirds having to balance the distance from feeding sites with distance to tall cover, visibility, microclimate, and the probability of disturbance (Rogers 2003).

The size of the available foraging area can strongly influence the presence and abundance of some shorebird species; in some places, shorebirds follow strict foraging itineraries according to the timing of exposed mudflat. For example, in the Dutch Wadden Sea, shorebirds can extend their foraging day by several hours by exploiting the differences in the time of high tide on different sides of barrier islands or watersheds (Kraan et al. 2009). This enables shorebirds to take advantage of resources patchily distributed over time and space (van Gils et al. 2003b). Shorebirds also align their foraging behaviour with the behaviour of their cryptic prey to minimise the time spent searching for prey rather than feeding (Kraan et al. 2009).

Migratory shorebirds should be economical in the rate-maximising decisions they make and foraging shorebirds on non-breeding grounds may therefore follow the ideal free distribution (IFD). This theory states that organisms may select habitat with the highest fitness rewards and that they are free to move between and within sites that may also support other species and individuals (Fretwell 1972). On non-breeding grounds, constraints on migratory shorebirds following an IFD are constrained by tidal conditions. Leyrer et al. (2012) found that shorebirds that followed an IFD foraging pattern were adult

birds and that the sequence of site occupancy was driven by the competitive ability of experienced birds. In addition, annual individual survival was higher on richer feeding grounds (Leyrer et al. 2012). While some shorebirds can behave in an ideal manner, birds may not be free to decide where to forage as patch availability varies with tide height and other environmental factors. Using the IFD model, van Gils et al. (2006b) found that shorebirds displayed spatially explicit foraging behaviour and balanced energy intake rates against travel costs by frequently feeding at suitable sites only if there was a roost nearby.

Although some studies report that shorebirds follow the IFD, it is possible that while shorebirds can behave in an ideal manner, many other factors constrain their foraging behaviour. Rogers et al. (2006a) modelled shorebird habitat use in a tropical bay and argued that it was unlikely that shorebirds had perfect knowledge of the energetic costs and benefits of a roost site; but experience of roost site conditions was nevertheless essential for choosing nocturnal roosts. They found that shorebirds were not entirely free to choose roosting and feeding sites, as the distance between sites significantly influenced the choice of roost, regardless of tidal conditions (Rogers et al. 2006a). Thus, the distance and connectedness between roosting and feeding sites, coupled with climate conditions and a lack of perfect knowledge about the availability and characteristics of different sites may significantly affect the foraging behaviour of an otherwise 'ideal' shorebird.

A full understanding of how habitat is used by shorebirds based on resource availability is complicated by resource partitioning between species and within species between the sexes (Catry et al. 2012; Alves et al. 2013; Franks et al. 2013). For species to coexist, they need to partition common resources among themselves. Thus, coexisting species have likely responded to selection pressures generated by interspecific competition, which has led to differences in resource use (Walter 1991). There is great variation among shorebirds in bill shape, type and length and this is probably the primary means by which shorebird species partition food resources (Nebel 2005). Furthermore, foraging shorebirds may be affected by their timing of arrival at non-breeding grounds, as resources may be depleted by other shorebirds that arrive earlier at a site. Competition between species for resources may be out-weighed by the benefit of having conspecifics in a foraging patch, as it may reduce the risk of predation through

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cooperative vigilance (Jackson and Ruxton 2006) and increase communication between flocking individuals about the availability of food in the patch (Folmer et al. 2010, Folmer and Piersma 2012). Conversely, there may be a difference in nearest neighbour distances based on foraging strategy. Shorebirds that feed by probing into the substrate are often found in higher densities than shorebird species that locate surface prey by sight (Rogers, 1999). Thus, communication and vigilance may differ between visual foragers and tactile foragers.

The individual ability of a foraging shorebird may constrain its energy intake rate, with some individuals having longer prey-handling times and hence longer foraging times than others (Santos et al. 2010). Such variation in individual ability may be related to age and experience; several studies have shown that immature birds have lower intake rates, and lower apparent foraging proficiency, than adults (Morrison et al. 1978, Puttick, 1978, Goss-Custard and Durell 1987, Hockey et al. 1998, Triplet et al. 1999). An additional constraint on foraging molluscivore shorebirds and their energy intake rate is the quality of the prey, the size of the gizzard (crushing organ), and size of the bird (as it sets the limit on maximum prey size) (van Gils et al. 2003a). The rate of digestive processing (crushing and processing of shell and non-metabolizable content) is related to the size of the gizzard and can constrain the energy intake rate of shorebirds and the need for digestive pauses while foraging (Zwarts and Blomert 1990, Kersten and Visser 1996, van Gils et al. 2005b).

Thus, it is likely that several synergistic factors influence shorebird habitat and resource use, which in turn limits shorebird population size on the non-breeding grounds. In addition to biological constraints and their environmental correlates, migratory shorebirds experience the usual ecological processes (e.g.: breeding success and mortality rate) that regulate population demographics; but, because migratory shorebirds spend most of the year in migration and on non-breeding grounds, understanding biological constraints may offer insights into the ecological requirements of shorebirds during the non-breeding season.

While shorebirds face a multitude of challenges existing within a highly dynamic natural system, they must also deal with a developing environment that is driven by anthropogenic changes. Natural wetlands are under pressure creating an ongoing human-wildlife conflict.

Conservation measures to reduce shorebird mortality in non-breeding and stopover sites

Population declines in shorebirds have been closely linked to reductions in habitat availability at stopover sites that birds use on migration (Studds et al. 2017), but recently efforts have been made to arrest the loss of stopover sites in China, where two internationally important sites on the shores of the Yellow and Bohai Seas have been granted UNESCO World Heritage status (UNESCO 2019). Additionally, the Chinese Government has changed policies to halt all business-related land reclamation (BirdLife International 2018). These actions demonstrate positive steps towards protecting the critical habitat on which shorebirds rely and have the potential to improve conservation success of threatened species.

However, coordinated management at a flyway level is required to improve the conservation outcomes for migratory species (Szabo et al. 2016). The conditions that shorebirds face elsewhere on the non-breeding grounds may also amplify the effects of habitat loss at stopover sites, thus influencing survival (Clemens 2016).

This includes Australia where shorebirds also face a multitude of pressures at some sites because of the intensity of the human population near shorebird habitat (Weston et al. 2012). Habitat change and disturbances to birds can reduce the quality of habitat for shorebirds and indirectly affect the breeding success and survival within the population (Aharon-Rotman et al. 2016). Australia thus plays a crucial role in the conservation of migratory shorebirds in the EAAF. Some ways Australia could prioritise the conservation of shorebirds are through improved monitoring programs, habitat restoration and preservation of coastal environs, protection of birds from disturbances, stronger environmental laws that regulate developments that may impact shorebird habitat in isolation and cumulatively. In Australia, the main protection of shorebirds is through the commonwealth legislation *Environment*

Protection Biodiversity Conservation Act 1999 and all actions that are deemed to interfere with protected migratory shorebirds are required to perform an environmental impact assessment (EIA). Coastal development proposals frequently trigger the EPBC Act and many EIAs are performed in isolation and often without considering cumulative impacts. As shorebirds use a network of sites within a region on the non-breeding grounds, it is vital that multiple habitat nodes are protected to ensure that non-breeding season populations remain viable.

To ensure Australia continues to provide the resources needed by migratory shorebirds, there is a need to understand, assess and monitor the birds and to identify the sites most important to shorebirds that require protection (Rogers et al. 2008), which will assist planners to mitigate potential impacts to species from development and expansion of industry along coastlines. In addition to the aesthetic desirability of maintaining our spectacular shorebird populations, the conservation of migratory shorebirds is a statutory requirement, as they are listed as Matters of National Significance under the EPBC Act and governments are also obliged to protect migratory shorebirds under several international conservation agreements; the Convention on the Conservation of Migratory Species of Wild Animals (Bonn Convention), Japan-Australia Migratory Bird Agreement (JAMBA), China-Australia Migratory Bird Agreement (CAMBA) and Republic of Korea-Australia Migratory Bird Agreement (ROKAMBA). These agreements recognise the need to protect shorebirds by cooperating across jurisdictions. As part of these agreements, Australia has obligations to protect migratory shorebird habitat and maintain sustainable populations when the birds are in Australia (Commonwealth of Australia 2015). Thus, planning for development in Darwin Harbour and at other sites across Australia should be consistent with international agreements.

Study aims

The overall aims of this thesis are to 1) understand how local conditions at individual sites limit local shorebird populations, and 2) improve knowledge of the habitat requirements of the shorebirds at a site in northern Australia to sustain shorebird numbers in a tropical harbour. My aim is to improve the practice of shorebird conservation within Australia.

Study region

Extensive monitoring and assessments have been undertaken for shorebirds in southern Australia, from about Perth to south-east Queensland, for almost 40 years (Lane 1987; Clemens et al 2016). and in north-Western Australia for the last 15 years. However, with the exception of north-Western Australia, where shorebird numbers have been monitored for the past 15 years (Rogers et al. 2019), little is known of shorebird trends across most of northern Australia, although it holds many shorebird sites. One of these is Darwin Harbour in the Northern Territory. The harbour is being developed as an international gas export hub and developments must meet environmental standards by law. The abundance, diversity and distribution of migratory shorebirds in Darwin Harbour have been little studied historically but this information is required to manage shorebirds and the harbour activities that affect them. Shorebirds could be useful indicators of environmental conditions and knowledge of their use of the harbour can help ensure that the mudflats and inlets in Darwin Harbour are managed to remain ecologically viable for shorebirds and other marine and intertidal biodiversity.

While there has been monthly monitoring of counts of shorebirds in Darwin Harbour there has been no analysis of trends or movements. Most information on migratory shorebirds in Darwin Harbour has come from monitoring under the BirdLife Australia Migratory Shorebirds Program (previously Shorebirds2020) and in more recent years at an artificial site (sites shown in Figure 3).
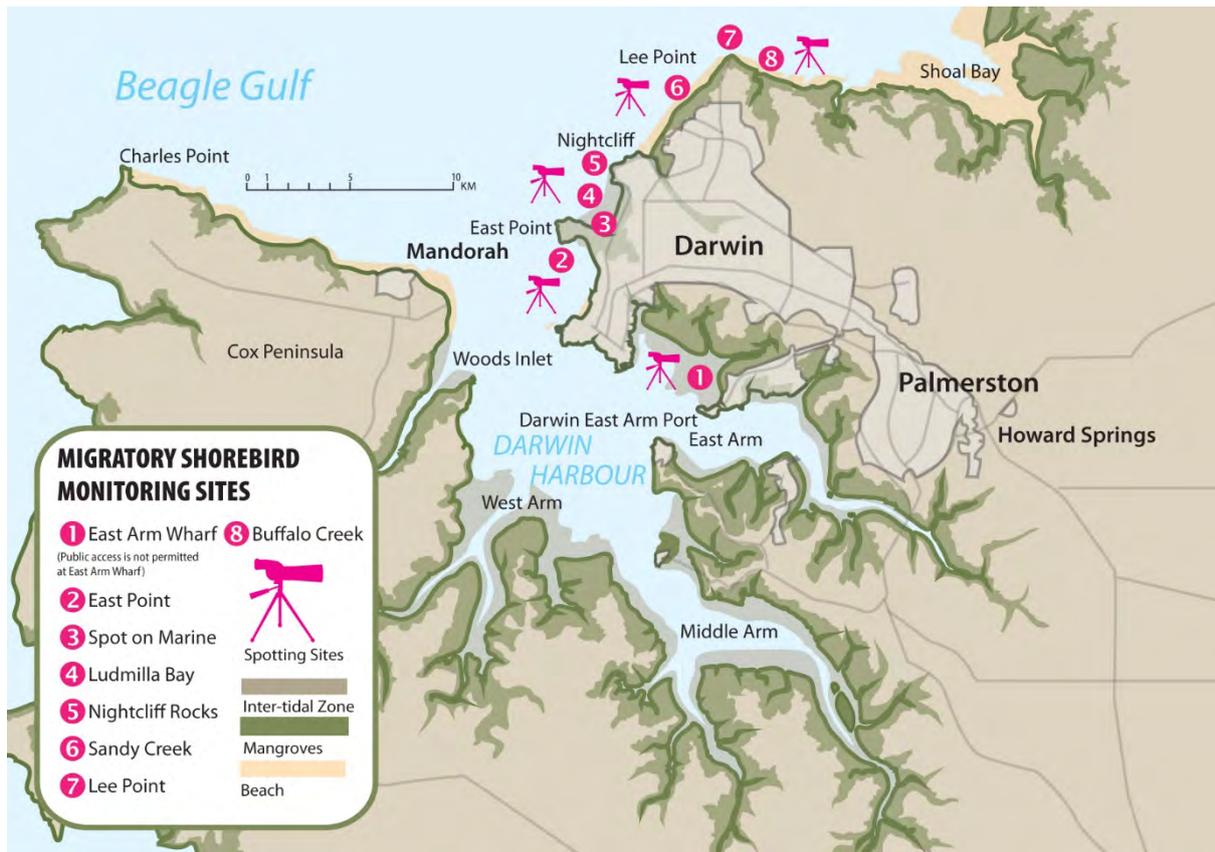
Figure 3. Map of migratory shorebird monitoring sites in Darwin Harbour, Northern Territory. Lee Point-Buffalo Creek, Sandy Creek, Nightcliff Rocks, East Point and Spot on Marine are natural roost sites; East Arm Wharf is artificial. Image credit: John Girdham.

The artificial site is at Darwin Port's East Arm Wharf (EAW), which is the largest import and export hub in northern Australia. It is close to the Darwin central business district and is constructed of dredge spoil. Within the wharf are several ponds (Figure 4) that are used during dredging activities for storage of materials and also as a water flow and retention system, but which also support many bird species.
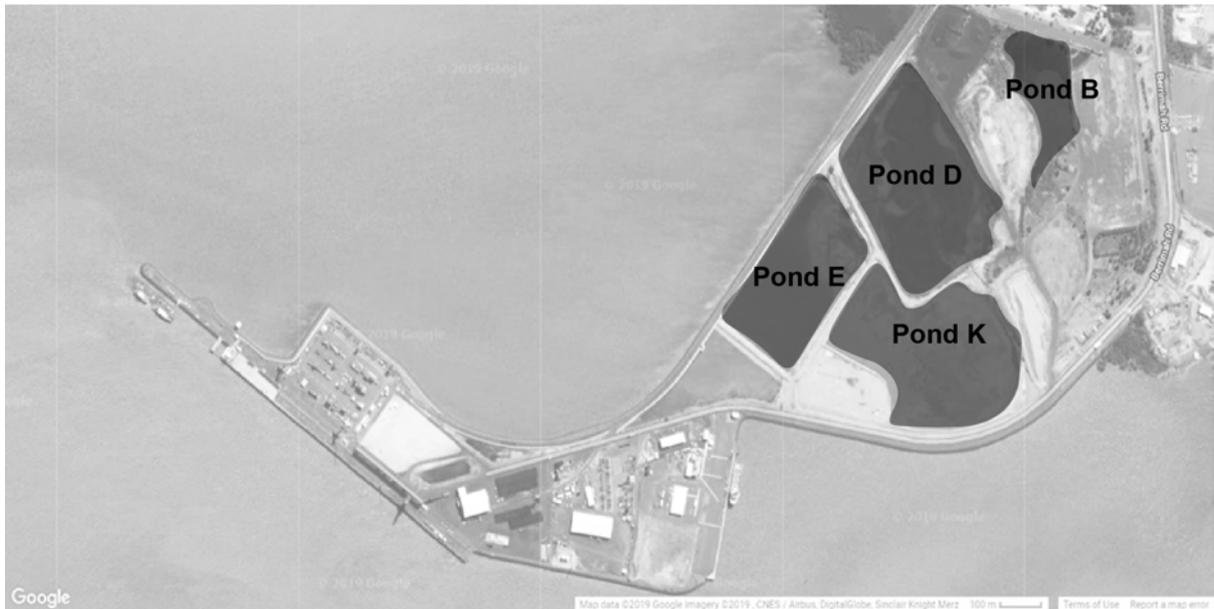
Figure 4. East Arm Wharf dredge ponds at the Darwin Port industrial site in the Northern Territory Australia.

Study species

Darwin Harbour regularly supports twenty-six species of migratory shorebird (Table 1). Of the regularly recorded shorebird species, seven are listed threatened species under the Environment Protection Biodiversity Conservation Act 1999. In chapters 2 and 3 I use data on a range of migratory shorebird species in the Darwin Harbour region and chapters 4 and 5 use the EAAF endemic Great Knot as the focal species (Figures 5 – 7).

Table 1. List of migratory shorebirds that have been recorded in Darwin Harbour and their conservation status under the *Environment Protection Biodiversity Conservation Act* 1999 and the IUCN Red List of Threatened Species.

Shorebird common name	Scientific name	EPBC Act	IUCN
Pacific Golden Plover	*Pluvialis fulva*		Least Concern
Grey Plover	*Pluvialis squatarola*		Least Concern
Little Ringed Plover	*Charadrius dubius*		Least Concern
Lesser Sand Plover	*Charadrius mongolus*	Endangered	Least Concern
Greater Sand Plover	*Charadrius leschenaultii*	Vulnerable	Least Concern
Oriental Plover	*Charadrius veredus*		Least Concern
Black-tailed Godwit	*Limosa limosa*		Near Threatened
Bar-tailed Godwit	*Limosa lapponica*	Vulnerable	Least Concern
Little Curlew	*Numenius minutus*		Least Concern
Whimbrel	*Numenius phaeopus*		Least Concern
Far Eastern Curlew	*Numenius madagascariensis*	Critically Endangered	Vulnerable
Terek Sandpiper	*Xenus cinereus*		Least Concern
Common Sandpiper	*Actitus hypoleucos*		Least Concern
Grey-tailed Tattler	*Tringa brevipes*		Near Threatened
Common Greenshank	*Tringa nebularia*		Least Concern
Marsh Sandpiper	*Tringa stagnatilis*		Least Concern
Wood Sandpiper	*Tringa glareola*		Least Concern
Ruddy Turnstone	*Arenaria interpres*		Least Concern
Asian Dowitcher	*Limnodromus semipalmatus*		Near Threatened
Great Knot	*Calidris tenuirostris*	Critically Endangered	Vulnerable
Red Knot	*Calidris canutus*	Endangered	Least Concern
Sanderling	*Calidris alba*		Least Concern
Red-necked Stint	*Calidris ruficollis*		Least Concern
Long-toed Stint	*Calidris subminuta*		Least Concern
Sharp-tailed Sandpiper	*Calidris acuminata*		Least Concern
Curlew Sandpiper	*Calidris ferruginea*	Critically Endangered	Least Concern

Figure 5. Great Knots roosting at high tide at Sandy Creek beach near Darwin, Northern Territory.

Figure 6. Migratory shorebird flock roosting at high tide at Sandy Creek beach near Darwin, Northern Territory.

Figure 7. Migratory shorebird flock roosting at high tide at Sandy Creek beach near Darwin, Northern Territory.

Figure 8. Great Knots *Calidris tenuirostris* in flight at Sandy Creek near Darwin, Northern Territory Australia.

Thesis overview

This thesis explores how non-breeding migratory shorebirds use habitat in tropical northern Australia during the austral summer and the potential constraints on populations.

In my PhD I examined available data from shorebird banding expeditions to look at possible differences in shorebird body condition across the Australian non-breeding grounds. I was interested in whether migratory shorebirds follow our theoretical understanding of the drivers of biological variation. There is inconclusive evidence about whether migratory animals follow Bergmann's Rule (whereby the mean body size decreases with decreasing latitude because larger individuals have a lower surface area to volume ratio than smaller individuals), and if species do, then what part of the lifecycle drives the observed variation. I use **Chapter 2**, to provide a national context for the PhD, and investigate the long-term changes and spatial variation in structural body size and mass of six shorebird species using a national dataset of 41 years. When investigating the variation across the non-breeding grounds I discovered that some species were following global trends in overall body size as well as showing distinct differences across the non-breeding grounds.

Recent exploration of local population monitoring data revealed some interesting trends of some shorebirds increasing in numbers despite global declines. Because of this, I was interested to investigate the population trends of all shorebirds that can be found in the Darwin Harbour region. I combined this exploratory approach with a detailed investigation into the habitat use of shorebirds in the region, where birds are found in natural and artificial sites. The occurrence of shorebirds at an artificial roost site has implications for the management of shorebirds in the region, and also scaling up to other areas on the non-breeding grounds. While the use of artificial habitat by shorebirds is common, the importance of artificial roosts within a network of roost sites is less well known and should be considered when managing regions holistically. Before managing shorebirds in a region, it is critical to know the current status of the bird population to allow for a review of management actions. Where shorebird trends are diverging from global or national population trends, there is a need to identify any possible drivers of population change or stability at the local level. In **Chapter 3**, using survey monitoring data, I explore

the population trends of migratory shorebirds in Darwin, Northern Territory on the non-breeding grounds and compare across a range of natural roost sites and one artificial site to explore the value of these sites.

Shorebirds follow a strict itinerary that is guided by phenological processes occurring across multiple ecosystems and hemispheres. When shorebirds are on the non-breeding grounds, they use a range of sites and habitat to satisfy their ecological requirements. Searching for food is a first condition for survival (Piersma 2006). Because of this and the dynamic nature of the intertidal zone, we hypothesised that shorebirds would persist as a metapopulation within the Darwin Harbour region. Based on this, I predicted that birds would use several roosting sites and would mix during their movements. We tested this using engraved leg-flags on birds and explored in **Chapter 4**, the connectivity and site fidelity of a local network of sites used by the Great Knot. It will be important to know how migratory shorebirds persist and use Darwin Harbour for the management of the coastline at a regional level to ensure that connectivity of sites remains.

Understanding how food resources are distributed across an ecosystem can help us understand how shorebirds select habitat (Piersma 2006). The environmental demands on shorebirds throughout their lifecycle dictates the physiological responses of birds, which therefore influences habitat choice (Piersma and van Gils 2011). Throughout the non-breeding season, shorebirds make decisions about their habitat choice, movements and foraging rates. In **Chapter 5**, I match the behaviour of the Great Knots to that of its principle prey species, a small bivalve. I hypothesised that there would be a density-dependent relationship between the Great Knot population and the density of invertebrate biomass. Additionally, I predicted that shorebirds would make decisions that influenced where they were found throughout the non-breeding season so that during the arrival and departure periods when maximum energy gain is needed for fattening up, the birds would make greater movements compared to the core non-breeding period.

Chapter 6 synthesises the research on the morphology, trends, movement ecology and biomass availability, to provide insight into the management of the habitat to maintain shorebird populations.

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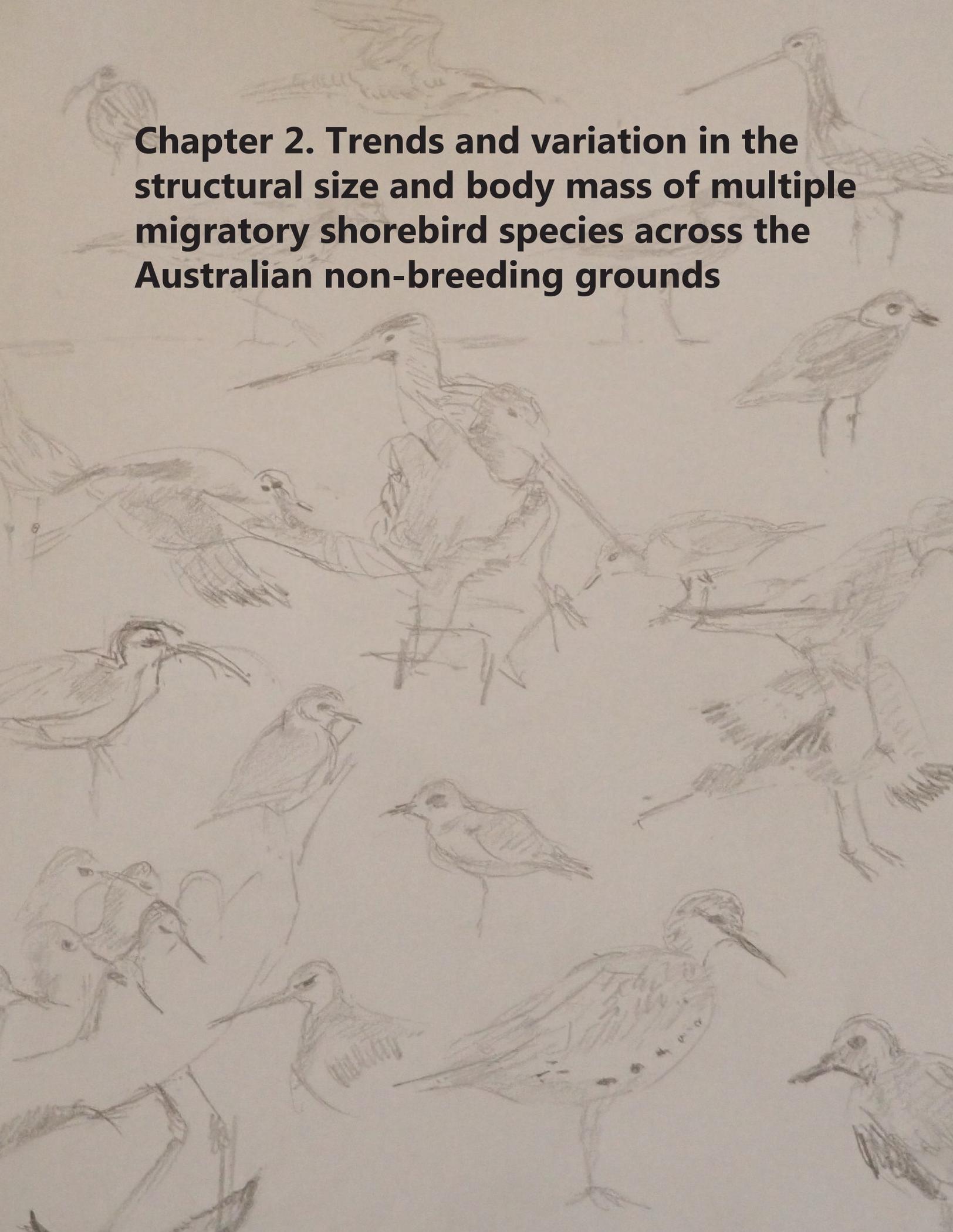
Chapter 2. Trends and variation in the structural size and body mass of multiple migratory shorebird species across the Australian non-breeding grounds

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Trends and variation in the structural size and body mass of multiple migratory shorebird species across the Australian non-breeding grounds

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Abstract

Bergmann's Rule on body size in relation to thermal environment predicts that warming temperatures with climate change should result in selection for smaller mean body sizes However, temperature is not the only influence on animal body size. Exploring the potential factors contributing to observed temporal trends in morphology and mass can potentially increase our understanding of stressors. Body mass can also be used as an index of food resource availability, while controlling for body size. One of the factors contributing to shorebird declines may be the impacts of climate change, and in particular increasing climate extremes. Many populations of shorebirds in the East Asian-Australasian Flyway are declining. Here, we examine whether warming temperatures over time have resulted in changes in body size and mass in six species of migratory shorebird in Australia, across a range of sites spanning a wide latitudinal temperature gradient. Changes in body size and mass may be indicative of selective adaptation to a warming world, and other responses to environmental factors. Here we use data collected from the non-breeding grounds of six species of migratory shorebird across six study regions in

Australia to compare geographical variation in temporal trends in size and mass. Firstly, we show that in the 40 years since 1980, there has been a significant increase in the mean temperature anomaly across the Australian non-breeding grounds. Three of the six species examined were lighter at sites in northern Australia and heavier in southern Australia, following Bergmann's Rule. Overall structural body size for two species (Greater Sand Plover and Ruddy Turnstone) decreased over time. Despite changes in structural size, Ruddy Turnstone body mass increased over time. Two species (Great Knot and Red Knot) decreased in body mass over time. Our results show that some species' body mass differs markedly between sites with the same climate, suggesting that factors other than temperature are influencing body size. We hypothesise that the observed differences are possibly due to variation in habitat condition on the non-breeding grounds, thus placing greater importance on maintaining high-quality habitat across the non-breeding grounds in a time of environmental change.

Introduction

Most endothermic animals follow Bergmann's Rule (Bergmann 1848), whereby the mean body size decreases with decreasing latitude because larger individuals have a lower surface area to volume ratio than smaller individuals. With the rapidly rising temperatures associated with climate change (Allen et al. 2019), there is an expectation that the mean body size of a species will decrease (Sheridan and Bickford 2011). Global climate change not only influences animal body size (Yom-Tov et al. 2006, Rode et al. 2010, Baudron et al. 2014, Furness and Robinson 2018), it also alters behaviour and habitat selection (Bailey et al. 2019) and disrupts the phenology of ecological systems and species, such as migratory shorebirds (van Gils et al. 2016, Kwon et al. 2019, Saalfeld et al. 2019). However, while climate change is causing distributional shifts and influencing abundances of many species (Parmesan et al. 1999, Thomas et al. 2004), there is ongoing debate as to whether or not the changes observed in body size in animals is truly an adaptation to climate change (Teplitsky et al. 2008, Teplitsky and Millien 2014). Central to this argument is the need to identify factors that might influence size changes that follow the patterns expected from Bergmann's Rule (Teplitsky and Millien 2014). Understanding factors such as environmental conditions that drive selection pressures within a species might help to disentangle the mechanisms behind observed temporal trends (Gardner et al. 2009, Gardner et al. 2011).

Migratory shorebirds are found on all continents except Antarctica and breed in the northern hemisphere, predominantly at high latitudes where they are facing phenological shifts in food resources, and changing climate conditions (van Gils et al. 2016, Wauchope et al. 2016). Migratory shorebirds are thus good models with which to investigate the effects of environmental change on morphology.

Thermoregulatory processes, which are one of many constraints on morphology influenced by shorebirds' migratory lifecycle (Cartar and Morrison 2005), can affect the body mass of birds based on their geographic location and corresponding climate conditions. For example, fuelling intake rates of shorebirds can differ latitudinally among sites (Piersma et al. 2005), with shorebirds having higher fuel deposition rates (FDR) at sites further from the equator (Aharon-Rotman et al. 2016). Costs of thermoregulation also vary with latitude; energy demands to maintain body temperature are higher in colder climates (Castro et al. 1992; Wiersma and Piersma 1994; Alves et al. 2013) and there is likely a need to maintain more reserves in cold climates where severe weather conditions might cause periods when foraging is impossible (Goss-Custard et al. 2006). While shorebirds may require lower reserves in tropical locations where food resources are more stable, they may lose foraging opportunities because they need to allocate more time to minimising heat stress through heat dissipation behaviours (Battley et al. 2003). It is therefore valid to test the hypothesis that the mass of shorebirds in tropical climates is lower than the mass of shorebirds in temperate climates. To make this comparison we examine what Rogers et al. (1996) termed the 'base weight' – the reasonably stable mass maintained through most of the non-breeding season, at a time of year when shorebirds are moulting flight feathers and are likely to be carrying minimal levels of nutrient stores (Rogers et al. 1996). The base weight of a shorebird differs from its arrival weight shortly after the bird has flown thousands of kilometres; arrival weights may be relatively variable, as they likely include some individuals that did not use all their fuel during migration, and others that may have not only used all their fuel but may also have depleted reserves (van der Meer and Piersma 1994).

Here we use data collected from six species of migratory shorebird (Charadriiformes) across six study regions over a period of 40 years to examine the patterns in variation across space and time on the

Australian non-breeding grounds. We hypothesise that 1) birds at southern temperate locations in Australia would need to maintain a higher base weight than those in tropical locations, and that shorebirds in the tropics have less weight to maintain during the non-breeding season, and we also examine variation in body condition between sites within the same thermoregion; and 2) structural body size and body mass has declined over the study period while the study regions have similarly experienced changing climatic conditions.

Methods

Data collection and study sites

We used data collected from banding studies conducted by the Australasian Wader Studies Group (AWSG), Queensland Wader Study Group (QWSG), Victorian Wader Study Group (VWSG) and Friends of Shorebirds South East (FoSSE). We pooled data from sites within each state/region and then refer to the state when comparing sites. We used data from 12 sites in Tasmania (TAS, average latitude -40° and data time series 2010-2016), 29 sites in Victoria (VIC, latitude -38° and data time series 1981-2017), 18 sites in South Australia (SE SA, latitude -37° and data time series 1996-2017), 23 sites in Queensland (SE QLD, latitude -27° and data time series 2007-2017), 12 sites in northern Western Australia (NWA, latitude -17° and data time series 1982-2016) and four sites in the Northern Territory (NT, latitude -12° and data time series 2008, 2014-2015) (Figure 1; average latitude was determined by the latitude of each site weighted by the number of birds caught there). The banding teams collected data from shorebirds caught during cannon-net catches conducted at high tide when shorebirds were roosting. We used data from the first four non-breeding months (September through to December; September was selected for the NT because we had data available for that month). For tropical sites (NT and NWA; Figure 1) this corresponds to the late dry to the early wet seasons; in southern temperate Australia (SE QLD, SE SA, VIC, and TAS) late spring and early summer. Base weights could not be calculated for the 2nd half of the non-breeding season because (1) data from February onwards was unsuitable, as mass was likely to be influenced by premigratory mass gain; (2) few data were available from January-February in northern Australian sites, particularly NT. Once birds were captured they

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were housed in shaded keeping cages and held for a maximum of four hours from the time of capture, before being released where they could resume normal feeding activities at low tide. The period of captivity was minimised because routine feeding cycles at low tide are important to migratory shorebirds, particularly immediately after migration, and shorebird body mass decreases the longer birds are held in captivity (Zwarts 1990, Wilson et al. 1999). We corrected the body mass decreases that occur after birds are captured using estimates from Wilson et al. (1999).
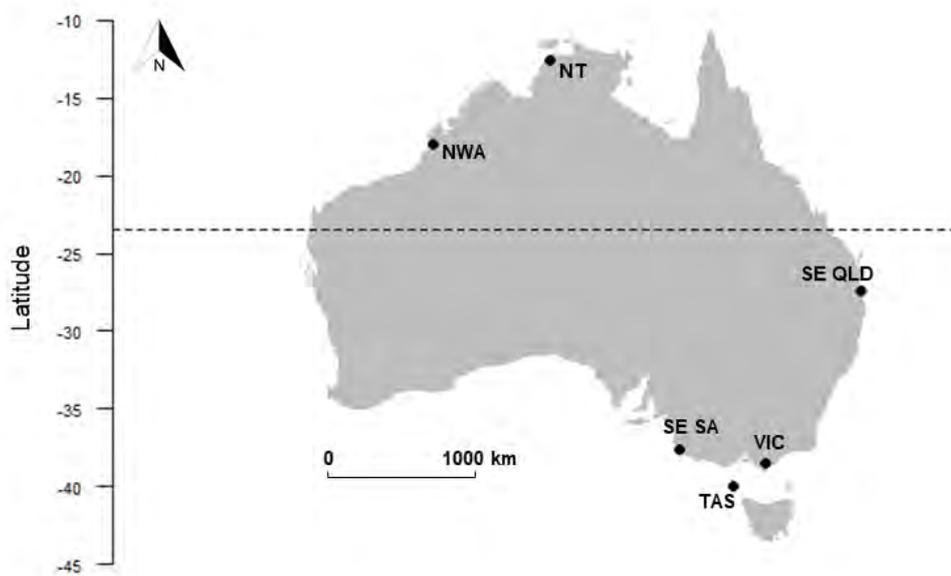
Figure 1. Map of study regions in Australia where migratory shorebirds were caught and processed. Dashed line shows the Tropic of Capricorn and provides a delineation between northern and southern regions in Australia.

Study species and morphometrics

We focused on six species of shorebird to make comparisons between the different study regions: Red-necked Stint, Lesser Sand Plover, Greater Sand Plover, Ruddy Turnstone, Red Knot, Great Knot (sample sizes listed in Table S1). Birds were aged based on plumage and wing-moult characteristics (Marchant and Higgins 1993, Higgins and Davies 1996) and weighed to the nearest 1 g. The following linear measurements were taken according to the methods described by Marchant and Higgins (1993):

wing length (maximum chord, to the nearest mm); head-bill, and bill (exposed culmen). Primary moult was recorded in all birds, with the wear and stage of growth of each primary classified following the methods summarised in (Rogers et al. 1986).

Statistical analysis

All analyses were performed in R v 4.0.2 (R Core Team 2020).

Climate variation on the Australian non-breeding grounds

It is generally assumed that with climate change there has been an increase in the average temperature, but we did not know if this trend varied across the Australian non-breeding grounds. We examined the mean maximum temperature (data from Bureau of Meteorology) for each region to show regional differences. To explore temporal variation, we used mean temperature anomaly data from Bureau of Meteorology (2020) for each state and each year since 1980. We plotted the data in R and modelled the temperature change (anomaly) by year and state in a linear model and checked model diagnostics. We used the modelled output to compare the differences between temperature change between states using a Tukey post-hoc multi-comparison of means test using the *glht* function in the 'multcomp' package (Hothorn et al. 2008).

Modelling variation in shorebird body size and mass

We combined banding data from all sites across Australia and removed re-trapped birds from the dataset to avoid doubled use of the same individual's morphometric data. We restricted analysis to birds aged in their second year or older. In most species, size differences between the sexes could not be detected, consistent with the analysis of Nebel et al. (2013). Variation in size by latitude or year could not therefore be attributed to differences in sex ratio. Female Red-necked Stints were slightly larger than males (e.g. mass was 3% higher, Higgins and Davies (1996)), but the difference was too slight to separate the sexes in all sites. Measurements of bill, head-bill, and wing length were combined in a principal components analysis (PCA) (*prcomp* function) to calculate the first principle component (PC1), which combines the three structural measurements in a single index of overall body size (termed

'body size') following van Gils et al. (2016), as single external metrics to represent body size in birds should be avoided (Freeman and Jackson 1990). Variables with a loading of >60% were considered important drivers of the maximum variation in the dataset (Figures S1-S7). We compared differences in overall body size (structural size using PC1 as the response variable) within a species over time in a linear model (LM) with year, state (factor) and temperature change (as a continuous variable) as fixed effects and an interaction term between year and state. Model reference levels were selected based on the state with the most data for comparative purposes. We also ran the model with latitude as a continuous variable but we our sample across the latitudinal gradient (only six latitudes) was not enough to show a clear gradient. We used the mean temperature anomaly (°C) from each year to represent climate variation over time, using data from Bureau of Meteorology (2020). Year and temperature change were centred before being included in the models. We then performed the same analysis using body mass as the response variable and included PC1 as an explanatory variable in the models to control for the effects of structural size. Model diagnostics were checked and for multicollinearity using variance inflation factor (*vif* function in the 'car' package (Fox and Weisberg 2018)). The variance inflation factor, which quantifies the severity of multicollinearity.

Results

Temporal and spatial climate variation on the non-breeding grounds

We used all historical climate data available to us to describe the variance across all six study regions and show that mean maximum temperature differs between regions (Figure S1). We show that in the 40 years since 1980, there has been a significant increase in the mean temperature anomaly across the Australian non-breeding grounds ($R^2 = 0.28$, slope. = 0.02, SE = 0.002, p-value = <.000; Table S1). In this study, the mean temperature anomaly was positive (showing an increase in mean temperature) in at least 70% of all years for the NT, TAS and WA, and at least 80% in QLD, SA and VIC (Figure 2). The slope of the increasing trend differed significantly between TAS and SA (p-value = 0.002) and TAS and QLD (p-value = 0.002), all other states had similar increasing trends over time (Figure 2).
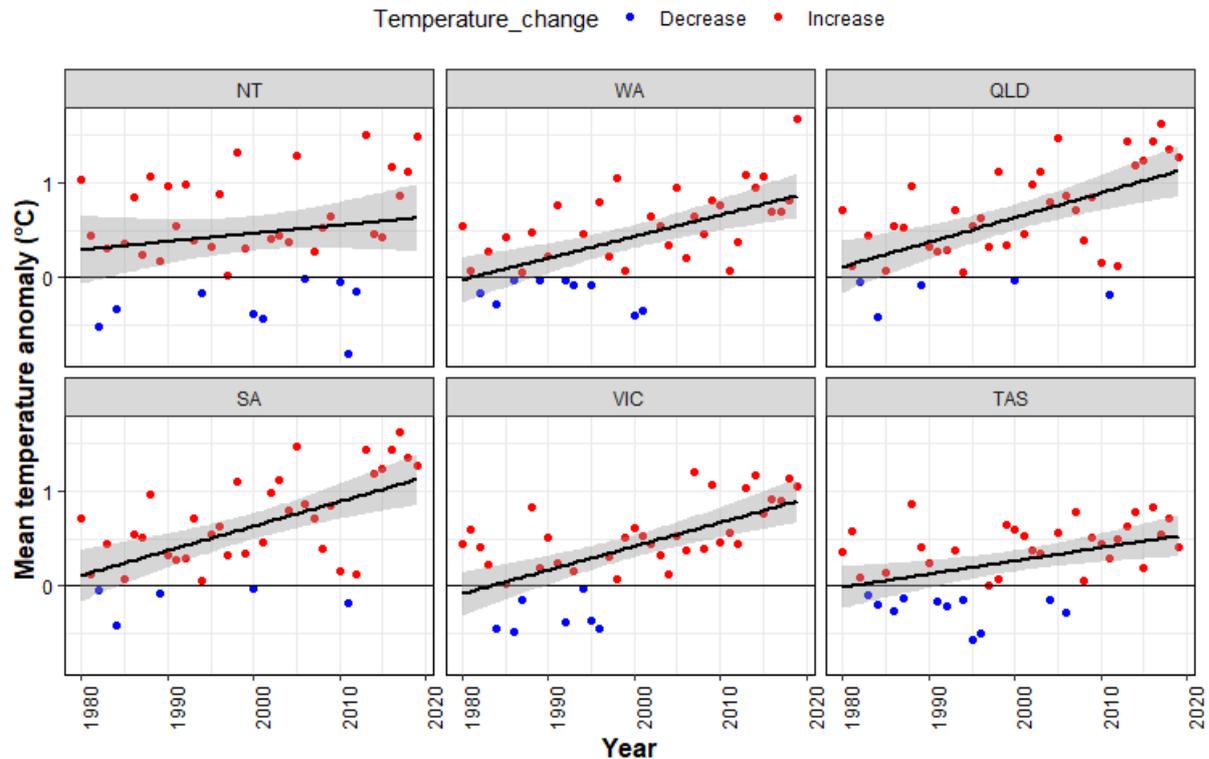
Figure 2. Mean temperature anomaly time series for six states across the Australian non-breeding grounds for the years 1980-2019. Black line shows a positive linear relationship over time and colours indicate the trend of positive or negative departures from the mean.

Temporal and spatial variation in structural size and mass of shorebirds across the non-breeding grounds

Weight was better explained by the candidate variables than was size (R^2 values; Tables 1 and 2). We found significant differences between states when we explored differences in structural body size (using PC1) and body mass in five of the six shorebirds (Tables 1-2). In most species these differences were consistent with a clinal pattern of higher structural size and mass at more southerly sites (Figures S8 – S21). Overall structural body size for two species (Greater Sand Plover and Ruddy Turnstone) decreased over time (Table 1). For Greater Sand Plover in NWA, there was a significant negative effect of year upon structural body size (95% CI -0.05 to -0.03, P = <.000). In Ruddy Turnstone in VIC, there was a significant negative effect of year upon structural body size (95% CI -0.03 to -0.00, P = <.003), but the species increased in body mass over time (95% CI 0.12 to 0.30, P = <.000). One species (Great

Knot) showed a significant positive effect of year upon structural body size (95% CI 0.01 to 0.03, P = <.000) but in NWA, there was a significant negative effect of year upon body mass (95% CI -0.33 to -0.14, P = <.000). Spatially, there was a significant difference in PC1 structural body size between NWA and NT, while accounting for temperature change. For Red Knot in VIC, there was a significant negative effect of year upon body mass (95% CI -0.52 to -0.32, P = <.000).

The temperature anomaly variable had a significant negative effect on body size and mass in Red-necked Stints. For every degree increase in temperature anomaly, the average estimated PC1 structural body size decreased by 0.28 units (95% CI -0.4 to -0.18, P<0.000) and the average estimated body mass decreased by 0.377 grams (95% CI -0.19 to -0.57, P<0.001)while accounting for year and state. For Red Knots, there was a significant effect of temperature on PC1 structural body size, the average estimated body size decreased by 0.316 PC1 units (95% CI -0.46 to -0.18, P = <.000) while accounting for year and state. In both sand plover species, temperature change had a significant negative effect on mass; for every degree increase in temperature anomaly, the average estimated body mass decreased by 1.89 grams (95% CI -3.73 to -0.03, P<0.046) in Lesser Sand Plovers, while the average estimated body mass decreased by 1.89 grams (95% CI -3.73 to -0.03, P<0.046) in Greater Sand Plovers while accounting for year, state and body structure.

Table 1. Results from linear model of changes in body structural size (PC1) over time. Bold denotes significance at the 0.05 α level.

Species	Model fit (state reference level)	Variable	Est.	0.025	0.975	t val.	p
Red-necked Stint	F(11,4322) = 17.401, p = 0.000, R² = 0.042 (VIC)	(Intercept)	0.275	0.200	0.351	7.124	**0.000**
		Year_centre	-0.007	-0.015	0.001	-1.759	0.079
		StateNT	-4.414	-11.708	2.881	-1.186	0.236
		StateNWA	-0.359	-0.491	-0.227	-5.325	**0.000**
		StateSE QLD	-0.953	-1.643	-0.263	-2.708	**0.007**
		StateSE SA	0.242	0.011	0.472	2.052	**0.040**
		StateTAS	0.353	-0.094	0.800	1.547	0.122
		Temp_change	-0.277	-0.384	-0.171	-5.109	**0.000**
		Year_centre:StateNT	0.386	-0.262	1.035	1.168	0.243
		Year_centre:StateNWA	-0.010	-0.027	0.008	-1.107	0.268
		Year_centre:StateSE QLD	0.044	-0.021	0.110	1.331	0.183
		Year_centre:StateSE SA	0.003	-0.027	0.034	0.209	0.834
		Year_centre:StateTAS					
Lesser Sand Plover	F(8,335) = 3.131, p = 0.002, R² = 0.070 (NWA)	(Intercept)	0.233	-0.092	0.558	1.411	0.159
		Year_centre	-0.009	-0.039	0.021	-0.583	0.560
		StateNT	-0.108	-1.787	1.572	-0.126	0.900
		StateSE QLD	-0.865	-1.806	0.075	-1.810	0.071
		StateVIC	0.353	-0.480	1.186	0.833	0.405
		Temp_change	0.059	-0.396	0.514	0.256	0.798
		Year_centre:StateNT	0.068	-0.116	0.252	0.725	0.469
		Year_centre:StateSE QLD	0.044	-0.055	0.142	0.875	0.382
		Year_centre:StateVIC	0.062	0.004	0.119	2.107	**0.036**
Greater Sand Plover	F(8,1320) = 14.543, p = 0.000, R² = 0.081 (NWA)	(Intercept)	-0.091	-0.221	0.038	-1.383	0.167
		Year_centre	-0.038	-0.050	-0.026	-6.182	**0.000**

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		StateNT	-2.162	-7.937	3.613	-0.734	0.463
		StateSE QLD	-1.941	-3.776	-0.106	-2.075	**0.038**
		StateVIC	0.639	-1.204	2.483	0.680	0.497
		Temp_change	-0.144	-0.299	0.010	-1.832	0.067
		Year_centre:StateNT	0.216	-0.142	0.574	1.185	0.236
		Year_centre:StateSE QLD	0.161	0.042	0.280	2.654	**0.008**
		Year_centre:StateVIC	0.100	-0.032	0.231	1.490	0.137
Ruddy Turnstone	F(12,2358) = 6.699, p = 0.000, R² = 0.033 (VIC)	(Intercept)	-0.054	-0.198	0.091	-0.728	0.467
		Year_centre	-0.015	-0.029	-0.001	-2.153	**0.031**
		StateNT	-0.304	-2.640	2.033	-0.255	0.799
		StateNWA	0.149	-0.143	0.441	0.999	0.318
		StateSE QLD	0.435	-0.501	1.370	0.911	0.362
		StateSE SA	0.149	-0.007	0.304	1.873	0.061
		StateTAS	-0.705	-1.112	-0.299	-3.401	**0.001**
		Temp_change	0.076	-0.050	0.201	1.180	0.238
		Year_centre:StateNT	0.066	-0.200	0.331	0.484	0.628
		Year_centre:StateNWA	0.012	-0.018	0.041	0.775	0.438
		Year_centre:StateSE QLD	-0.038	-0.153	0.076	-0.655	0.512
		Year_centre:StateSE SA	0.000	-0.018	0.018	-0.014	0.989
		Year_centre:StateTAS	0.066	0.016	0.115	2.598	**0.009**
Great Knot	F(8,1865) = 4.768, p = 0.000, R² = 0.020 (NWA)	(Intercept)	0.089	-0.024	0.202	1.552	0.121
		Year_centre	0.019	0.010	0.028	4.080	**0.000**
		StateNT	-1.612	-2.569	-0.656	-3.307	**0.001**
		StateSE QLD	0.324	-1.344	1.992	0.381	0.703
		StateVIC	0.040	-0.311	0.390	0.222	0.825
		Temp_change	-0.082	-0.221	0.058	-1.153	0.249
		Year_centre:StateNT	0.126	0.043	0.209	2.986	**0.003**

		Year_centre:StateSE QLD	-0.046	-0.183	0.090	-0.665	0.506
		Year_centre:StateVIC	0.005	-0.021	0.030	0.364	0.716
Red Knot	F(8,1629) = 6.488, p = 0.000, R² = 0.031 (VIC)	(Intercept)	0.209	0.103	0.315	3.863	**0.000**
		Year_centre	-0.007	-0.018	0.004	-1.229	0.219
		StateNT	-23.612	-51.404	4.180	-1.666	0.096
		StateNWA	-0.221	-0.355	-0.087	-3.223	**0.001**
		StateSE QLD	14.414	-2.780	31.608	1.644	0.100
		Temp_change	-0.316	-0.456	-0.176	-4.420	**0.000**
		Year_centre:StateNT	1.613	-0.283	3.510	1.669	0.095
		Year_centre:StateNWA	0.008	-0.011	0.027	0.838	0.402
		Year_centre:StateSE QLD	-1.122	-2.546	0.301	-1.546	0.122

Table 2. Results from linear model of changes in body mass over time. Bold denotes significance at the 0.05 α level.

Species	Model fit	Variable	Est.	0.025	0.975	t val.	p
Red-necked Stint	F(12,4321) = 72.376, p = 0.000, R² = 0.167 (VIC)	(Intercept)	29.035	28.900	29.170	422.117	**0.000**
		PC1	0.629	0.576	0.682	23.379	**0.000**
		Year_centre	0.014	-0.001	0.028	1.871	0.061
		StateNT	-7.723	-20.626	5.179	-1.174	0.241
		StateNWA	-0.140	-0.375	0.094	-1.174	0.241
		StateSE QLD	0.086	-1.136	1.307	0.138	0.890
		StateSE SA	0.368	-0.040	0.776	1.767	0.077
		StateTAS	-0.274	-1.065	0.516	-0.680	0.497
		Temp_change	-0.377	-0.565	-0.188	-3.914	**0.000**
		Year_centre:StateNT	0.310	-0.837	1.457	0.530	0.596

		Year_centre:StateNWA	-0.033	-0.064	-0.003	-2.129	**0.033**
		Year_centre:StateSE QLD	-0.075	-0.190	0.041	-1.271	0.204
		Year_centre:StateSE SA	-0.066	-0.120	-0.013	-2.426	**0.015**
		Year_centre:StateTAS					
Lesser Sand Plover	F(9,334) = 12.715, p = 0.000, R² = 0.255 (NWA)	(Intercept)	59.069	57.743	60.396	87.599	**0.000**
		PC1	0.482	0.045	0.920	2.171	0.031
		Year_centre	-0.044	-0.165	0.078	-0.709	0.479
		StateNT	-1.283	-8.114	5.547	-0.370	0.712
		StateSE QLD	10.956	7.111	14.800	5.606	**0.000**
		StateVIC	4.512	1.120	7.903	2.617	0.009
		Temp_change	-1.882	-3.732	-0.032	-2.001	**0.046**
		Year_centre:StateNT	0.452	-0.296	1.201	1.189	0.235
		Year_centre:StateSE QLD	-0.255	-0.657	0.146	-1.253	0.211
		Year_centre:StateVIC	-0.009	-0.244	0.226	-0.076	0.940
Greater Sand Plover	F(9,1319) = 22.822, p = 0.000, R² = 0.135 (NWA)	(Intercept)	74.054	73.507	74.601	265.504	**0.000**
		PC1	1.057	0.829	1.285	9.106	**0.000**
		Year_centre	-0.010	-0.062	0.042	-0.369	0.712
		StateNT	-11.978	-36.334	12.377	-0.965	0.335
		StateSE QLD	29.697	21.947	37.448	7.517	**0.000**
		StateVIC	14.554	6.779	22.329	3.672	**0.000**
		Temp_change	0.005	-0.648	0.658	0.016	0.987
		Year_centre:StateNT	0.563	-0.946	2.072	0.732	0.464
		Year_centre:StateSE QLD	-1.730	-2.233	-1.227	-6.746	**0.000**
		Year_centre:StateVIC	0.622	0.067	1.177	2.199	**0.028**
Ruddy Turnstone	F(13,2357) = 27.043, p = 0.000, R² = 0.130 (VIC)	(Intercept)	99.090	98.296	99.884	244.805	**0.000**
		PC1	1.744	1.522	1.965	15.439	**0.000**
		Year_centre	0.196	0.120	0.272	5.055	**0.000**

		StateNT	-7.669	-20.485	5.147	-1.173	0.241
		StateNWA	-1.860	-3.464	-0.256	-2.274	**0.023**
		StateSE QLD	8.224	3.092	13.356	3.142	**0.002**
		StateSE SA	-0.493	-1.347	0.361	-1.132	0.258
		StateTAS	-1.712	-3.948	0.523	-1.502	0.133
		Temp_change	0.604	-0.085	1.293	1.720	0.086
		Year_centre:StateNT	0.267	-1.191	1.724	0.359	0.720
		Year_centre:StateNWA	-0.280	-0.443	-0.117	-3.368	**0.001**
		Year_centre:StateSE QLD	-1.111	-1.738	-0.484	-3.473	**0.001**
		Year_centre:StateSE SA	-0.211	-0.311	-0.111	-4.137	**0.000**
		Year_centre:StateTAS	0.233	-0.040	0.506	1.675	0.094
Great Knot	F(9,1864) = 58.851, p = 0.000, R² = 0.221 (NWA)	(Intercept)	146.705	145.568	147.841	253.192	**0.000**
		PC1	-3.669	-4.127	-3.212	-15.730	**0.000**
		Year_centre	-0.234	-0.326	-0.141	-4.963	**0.000**
		StateNT	-6.954	-16.616	2.707	-1.412	0.158
		StateSE QLD	10.964	-5.843	27.771	1.279	0.201
		StateVIC	8.771	5.244	12.298	4.877	**0.000**
		Temp_change	-0.625	-2.031	0.780	-0.873	0.383
		Year_centre:StateNT	0.183	-0.651	1.018	0.431	0.667
		Year_centre:StateSE QLD	-0.509	-1.887	0.869	-0.724	0.469
		Year_centre:StateVIC	-0.079	-0.333	0.175	-0.613	0.540
Red Knot	F(9,1628) = 87.156, p = 0.000, R² = 0.325 (VIC)	(Intercept)	119.441	118.482	120.401	244.231	**0.000**
		PC1	3.043	2.606	3.480	13.649	**0.000**
		Year_centre	-0.426	-0.524	-0.327	-8.478	**0.000**
		StateNT	-41.197	-291.505	209.111	-0.323	0.747
		StateNWA	-11.931	-13.145	-10.718	-19.281	**0.000**
		StateSE QLD	60.193	-94.660	215.047	0.762	0.446

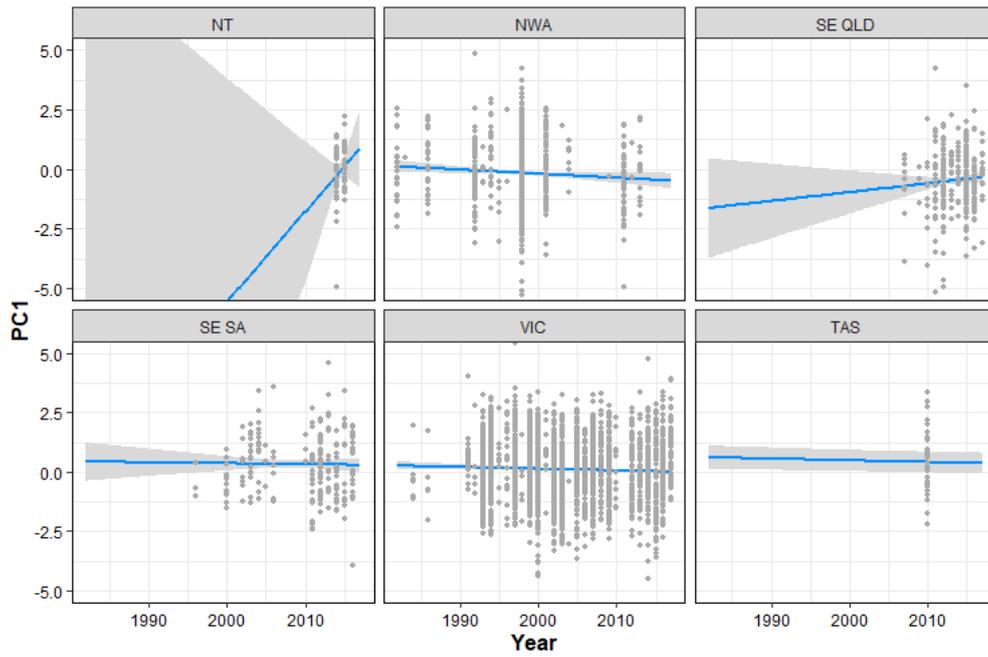|						
		Temp_change	0.183	-1.085	1.452	0.284	0.777
		Year_centre:StateNT	2.706	-14.374	19.785	0.311	0.756
		Year_centre:StateNWA	0.505	0.332	0.677	5.735	**0.000**
		Year_centre:StateSE QLD	-4.829	-17.653	7.994	-0.739	0.460

Figure 3. Changes in overall body size based on PC1 of structural measurements over time in Red-necked Stint. Confidence bands are 95% confidence intervals.
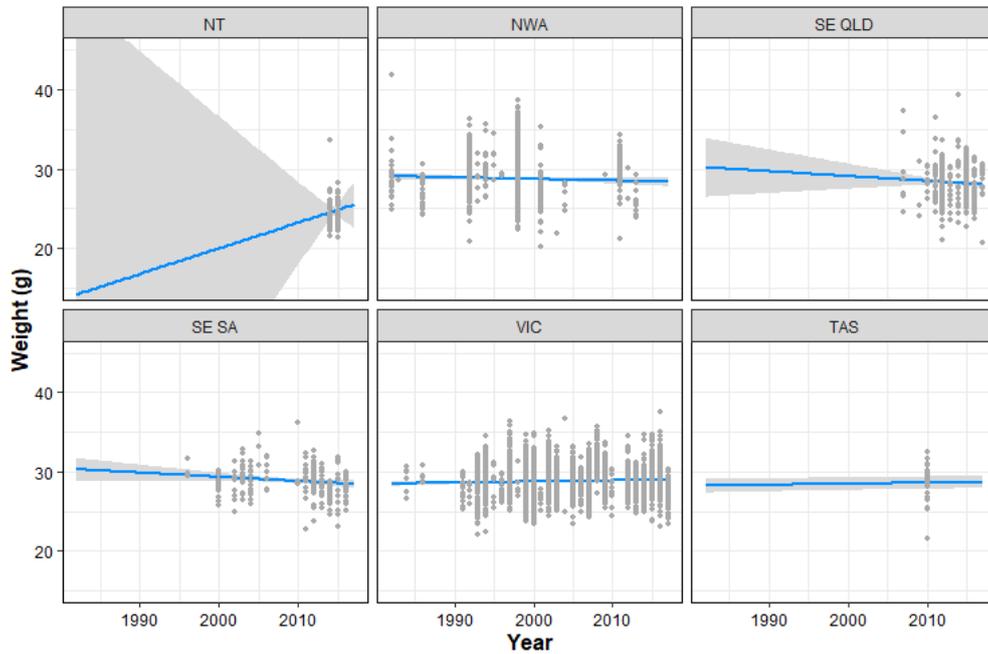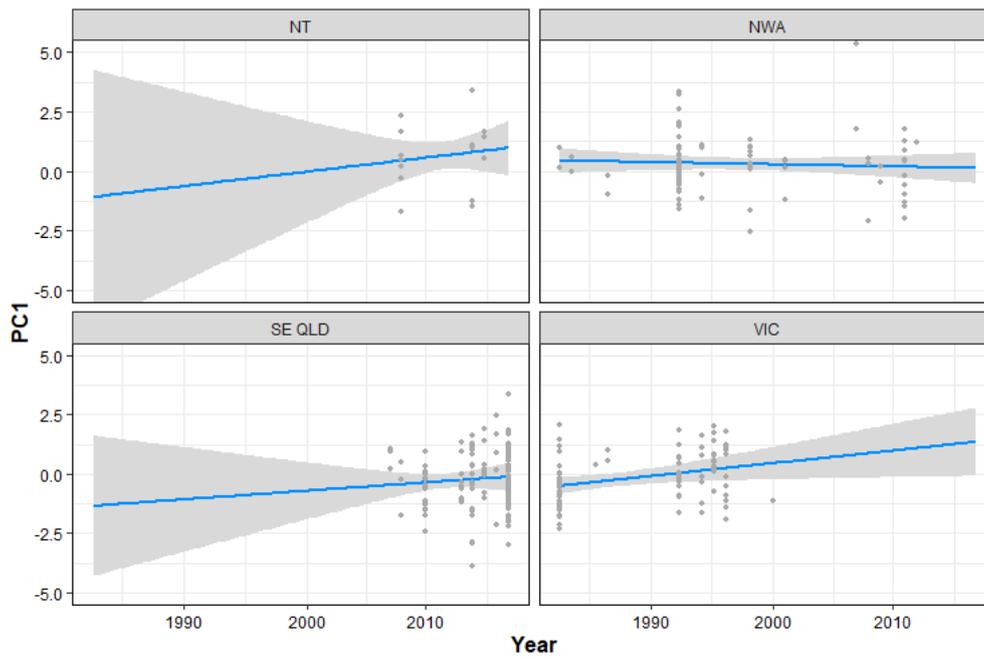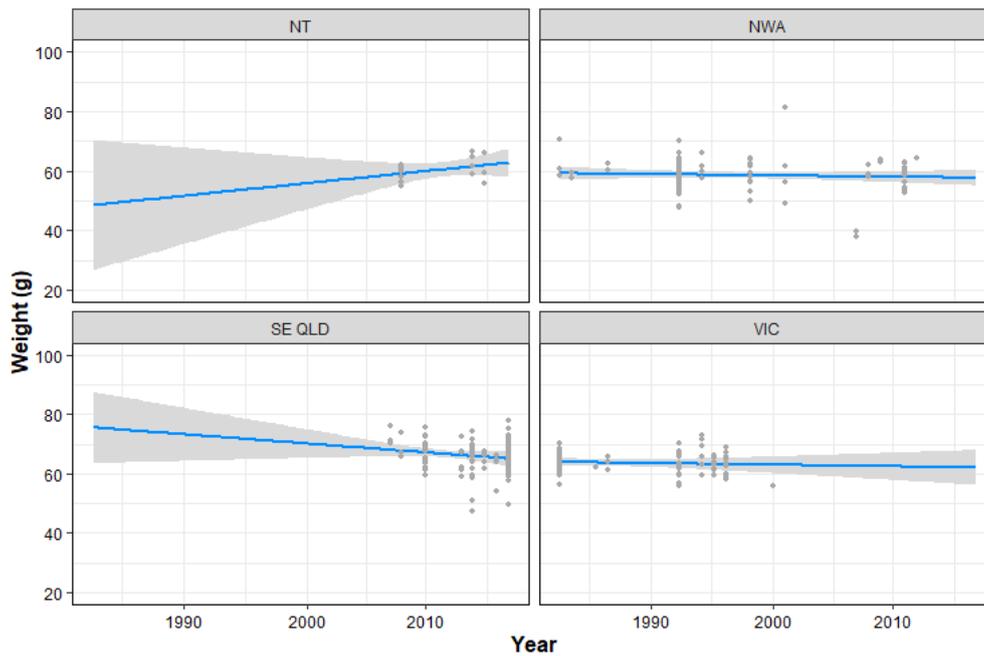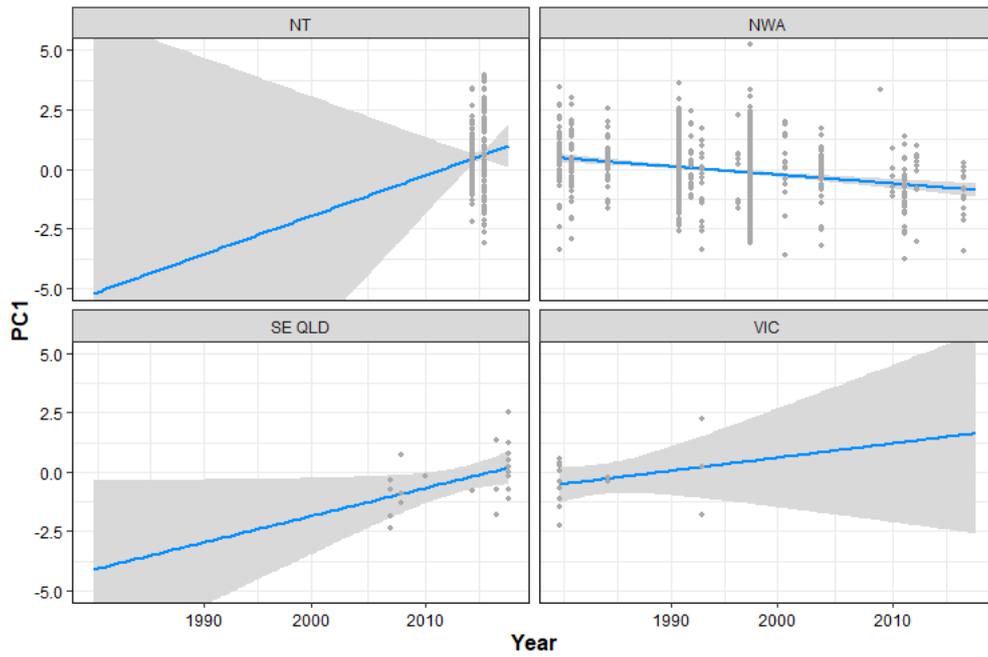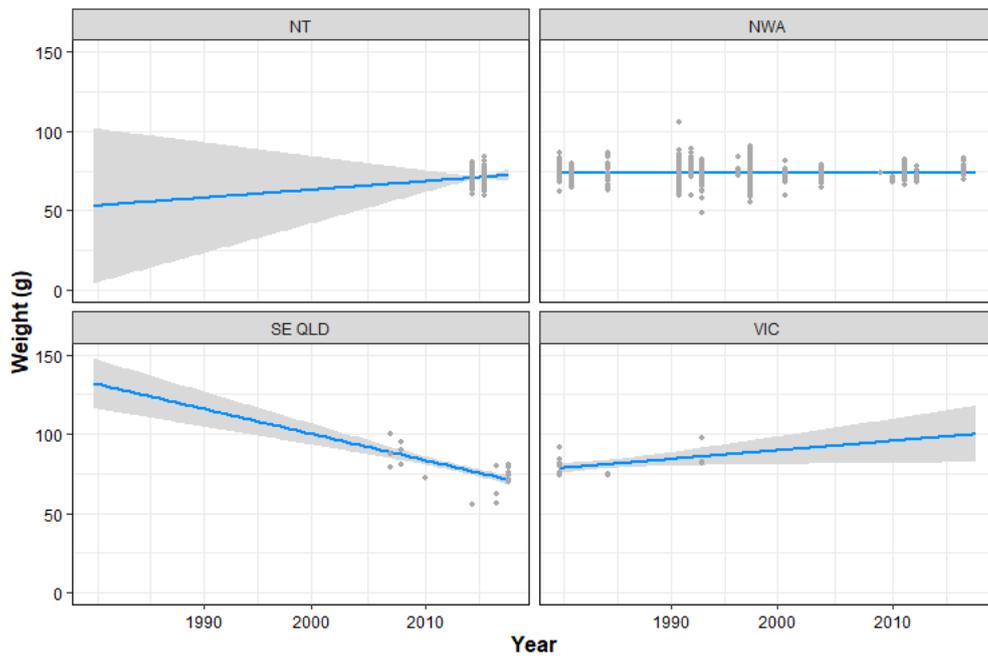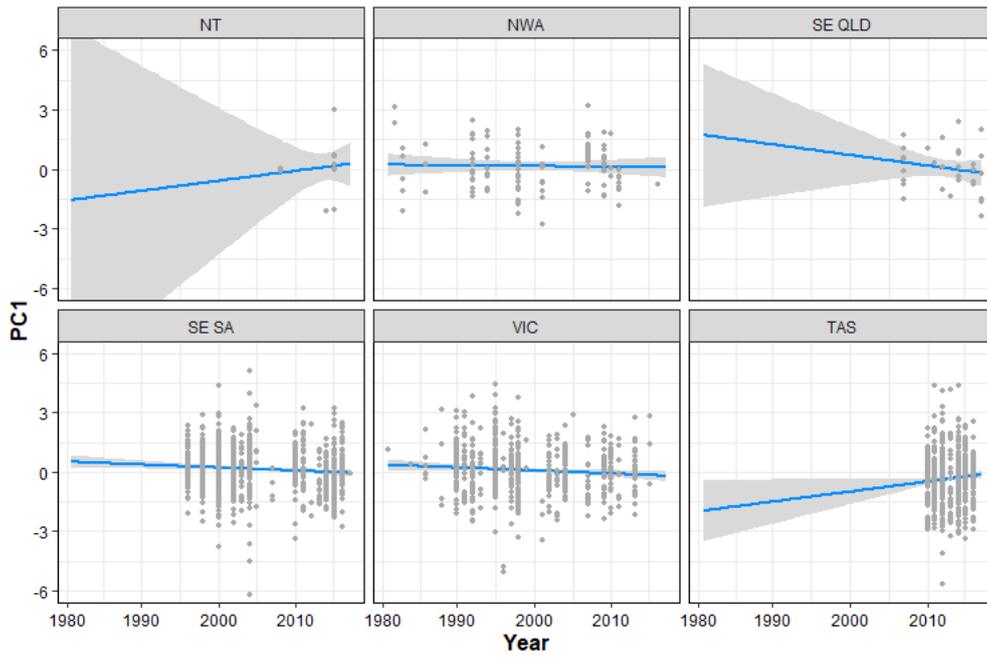

Figure 4. Changes in weight over time in Red-necked Stint. Confidence bands are 95% confidence intervals.

Figure 5. Changes in overall body size based on PC1 of structural measurements over time in Lesser Sand Plover. Confidence bands are 95% confidence intervals.
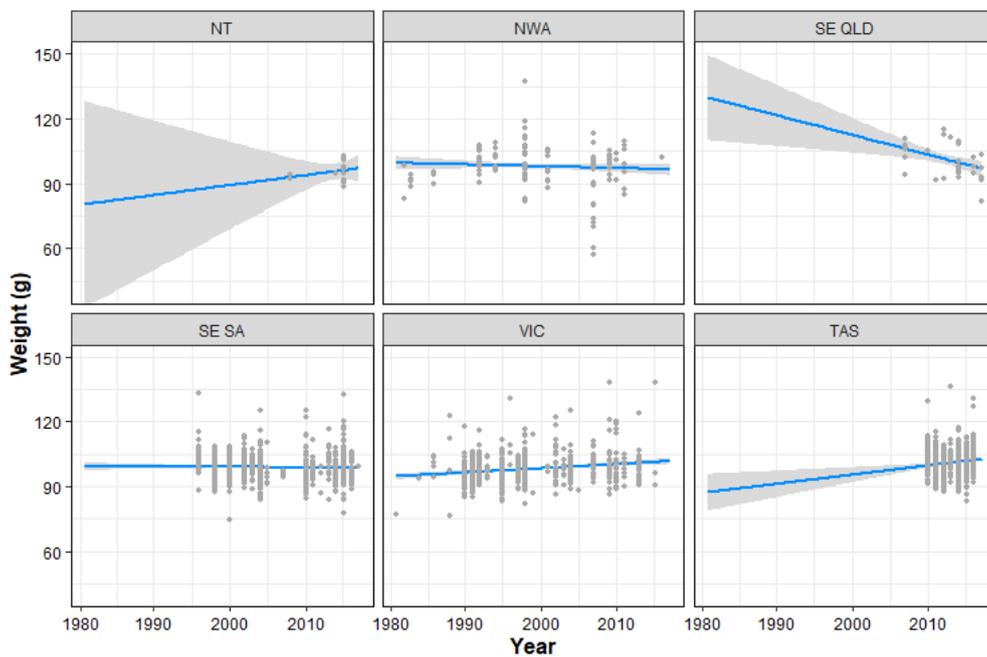

Figure 6. Changes in weight over time in Lesser Sand Plover. Confidence bands are 95% confidence intervals.
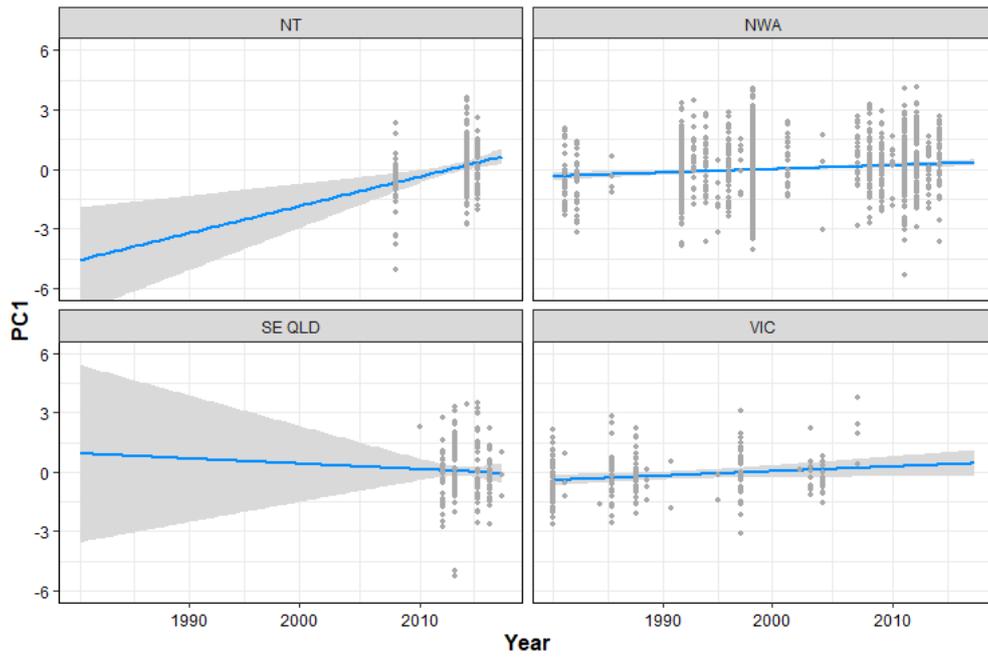
Figure 7. Changes in overall body size based on PC1 of structural measurements over time in Greater Sand Plover. Confidence bands are 95% confidence intervals.

Figure 8. Changes in weight over time in Greater Sand Plover. Confidence bands are 95% confidence intervals.

Figure 9 Changes in overall body size based on PC1 of structural measurements over time in Ruddy Turnstone. Confidence bands are 95% confidence intervals.

Figure 10. Changes in weight (g) over time in Ruddy Turnstone. Confidence bands are 95% confidence intervals.

Figure 11 Changes in overall body size based on PC1 of structural measurements over time in Great

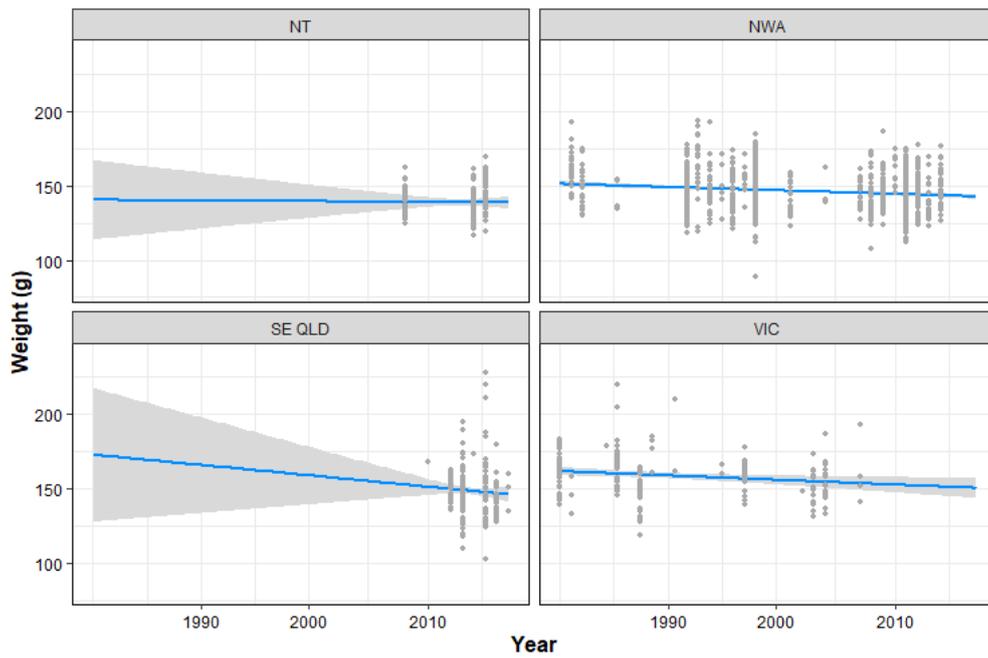Knot. Confidence bands are 95% confidence intervals.

Figure 12. Changes in weight (g) over time in Great Knot. Confidence bands are 95% confidence
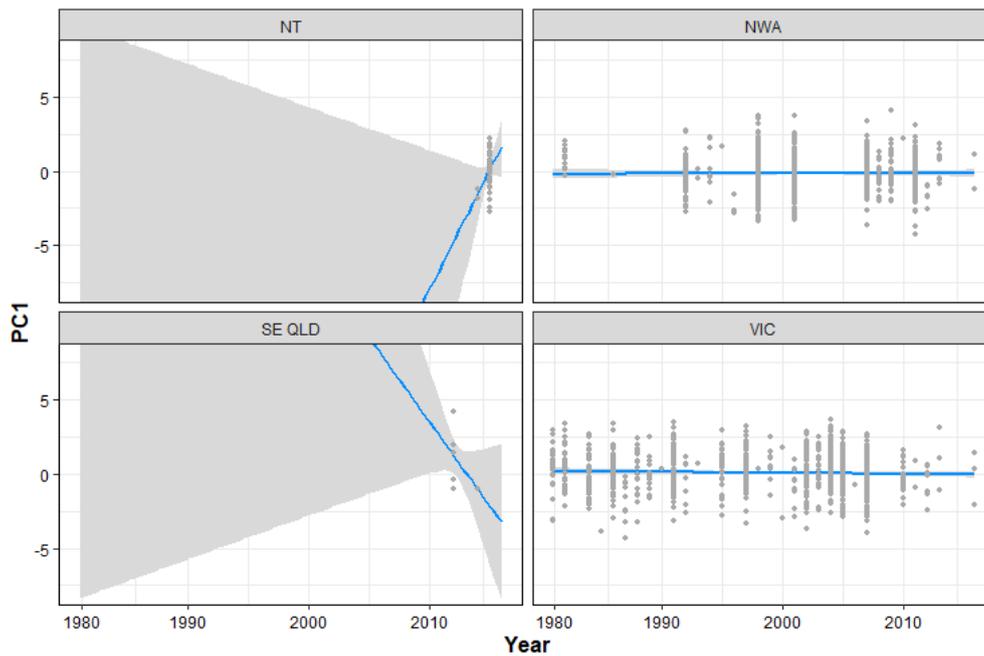
intervals.

Figure 13 Changes in overall body size based on PC1 of structural measurements over time in Red Knot. Confidence bands are 95% confidence intervals.
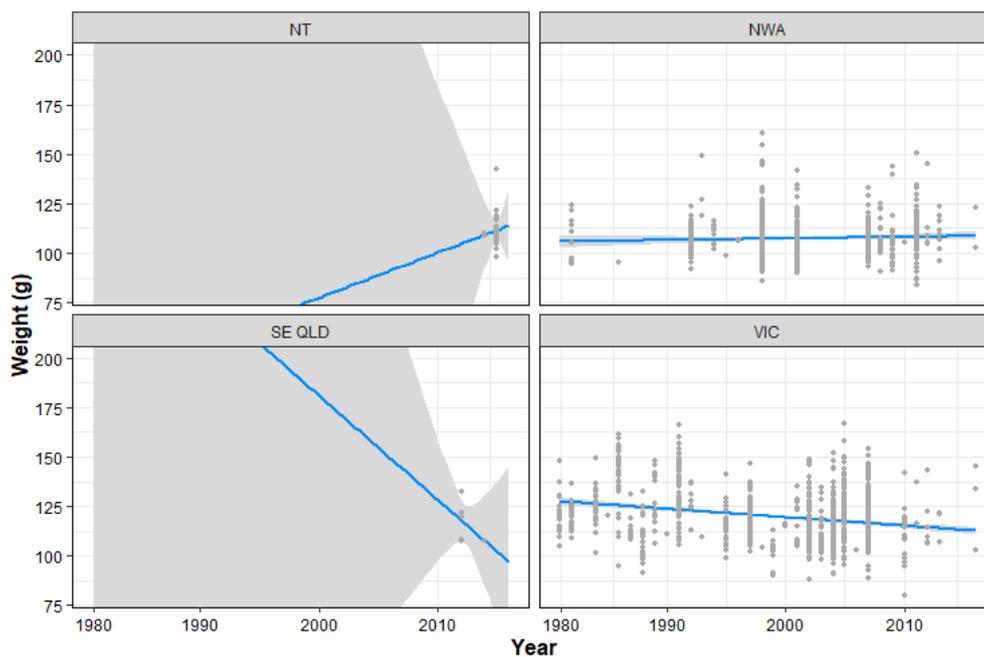

Figure 14. Changes weight (g) over time in Red Knot. Confidence bands are 95% confidence intervals.

Discussion

Our study is the first to provide evidence for declines in the structural body size and body mass of migratory shorebirds that use the East Asian-Australasian Flyway where many species have declined

in population size over several decades (Clemens et al. 2016; Studds et al. 2017). We demonstrate that on the non-breeding grounds there is significant variation between regions. The differentiation between structural size and body mass of shorebirds has allowed us to investigate both geographical variations in size within a species (structural size variable), and nutritional status, which is more phenotypically plastic and can be influenced by age, time of day, year, reproductive status and habitat quality (body mass variable) (Piersma and Davidson 1991).

Temporal differences in structural size and weight of shorebirds

Our individual analyses of changes in both structural size and body mass of shorebirds over time revealed several significant relationships, suggesting that some species (Greater Sand Plover and Ruddy Turnstone) have decreased in their overall body structural size, and some species decreased in body mass (after correcting for structural size) over time (Great Knot and Red Knot) (after correcting for structural body size). Body shrinkage in Red Knots over time has been related to a changing climate, with increasing global temperatures causing a reduction in structural size to better enable heat dissipation for body thermoregulation (van Gils et al. 2016). Australian passerines have also shown significant decreases in body size over the last 100 years (Gardner et al. 2009, Gardner et al. 2019), a change hypothesised to be linked to major environmental change, rather than a response to changes in nutrition (Gardner et al. 2009). In contrast the work on Red Knots by van Gils et al. (2016) showed a probable link to malnutrition in early life. Our results show that changes in body mass over time might be an indication that there is a decrease in habitat condition – perhaps at one or multiple sites throughout their migratory range. However, if mass loss is a strategic adaptation to increasing temperatures, then we predict that there will be selection for smaller structural size (which is strongly correlated with mass) to adapt to temperature decreases. We note however that there are likely to be limits to selection for smaller size, not least because shorebirds also need to deal with cold temperatures while on the breeding grounds. Moreover, larger individuals can carry larger fuel stores than smaller individuals, so decreases in structural size may restrict the flight range of migrating shorebirds when making long ocean crossings (Zhao et al. 2016).

The changes in body size and mass we report here for six migratory shorebird species should raise further concern for the conservation of this group of birds as three of the species are listed on the IUCN red list of threatened species (Red-necked Stint *near threatened*, Red Knot *near threatened*, Great Knot *endangered*). As the environment is altered by a warming climate, shorebird species that are under pressure and suffering population declines may be less resilient to climate extremes (Dhanjal-Adams et al. 2019). It is possible that these changes may lead to ecosystem imbalances through changes in energy expenditure at the individual level, which may lead to reduced breeding output as larger females will usually produce larger eggs, and thus larger offspring, which are more likely to survive (Sheridan and Bickford 2011). Further, our results showing weight decreases over time supports the notion that changes to trophic interactions on the non-breeding grounds might be pushing selection for smaller birds (as smaller birds do not need to carry such large reserves).

Differences in structural size and weight of shorebirds across the non-breeding grounds

In addition to temporal changes in body size, our results show a latitudinal clinal effect where shorebirds in southern temperate environments are larger than their northern tropical equivalents. We therefore accept hypothesis 1 – that birds at southern locations in Australia would need to maintain a higher base weight than those in tropical locations, and that shorebirds in the tropics have less weight to maintain.

Shorebird body mass is influenced by structural size, nutrient stores (fuel for migration), and nutrient reserves (fuel for daily functioning) (Lindstrom and Piersma 1993, Rogers et al. 1996). There has been some suggestion that shorebirds maintain higher base weights in colder climates to offset starvation risks in case of severe weather conditions (Davidson and Evans 1982, Rogers et al. 1996). However, this is unlikely to explain the differences we found in structural size or mass of birds across different Australian non-breeding grounds, as there is minimal risk of starvation to shorebirds from freezing conditions in Australian non-breeding grounds (Figure S1, where climates range from warm temperature to tropical). Alternatively, birds with higher mass generate more body heat, so may be easier for them to stay thermoneutral in cool conditions, and harder for them to stay thermoneutral in hot conditions. It is possible that birds strategically adjust their mass to make heat dissipation achievable

in hot conditions. It has been suggested that climate may indirectly influence body size of shorebirds that spend their time in tropical environments where high ambient temperatures restrict the rate at which individuals can take in prey (Lindström 2003), due to the need to expend energy dissipating heat (known as the heat dissipation limit theory, Speakman et al. (2010)) rather than foraging or digesting food (Battley et al. 2003, Aharon-Rotman et al. 2016). But conversely, shorebirds may be lighter in the tropics because they avoid foraging so intensively to maintain a lower body mass, thus carrying fewer reserves to better cope with increasing temperatures. If this is true, then there may be selection over time for smaller individuals within the population.

There was geographical variation in base weight outside that which could be explained by variation in structural mass, suggesting that base weight is influenced by local habitat quality. Although we cannot determine if these trends are indeed linked with lower biomass values across the study sites, there is evidence for a latitudinal effect on fuel-deposition rate, with FDR lowest at sites around the equator, and highest away from the equator (Aharon-Rotman et al. 2016). On further examination of the latitudinal trends, we found that for some species, there were significant differences in body mass between the study regions within the same climatic environment. Great Knot have increased in structural size in north-Western Australia over time and were structurally smaller than their counterparts in the Northern Territory. In three species (Red-necked Stint, Greater Sand Plover, Great Knot) the average weights were lower in the Northern Territory than in north-Western Australia – both regions have tropical climates. This might suggest that local climate conditions are not the only influencing factor. We expect this is likely due to variation in the condition of food resources for migratory shorebirds between the regions.

Genetically different populations occupying different areas

The apparent latitudinal trends we report here might be driven by genetically different populations occupying different areas. In two of the six species examined in this study (Lesser Sand Plover, Red Knot), multiple subspecies are known to occur in Australia (Marchant and Higgins 1993, Rogers et al. 2010). In the other four species only one subspecies is recognised in Australia, but there may be

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geographical variation that has not been recognised in taxonomic studies. Whether or not subspecies are recognised in the future, it is quite possible that the size differences between populations have evolved in part because of the conditions birds experience on the non-breeding grounds where they spend over half their lives.

Subspecies *piersmai* and *rogersi* of the Red Knot both migrate through the EAAF (Tomkovich et al. 2013). The subspecies differ largely in colour of breeding plumage, but subspecies *piersmai* is also thought to be smaller overall than *rogersi* (Tomkovich 2001). Currently, it is known that the proportions across the Australasian non-breeding grounds are 80% *piersmai* to 20% *rogersi* in NWA, 35% *piersmai* to 65% *rogersi* in VIC, and 20% *piersmai* to 80% *rogersi* in NZ (Rogers et al. 2010). Subspecies *piersmai,* which predominate in tropical Australia, migrate to and breed at the New Siberian Islands, at more northerly latitudes than subspecies *rogersi*, which spends the non-breeding season predominately in southern Australia and New Zealand and migrates to breeding grounds in Chukotka (Higgins and Davies 1996, Piersma et al. 2005). Our results show that Red Knots in NWA have the lowest average body weight, while those in VIC have significantly higher average body weights than NT, NWA and SE QLD. Surprisingly, the Red Knots from NWA had significantly larger average structural body sizes than those in VIC.

Lesser Sand Plovers in NT and NWA had lower average body weights and larger body sizes compared to those from SE QLD and VIC, suggesting that birds on the east coast of Australia might predominantly be the subspecies *stegmanni* while those in north-Western Australia and the Northern Territory might predominantly be the *mongolus* subspecies based on morphometrics (Hadoram 2000).

Conclusion

We demonstrate that the overall structural body size of two of six species of migratory shorebirds in the East Asian-Australasian Flyway has significantly declined over varying periods within the last 40 years. We speculate that this shift over time may be linked to changing climate conditions. Overall body mass has significantly decreased over the same period in two of the six species, a cause for concern as one of those species is globally Endangered and the other Near Threatened. Three of the six species we

examined were lighter in the Northern Territory than all other regions. Our results also show that within species we are seeing significant differences in weights of birds in the same climatic region, suggesting that factors other than a warming climate are influencing body condition.

Acknowledgements

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Chapter 3. An artificial site provides valuable additional habitat to migratory shorebirds in a tropical harbour

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An artificial site provides valuable additional habitat to migratory shorebirds in a tropical harbour

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Abstract

Migratory shorebirds are declining in all trans-equatorial flyways, most rapidly in the East Asian-Australasian Flyway. Population trends for shorebirds have been derived at a flyway and continental scale, but changes at the local scale are less well understood. Here we compare trends in migratory shorebird populations using natural and artificial roost sites within a tropical harbour, examine possible drivers of change, and identify appropriate conservation management responses. Counts of 19 migratory shorebird species from 2010 and 2018 showed that total abundance increased at an average annual rate of 3.3% (95% CI = 1.3-5.4%, P = 0.001) across five natural roost sites. This was driven largely by increases in Great Knot with most other species declining. At an artificial site in an adjacent shorebird area, total abundance increased at an average annual rate of 14.5% (95% CI = 10.5-18.6%, P = <0.000) with few species declining. These results suggest there is a need to include both natural and artificial

sites within shorebird conservation and management planning and that trends in different species can be driven by a combination of local and external drivers.

Key words: waders, non-breeding grounds, tropical ecology, population change

Running heading: an artificial site is valuable to migratory shorebirds

Introduction

Coastal wetlands are highly productive ecosystems under such intense human pressure that there has been a loss of at least 33% across the globe due to land use change (Hu *et al.* 2017). Much of this reduction in wetland extent has occurred in Asia (Hu *et al.* 2017), including a loss of up to 65% of tidal flats in the Yellow Sea region in the past five decades (Murray *et al.* 2014). Coastal wetlands provide habitat for migratory shorebirds and the loss of wetlands and tidal flats has been linked to the flyway-wide collapse of shorebird populations in the East Asian-Australasian Flyway (EAAF) (Amano *et al.* 2010; Piersma *et al.* 2016; Studds *et al.* 2017). Sustained high rates of land use change in the Yellow Sea region (Studds *et al.* 2017) have led to the natural habitats occupied by the birds during the non-breeding season becoming progressively converted into a variety of land uses, many associated with human production activities. Some land uses such as dredge ponds within ports, salt production ponds, aquaculture ponds and farmland can provide artificial habitat for some shorebirds (e.g.: Choi *et al.* 2014; Houston *et al.* 2012; Jackson *et al.* 2019; Lei *et al.* 2018). Understanding how shorebirds use artificial habitat is therefore critical to managing these species in changing coastal landscapes.

Land use changes have caused degradation in many aspects of wetland quality, including increases in heavy metals and pollutants, spread of weeds, increased human disturbance and competition between birds for space and food resources (Studds *et al.* 2017). Yet, artificial environments can provide suitable supratidal habitat for shorebirds, sometimes with reduced disturbance (Ma *et al.* 2004). Because of this there are differences in the use and uptake of artificial habitat compared with natural habitat nearby (Ma *et al.* 2004). Differences in local population trends between species or for different populations of the

same species may therefore be explained by differences in use of artificial and natural habitats by those species or populations respectively.

Shorebird declines have been occurring in Australia for over 30 years (Hansen 2011), with the greatest losses in southern Australia at the migration terminus for many species (Clemens *et al.* 2016; Hansen *et al.* 2015). Much less is known about trends in shorebirds that spend the non-breeding season in northern Australia, although local-scale increases have been reported in the Northern Territory (Clemens *et al.* 2016; Lilleyman *et al.* 2016b). Species that have increased in Darwin Harbour include the Far Eastern Curlew (*Numenius madagascariensis*) (Lilleyman *et al.* 2016b) which has been declining so rapidly at a national and flyway level (Studds et al. 2017) that it has been listed as Critically Endangered under national legislation and Endangered on the IUCN Red List (BirdLife International 2017). While the current habitat of Darwin Harbour in the Northern Territory is in excellent environmental condition (Munksgaard *et al.* 2018), there has been some coastal development, and there are also plans for further expansion of industry in this coastal setting.

The possibility that local trends in a tropical harbour in northern Australia differ from trends elsewhere warrants more detailed investigation. For example, the anomalous trends observed for the Far Eastern Curlew might result from local factors leading to redistribution of birds within Darwin Harbour. Alternatively, the artificial site where the increases have occurred, East Arm Wharf, may be providing habitat features that are missing from other shorebird sites in the region, attracting a larger population to the region than it would otherwise support. These possibilities require simultaneous analysis of shorebird trends at this artificial site and other natural sites in the locality. A more detailed understanding of trends across natural and artificial sites in Darwin Harbour, Northern Australia can fill a knowledge gap in an important and understudied part of the flyway, and also inform the management of artificial and natural sites elsewhere. Given the wide-ranging declines of species dependent on coastal wetlands in the region, enhanced planning to avoid negative effects of development on shorebirds and wildlife is critical.

This paper therefore has three objectives: (1) to provide detailed documentation and understanding of shorebird trends in the Darwin Harbour region to fill a spatial gap in flyway knowledge, (2) to determine whether the anomalous trends in Far Eastern Curlew numbers in Darwin Harbour are exceptional or indicative of trends across multiple species, (3) to compare trends in artificial and natural roosting habitats to explore whether artificial habitats could help to buffer loss of habitat across the broader landscape.

Methods

Study area

Counts of shorebirds were obtained from five natural high tide roosts in Darwin Harbour, Northern Territory, Australia including Lee Point, Sandy Creek, East Point, Nightcliff Rocks and Spot on Marine, and one artificial site, the East Arm Wharf (Figure 1). Lee Point and Sandy Creek are sandy beaches at the higher edge of extensive intertidal sandflat. They are part of the Casuarina Coastal Reserve managed by the Northern Territory Parks and Wildlife Commission and are open to the public who use them for recreation such as exercise or dog-walking. East Point and Nightcliff Rocks are rocky outcrops connected to a tidal bay where shorebirds feed. Spot on Marine is an open saltpan bordered by mangroves.

East Arm Wharf (an area managed by Darwin Port) is the main point of departure for exports from Darwin and is surrounded by industrial infrastructure. The wharf was established in 2000 and the pond system is estimated to be 15 years old. The site contains four artificial ponds used to store stormwater runoff and to settle dredge spoil from Darwin Harbour. Some of these ponds have changed over time based on port operations and each pond is a different age. Two ponds at the site have become more attractive to shorebirds over time. One is flushed by the tide and always has water. The other three are freshwater and tend to be dry by September but start filling during the wet season to the point where little water shallow enough for shorebirds is available by February. Human access is only allowed by permit, and the site is rarely disturbed by people. Shorebirds that roost at East Arm Wharf feed on intertidal mudflats nearby when the tide recedes (pers. obs, AL).

The Darwin area is macrotidal with a tidal range of 0.7 - 8.0 m. During high tides of 6 m, the total area of all the natural sites combined is slightly larger than the area available at East Arm Wharf (Table S2). At tides of >7 m, Nightcliff Rocks, Spot on Marine and East Point roost sites are inundated, and Lee Point and Sandy Creek are very narrow strips of beach. These too are covered entirely on the highest tides. In contrast, East Arm Wharf is available for roosting at all tides. A separate study of movements among and between sites (Lilleyman, A. unpublished data) showed that the birds roosting at the inter-connected natural sites and birds roosting at East Arm Wharf constituted two separate sub-populations within Darwin Harbour.

The sites were all chosen because monitoring data exist from an established program that covers the main roost sites in the area from East Arm Wharf to Buffalo Creek (Figure 1). Previous survey work in Darwin Harbour has shown that the East Arm Wharf roost site is the only available roost site for shorebirds when the tide is >7.6 m as available roosting space at all other survey sites is greatly reduced (Lilleyman et al. 2018).
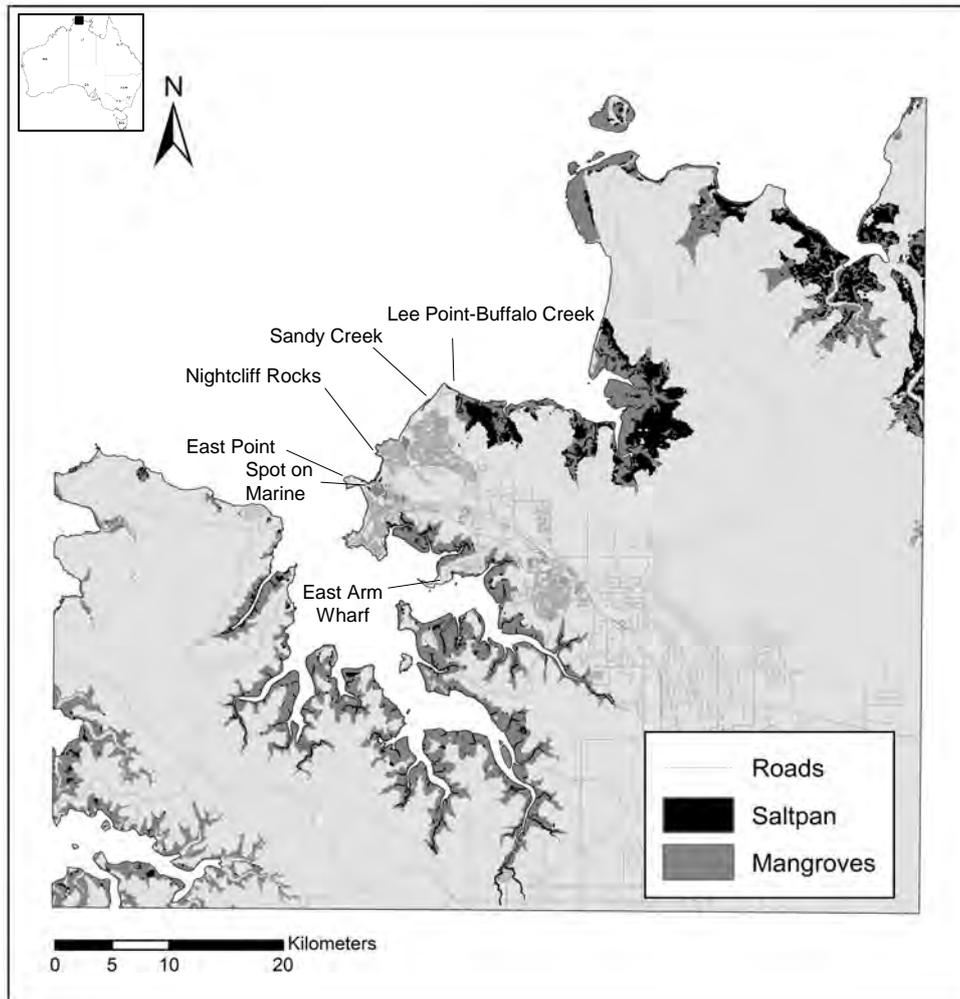
Figure 1. Map of migratory shorebird monitoring sites in Darwin Harbour, Northern Territory. Lee Point-Buffalo Creek, Sandy Creek, Nightcliff Rocks, East Point and Spot on Marine are natural roost sites; East Arm Wharf is artificial.

Count data

We used data collected from shorebird high-tide roost surveys conducted at the five natural sites around Darwin Harbour between 2010 and 2018 from the BirdLife Australia Shorebirds 2020 national program and data collected by A. Lilleyman or G. O'Brien at East Arm Wharf to determine population trends at these sites. The surveys included were conducted by experienced shorebird counters and vetted by BirdLife Australia staff. Some roosts could be counted from a single point, and others were surveyed by walking along a stretch of beach. On average it took 75 minutes to count the birds at each roost at

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the natural sites and 96 minutes at East Arm Wharf. Time was recorded to calculate the tide height at the time of the count; we only included counts from surveys that were performed when tides were >6 m by which time most shorebirds had moved to roosts because their foraging habitat was covered by the sea.

Significance thresholds

We used the full dataset from BirdLife Australia's Shorebirds 2020 program from 1980-2017 for natural sites and the East Arm Wharf dataset from 2010 - 2018 to record the number of times the thresholds for national (0.1% of the flyway population) and international (1% of the flyway population based on estimates from Hansen *et al.* (2016) significance were exceeded at each of the sites, as this is used as an indicator of site-level conservation significance for environmental impact assessments (Commonwealth of Australia 2015).

Drivers of change: Disturbance

Disturbance is considered a major threat to migratory shorebirds with high energy costs for shorebirds (Lilleyman *et al.* 2016a; Weston *et al.* 2012). We recorded all observed disturbances to shorebirds during high tide counts at the artificial East Arm Wharf site and at the natural sites Lee Point, Nightcliff Rocks, Sandy Creek, and Spot on Marine during the non-breeding austral summer months of 2014, 2015 and 2016. We recorded disturbance types (bird of prey, human, human + dog/s, aircraft), and categorised shorebird responses to disturbances as flight, non-flight (i.e. walking away from the disturbance), or no response. We used the sum of disturbances across survey months at a site to score it as having low (<20 disturbances), medium (20-40 disturbances), or high (40-60 disturbances) disturbance levels relative to the other sites.

Statistical analyses

Model parameters and selection for population change estimates

Data from the five natural sites were combined because individually marked shorebirds regularly moved between them (A. Lilleyman, unpublished data) and three of the sites were regularly flooded by the

highest tides. We analysed the natural sites separately to those from the artificial site at East Arm Wharf because: 1) the East Arm Wharf site is relatively new (less than 15 years old); 2) observations of individually marked shorebirds suggests little movement between East Arm Wharf and the natural sites (Lilleyman, *et al*, in prep.); and 3) the habitat type in and around the East Arm Wharf dredge ponds differs from the natural sites, which influences species composition at the site.

We examined boxplots of monthly counts for species over the survey years and found a strong seasonal effect where most species had higher abundances during the austral summer (November through February) as would be expected with seasonally migratory species (Clemens *et al.* 2016). For species with peak abundance during this period we combined count data from November and December in one year with data from January and February the following year; this we labelled the summer season. We modelled count data for each species at the natural sites and then ran separate models for the species at the artificial site. We used a negative binomial generalised linear model (GLM) using the *glm.nb* function in the 'MASS' package in R 3.5.0 (R Core Team 2018; Venables 2002). We ran models using count data as the response and year as the explanatory variable and then tested for any effects of additional variables (month, site, survey effort (hours), tide height (m)), and scaled survey effort and tide height before running the models. For the artificial site we tested if mudflat coverage was important by modelling tide height as a binary covariate ($0 = <7$ m, $1 = >7$ m). We compared models by assessing the fit of the model through deviance residuals and selected the most strongly supported model with the lowest Akaike Information Criterion (AIC) value. If this model included explanatory variables, we then tested for collinearity of these using variance inflation factor (*vif* function in the 'car' package (Fox 2018)). The vif, which quantifies the severity of multicollinearity, was always <5 in the output, indicating low correlation among variables. We then exponentiated the coefficients and confidence intervals from the best models to present as the odds ratio, which is the overall trend for each species expressed as an annual percentage change. To understand the influence of disturbance on rates of change we compared trends at the natural and artificial sites with average flight-initiation distances (FIDs) derived from (Weston *et al.* 2012) and (Lilleyman *et al.* 2016a) against the exponentiated coefficient estimates in a linear model (*lm*).

Results

One of the natural sites (Lee Point) regularly supported up to 9000 shorebirds during the summer season; the artificial site never supported more than 1500 shorebirds at any one time over the survey period. The 'natural site' network met the threshold for national importance for 15 species since 1980 recorded based on the maximum count for each species across the network; 10 species exceeded the thresholds at least once since 2010 at the artificial East Arm Wharf site (Table S1). The Lee Point roost site regularly met the threshold for international importance for Great Knot (*Calidris tenuirostris*) throughout most of the summer season, while Greater Sand Plover (*Charadrius leschenaultii*) and Black-tailed Godwit was recorded in internationally important numbers on one occasion at this site (Table S1).

Overall population trends of shorebirds in Darwin Harbour

Total abundance of migratory shorebirds increased across the natural sites at a rate of 3.3% per year (95% CI = 1.3-5.4) in Darwin Harbour for the years 2010 - 2018 (coefficient 0.03 ± se 0.00, P = <0.0001; Table 1 and Figure 2). However, individual species trends differed; there were significant annual decreases for Bar-tailed Godwit (*Limosa lapponica*) (-15.2%, P = 0.003), Greater Sand Plover (-12.7%, P = 0.041), Whimbrel (*Numenius phaeopus*) (-15%, P = 0.004), and Grey Plover (*Pluvialis squatarola*) (-12%, P = 0.035) at the natural sites (Table 1). Conversely, numbers of Common Greenshank (*Tringa nebularia*) increased significantly (18.8%, P = <0.000). Shorebird numbers increased at the East Arm Wharf artificial site at a rate of 14.5% per year (95% CI = 10.5-18.6) over the same time period (coefficient 0.14 ± se 0.02, P = <0.0001; Figure 3). Common Greenshank and Whimbrel populations increased significantly during the survey years with annual population increases of 24.5% (P = <0.005) and 56.9% (P = <0.05), respectively, whereas Curlew Sandpiper (*Calidris ferruginea*) and Lesser Sand Plover (*Charadrius mongolus*) had annual population declines of 44.4% and 39.5%, respectively (Figure 4). Trends for other species were not significant (Table 1), including those for the Far Eastern Curlew when calculated over a longer period with different statistical methods than in Lilleyman *et al.* (2016b).

Table 1. Model results from negative binomial GLM and estimated population change for all migratory shorebirds at five natural sites and one artificial site (years = 2010 - 2018) in Darwin Harbour. Species in bold represent significant trends. Negative estimated coefficients indicate a decreasing trend for that species. Species are presented in alphabetical order by site class (artificial and natural).

| Site class and species	Best model formulae	Estimated coefficient	P-value	% change per year	95% CI
Artificial site	**count ~ year**	**0.14**	**0.000**	**+14.5%**	**10.5-18.6**
Bar-tailed Godwit	count ~ year + decimal_effort + tide_height	-0.29	0.097	-24.80%	11 - 50.6
Black-tailed Godwit	count ~ year	-0.16	0.557	-14.7%	32.3-50.3
Common Greenshank	**count ~ year + tide_covered**	**0.21**	**0.007**	**+23.9%**	**3.4 - 47.1**
Common Sandpiper	count ~ year	-0.04	0.704	-3.8%	20.2-23.1
Curlew Sandpiper	**count ~ year + month**	**-0.58**	**0.000**	**-44.4%**	**29.5 - 57.7**
Far Eastern Curlew	count ~ year	0.25	0.131	+28.2%	4.6-66.0
Great Knot	count ~ year	0.26	0.086	+28.2%	19.2-78.6
Grey Plover	count ~ year	-0.10	0.495	-9.3%	17.0-31.5
Greater Sand Plover	count ~ year + tide covered	0.10	0.534	+10.8%	23.2-49.6
Grey-tailed Tattler	count ~ year	-0.34	0.122	-28.9%	11.0-58.2
Lesser Sand Plover	**count ~ year**	**-0.50**	**0.003**	**-39.5%**	**18.0-56.4**
Red-necked Stint	count ~ year	0.06	0.603	+6.1%	14.1-29.6
Sharp-tailed Sandpiper	count ~ year	0.09	0.493	+9.1%	11.8-33.5
Whimbrel	**count ~ year**	**0.45**	**0.014**	**+56.9%**	**12.3-108.9**
Natural sites	**Total ~ year + tide_covered**	**0.03**	**0.001**	**+3.30%**	**1.3 - 5.4**
Bar-tailed Godwit	**count ~ year + site + month**	**-0.16**	**0.003**	**+15.20%**	**4.4. - 25**
Black-tailed Godwit	count ~ year + site + month	-0.06	0.547	+6.10%	**17.6 - 25**
Common Greenshank	**count ~ year + site + month**	**0.17**	**0.000**	**+18.80%**	**9.6 - 29**
Common Sandpiper	count ~ year	-0.07	0.165	-6.70%	4 - 16.2
Curlew Sandpiper	count ~ year	-0.09	0.548	-8.60%	**19.4 - 30.9**
Far Eastern Curlew	count ~ year	0.01	0.868	+0.90%	10.5 - 13.9
Great Knot	count ~ year	0.13	0.076	+13.40%	0.3 - 29.2
Greater Sand Plover	**count ~ year + decimal_effort + tide_height**	**-0.14**	**0.041**	**-12.70%**	**1.9 - 22.5**
Grey Plover	**count ~ year + decimal_effort + tide_height**	**-0.13**	**0.035**	**-12.00%**	0.5 - 22.3
Grey-tailed Tattler	count ~ year	0.08	0.278	+7.90%	7.3 - 26
Lesser Sand Plover	count ~ year	0.00	0.950	-0.50%	13 - 136
Pacific Golden Plover	count ~ year + tide_covered	-0.09	0.315	-8.70%	10.1 - 24.8

Red Knot	count ~ year	0.13	0.167	+14.10%	3.7 - 35.3
Red-necked Stint	count ~ year	0.02	0.776	+2.30%	14.5 - 23.3
Ruddy Turnstone	count ~ year + decimal_effort + tide_height	-0.01	0.917	-0.70%	10.1 - 10.7
Sanderling	count ~ year + decimal_effort + tide_height	0.01	0.933	+0.90%	16.8 - 21.8
Terek Sandpiper	count ~ year	-0.03	0.741	-2.70%	13.8 - 16.5
Whimbrel	**count ~ year + decimal_effort + tide_height**	**-0.16**	**0.004**	**15.00%**	**3.4 - 25.3**
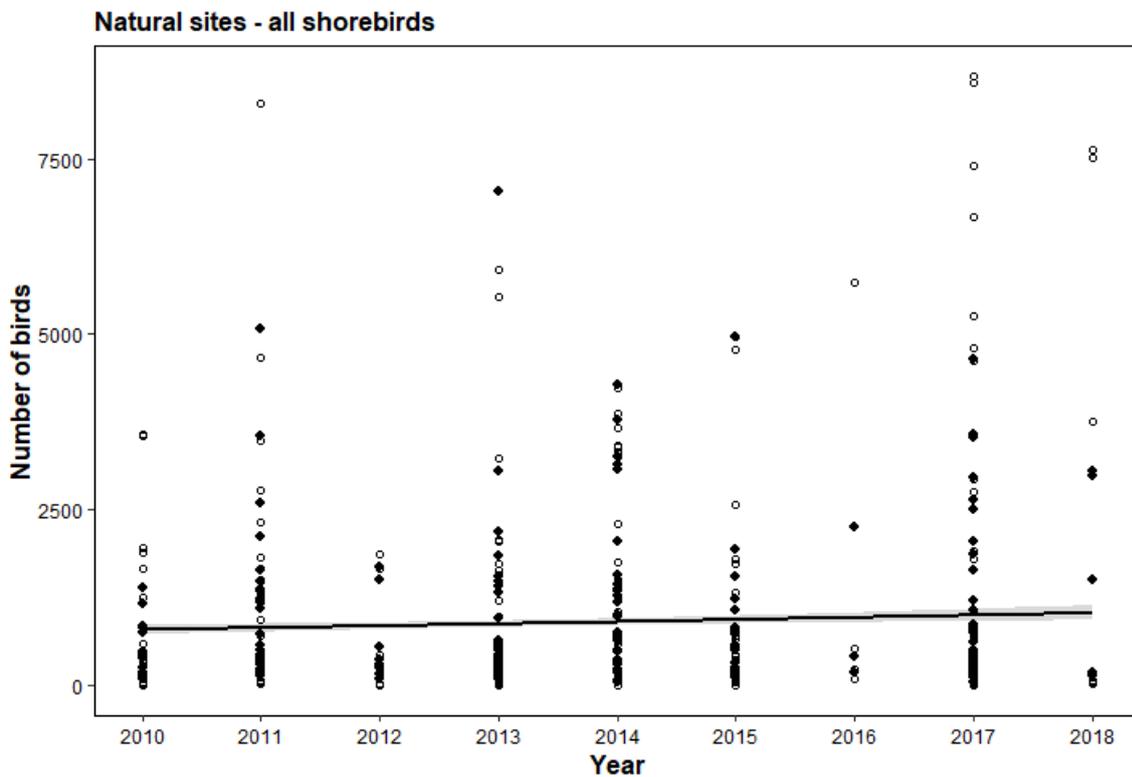
Figure 2. Modelled (black dots = estimated data, empty dots = raw count data) local annual population trends (species combined) based on a negative binomial GLM of all migratory shorebirds across an inter-connected suite of five natural sites in Darwin Harbour for the years 2010 - 2018.
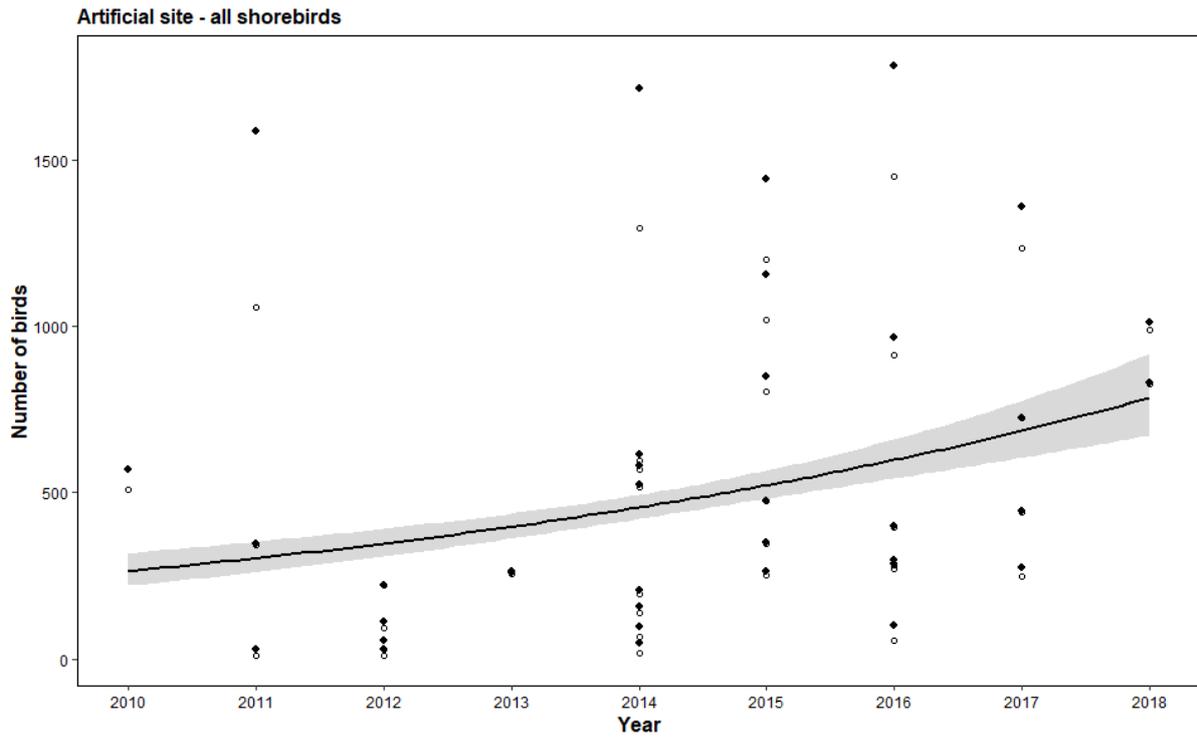
Figure 3. Modelled (black dots = estimated data, empty dots = raw count data) local annual population trends (species combined) based on a negative binomial GLM of all migratory shorebirds at East Arm Wharf, an artificial site in Darwin Harbour, for the years 2010 - 2018.
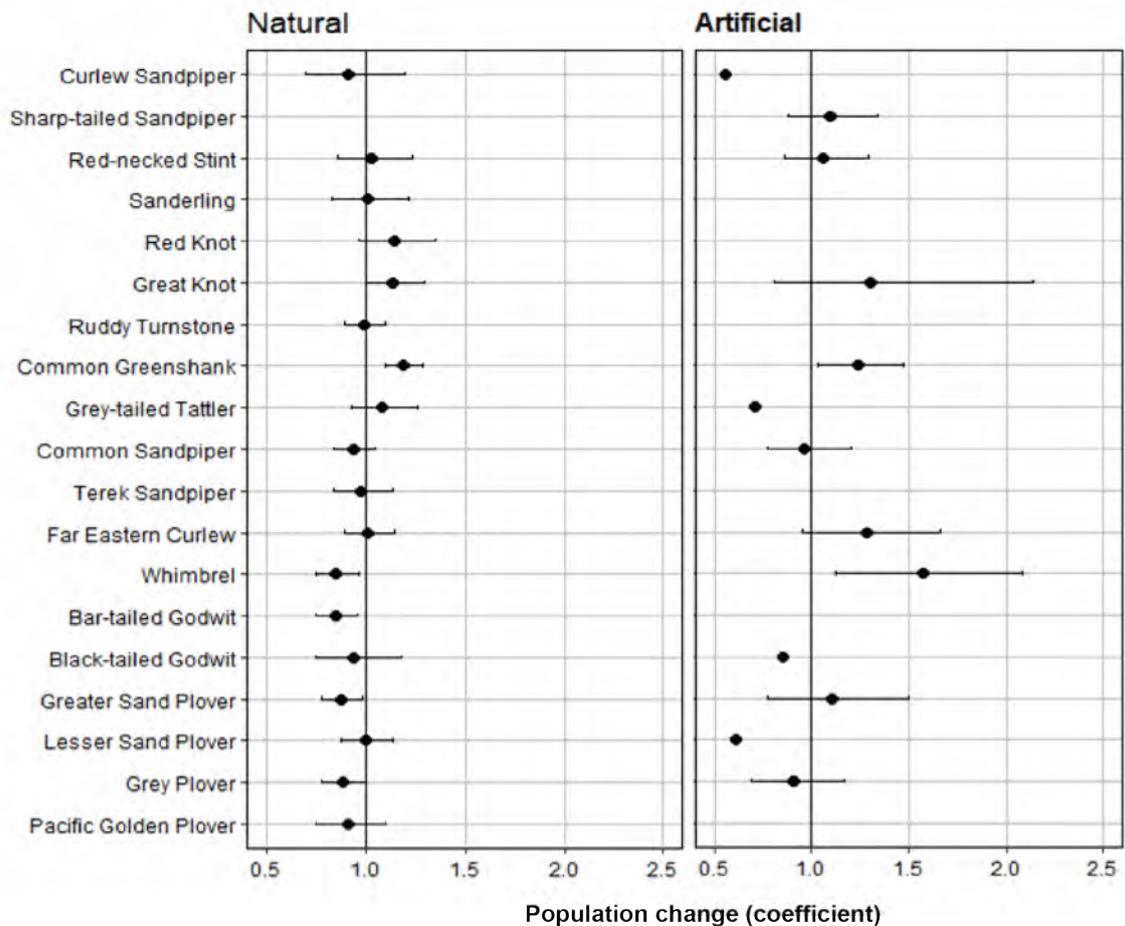
Figure 4. Annual population trends in non-breeding season counts for migratory shorebirds in Darwin Harbour at an artificial site and five inter-connected natural sites. Species to the left of the black vertical line (i.e. <1.0) decreased and species to the right of the vertical line (i.e. > 1.0) increased over the period studied.

Disturbance

We recorded 81 disturbances over 26 surveys at five sites within the Darwin Harbour region during the 2014 - 2016 austral summer months of which 92.6% were at the natural sites (Table S3). Most disturbances (98.7%) were recorded at the two natural sandy-beach sites (Lee Point and Sandy Creek) which have historically supported the highest number of birds from across the surveyed sites in Darwin Harbour. Humans (with or without dogs) made up over 70% of disturbances across the sites with birds of prey causing <16% of total recorded disturbances. Humans (and humans with dogs) stayed within the flight-initiation distance zone of the shorebird flocks for 1 to 10 minutes. Whether or not a species

was declining or increasing at the natural sites was not significantly correlated with flight-initiation distance (P = 0.881), with some of the flightiest species, such as Far Eastern Curlew and Common Greenshank, being among species with positive (but not significant) trends at the more disturbed sandy beach sites while other species with relatively high tolerance (i.e.: shorter FIDs), such as sand plovers, declined (Figure S1). Contrary to this, there was a significant relationship (P = 0.022) between the FID and population trends for shorebirds at the artificial site (Figure S2).

Discussion

Population trends of migratory shorebirds in Darwin Harbour

Population declines among migratory shorebirds along the EAAF tend to be reported collectively based on population-wide trends (Clemens *et al.* 2016; Studds *et al.* 2017). When examined at a finer scale, however, our results reveal a hidden complexity. While both natural and artificial sites showed increases in overall shorebird abundance in a nine-year period, individual species trends varied. Differences between species, and within species at artificial and natural sites, suggests a combination of local and external factors driving population change within this system. Only one species (Common Greenshank, population increasing) had the same trend at both natural and artificial sites over the survey period. However, the overall population increases for all species at both natural and artificial sites is in line with other reported increases for the region (National Environment Science Programme 2018).

For species listed as threatened under Australian legislation, in Darwin Harbour we observed declines in Greater Sand Plover, Lesser Sand Plover, Bar-tailed Godwit and Curlew Sandpiper consistent with strong declines reported previously, but observed trends in Far Eastern Curlew and Great Knot at both natural and artificial sites (no significant declines and a significant increase, respectively) that are inconsistent with strong national declines reported previously (Studds et al. 2017), requiring explanation. While the Great Knot is globally listed as Endangered, another study found little evidence of decline (Clemens *et al.* 2016). At our study region the increase in Great Knot explained the increase in total shorebird abundance at the natural sites; when Great Knot was removed from the overall shorebird abundance analysis at the natural sites, the trend for the remaining shorebirds showed a

significant decline. For the Far Eastern Curlew, East Arm Wharf is now particularly important: over 80% of the local Darwin Harbour population of Far Eastern Curlew roost there during the highest tides (Lilleyman et al. 2018), which is close to 1% of the global population of this species. While our current study, using a different statistical approach, did not find the same increase in Far Eastern Curlew detected by Lilleyman et al. (2016b), the lack of a steep decline is anomalous compared to global trends. Several hypotheses, (not mutually exclusive) that might explain these anomalous results are considered below: (1) birds are responding to local disturbance trends and regimes, (2) local increases, or failures to decline, are being driven by provision of habitat at East Arm Wharf that is suitable for roosting at all tides and superior to habitat available locally before this site was built, (3) populations of some species in Darwin Harbour are genuinely increasing because the provision of a new roost provides access to foraging areas that could not be exploited before.

Hypothesis 1: Disturbance causes local redistribution

The natural sandy beach at Lee Point has high levels of disturbance that are sometimes sufficient to cause biologically significant energetic cost to sand plovers and knots roosting there (Lilleyman *et al.* 2016a). The current study also noted that the two sandy beach sites with the highest counts of roosting shorebirds also have the highest disturbance rates by humans and humans with dogs. In contrast we recorded no human disturbances from the artificial East Arm Wharf site during the study period. A hasty inference might therefore be that birds from the northern beaches are moving to East Arm Wharf where they are disturbed less often. Three pieces of evidence suggest this cannot be true. First, no evidence of movement between the natural and artificial sites was detected by radio-tracking or flagging studies (Lilleyman, A, unpublished data). Second, the species that declined on the natural sites, Bar-tailed Godwit and Curlew Sandpiper, also declined at East Arm Wharf and have declined nationally (Studds *et al.* 2017), suggesting that it is the losses of habitat in the flyway driving all declines in these species with minimal local influence. Third, the species with some of the longest flight-initiation distances among those present, such as Far Eastern Curlew and Common Greenshank (Weston *et al.* 2012), increased or at least had steady population trends at both natural and artificial sites whereas many

of the least sensitive species declined, e.g.: sand plovers. Thus, while disturbance at roost sites is not desirable (Lilleyman *et al.* 2016a), it is unlikely to explain the local population trends that we observed.

Hypothesis 2 & 3: East Arm Wharf provides roosting habitat near foraging grounds, causing local redistribution or genuine increase

The numbers of shorebirds now being recorded at East Arm Wharf have not previously been reported in surveys of Darwin Harbour in the vicinity of the wharf (Chatto 2012), suggesting there are now more individuals using this system as a whole or that there is a redistribution of shorebirds in the harbour. However, single-season radio-tracking studies, and regular searches for marked birds, showed little evidence of birds moving between the natural and artificial sites (Lilleyman, A. unpublished data), suggesting that the increase at the artificial site was unlikely to be driven by relocation of birds from the natural sites. We are unable to tell whether the influx of birds comes from outside Darwin Harbour, or if the 'new' birds have relocated from undiscovered roosts of the southern/central harbour. Nevertheless, they could be the result of a longer-term transition of birds from the natural to the artificial site that are not picked up in mark recapture/tagging studies. We inspected demographic data from catching and marking studies and did not find that that either natural or artificial sites supported a higher proportion of juvenile birds, which could have been driving the local increases. Further research on marking and tracking birds in the region could help unravel this story. Some flexibility in roosting behaviour has been demonstrated for shorebirds in both the Darwin region (Lilleyman *et al.* 2016b) and elsewhere in the EAAF where loss of roost sites is widespread (Lee *et al.* 2017; Melville *et al.* 2015; Moores *et al.* 2016; Rogers *et al.* 2010; Round 2006), but the increases at East Arm Wharf do suggest it is increasingly being used as a roost site. It is possible that the East Arm Wharf site has become more attractive to shorebirds that forage nearby over time, resulting in a genuine increase in the local shorebird population. In particular, increased numbers at the East Arm Wharf roost may indicate that there is a long-standing shortage of suitable roosting habitat in Darwin Harbour, especially at the highest tides when saltpans are inundated and all but a few sites around the mangrove-lined harbour are under water. While shorebirds can, and sometimes do, roost in the branches of mangroves, the frequency of

most species at open roosts suggests that this is not a favoured option. Many factors constrain shorebird populations in their non-breeding habitat, including food resources (Dias *et al.* 2006; van Gils *et al.* 2003), disease and parasite load (Aharon-Rotman *et al.* 2016), extreme heat loads (Battley *et al.* 2003), available space, commuting distances and disturbance rates at a site (Lilleyman *et al.* 2016a; Rogers *et al.* 2006) and predation (Johnston-González and Abril 2018). Yet if roost sites are a scarce resource, provision of the artificial roost site may be allowing more shorebirds to visit and exploit the resources of Darwin Harbour than was previously possible. This suitable roost site could be providing access to foraging areas that could not be exploited before due to high commuting distances between roosting at the natural roost sites and feeding grounds closer to where the artificial site is now located.

The natural roost sites supported more birds of more species, and there were also species at natural roost sites that were absent completely (e.g.: Sanderling, Ruddy Turnstone) or there was not sufficient data for the study period that population trends could not be modelled (e.g.: Pacific Golden Plover, Terek Sandpiper) from the artificial site. This may indicate that there are no suitable foraging areas nearby to support species such as Sanderling and Ruddy Turnstone, which prefer to forage on open coastal beaches, and that some species are less abundant during the study period (true for Terek Sandpiper, which has higher abundances at the artificial site during July, August, September). Artificial sites may only be suitable for some species and the results from our study show that shorebird management across natural and artificial sites needs to consider each individual species and their specific ecological requirements.

In managing a network of natural and artificial sites, it will be important to consider possible long-term changes in the environment. Over the longer term, artificial sites might be less vulnerable to sea-level rise than natural sites such as claypans. The sea level along the northern coast of Australia has already been rising at among the fastest rates in the world, driven partly by the thermal expansion of the large and relatively shallow Arafura Sea to the north (Valentine and Tan 2009) and, in the Darwin region, there has been expansion of mangroves on to areas that were previously bare salt-flats, and therefore

suitable for roosting during some high tides (Williamson *et al.* 2011) so there is likely to be increasing pressure on what were traditional roost sites.

On the whole, these results suggest that artificial roost sites, especially in areas with little other development and so retaining high quality feeding habitat, may play an increasing role in migratory shorebird conservation, particularly as sea levels rise. But importantly, the presence of the artificial roost should not be a replacement for management of existing natural roost sites, as our results show that the different sites are used by different populations of shorebirds in the region.

Conclusion

We present population trends for migratory shorebirds from natural and artificial sites in Darwin Harbour where overall, shorebirds increased at both natural and artificial roost sites over a nine-year period. Species-specific trends were heterogeneous over the survey period and at the different sites. Our study shows that, in addition to external influences driving global population change for these species, local factors on the non-breeding grounds such as provision of a supratidal roost site available at all tide heights may influence the distribution of some threatened migratory shorebirds during the non-breeding season. Specifically, our study suggests that the attractiveness of Darwin Harbour as non-breeding habitat for shorebirds has been maintained, or even increased, over the last decade, and that the availability of the artificial roost site at East Arm Wharf has been a contributing factor. Ongoing monitoring of the local population is needed to underpin careful long-term management of *both* natural and artificial sites to ensure ongoing availability of suitable shorebird roosting and feeding habitat in Darwin Harbour, particularly in the context of steep regional shorebird declines.

Acknowledgements

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Chapter 4. Roost site fidelity of an endangered migratory shorebird in the East Asian-Australasian Flyway
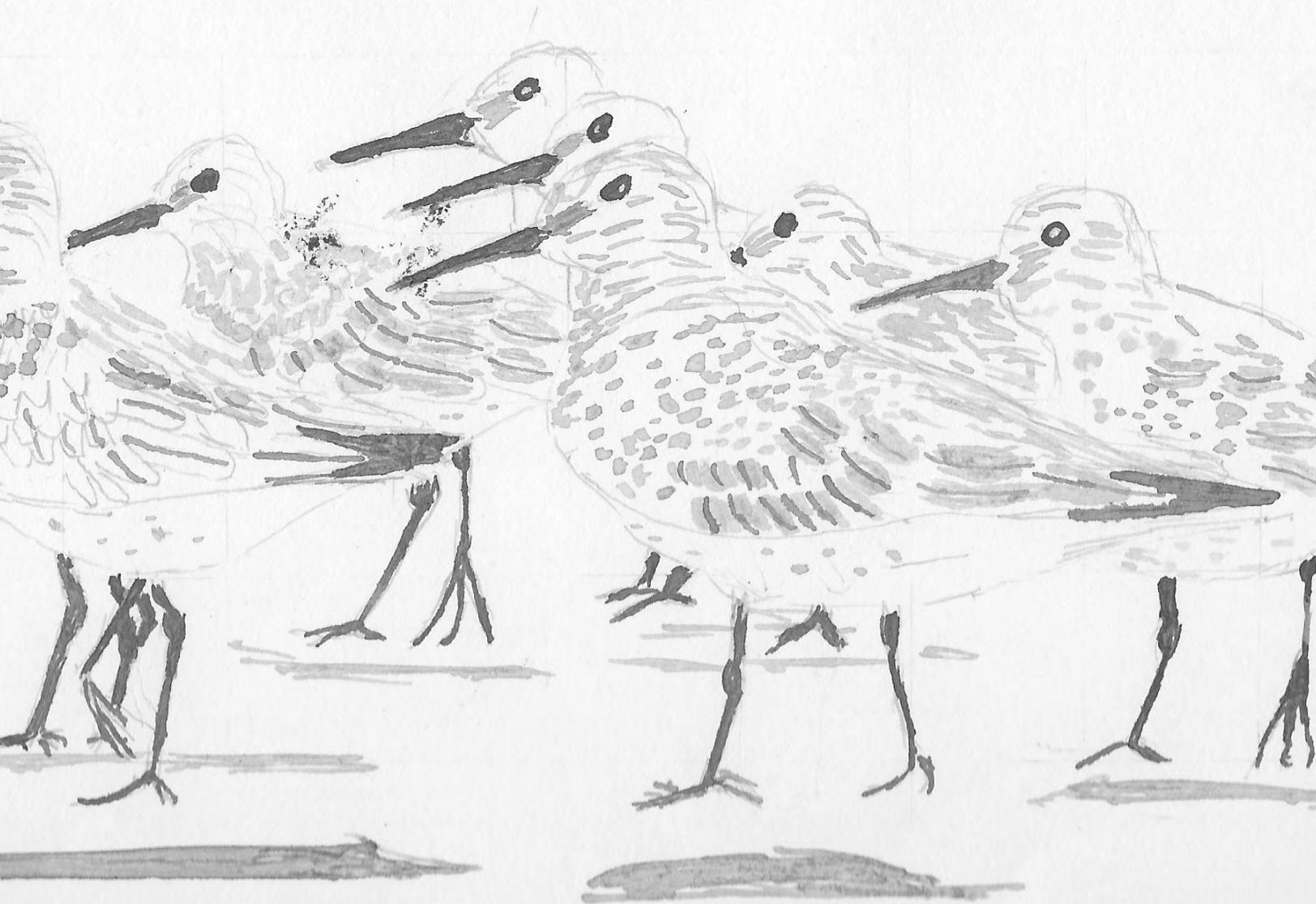
Chapter 4. Roost site fidelity of an endangered migratory shorebird in the East Asian-Australasian Flyway

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Roost site fidelity of an endangered migratory shorebird in the East Asian-Australasian Flyway

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Abstract

The connectivity and availability of suitable habitat is crucial for the survival of migratory shorebirds that travel between hemispheres every year. While these birds require several connected sites along the flyway during their migration, they also need suitable habitat at their non-breeding grounds to allow them to safely feed, roost and recover. Within non-breeding sites it is critical to maintain and conserve a network of both feeding and roosting subsites, but identifying these key sites is challenging because habitat use and site fidelity may differ between species. Understanding site fidelity of migratory shorebirds is needed to inform the protection of coastal environments and mitigate the effects of coastal development. We use the Great Knot (*Calidris tenuirostris*), a globally endangered migratory shorebird that is endemic to the East Asian-Australasian Flyway as our model species and its presence to indicate the local habitat quality as this species is the most abundant shorebird in the region. We used engraved leg-flag resighting data from a site on the non-breeding grounds in tropical northern Australia to examine connectivity and roost site fidelity. We show that the species is highly site faithful to roost sites in the region. Within the region the species will explore new feeding grounds during the pre-

migratory months. Management of Great Knot and other migratory shorebirds should operate at a local network scale to allow for the long-term preservation of biodiversity in the coastal region.

Introduction

For migratory shorebirds that travel between hemispheres every year, the connectivity and availability of suitable habitat is crucial for their survival. Shorebirds that migrate within the East Asian-Australasian Flyway (hereafter the EAAF) face a plethora of threats, with the loss and deterioration of habitat being the major contributor to the decline of many species (Murray et al. 2014, Clemens et al. 2016, Studds et al. 2017). On the staging grounds in the Yellow Sea, 65% of tidal flats have been lost in the last five decades (Murray et al. 2014), causing declines in shorebird numbers (Moores et al. 2016). Currently, seven of the 37 migratory shorebird species that regularly migrate through the EAAF to non-breeding grounds in Australia are considered vulnerable, endangered or critically endangered under the Australian Commonwealth's *Environment Protection and Biodiversity Conservation Act* 1999, with an extinction wave predicted if appropriate conservation action is not taken (Piersma et al. 2016). Although a number of bilateral agreements are in place, the current rate of decline of shorebird species suggests that the existing approaches to shorebird conservation are failing (Szabo et al. 2016). Habitat protection is the key determinant of the successful conservation of shorebird species (Szabo et al. 2016) but is also the most challenging ecological correlate to manage in the EAAF. In Australia, coastal habitats are used by non-breeding shorebirds for over half of the year, as they recover from southwards migration, carry out their annual moult of flight feathers and then fuel for northwards migration. Coincidently, many of these coastal habitats are of high economic and recreational value, and humans and industry compete with shorebirds for access to coastal habitat, placing pressure on migratory shorebirds throughout the non-breeding season (Lilleyman et al. 2016a).

Migratory shorebirds require a network of high-quality sites at a flyway level and at a regional-scale to successfully migrate and breed each year (Aharon-Rotman et al. 2016). While these birds require several connected sites along the EAAF during their migration (Choi et al. 2016), they also need suitable available habitat at their non-breeding grounds to allow them to safely feed, roost and recover (Rogers

et al. 2006b). On non-breeding grounds, most coastal migratory shorebirds feed on invertebrates in the intertidal zone and rest at high tide at roosts above the high tide line, preferring open and exposed roosts where they are best able to detect and avoid predators (Rogers 2003, Rogers et al. 2006a). Roosts are usually close to feeding grounds to allow short commutes that occur at least twice a day, and in tropical locations both roosting and feeding sites need to be where birds can thermoregulate to avoid heat stress (Rogers et al. 2006b). Shorebirds also require a range of feeding and roosting sites in a region because some species shift their feeding areas at times in response to changes in the availability of ephemeral foods (Kraan et al. 2009) and still need nearby roosts to conserve energy and avoid disturbances (Rehfisch et al. 1996). Maintaining and conserving a network of both feeding and roosting sites is critical, as different shorebird species have different degrees of habitat fidelity and preferences in a region (Warnock and Takekawa 1996, Leyrer et al. 2006, Buchanan et al. 2012, Piersma et al. 2016). Additionally, different age and sex classes within a species (the latter often with differing morphological features associated with foraging i.e. bill length) have different habitat requirements and preferences (Catry et al. 2012).

On the non-breeding grounds of Australia, coastal development threatens important shorebird habitat and perturbations to habitat can force birds away from preferred subsites (Harding et al. 2007). Movements between roosting and foraging grounds is related to food distribution, predation risk and disturbance (Rehfisch et al. 2003). Displaced individuals that move to other feeding or roosting sites may experience lower prey intake rates, or place pressure on surrounding local populations by increasing competition for resources (Goss-Custard et al. 2002). Shorebirds can be constrained by environmental conditions (van Gils et al. 2006). Shorebirds that balance their daily energy needs are considered "satisficers", and shorebirds that maximise their daily energy needs are considered "rate maximisers", and the decisions that shorebirds make influence the movements and habitat choice (van Gils et al. 2006). Shorebirds are also constrained by the time available to forage (dictated by tidal cycles) and the availability of space at high tide roosts (Rogers et al. 2006b). Thus, displacement of birds off habitats may affect the survival rate of migratory shorebirds by decreasing intake rates at poorer quality feeding sites and increasing commute times (Burton et al. 2006). These ecological constraints, coupled

with increasing pressure from coastal development and human disturbances, place migratory shorebirds at the forefront of potential impacts. Attention to conserving coastal habitat is urgently required to manage migratory shorebird populations.

Whether shorebirds use a network of local sites and the extent to which they are faithful to roosting sites is important knowledge needed to inform the protection of coastal environments and mitigate the effects of coastal development. We examined the connectivity of several subsites used by shorebirds within a tropical harbour to focus management on important habitat and the size of a network of sites that is needed to conserve populations of shorebirds. The objectives of this study were to examine the site fidelity, consistency of roost site choice and benefits of roosting with a flock at traditional roost sites at a non-breeding site in the tropics of northern Australia. We use the Great Knot (*Calidris tenuirostris*), a globally endangered migratory shorebird that is endemic to the EAAF (BirdLife International 2016) as our model species.

Methods

Study area

This study was conducted in the Darwin Harbour region (12.50°S, 130.82°E), Northern Territory, Australia within the East Asian-Australasian Flyway. We monitored the movement of the Great Knot across six roost sites: East Point, Spot On Marine, Nightcliff Rocks, Sandy Creek, and Lee Point on the northern beaches and East Arm Wharf in Darwin Harbour (Figure 1) from engraved leg-flag resightings and roost count estimates. Lee Point and Sandy Creek are sandy beaches connected to an extensive intertidal sandflat. These beaches are part of the Casuarina Coastal Reserve, are managed by the Northern Territory Parks and Wildlife Commission and used extensively by the public for walking, jogging, or dog-walking. East Point and Nightcliff Rocks are rocky outcrops connected to nearby Ludmilla Bay where shorebirds feed. Spot On Marine is an open saltpan bordered by mangroves. East Arm Wharf is the main exporting port in Darwin and is surrounded by industrial infrastructure. The site contains several artificial ponds used to store dredge spoil from Darwin Harbour. These artificial ponds

are used as roosting sites by large numbers of shorebirds; human access is only by permit, and the site is rarely disturbed by people (Lilleyman 2016, Lilleyman et al. 2016b, Lilleyman et al. 2018).

The sites vary in physical characteristics and support different assemblages of shorebird species at different times of the year. All the sites within the Darwin region studied here have a semidiurnal tidal regime with a tidal range of 0.7 – 8.1 m. During spring tide cycles the high tides occur close to sunrise and sunset. The region is tropical with an average temperature that ranges between 25°C and 32°C (Bureau of Meteorology 2019).
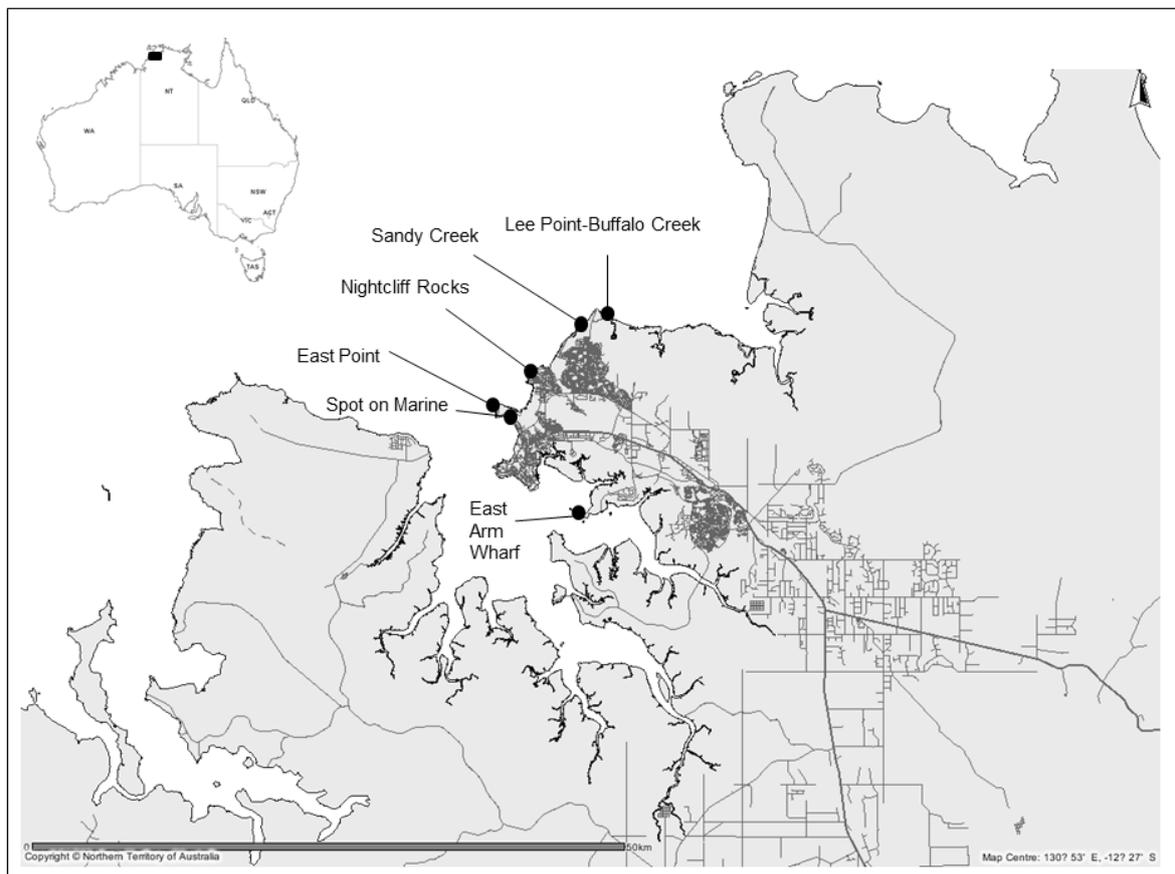
Figure 1. Map of migratory shorebird roost sites in Darwin Harbour, Northern Territory, Australia. Main roads shown to indicate urban areas and accessibility to shorebird survey sites.

Catching and marking of Great Knots

Great Knots were captured using cannon nets at one site (Lee Point, n=292) during September 2014 and October 2015 during expeditions to catch and mark a range of shorebird species as part of a larger project. Cannon nets were set at high tide when shorebirds were roosting. Great Knots are the most abundant shorebird in the Darwin Harbour region and regularly gather in flocks at the sites that we positioned nets at (Lilleyman et al, 2020). We caught a total of 292 Great Knots over the catching period: 96 individuals in 2014, 196 in 2015. We measured the biometrics of all birds and banded and marked birds with flags (yellow flag above a blue flag on the right tibia, indicating the bird was banded in the Northern Territory, following the East Asian-Australasian colour flagging protocol). All yellow flags were engraved with unique alphabetical or numerical combinations which can be read (through spotting scopes) at long range on wild birds after they are released.

Great Knots were then resighted during standard monthly monitoring of birds in the Darwin Harbour region where all six study sites are monitored from late-2014 through to end-2017. Average count survey effort across all roost sites and years was 76.4 minutes (range = 5-192 minutes). When observers sighted birds, they would confirm the species identification and record the engraved leg-flag code and then report the marked bird via email or on social media pages. Here we present the movements of Great Knots both locally by summarising resighting observation data. We used a straight-line distance to estimate the minimum distance moved by birds from the original site of capture to the site of resighting. We then used a Kruskal-Wallis rank sum test to investigate differences between distances moved by Great Knots over the months of the study period and by age classes. We used R v 4.0.2 (R Core Team 2020).

Results

Of the 292 Great Knots caught during the catching occasions in the Darwin Harbour region, 83.6% were adult birds (aged as 3+ years), 13.5% were second-year birds, and 3% were juvenile birds (first-year birds). We recorded 1149 resightings of the 292 marked Great Knots during the years 2014 – 2017 in the Darwin Harbour study region. We resighted 250 individuals of the 292 individually marked Great

Knots, an overall return rate of 85.6% for the survey period. Within and between season return rates of resighted birds were quite good but showed a steady decline in sightings over the subsequent austral summer season (Table 1). Five birds were resighted in all four austral summer seasons, 28 birds were resighted in three austral summer seasons, while 93 were resighted in two austral summer seasons and 124 were resighted in only one austral summer season.

Table 1. Numbers of leg-flagged Great Knots banded and resighted during each austral summer season in the Darwin Harbour study region. Figures in brackets are percentages.

Banding season	Total number of Great Knots flagged	Number resighted in 2014-15 season	Number resighted in 2015-16 season	Number resighted in 2016-17 season	Number resighted in 2017 season
2014	96	83 (86.5)	75 (78.1)	17 (17.7)	20 (20.8)
2015	196	4 (2.0)	139 (70.9)	41 (20.9)	35 (17.9)

Local movement between sites

Great Knots show a high degree of site faithfulness, with most resightings of Great Knots in the Darwin region from the main banding site at Lee Point and close by at Sandy Creek, and then Nightcliff Rocks and East Point (Table 2 and Figure 2). There were no resightings of flagged Great Knots in the study area during the austral winter. Great Knots were resighted at all roost survey sites except for Spot On Marine.

Table 2. Percent of resightings of Great Knot (from 292 individually-flagged Great Knots) based on the banding site in Darwin Harbour, Northern Territory over the study period. Sites ordered geographically (south-west to north-east) to show where birds moved to.

	Site banded
Site resighted	Lee Point-Buffalo Creek

East Arm Wharf	0.1
East Point	7.0
Spot on Marine	0.0
Ludmilla Bay	0.4
Nightcliff Rocks	10.5
Sandy Creek	22.6
Lee Point-Buffalo Creek	59.3

We used a straight-line distance to estimate the minimum distance (km) Great Knots moved from the banding site to sites where they were resighted. The minimum distance moved ranged from 1 km where birds were resighted nearby at Buffalo Creek, 2.2 km away at Sandy Creek, 8.5 km away at Nightcliff Rocks, 9.7 km away at Ludmilla Bay (during low tide), 12.6 km away at East Point, and 17.2 km away at East Arm Wharf (Figure 2).
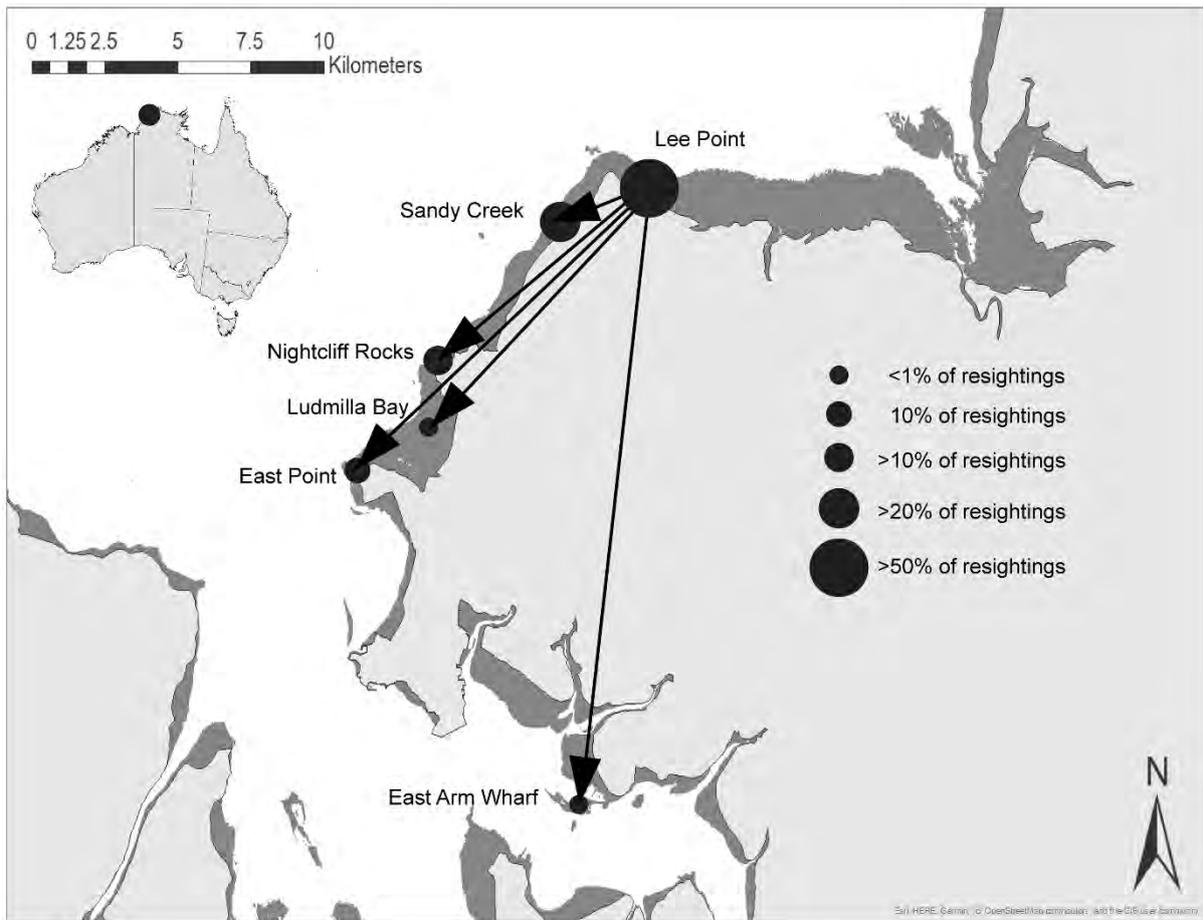
Figure 2. Network plot of resightings of Great Knots in the Darwin Harbour study region for the years 2014 – 2017. Intertidal zone shown as dark grey.

Out of the 250 birds that were resighted in the Darwin Harbour region, the average resighting distance away from the banding site was 2.2 km (SD ± 1.7 km; Table S1). There was a significant difference in minimum distance moved over the months of the study period (χ^2 = 289.87, P-value = <.0000), with greater average distances in February and March of each year (Figure 3). There was no significant difference in distances moved by different age classes of Great Knots (χ^2 = 0.65581, P-value = 0.7204; Figure 4).
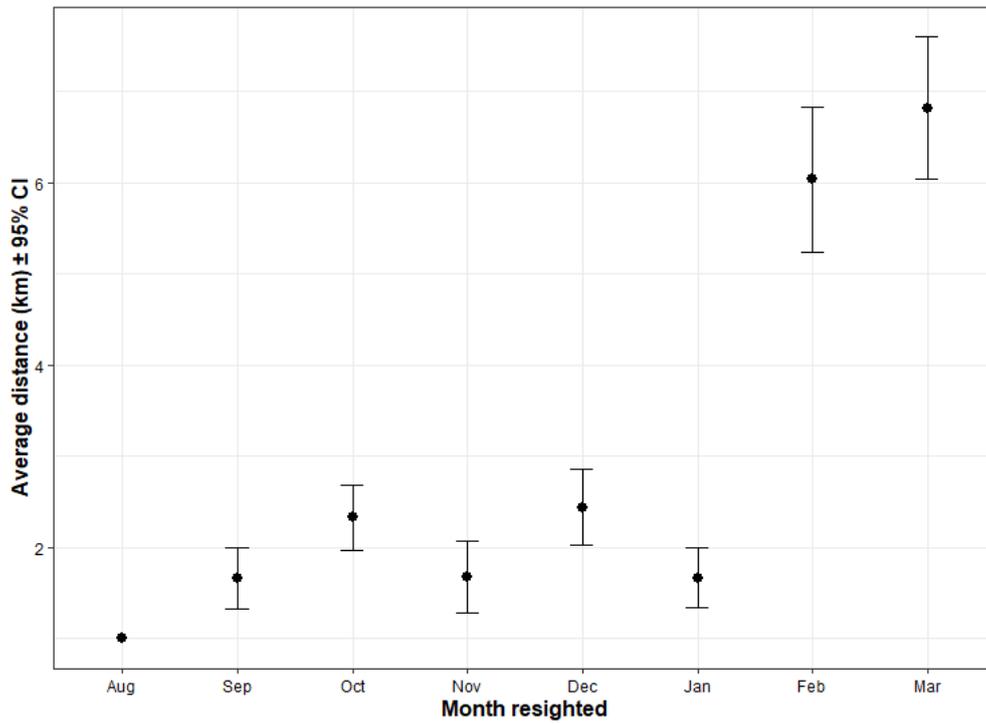
Figure 3. Distance (km) of resightings of Great Knots from the original banding site in Darwin, Northern Territory throughout the months of the study period.
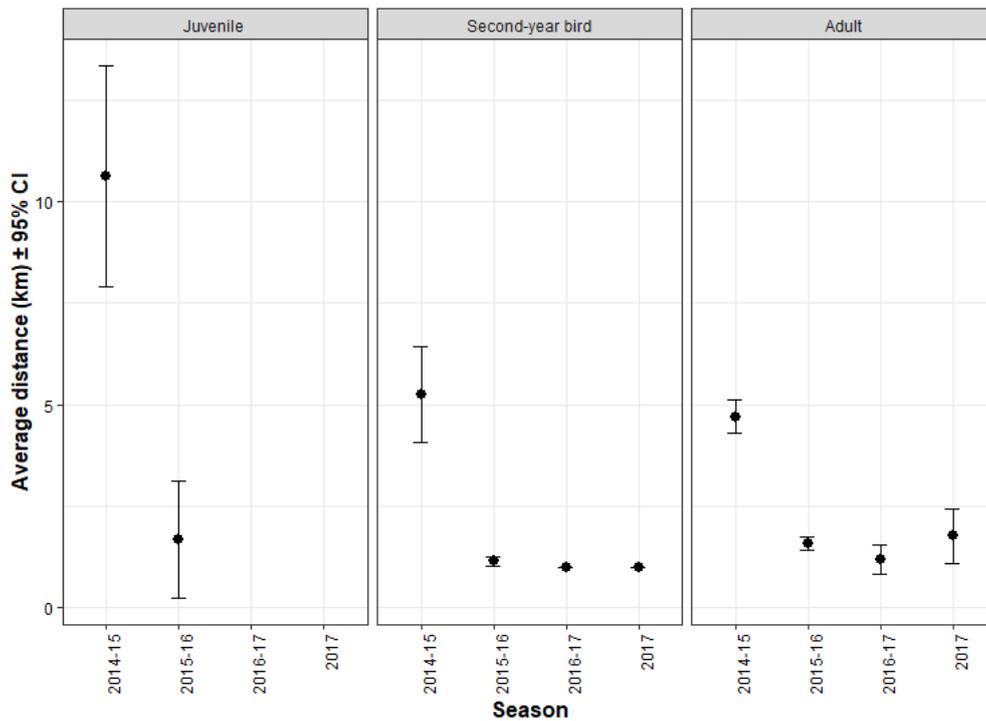
Figure 4. Distance (km) of resightings of Great Knots for three age classes from the original banding site in Darwin, Northern Territory throughout the study period by austral summer seasons. Age classes were updated dynamically as individual birds aged, hence there were no juvenile birds in the seasons 2016-17 and 2017.

Most resightings (72.9%) from Lee Point and Sandy Creek were from September through to January throughout the study period, and the resightings from East Point and Nightcliff Rocks during February and March accounted for more than 50% of resightings during that time of year (Figure 5).
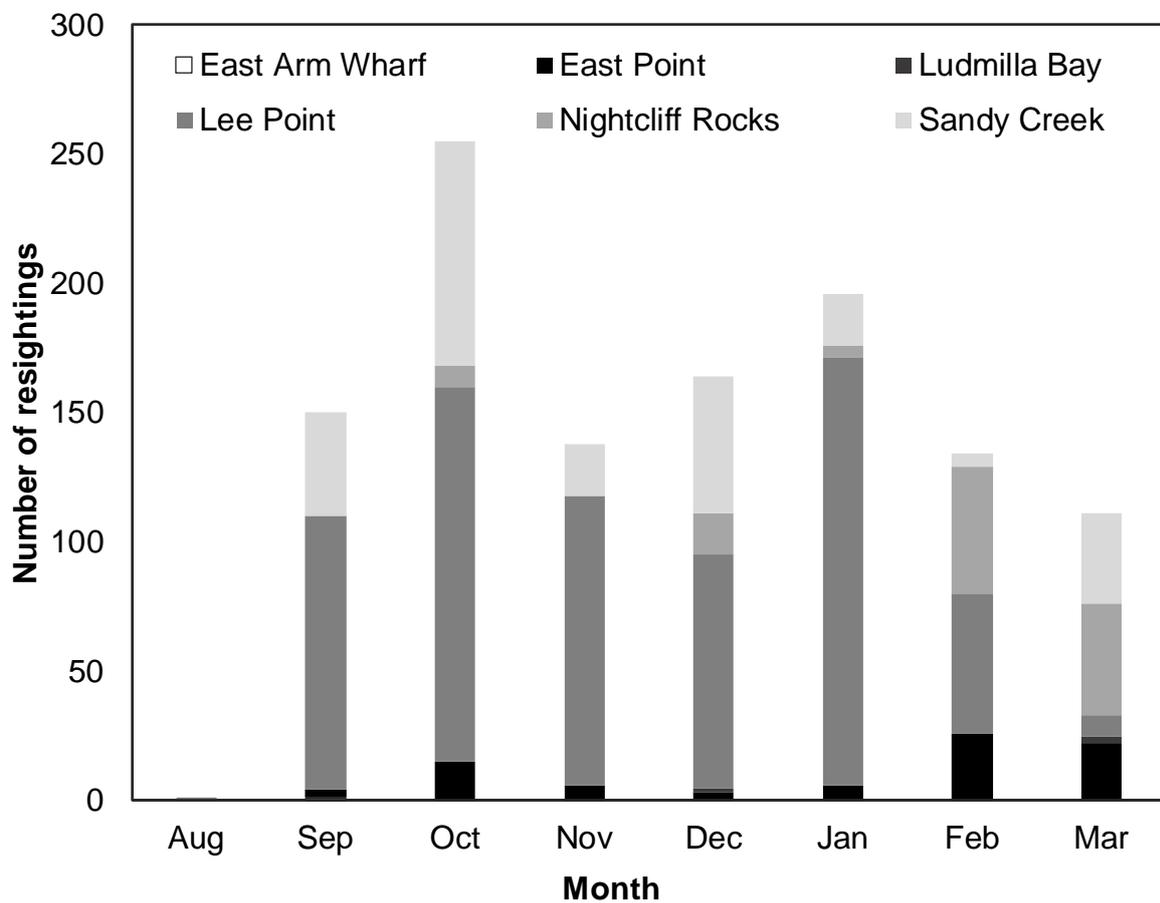
Figure 5. Number of resightings of Great Knots by month at sites in the Darwin Harbour study region for the study period 2014 - 2017.

Discussion

Our study shows that the globally endangered Great Knot is site faithful to a region on the non-breeding grounds with individual birds returning to the same area over several years. Individuals habitually returned to the Darwin region year-after-year and repeatedly used the same high tide roosting sites within and between years. Great Knots were most often resighted at the banding site, and elsewhere resightings were most often made at roosts close to the original banding site. Individuals moved a fair distance within the study area; the home range of banded birds effectively extended along 10-15 km of coast. Using engraved leg-flag resighting data was an adequate tool to assess individual site fidelity at roost sites, but the strength of this method relied on resighting observations remaining at a constant effort over years following initial flagging.

In our study, we have assumed that roost site fidelity equates to foraging site fidelity to a nearby foraging site and confirm that Great Knots often feed near the roost sites mentioned in this study. Although our data are not able to directly show site fidelity to foraging sites, we show that Great Knot are site faithful to roosting areas and we postulate that a reliable network of roost sites is just as important to shorebird condition and survival as foraging sites. Many species of bird display strong site fidelity to areas throughout their life cycle (Newton 2008). Site fidelity is beneficial to individuals as it can improve survival indirectly through knowledge habitat resources (Newton 2008). Having strong site fidelity can however negatively affect shorebirds in coastal areas where there are competing interests such as coastal development (Rehfisch et al. 2003). The removal of a site can impact an individual's fitness through poor body condition and reduced survival (Burton et al. 2006). Where shorebird site fidelity is high, there is the potential that habitat loss could be detrimental to the species' population (Rehfisch et al. 2003). This places importance on a network of sites being available to shorebirds so that if an important site is lost through development or recreational purposes (disturbance), then birds can take refuge elsewhere.

It may be necessary for migratory shorebirds to show some degree of site fidelity to a non-breeding region, as it is possible that individuals from within a population show adaptations to non-breeding

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areas through body size and condition (Lilleyman et al., *in prep* a). Further research into the drivers of site fidelity is needed; importantly, this should include how environmental conditions on the natal grounds affect individuals (Gill et al 2019). Shorebirds have the capacity to move around during the non-breeding season, but our study does not demonstrate the extent to which the flagged Great Knots moved around because we based our analysis on engraved leg-flags. We show that that individuals return year-after-year and have preferences to particular roosting sites. Further research on Great Knots in the Darwin Harbour region could involve GPS or satellite tracking to determine local movements and both intra and inter-continental migration movements.

Local movement between sites

Great Knots moved between sites in the study area, however most resightings of flagged birds were from the site they were caught and banded; an area where the stronghold of this species' population exists in the region (Lilleyman et al., 2020). All sites within the network are connected to each other and some sites are more important at certain times of the year, depending on resource availability and the needs of the birds. The results from our study suggest there is a hierarchy of importance in the network of sites. Great Knots show preference to Lee Point and Sandy Creek but will move to sites up to 13 km away, and occasionally even 17 km away to an artificial roost site. The Lee Point-Buffalo Creek roosting area is possibly more important during the southward migration months (September, October, November) when birds might be more reluctant to fly far in the early stages of wing moult, when more flight feathers are growing at one time. Alternatively, birds might be responding to the perceived threat of predators in the region. Sites such as East Point and Nightcliff might be perceived as more dangerous places to roost because the distance to tall cover is less at these sites compared to Lee Point and Sandy Creek. Additionally, raptor (predator) abundance is lower in the Darwin region during the wet season (December through to March) once rains begin (McCrie and Noske 2015).

Once birds arrive on the non-breeding grounds, most will begin their primary moult if they are at their non-breeding destination. The ability of birds to quickly replenish fat stores after long-distance migration may be assisted by their prior knowledge of an area, hence having prior knowledge of the

habitat might drive a species' site fidelity. Most movements away from this site were made during the pre-migratory months of the year when birds have greater energy requirements as they fatten up for migration. The Great Knots that roosted at East Point and Nightcliff Rocks feed close by at Ludmilla Bay (1 km between sites; pers. obs. AL) and this shift to a different feeding ground (away from the Lee Point-Buffalo Creek area) usually happens in January during the onset of the monsoon season.

Local site management

Great Knots moved between all roost sites in Darwin Harbour, suggesting that having a network of sites available is important. Great Knots make up a large proportion of the migratory shorebird population in the Darwin Harbour region and this species can be used as an indicator for the quality of intertidal habitat. The protection and maintenance of roosting and feeding sites in the region could help conserve a whole suite of migratory shorebirds and biodiversity that exists within the intertidal zone. Our study provides information that could help in the management of a network of coastal sites for this globally endangered shorebird. We recommend that managers consider a holistic approach and work across land and sea tenures and organisations to manage this species and other migratory shorebirds in the region.

Conclusion

Our study has demonstrated that the Great Knot is a site faithful migratory shorebird while on the non-breeding grounds and birds will move between sites at a local scale, likely in response to environmental and biological cues. It will be important to maintain and conserve the most important roosting and feeding site (Lee Point-Buffalo Creek) for Great Knots in the Darwin Harbour area, throughout all austral summer months and particularly during the southward migration months, but useful to manage additional sites in the network so that birds can move between sites based on their ecological requirements. Great Knots use a range of sites within a small local network and this knowledge can assist managers and planners in the long-term preservation of the coastal region.

Acknowledgements

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Chapter 5. Reliability of prey influences site selection in a migratory shorebird on the tropical non-breeding grounds

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Reliability of prey influences site selection in a migratory shorebird on the tropical non-breeding grounds

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Abstract

Understanding the abundance and distribution of invertebrate prey on which migratory shorebirds feed can help in management of areas that shorebirds use, as well as provide an indication of the health and quality of the marine landscape. In this study we examined the environmental variables that might influence invertebrate biomass (as ash-free dry mass) and its relationship to the abundance of a globally endangered migratory shorebird, the Great Knot (*Calidris tenuirostris*). We found that a single bivalve species (*Paphies altenai*) dominated the samples and occurred primarily in the top 5 cm of the samples where it was available to foraging Great Knots. Biomass was positively correlated with distance to prominent headlands at one site only. Abundance of Great Knots was positively correlated with biomass at only one site with our results suggesting that for most of the non-breeding season commuting movements between sites constituted only 5% of the daily energy use in Great Knots because they fed close to their roost site. However, biomass at one site further from the main roost site varied with season, attracting birds to take advantage of the better foraging conditions. The results highlight the need to assess the importance of sites to shorebirds over extended periods if ephemeral periods of optimal suitability are not to be overlooked.

Key words: Shorebirds, ornithology, foraging, biomass, population constraints

Introduction

The ability of birds to migrate across the globe depends on physiological changes which allow for the accumulation of fat reserves, as well as other processes, to sustain them during flight (Newton 2008, Piersma and van Gils 2011). Although shorebirds have high energy costs during all stages of their lifecycle (Kersten and Piersma 1987), energy costs during the non-breeding season are mainly associated with maintenance, thermoregulation and digestion of food (Piersma et al. 1995, Piersma 2002, Piersma et al. 2003). In the few weeks preceding long distance migration, however, the birds must rapidly accumulate the fat and protein reserves needed to fuel flights extending thousands of kilometres (Piersma et al. 2005). This time is critical to an individual's ability to survive migration and then reproduce (Aharon-Rotman et al. 2016) as large reserves not only support their flights but increase their chances of coping with changed conditions along their migration pathways.

In coastal shorebirds in particular this extra energy demand must be conducted within the limitations imposed by the tidal cycle on food availability (van de Kam et al. 2004) and despite competition within and between species and disturbance from potential predators (Rogers et al. 2006b) that can require costly additional flights (Danufsky and Colwell 2003, Cardoni et al. 2008) and increased vigilance (Lilleyman et al. 2016). The availability of high quality, low disturbance feeding habitat when fattening before migration is therefore critical to shorebirds and may limit their local abundance. One strategy for maximising intake at this time is to retain knowledge of high-quality foraging patches (van Gils et al. 2003;Oudman et al. 2018).

Competition among migratory shorebirds is to some extent mitigated by diet-related morphological specialisations and size-dependent differences that influence the choice of invertebrate prey (Novcic 2016). The amount of suitably sized prey influences the relative distribution of shorebird species on tidal flats, depending on how preferred invertebrates are influenced by wave action, drainage, and the grain size of the sediment (Ponsero et al. 2016). The size of the available foraging area can also strongly influence the presence and abundance of some shorebird species (Kraan et al. 2009) with many coastal shorebirds following the tide as it recedes to exploit prey that only becomes available as the tide ebbs

(Granadeiro et al. 2006, Piersma et al. 2006, Rogers 2006). These factors and the selection of non-breeding sites can influence the foraging conditions that a shorebird faces.

Understanding habitat choice among shorebirds must therefore appreciate the key factors that can influence energy intake rates (Grond et al. 2015) but is essential if critical highly productive coastal habitat is to be managed and protected. Because migratory shorebirds are top predators within the marine intertidal ecosystem, their protection can then ensure that coastlines and marine intertidal invertebrates are also protected. Here we provide insights into foraging conditions at the tropical non-breeding grounds of one of the most abundant migratory shorebirds in the East Asian-Australasian Flyway, the Great Knot (*Calidris tenuirostris*), using it as a case study species to understand the relationship between the biomass of invertebrates across the intertidal zone of the study region and the numbers of Great Knot exploiting the resource. We also explore the influence of environmental variables on invertebrate prey and whether prey availability limits the size of the Great Knot population at our sites. Finally, we discuss how this information can be employed to inform management of the marine intertidal zone in a tropical harbour.

Methods

Study area

This study was conducted in the Darwin Harbour region, Northern Territory, Australia (Fig. 1), a macrotidal region (tides 0.1 - 8.1 m) where spring high tides occur close to sunrise and sunset. The region is tropical with an average temperature that ranges between 25°C and 32°C (Fig. S1) (Bureau of Meteorology 2019). Most rainfall occurs between October and April (Fig. S2). Invertebrate samples were taken monthly from three foraging study sites: Buffalo Creek (12.33°S, 130.91°E), Ludmilla Bay (12.39°S, 130.84°E), and Sandy Creek (12.34°S, 130.84°E), all sampling sites were within two kilometres of a roost site to which shorebirds retreat during high tide. Birds that fed at Ludmilla Bay were observed roosting at Nightcliff or East Point; there is no roost site at Ludmilla Bay as the bay becomes covered during high tide. During the austral summer months (October-March) these sites can collectively support up to 10,000 individuals of migratory shorebird.

Study species

One of the most locally abundant of the shorebirds are Great Knots (averaging at least 60% of the total Darwin local population), tactile foragers that probe their bill into soft sediments to retrieve their preferred prey – molluscs – which they crush in their gizzard (Rogers 2006). Great Knots follow the tide as it falls to retrieve accessible molluscs (Rogers and de Goeij 2006). The species is currently listed globally as endangered under the IUCN red list for threatened species (BirdLife International 2016) and as critically endangered under Australia's national environmental legislation – the *Environment Protection and Biodiversity Conversation Act* 1999 (Department of the Environment 2019). The species has previously declined mainly due to loss of habitat in the Yellow Sea region where birds refuel on migration (Studds et al. 2017). Monthly surveys of all shorebird species have been conducted at roost sites in Darwin Harbour for approximately 15 years. The Darwin Harbour study sites support 1% of the East Asian-Australasian Flyway Great Knot population during the non-breeding season and the three study sites are individually classified as internationally important habitat under the *Environment Protection and Biodiversity Conservation Act* 1999.
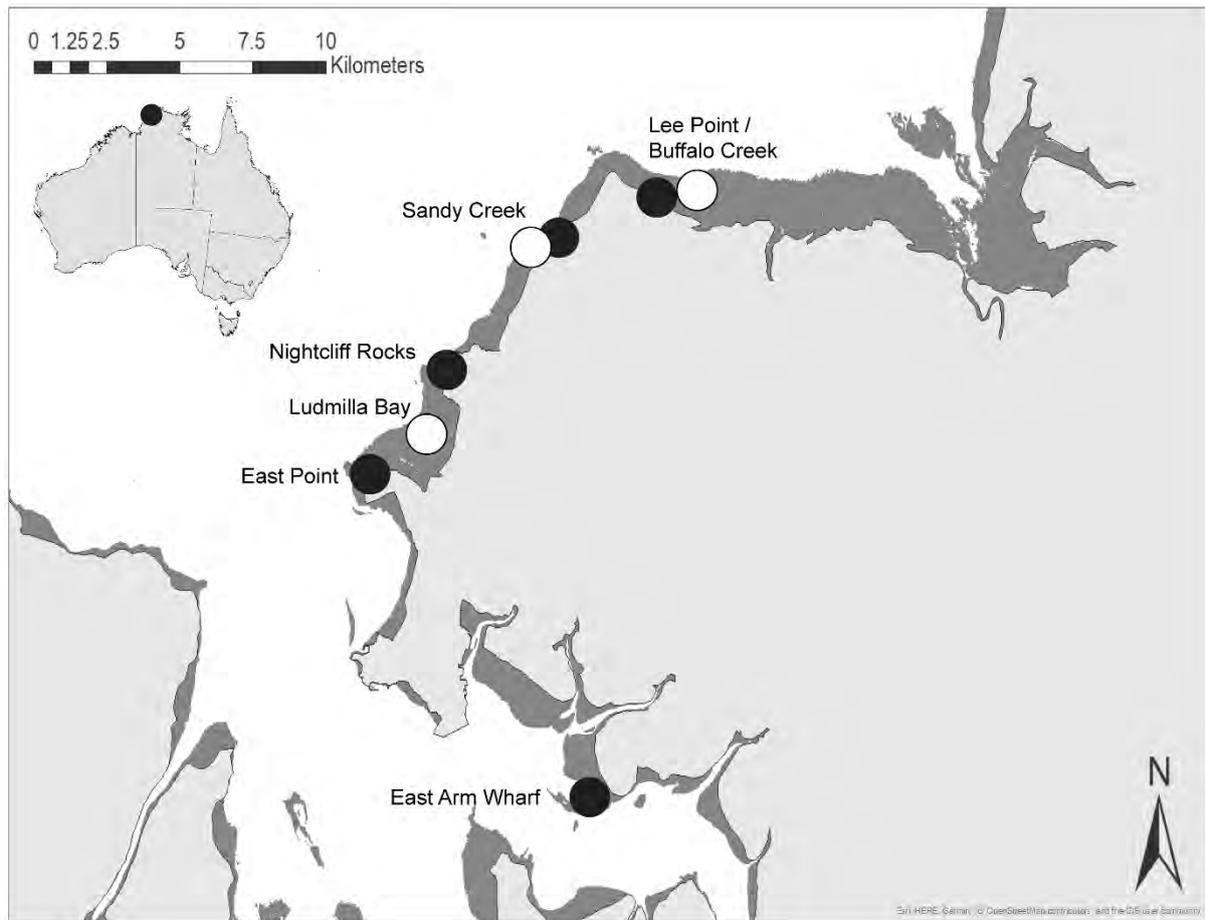
Fig. 1. Map of study sites in Darwin Harbour, Northern Territory (inset Australia). Intertidal zone shown as grey. Roost sites are shown by filled black circles. Foraging/benthos sampling sites shown as white circles.

Benthos sampling

We sampled benthic invertebrates at the three study sites from December 2014 through to April 2015 and from August 2015 through to April 2016 (n = 14 months) to determine how the abundance of benthic shorebird prey varied over space and time. We took five cores at each of the four fixed stations, approximately 250 m apart from each other at each site over a 1-km transect parallel to the tide line (20 cores per site) for each month of the study period (Fig. 2). We used a handheld GPS to find the four sampling stations. We always followed the edge of the tide to mimic the foraging style of Great Knots. Cores were spaced 5 m apart and were taken on falling spring and neap tides of at least 5.5 m during daylight hours. Median sampling days per month across the years were between the 15th and 29th based

on suitable tidal conditions. We took a core sample at the tide edge and by the time we had sieved and bagged the sample the tide had receded so we would pace out 5 m to take the next core. We paced along the tide edge, so this was parallel to the water's edge, rather than into the water. Each core was taken using a PVC corer (diameter 9 cm, depth 20 cm, total area 0.0693 m^2), partitioned at three depths (0-5, 5-10, 10-20 cm) using an offcut of the PVC material to slice through the cylindrical core and sieved using a 1 mm mesh sieve in the field. All invertebrates were stored live in bags and taken straight to the lab for sorting. From the 840 cores taken, we collected a total of 2,520 samples and counted 20,681 benthic invertebrates from across the three sites. Invertebrates were sorted, counted and identified to the lowest possible taxonomic rank, the maximum length measured to the nearest mm and then stored in 70% ethanol.
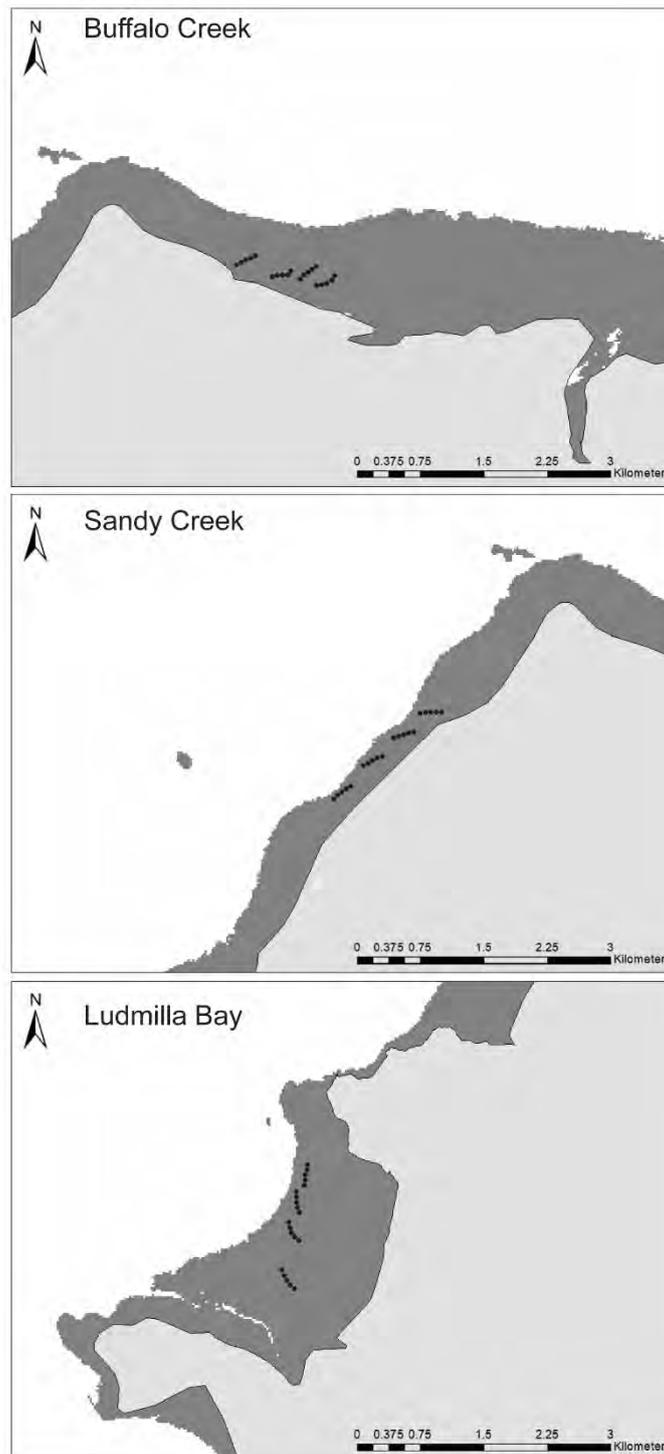
Fig. 2. Map of the sampling regime for collecting benthic invertebrates (and sediment samples) across three sites in the Darwin Harbour region. Dark grey shading is the intertidal zone and black dots show the sampling locations of each core taken.

Sediment grain size

We took 20 core samples at the fixed stations at the three study sites in October 2015 during a falling high tide using a PVC corer following the same methods and same sites detailed above. We used a wheelbarrow across the intertidal zone (not muddy) to carry the sediment samples back to the car. To assess grain size, we stored core samples overnight at 2°C. The following day each sample was broken down and dried in an oven at 100°C for 4 days. We then homogenised the dry samples and sieved a 500 g sub-sample through stacked sieves of 1, 0.600, 0.250, 0.125 mm mesh size. The remaining portion in each sieve we then weighed and stored separately.

Statistical analysis

We performed all statistical analyses in R.4.0.2 (R Core Team 2020).

Biomass, diversity and abundance of invertebrates

We calculated the biomass (total quantity of invertebrate organisms in a given area) at each site using a regression equation for ash-free dry mass (AFDM) = $a.length^b$ (following Rogers 2006) to translate length into AFDM where a and b are constants that vary with species. We used equations from Rogers (2006), applying the equation from the most morphologically similar species when we did not have a direct conversion equation (Table S1). Biomass is presented as mg per m^2.

Drivers of the Great Knot population in the region

There was observational evidence that birds that roost at Nightcliff Rocks (where shorebird surveys were conducted) forage nearby at Ludmilla Bay (Lilleyman et al. *in prep* a). As part of monthly monitoring of shorebirds in the region, we had access to survey count data from the years 2014, 2015 and 2016. We examined the relationship between biomass (mg AFDM m^{-2}) and Great Knot abundance (counts of Great Knots from survey roost sites (shown in Fig. 1), performed at various tide heights (range: 0.48 – 7.96 m, median: 6.23 m)). We had no a priori reason to expect the relationship between benthic biomass and Great Knot density would be linear, so we initially fitted the relationship using a generalised additive model (GAM) using the *gam* function from the 'mgcv' package (Wood 2011) with month as a smoothed factor using the cyclic cubic regression spline and density as a smoothed variable.

The results showed that the relationships across the sites and over the months were mostly linear (all edf values were <4, indicating weak non-linearity). We then used a negative binomial generalised linear model (GLM) to examine the relationship. We used raw counts of Great Knots for each site as the response variable and the average biomass as mg AFDM m^{-2} as an explanatory variable. We used site (Buffalo Creek, Sandy Creek, Ludmilla Bay) and month as fixed effects using the *glm.nb* function in the 'MASS' package (Venables 2002). We checked for an effect of tide height (m) and survey effort (hours spent surveying for shorebirds) by including these variables in the model. We performed model selection using AIC values and selected the most parsimonious model with the lowest AIC value. We then performed model checking procedures to ensure variation among the residuals and that the model fit was not over-dispersed. We performed a Tukey post-hoc multi-comparison of means test using the *glht* function in the 'multcomp' package (Hothorn et al. 2008) to identify significant differences among categorical fixed effects.

We expected that a feature such as nearby headlands might influence the distribution of biomass along the intertidal zone as distance to seawalls and channels have been found to be important environmental factors that can influence spatial patterns in benthic invertebrates (Choi et al 2014). We measured the distance of the nearest headland to each core sampling location at each site using the ruler tool in Google Earth. We were also interested in how sediment particle size might influence benthos biomass. We used a GLM with a Gamma distribution to examine the effect of distance (m) to the nearest prominent headland, distance (m) to the nearest creek, sediment particle size, and site on average biomass (mg AFDM m^{-2}). We also tested for an interaction effect of site. We assessed model performance based on the principle of parsimony and selected the model with the lowest AIC value. We then performed model checking procedures to assess variation among the residuals and that the model fit was not over-dispersed.

We mapped the extent of available intertidal zone for the study areas and calculated the cumulative intertidal area exposed at the lowest low tide in ArcMap 10.4.1 to show the extent of intertidal soft

substrate that is available for foraging shorebirds. We use this to estimate the extent of exposure within each tidal band and across spring-neap tide cycles.

Energy costs for Great Knots on the non-breeding grounds in Darwin

We obtained data on the weights (g) of Great Knots caught in the Darwin region at a range of sites in 2008, 2014, 2015 and 2017 using cannon or mist nets (n = 189 birds, range = 112-190 g). We used the weight to calculate (1) the basal metabolic rate, defined as the energy cost of a resting bird (BMR in kJ) using the equation $BMR = 437 \times M^{0.73}$ where M is the mass of the bird (in kg); (2) the daily energy expenditure, defined as the energy cost for normal daily activities of a shorebird (DEE in kJ; $BMR \times 2.5$) Piersma (2002); and (3) the required daily consumption of dry mass food (g; $V_d = DEE/0.8/23$) Piersma et al. (1995), Piersma et al. (2003) for all individuals in our dataset (n = 189), across three age classes (juvenile, second-year and adult birds). We note that these equations were derived from experimental procedures on Red Knots (*C. canutus*) so the estimates we produce here should be taken with caution. We estimated that average commuting flight speed was approximately 54 kph (following Kvist et al. (2001)) to calculate the metabolic costs of flight by estimating commuting distances between roosting and foraging sites, and then dividing the distance by speed to estimate time spent in flight, then estimating the cost of flight using the power input multiplied by time spent in flight and converted that value to kJ .

Results

Biomass, diversity and abundance of invertebrates

We retrieved at least 20,681 specimens of approximately 105 intertidal invertebrate species representing 17 orders and 37 families from our samples of which between 15 and 23 species of polychaete worm are probably new undescribed species. The most abundant species collected was *Paphies altenai*, a small clam (class: Bivalvia) which had an average biomass density of 12.6 mg AFDM m[-2] at Buffalo Creek and 12.3 mg AFDM m[-2] at Sandy Creek but was not present in the sampled area of Ludmilla Bay. Class Bivalvia made up 58% of the total biomass across the three sites, while class Polychaeta made up 35% of biomass, and the remaining biomass identified in the samples belonged to the other 15

classes. Average biomass across all species and all months of the sampling years at Buffalo Creek was 40.8 mg AFDM m^{-2} (range: 9.5-317 mg AFDM m^{-2}), at Sandy Creek 26.6 mg AFDM m^{-2} (range: 5.6-151 mg AFDM m^{-2}), and at Ludmilla Bay 249.7 mg AFDM m^{-2} (range: 7-848 mg AFDM m^{-2}) (Fig. 3). Bivalves were the most common invertebrates in the Buffalo Creek and Sandy Creek samples, while polychaetes were most common in the Ludmilla Bay samples.
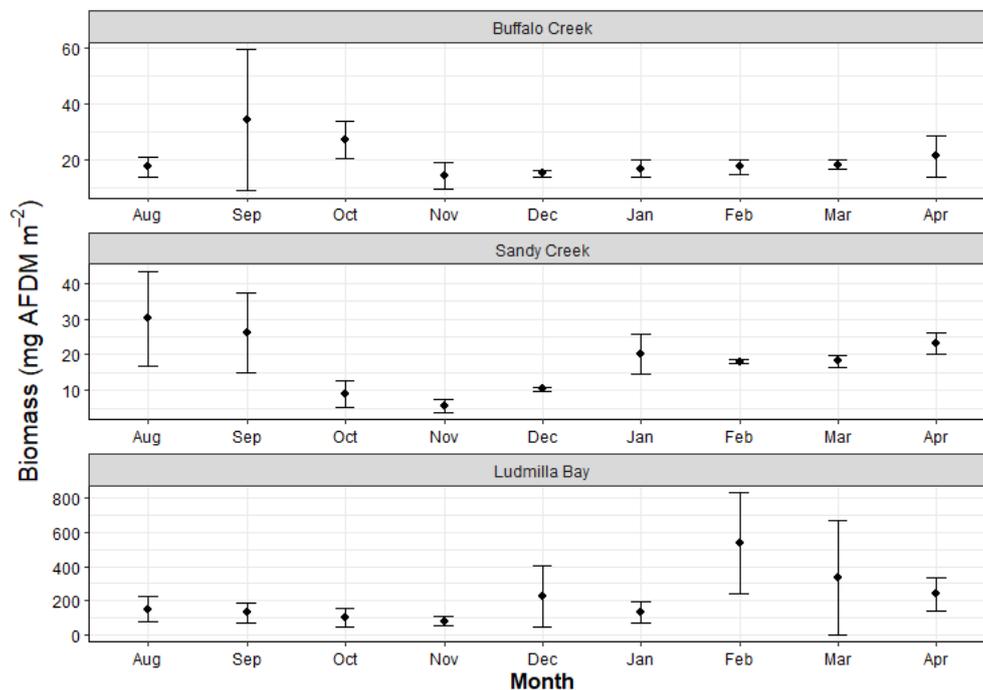

Fig. 3. Average biomass (± 95% CI) as mg AFDM m^{-2} for each site in Darwin Harbour during 2014 – 2016 Note variable values on the y-axis.

Accessible biomass

Across the three sites, more than 78.7% of all biomass was obtained from the top 5 cm of sediment, 10.1% was from the 5-10 cm component and the remaining 11.2% was in the 10-20 cm component of the core sample. The average bill length of Great Knot in Darwin Harbour is 4.39 ± 0.016 (SE) cm (AWSG and A. Lilleyman unpublished data). As they often probe the full length of their bill (up to

eyes) into sediment (Rogers 2006), they could therefore reach most prey in the top 5 cm of sediment. Thus, almost 80% of biomass across the sampled patches at the three study sites would be available to foraging Great Knots. Most invertebrates had average lengths that were within the size range that Great Knots can swallow (Tulp and de Goeij 1994) (Table 1; Fig. S3-S6).

Table 1. Minimum, maximum and average lengths (mm) ± standard error of invertebrates sampled across three sites in the Darwin Harbour region.

Invertebrate class	Minimum length (mm)	Maximum length (mm)	Average length (mm)	SE
Arthopoda	1.00	10.00	6.0	1.5
Bivalvia	1.00	40.00	3.9	0.0
Chordata	15.00	15.00	15.0	NA
Echinodermata	17.00	19.00	18.0	1.0
Echinoidea	3.00	10.00	9.1	0.9
Gastropoda	12.00	23.00	15.8	1.9
Hemichordata	7.00	26.00	16.5	4.0
Holothuroidea	4.00	38.00	15.1	1.5
Isopoda	4.00	5.00	4.5	0.3
Malacostraca	1.00	13.00	5.8	0.5
Mollusc	2.00	2.00	2.0	NA
Nemertea	4.00	87.00	16.1	1.6
Ostracoda	4.00	4.00	4.0	NA
Polychaeta	2.00	116.00	16.6	0.4
Scaphopoda	18.00	26.00	22.0	4.0
Turbellarian	35.00	35.00	35.0	NA
Unknown	1.50	27.00	4.8	1.1
Unknown lesser deuterostome	26.00	26.00	26.0	NA

Drivers of the Great Knot population in the region

We modelled Great Knot abundance by average biomass density and found an overall positive relationship with a significant site effect (slope est. = 0.006, P = <.000; Fig. 4). The relationship between biomass density and Great Knot abundance at Ludmilla Bay significantly differed from both Sandy Creek and Buffalo Creek (P = <.000). Although we detected a site effect, with Great Knots significantly more abundant at Buffalo Creek than at the other sites, the relationship between Great Knot abundance

and biomass density was slightly negative within this site and within Sandy Creek (Fig 4). There was a positive relationship between Great Knot abundance and biomass density at Ludmilla Bay.
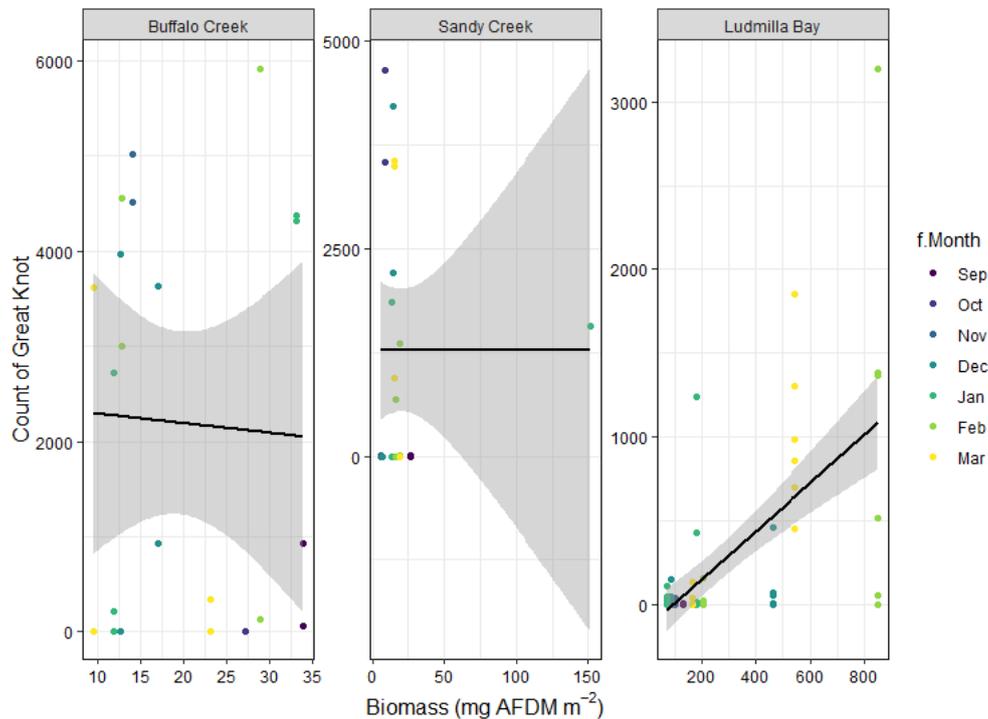

Fig. 4. Modelled relationship between the count of Great Knots across all three sites and biomass density (mg AFDM m^{-2}) showing survey months (as a factor) by colour. There were multiple shorebird surveys performed at each site per month.

The best model in the candidate set of models included the interaction between distance to the nearest headland and site. There was a significant interaction effect between distance to the nearest headland and site, with a significant negative effect of benthos biomass with increasing distance from the prominent headland near Sandy Creek (P = <.008). This differed to the relationships between these variables at the other two sites (Fig 5).

Sediment grain size and tide height were not important variables in the model. Sediment grain size was homogenous across the three study sites and most of the core sample was made up of fine sand (.125 mm class) (Fig S7).
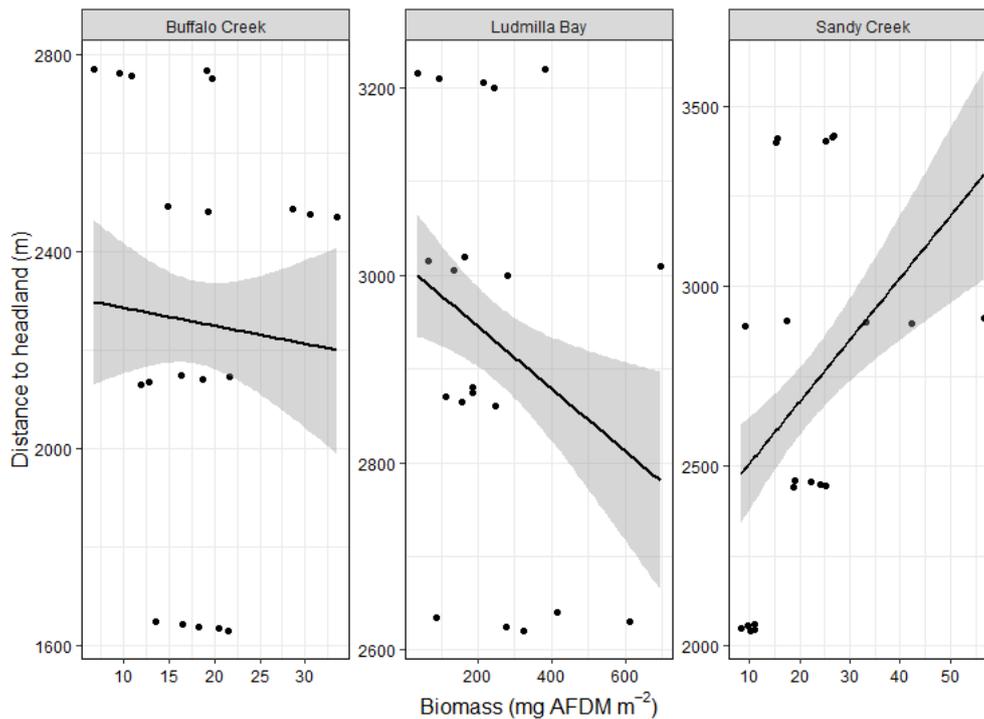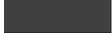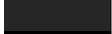
Fig. 5. Modelled output from generalised linear model of the effect of distance (m) to the closest prominent headlands on average biomass as AFDM (mg m^{-2}) across the three study sites.

The large variation in tidal amplitude of the survey area means that at low tide during the spring tide cycles there is greater intertidal area exposed than during the low tide during a neap tide cycle (Fig. 1). During the lowest tide of the spring tide cycle there is at least 16.5 km^2 of intertidal substratum exposed (Table 2), representing a vast area in which shorebirds can forage (Fig. 1).

Table 2. Results of intertidal zone mapping showing area and cumulative area km^2 of each substratum for the study sites in Darwin Harbour. OTR = Observed Tidal Range.

Band	Band substratum	Band colour in Fig. 1.	Area (km^2)	Cumulative area of exposed tidal flat (km^2)	Cumulative area of exposed tidal flat (%)	Band description	Proportion of full extent exposed during particular decile
0	Sea		84.17		0	area always under water during OTR	
1	Intertidal		2.13	2.13	12.9	area exposed at 0-10% of OTR	3%
2	Intertidal		2.51	4.65	28.1	area exposed at 10-20% of OTR	6%
3	Intertidal		2.24	6.88	41.6	area exposed at 20-30% of OTR	8%
4	Intertidal		2.79	9.67	58.5	area exposed at 30-40% of OTR	12%
5	Intertidal		2.46	12.13	73.4	area exposed at 40-50% of OTR	15%
6	Intertidal		2.36	14.49	87.7	area exposed at 50-60% of OTR	18%
7	Intertidal		0.91	15.41	93.2	area exposed at 60-70% of OTR	19%
8	Intertidal		1.13	16.53	100	area exposed at 70-80% of OTR	20%
9	Land		76.6			area exposed at 80-100% of OTR	
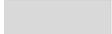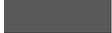
Energy expenditure

The daily energy expenditure of Great Knots from Broome in north-western Australia was estimated as 326 – 363 kJ per day depending on where birds roosted (Rogers et al. 2006b). Estimated daily energy expenditure is much lower for Great Knots in Darwin (Table 3). Commuting flights between roost sites and feeding sites are common for shorebirds that feed within a dynamic tidal system. Most of the Great Knot population in the Darwin region roosts at the Lee Point – Buffalo Creek roost site. Assuming that the relationship between the energy cost (kJ) of a commuting flight and commuting distance is linear, birds flying one way from Lee Point to the nearby intertidal flats at low tide would expend, on average, 1.7% of their DEE. Flying to the next closest intertidal feeding ground near the Sandy Creek roost site would cost on average 3.7% of their DEE while knots commuting between Lee Point and to the Ludmilla Bay feeding grounds would expend an average of 14.9% of their DEE in flying. Birds commuting between the foraging site at Ludmilla Bay and roosts at East Point or Nightcliff, would expend only 3.0% of their DEE but these roost sites are inundated by the highest tides.

Table 3. Average values ± SE for basal metabolic rate and daily energy expenditure of Great Knots in the Darwin region.

	Average (± SE) BMR kJ^{-day}	Average (± SE) DEE kJ^{-day}
Adult	101.28 (± 1.00)	253.21 (± 2.51)
Juvenile	100.73 (± 2.38)	251.83 (± 5.95)
Second-year	106.73 (± 1.98)	266.84 (± 4.96)

Discussion

Our study shows that during most of the non-breeding season, there is a stable supply of food resources available for Great Knots in Darwin Harbour region. When the knots first arrived after migration they would have been expected to select the roosting site closest to the feeding site with the most profitable biomass, but our roost count data showed that Great Knots consistently used the Lee Point roost despite higher biomass estimates at Ludmilla Bay.. Once the monsoon rains arrived in December and January, however, the biomass of Ludmilla Bay increased by over an order of magnitude and remained much higher than the other sites until after the knots had departed on northward migration. At least some of the knots responded to this possible increase in benthic biomass by flying to Ludmilla Bay despite the greater distance they had to travel back to the roost site, although on more moderate tides they could roost close by (pers. obs., AL). Ludmilla Bay may only be worthwhile for the knots to commute to once the biomass density is above 300 mg m^{-2}. The commuting distances of Great Knot in Darwin Harbour are lower than those reported for Great Knots in Roebuck Bay in north-Western Australia (Rogers et al. 2006b) and for a range of shorebird species in the Gladstone Harbour region (Choi et al. 2015). As a result, the energetic costs of commuting are relatively low for Great Knots in Darwin Harbour. Moreover, the energetic demands of Great Knots in Darwin Harbour are expected to be lower than those of Great Knots in Roebuck Bay (north-western Australia), as Great Knots average significantly lighter than those that spend the non-breeding season in north-Western Australia (Lilleyman et al, *in prep* b). Average biomass available for Great Knots was lower in Darwin than in north-Western Australia (Rogers 2006).

This increase in knot numbers through the season at Ludmilla Bay has multiple implications. First it suggests that Great Knots were able to track benthic biomass at Ludmilla Bay, and to respond when

prey abundance there spiked. It is not clear how they tracked biomass: perhaps some of the knots either knew there were seasonal increases in abundance from previous years, or perhaps a proportion had been prospecting during the season or during the night to see if conditions for feeding were suitable. Shorebird movement within a network of sites is often dynamic and in responsive to changes in local conditions (Rogers et al. 2006a, Kraan et al. 2009). That the number of birds at Ludmilla Bay represented only about 20% on average through the year of the number at the other two sites suggests that there is flexibility in prospecting strategies at a population level. Further investigation is warranted into how birds use the network of sites at which to find food or roost and the demographic characteristics of different strategies adopted as immature birds are known to move greater distances than adults during the non-breeding season (Lilleyman et al, *in prep* a) – e.g. is it immature birds that tend to be more exploratory or does the variation in behaviour reflect the risk tolerances of individuals?

The second implication is that any visit to Ludmilla Bay to assess the importance of the site for shorebirds would have scored it poorly unless the surveys had been undertaken over the short period when many more birds were using the site and roosting nearby at Nightcliff Rocks or East Point. Most faunal surveys undertaken to assess the environmental significance of a site involve one or two site visits but lack knowledge of temporal use to know when such surveys should be undertaken. A site does not necessarily have to be used all the time for it to have an important role in the annual cycle (Runge et al. 2016). For migratory birds stop-over sites have long been recognised as having seasonal value but there has been less appreciation of variability in site use within the non-breeding season. Again, understanding that sites are a part of dynamic networks can improve their conservation management.

The within site variability also has management implications. Coastal development often disrupts sediment flows in the same ways that headlands did in this study (Choi et al. 2014), so that it is not necessarily the immediate footprint of a development that needs to be considered but also the downstream effects. In this case substrate productivity varied up to several kilometres from the headlands, presumably because of changes to sediment flow, but this relationship differed between sites. Shoreline topography and oceanic circulation can influence the distribution of invertebrates and

recruitment of individuals in the population can depend on upwelling patterns (Morgan et al. 2011, Pfaff et al. 2011). That productivity declined with distance for two of the sites studied may also be important, but whether this pattern can be generalised to other sites needs a larger and more varied sample size. Potentially there may even be potential to increase site productivity by manipulating sediment flow.

The final result worth noting is that the largest numbers of Great Knot were in the place with the greatest reliability of preferred mollusc prey even if it did not always have the greatest biomass (Fig S8). While the small clams knot prefer to eat were most prevalent at Buffalo Creek, the greater variety of prey available at Ludmilla Bay may have compensated for any dramatic changes through the season, again favouring risk-averse, site-faithful birds over those exploiting less diverse but more abundant prey elsewhere.

Limitations

One limitation of this study was that the Great Knot abundance estimates taken from monthly monitoring did not temporally align with the timing of benthos sampling and this may have implications for the modelled results showing how Great Knots possibly respond to food availability. Future studies could undertake counts at roosts near benthos sampling sites during sampling sessions so that datasets align.

Conclusion

Our study of food availability and use by Great Knots in Darwin Harbour has revealed the great density of bivalve-prey species potentially available to migratory shorebirds in the region but, to maximise exploitation of that resource requires foraging in several different sites at different times. Some birds chose to do this, exploiting the ephemeral but highly productive site at Ludmilla Bay when fattening up before migration, but others apparently found the resources available at the site closest to the best high tide roost in the region adequate for their needs. This variability in behaviour may act as a valuable buffer against extinction of the species, but to fully understand its significance and implications for management points to a need for more detailed investigation of the use of a migratory network model.

Acknowledgements

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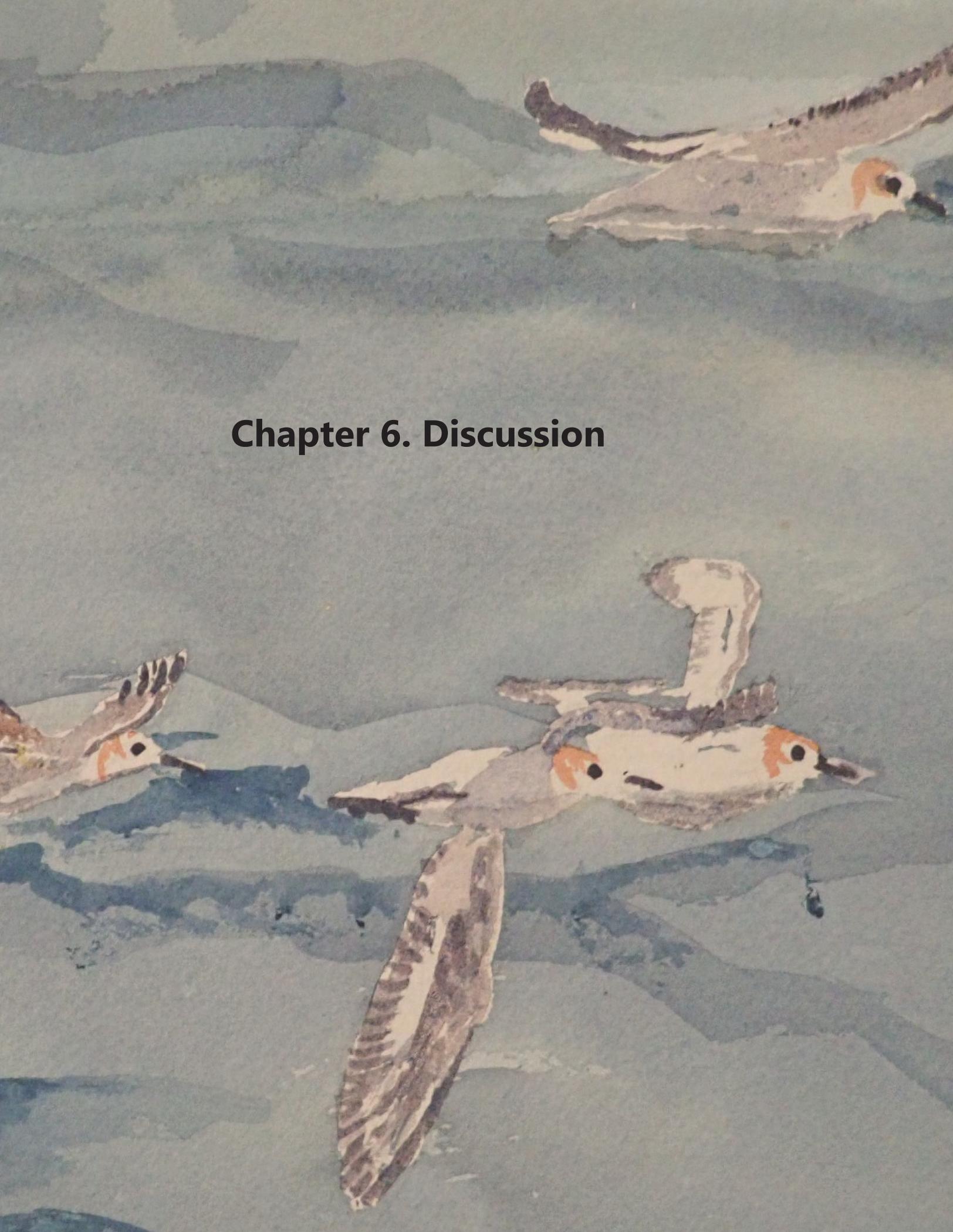
Chapter 6. Discussion

Chapter 6. Discussion

Summary

While there is strong evidence that the migratory shorebirds from the East Asian-Australasian Flyway have experienced population declines due to reduced habitat quality of staging sites in the Yellow Sea region (Studds et al. 2017), much less is known about how conditions on the non-breeding grounds interact with or amplify the responses of shorebirds to the environments they use throughout their lifecycle.

The overall aims of this thesis have been to 1) understand how local conditions at individual sites limit local shorebird populations, and 2) improve knowledge of the habitat requirements of the shorebirds at a site in northern Australia to sustain shorebird numbers in a tropical harbour. Ultimately the objective of my research is to improve the practice of shorebird conservation within Australia.

Significance of the findings

I start by placing the shorebirds at my study site in northern Australia within a national context. My work in **Chapter 2** on the trends and variation in body size of migratory shorebirds in Australia provides a first look at the ways species have changed over time and across regions of the non-breeding grounds. While some of our results were consistent with trends in similar species reported elsewhere, with declines in overall body size and mass over the 40-year period for which I was able to obtain data, the trend was not uniform across all shorebird species.

Changes in overall body size and mass will affect an individual's basal metabolic rate (BMR) and their energy requirements. I have shown that there is not only a temporal trend in morphology (body mass and structural body size decreases) but also a latitudinal effect for several of the shorebird species analysed (larger-bodied animals and higher body mass in higher latitudes). This may in turn influence how species interact with the environment and competitors in the ecosystem (possible niche-overlap as suggested above). For the Great Knot that has decreased mass across all its non-breeding range, there are also stark differences between the regions in Australia. However, across the Australian non-breeding

grounds the relationship between wing and bill length in the Great Knot is consistent with historical scaling relationships and has not changed over time, possibly suggesting that individuals are responding to the environmental conditions and not to other drivers of change for which some researchers have found evidence e.g.: predation risk (*sensu* Anderson et al. 2019).

One of the key aspects in conservation science is understanding population trends over time to provide baseline knowledge before any adaptive measures are taken. There had been no previous analysis of shorebird population trends in the Darwin Harbour region that compared sites used by shorebirds. My analysis of population trends (**Chapter 3**) included not only natural sites but also the trends in birds using an artificial site. I identified which species are conforming to the global trends and which are anomalies. I was surprised to find that the Great Knot, a species that has been documented as experiencing such steep declines that it was listed as Vulnerable by the IUCN in 2010 and Endangered in 2015 (BirdLife International 2016) and Critically Endangered under the Australian *Environment Protection and Biodiversity Conservation Act* 1999 in 2016 (Department of the Environment 2020) had near-significant increases at both natural and artificial sites – thus the species is stable in Darwin Harbour. However, while the result from the Great Knot appears to reflect trends across its range, so that it is now recommended that it be downlisted to Near Threatened (Clemens et al. *in press*), the trends in Common Greenshank in Darwin Harbour, contrast strongly with the global trends of this cosmopolitan species. Numbers of Common Greenshank have increased significantly across the local Darwin sites but the population is declining steeply across the south-eastern parts of its Australian range (Clemens et al. 2016), with the Australian population being recommended for listing as Vulnerable (Clemens et al. *in press*). Similarly, the Red-necked Stint, which has declined in south-eastern Australia (Clemens et al. 2016) to the extent that it is now recommended for listing as Near Threatened (Clemens et al. *in press*), had mostly stable population trends across both natural and artificial sites in the Darwin Harbour region. These two species – Common Greenshank and Red-necked Stint - are both habitat generalists, using both freshwater wetlands and coastal areas during the non-breeding season. Their trends in Darwin may suggest that (for these two species) local habitat quality has been favourable, potentially leading to better survival, whereas this may not have been the case for birds overwintering

elsewhere. Such speculation, however, can only be tested with a longer time series and more data on survival and mobility.

In addition to reporting the local population trends for a range of migratory shorebirds in the Darwin Harbour region, the results presented in **Chapter 3** show that artificial habitat can provide a safe, reliable roost site for shorebirds in a tropical harbour where the numbers of shorebirds may be constrained by the availability of high quality roosting habitat. I show that the Darwin Harbour study region is internationally important for migratory shorebirds. Shorebirds had high site fidelity and the faithfulness of individuals reported in **Chapter 4** also indicates most used sites for shorebirds in the region have retained their value to shorebirds despite ongoing disturbances (Lilleyman et al. 2016).

Another key to understanding a species' abundance is how individuals use the environment. Untangling the mechanisms that drive habitat use at a local scale can help managers protect species and habitat. In **Chapter 5** I explore some of the drivers of local mobility by estimating the invertebrate biomass available to Great Knots and other mollusc-eating shorebirds in the Darwin Harbour region at different sites through the non-breeding season. I show that across the dynamic intertidal zone, the hidden prey on which the Great Knot feed and the reliability of this food source allows most birds to feed close to their high tide roost sites. Some of the birds, however, took advantage of a peak in biomass availability at a second site further from the roosting areas, explaining the patterns of movement described in **Chapter 4**. The combined conclusion of both chapters is that the shorebirds need a network of sites in which to forage through the non-breeding season. The absence of birds from a site at one time of year does not necessarily mean it is not important. There is a diversity of strategies among individuals with some remaining at a reliable site with moderate food densities but others abandoning that for a better site when that became available. One could hypothesise that the pattern of network use is likely to change from year to year depending on local variation in site resource availability and the relative survival of the birds adopting the different strategies during the period of pre-migratory fattening.

Most of Australia's shorebirds spend the non-breeding season in tropical latitudes indicating that shorebirds do not find tropical conditions unsuitable. While shorebirds that spend their non-breeding

season in the tropics can have higher disease and parasite loads and lower fuelling rates than do birds migrating to temperate environments (Aharon-Rotman et al. 2016), southern temperate latitudes have challenges like higher thermoregulation costs and longer migrations. While the annual survival of some species is lower for individuals spending the non-breeding season in tropical environments because of poor ecological conditions (Reneerkens et al. 2020), my findings suggest that such conclusions may not be universal and this warrants further research on survival of smaller-bodied shorebirds in both tropical and temperate climates. I demonstrate that some species of shorebird show a high degree of site fidelity to tropical non-breeding sites and that numbers in Darwin are increasing when they have been declining elsewhere. I show that, while food availability is constant close to the roost site that attracts most birds, the birds use a network of sites which allows them to take advantage of bursts of productivity at sites further from roost sites. I suggest that improving roost site availability may allow even more birds to use tropical shorelines in the region than do so currently. Climate change may be playing a role in these trends with apparent selection for smaller birds that are better suited to tropical conditions, but such hypotheses still need to be tested.

Main findings

Table 1. Main findings in this thesis.

Main findings	Source
Structural size and body mass of multiple species has changed the last three decades.	Chapter 2
Greater Sand Plover and Ruddy Turnstone body size has decreased over time. But Ruddy Turnstone body mass increased over time.	Chapter 2
Great Knot structural body size significantly increased over time, but Great Knot and Red Knot body mass decreased over time.	Chapter 2
Great Knot and Red-necked Stint weights are lower in Darwin than in the rest of Australia, including tropical sites in north-Western Australia.	Chapter 2
Darwin Harbour is *internationally important* for three species of migratory shorebird (Great Knot, Greater Sand Plover and Black-tailed Godwit).	Chapter 3
There were overall increases in shorebird population numbers at both artificial and natural sites in Darwin Harbour. Multiple shorebird species numbers increased over 9-year period.	Chapter 3
Artificial sites may only be suitable for some species and the results from our study show that shorebird management across natural and artificial sites needs to consider each individual species and their specific ecological requirements.	Chapter 3
Despite high disturbance rates at the roost sites that supported the highest population counts, shorebird numbers generally increased over time.	Chapter 3
Great Knot were site faithful between years and within years to the Darwin Harbour region. Birds move within a network of sites. Some birds make greater movements during the pre-migratory months.	Chapter 4
A single bivalve species (*Paphies altenai*) dominated the samples and occurred primarily in the top 5 cm of the samples where it was available to foraging Great Knots.	Chapter 5

Biomass was positively correlated with distance to prominent headlands at one site only. Abundance of Great Knots was positively correlated with biomass at only one site.	

Limitations of the research

In this thesis I have investigated habitat use at a local shorebird site in the tropics of northern Australia in the hope that this study on a small portion of the shorebirds that use the EAAF can contribute to the overall conservation of these threatened birds.

In **Chapter 2** on the variation and trends of shorebird body size and mass, I identified significant changes in multiple species over a 40-year period and that in some species there is a strong effect of the local region contributing to the condition of shorebirds and that there is more than a warming climate influencing the phenotypic flexibility of these birds. Investigating this further would be a useful exercise as it would rank the regions across the non-breeding grounds and could provide a measure of ecosystem health. The trends I reported are for only a few of the migratory shorebirds that visit Australia each year, and there is potential to expand this analysis to look at other species within each region (without the focus on comparing species within Australia).

In **Chapter 3** I provided a detailed assessment of multiple shorebird species' population trends over time and recommended management actions for the region. What I did not include in the analysis was an assessment and comparison of the individual natural subsites and how to manage each site. This is important at the local level as each subsite will have different challenges. A management plan for this region should include an assessment and actions for each subsite. Holistic management across this region should also consider the results from **Chapters 4** and **5**, even though they focus on one species. The Great Knot was the model species in those chapters because it is the most abundant shorebird in the region. It can be used as an umbrella species generally, but this approach may leave some species vulnerable to threats that were not identified in the research.

Future work on the site fidelity of shorebirds in the region could include a range of species that are marked during catching expeditions. The results on Great Knot site fidelity from **Chapter 4** are based mostly on adult birds because catching took place before most young birds had arrived in northern Australia. My results therefore show a bias to adult bird movements and faithfulness to the region.

Most of the research from Darwin Harbour was conducted during spring tide cycles which has meant there is a major knowledge gap on how the neap tide cycles influence the behaviour and movement of shorebirds in the region. We know that at some tide heights during neap cycles there is no intertidal mudflat available for shorebirds to forage in Darwin Harbour. It is unknown how much this affects the conditions of shorebirds and whether birds move greater distances during these times.

Future directions of the work

Future work that continues on the theme of how conditions on the non-breeding grounds might constrain population size of shorebirds could include further investigation into the wing lengths of migratory shorebirds and the migration distances flown, building on the recent research by Anderson et al. (2019). In addition to this, there is potential to uncover new knowledge on the genetic connections and variation and level of relatedness in shorebirds and determine the level of genetic mixing on the non-breeding grounds. Further work into the processes that lead to recruitment in the population and whether those processes are random or non-random on the non-breeding grounds would be useful to management across Australia (Gill 2019).

There is an opportunity to explore the trends in shorebird populations of northern Australia and the quantity of wet season rainfall in the region to fully understand the increases and stability of some species (Common Greenshank and Red-necked Stint, respectively) that respond to inland rain events.

While we know the importance of roosting and feeding sites for migratory shorebirds, these coastal environs are vulnerable to incremental losses from small developments that do not consider the cumulative impact on species that depend on these areas. Research into strategically planning development within regions will help to combat this issue. As well as this, there is a need to further

explore the value of managing artificial wetlands as roost sites on the non-breeding grounds where roost-site availability constrains shorebirds.

Work on the exploratory movement and decision-making in birds could help us understand and predict movements across landscapes. The movement of Great Knots in the Darwin Harbour study region revealed a high level of site fidelity within and between years, but what is unknown is the level of information sharing that is going on within the population. One way to investigate this is to look at the timing of arrival at a roost site (Bijleveld et al. 2010). Because smaller individuals have been found to be more exploratory when compared to larger individuals in the population (Bijleveld et al. 2014), there is the possibility that birds may become more exploratory in their behaviour as they decrease in body size and mass. A way to study this could be to examine the movement of individuals in the population using satellite tracking devices and the time of arrival at roost sites of different individuals.

Management recommendations for local non-breeding sites

Across the non-breeding grounds there is a need to identify important sites for migratory shorebirds and improve the coverage of monitoring across those areas (Weller and Warren 2017). This urgency is required as the rate of anthropogenic changes to the environment has caused monumental changes to species and ecosystems (Piersma 2006). Following a conservation action plan approach to managing shorebirds at non-breeding sites, a series of goals, actions required, and the people or stakeholders can be identified to manage threatened species and their habitats adaptively.

There are many things that organisations and stakeholders in the Darwin Harbour region can do to improve the conservation outcomes for migratory shorebirds (Table 2). Through this thesis, I have shown that there is a need to continue preserving habitat and providing a safe haven for the populations of shorebirds that visit the region. In the Darwin Harbour study region example, the primary objectives of a conservation plan would be to:

1. Raise awareness of the value of migratory shorebirds that use Darwin Harbour within the local community.

2. Connect with local stakeholders to learn about current management of shorebirds and the coastline.

3. Improve current management strategies and create a holistic plan to manage shorebirds in the Darwin Harbour region.

Table 2. List of management recommendations for local non-breeding sites in the Darwin Harbour region, actions and responsible organisations/stakeholders.

Recommendation	Action	Responsibility
Improve our understanding of local movements of shorebirds between Darwin Harbour and Shoal Bay to allow for better planning within harbours	Example of techniques available: Set up automated telemetry array towers within site network and tag shorebirds using bands, engraved leg-flags and coded VHF tag	Academic/research institutions
Regulate activities across coastal intertidal zones	Regulatory body to provide policy on how coastal environments can be used by various stakeholders	Local State government
Establish and maintain regular coastal zone patrol	Regulatory officers or local Indigenous rangers to patrol coastal area for non-compliance issues (e.g.: dog boat and airboat disturbances)	Local government and local rangers
Review signage across all coastal areas and establish consistent messaging across all signs in shorebird zones	Undertake assessment of all signs relating to shorebirds across the study region and provide consistent messaging	Local government, local council and local Indigenous rangers

Continue current monthly monitoring of all shorebird roost sites	Support volunteer groups that conduct regular monitoring	BirdLife Australia, BirdLife Top End
Engage local community on shorebird conservation	Hold regular community events to raise awareness of shorebirds	Community groups, Parks and Wildlife, local council
Create charter of management within harbour and have stakeholders sign on to establish a holistic management plan for the region	Establish a charter documenting holistic management of shorebirds and their coastal habitats within a defined region	Community group with buy-in from local stakeholders
Investigate changes in shorebird habitat and address issues with appropriate adaptive management, i.e: vegetation expansion across beaches and mangrove expansion within saltmarsh areas	Assess any changes to vegetation extent across roost sites and changes to available area at foraging sites	Academic/research institutions
Conduct annual biomass monitoring at key sites to determine quantity of prey resources available for shorebirds	Establish monitoring program and undertake field and lab work	Academic/research institutions, community groups, local council, Parks and Wildlife

The importance of Darwin Harbour in northern Australia for migratory shorebirds

Darwin Harbour supports internationally important populations of three species and several sites are further classified as nationally important. Migratory shorebirds are distributed throughout the intertidal zone in Darwin Harbour at low tide and then concentrated at roosts at high tide (Lilleyman et al. 2018). While Lee Point and Buffalo Creek support more roosting migratory shorebirds than the artificial site at East Arm Wharf in Darwin Harbour, some sites in Darwin Harbour still support more than 30% of the total Darwin Harbour waterbird population (Lilleyman et al. 2018) (**Appendix S1**). As there is a lack of available roost sites for shorebirds during high tides above 7.4 m, the artificial roost sites are becoming particularly important: over 80% of the local Darwin Harbour population of Far Eastern Curlew now roost at East Arm Wharf, during the highest tides (Lilleyman et al. 2018), close to 1% of the global population of this species (**Appendix S2** and S**3**).

Darwin Harbour, and most likely many other areas of northern Australia, acts as a steppingstone for shorebirds on their way to non-breeding grounds further south, with some individuals remaining in the region for the duration of the non-breeding season and some fattening up before flying further south or east (**Appendix S4**). Because Darwin Harbour is in such good condition, there is a major opportunity to manage it in a manner that retains the shorebird numbers that currently use it. This will require more detail of the way that the harbour is used by shorebirds and how they might respond to changes in the environment.

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Appendices

Chapter 2. Supplementary material
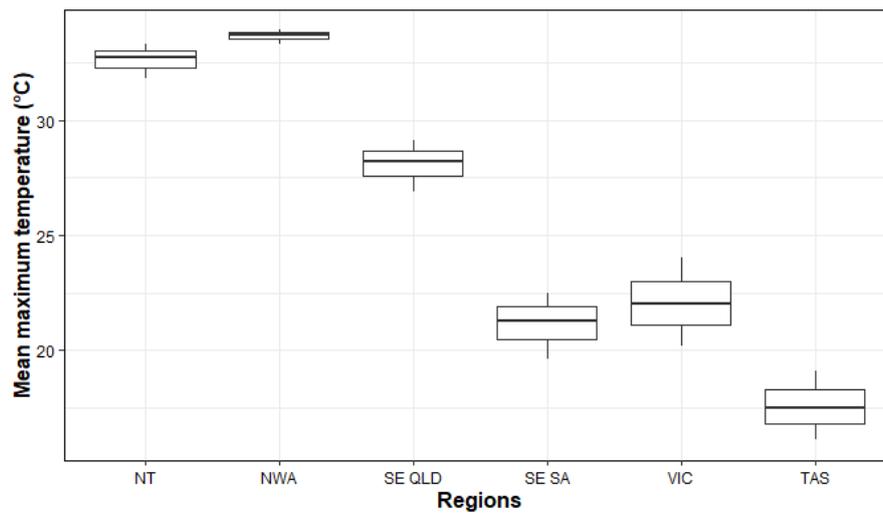
Figure S1. Boxplot of mean maximum temperature (°C) for months September through to December in northern tropical states NT (years 1941-2019), NWA (years 1939-2019) and southern temperate states SE QLD (years 1994-2019), SE SA (years 1884-2019), VIC (years 1991-2019), TAS (years 1985-2019) where shorebirds were captured for this study. Source data: Bureau of Meteorology (2019).

Table S1. Output from linear model of mean temperature anomaly over the years 1980-2019 for all states in this study. $F_{(6,233)} = 15.518$, $p = 0.000$, $R^2 = 0.286$, Adj. $R^2 = 0.267$.

	Est.	2.50%	97.50%	t val.	p
(Intercept)	-40.229	-49.67	-30.789	-8.396	0.000
Year	0.02	0.016	0.025	8.492	0.000
StateWA	-0.039	-0.228	0.15	-0.41	0.682
StateQLD	0.16	-0.029	0.349	1.667	0.097
StateSA	0.16	-0.029	0.349	1.667	0.097
StateVIC	-0.053	-0.241	0.136	-0.548	0.584
StateTAS	-0.203	-0.392	-0.014	-2.116	0.035
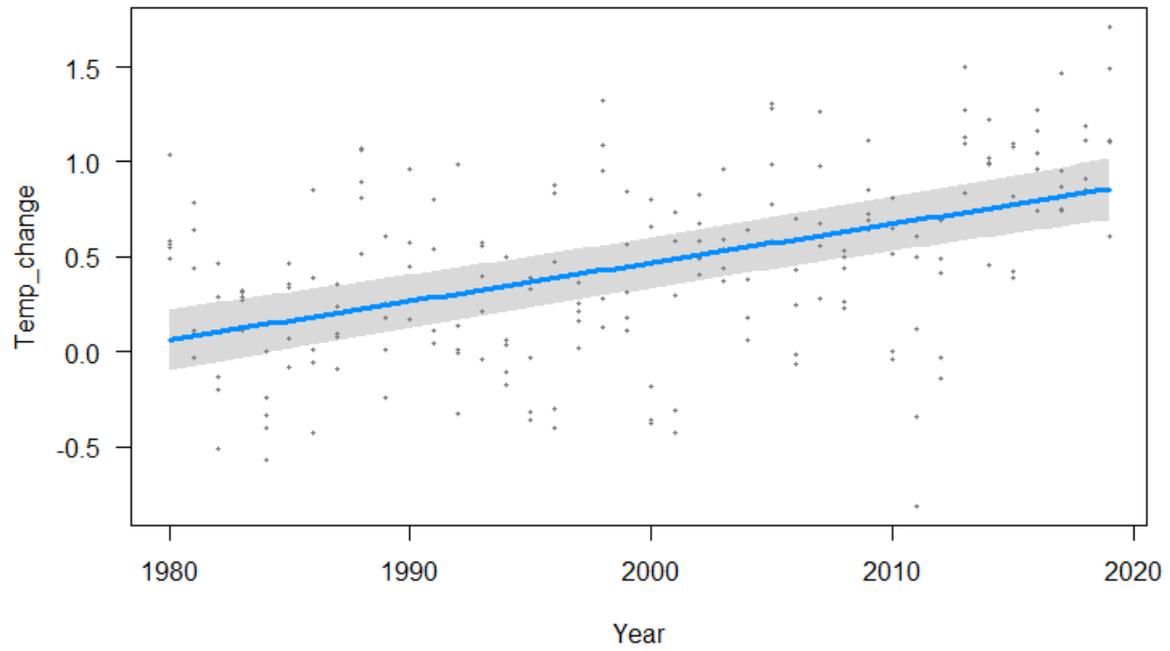
Figure S2. Modelled output of temperature changes as mean anomaly across all states in the study for
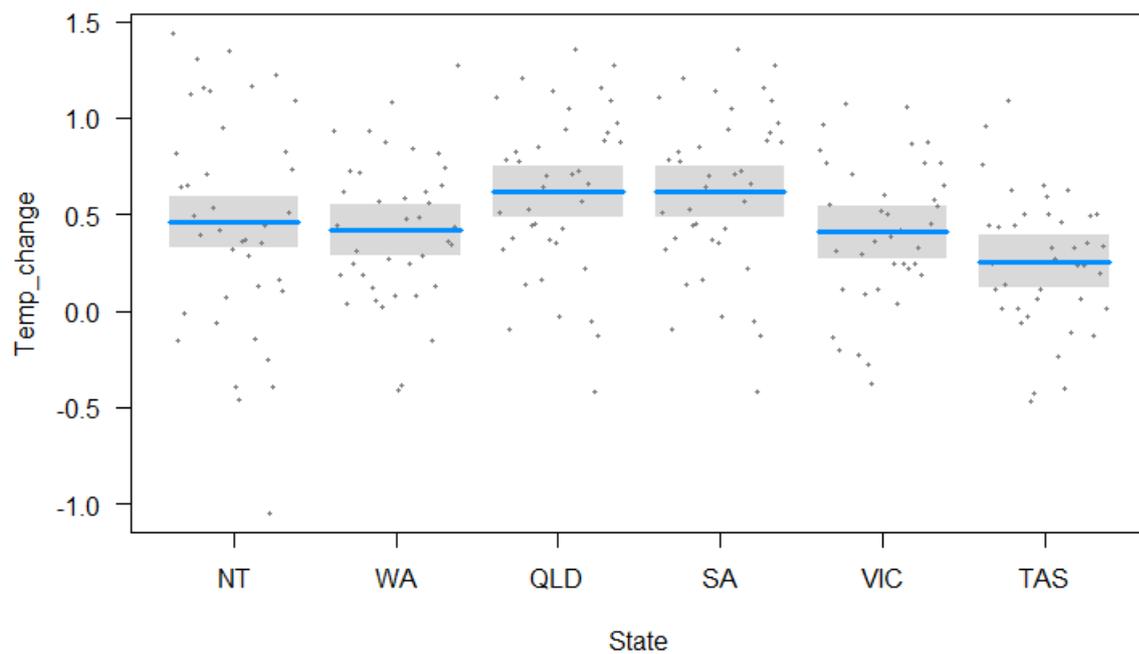
the years 1980-2019.

Figure S3. Modelled output of temperature changes as mean anomaly by states in the study for the years
1980-2019.

Table S2. List of shorebird species and number of individuals from each region used in this study.

Shorebird	NT	NWA	SE QLD	SE SA	VIC	TAS	Total
Red-necked Stint	59	1110	337	253	2543	32	4334
Lesser Sand Plover	15	92	148		89		344
Greater Sand Plover	174	1120	21		14		1329
Ruddy Turnstone	12	118	32	921	652	636	2371
Great Knot	153	1363	167		191		1874
Red Knot	32	686	6		914		1638
Total	445	4489	711	1174	4403	668	11890
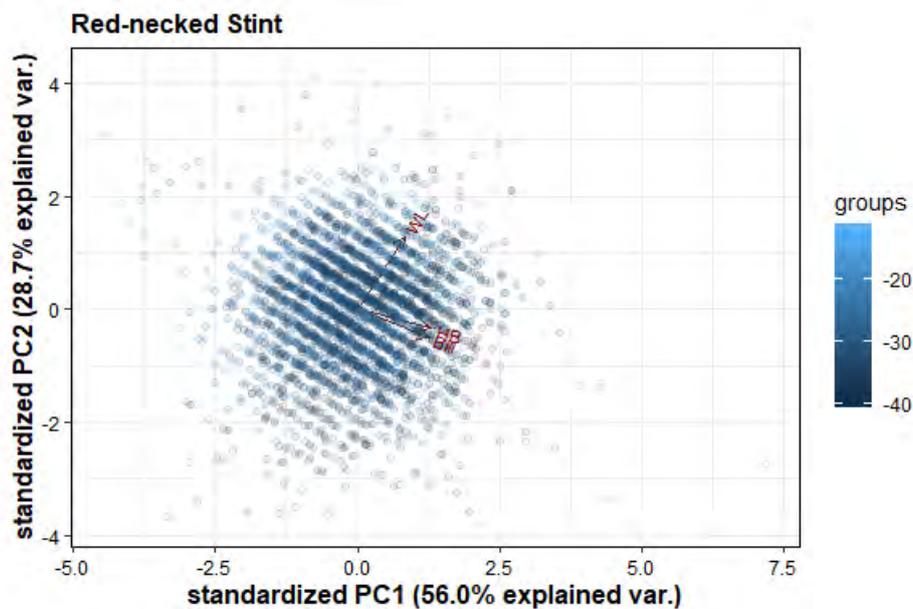
Figure S4. Results of PCA for Red-necked Stint. Data are shown by degrees latitude (legend) of the
study regions. Contributing variables to PC1 (Bill = 0.63, HB = 0.65, WL = 0.41) are shown in red and
the arrow shows the direction and relative loading within each principle component.
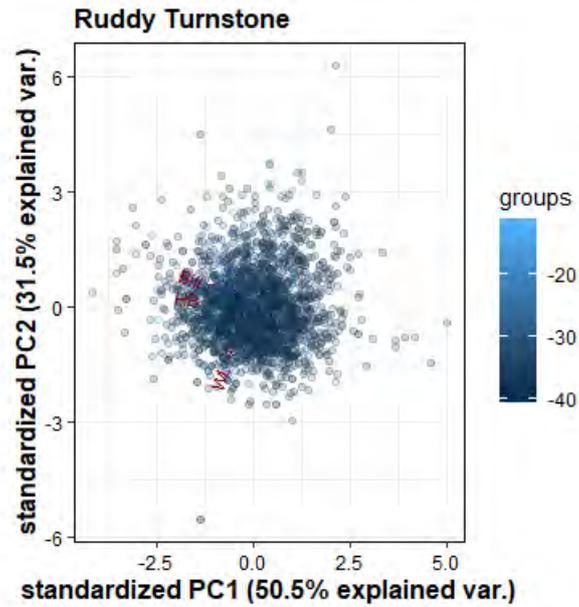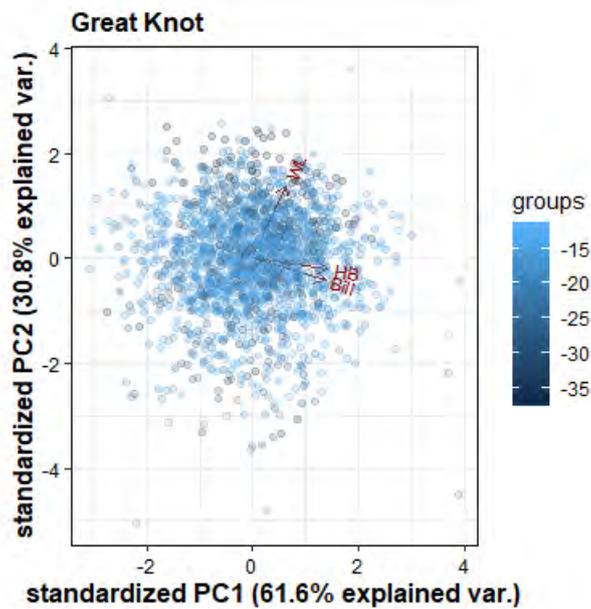
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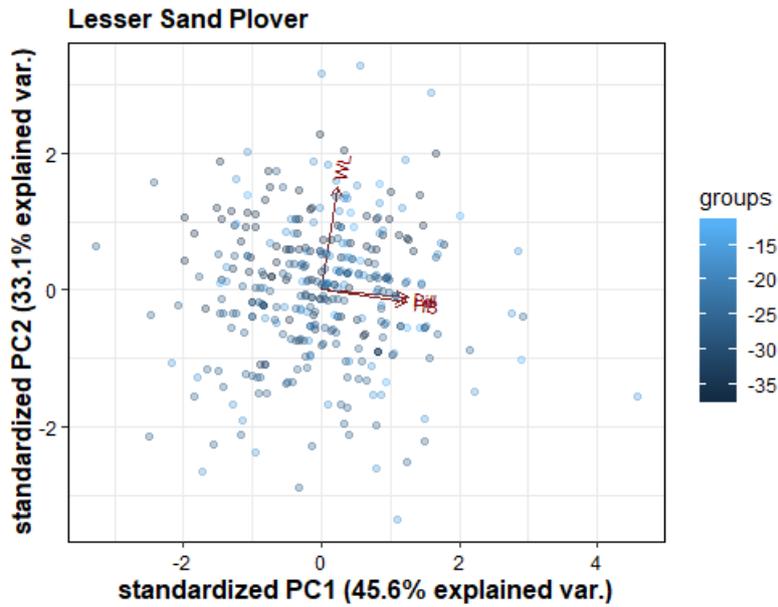
Figure S5. Results of PCA for Lesser Sand Plover. Data are shown by degrees latitude (legend) of the study regions. Contributing variables to PC1 (Bill = 0.70, HB = 0.69, WL = 0.14) are shown in red and the arrow shows the direction and relative loading within each principle component.
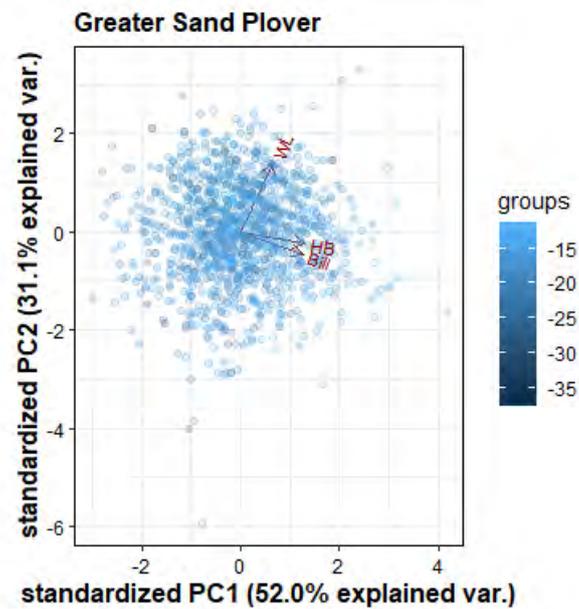
Figure S6. Results of PCA for Greater Sand Plover. Data are shown by degrees latitude (legend) of the study regions. Contributing variables to PC1 (Bill = 0.65, HB = 0.68, WL = 0.33) are shown in red and the arrow shows the direction and relative loading within each principle component.

Figure S7. Results of PCA for Ruddy Turnstone. Data are shown by degrees latitude (legend) of the study regions. Contributing variables to PC1 (Bill = 0.64, HB = 0.68, WL = 0.35) are shown in red and the arrow shows the direction and relative loading within each principle component.
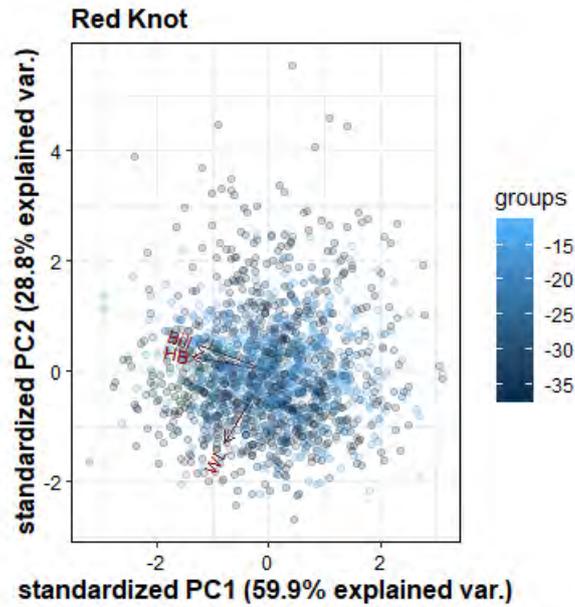

Figure S8. Results of PCA for Great Knot. Data are shown by degrees latitude (legend) of the study regions. Contributing variables to PC1 (Bill = 0.66, HB = 0.68, WL = 0.30) are shown in red and the arrow shows the direction and relative loading within each principle component.

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Figure S9. Results of PCA for Red Knot. Data are shown by degrees latitude (legend) of the study regions. Contributing variables to PC1 (Bill = 0.64, HB = 0.66, WL = 0.39) are shown in red and the arrow shows the direction and relative loading within each principle component.
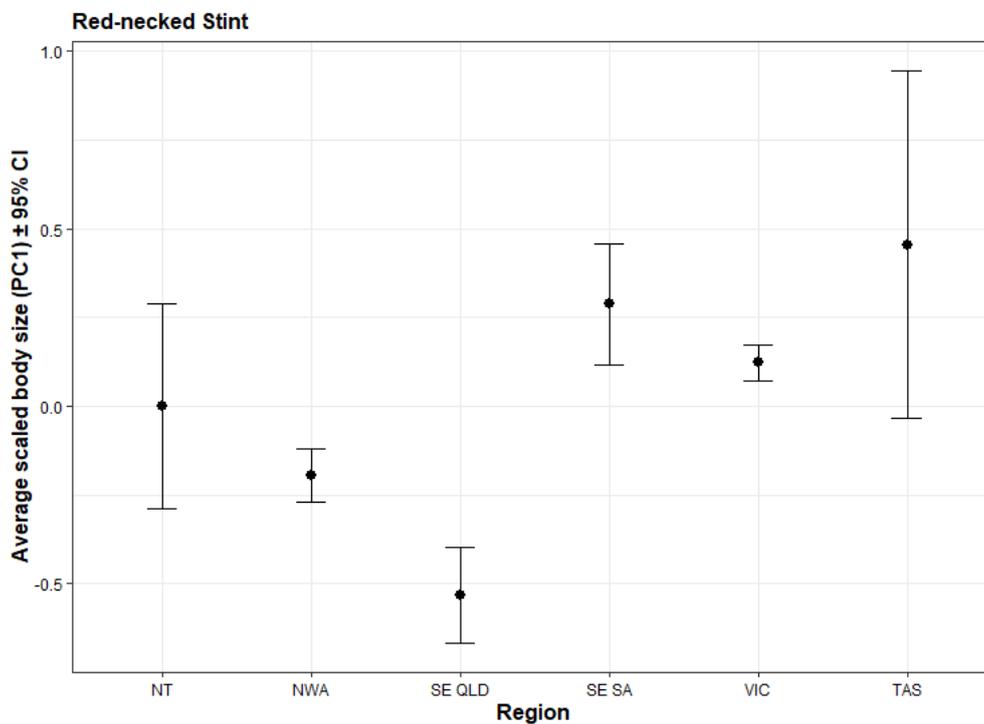
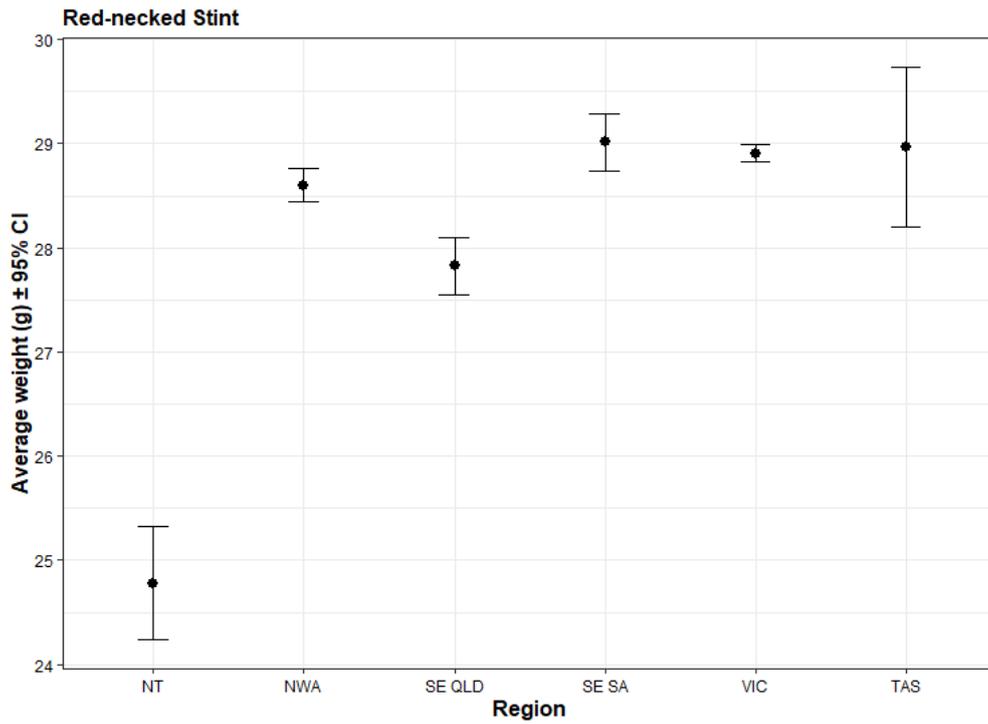Figure S10. Average ± 95% confidence interval structural body size (PC1) of Red-necked Stints by region.

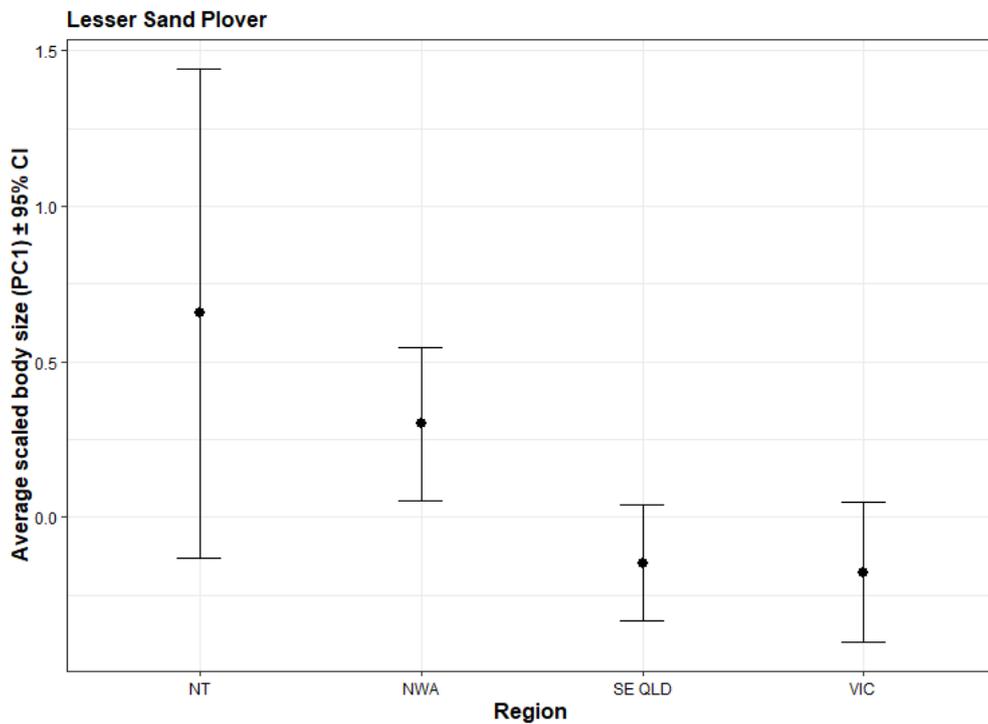Figure S11. Average weight (g) ± 95% confidence interval of Red-necked Stints by region.

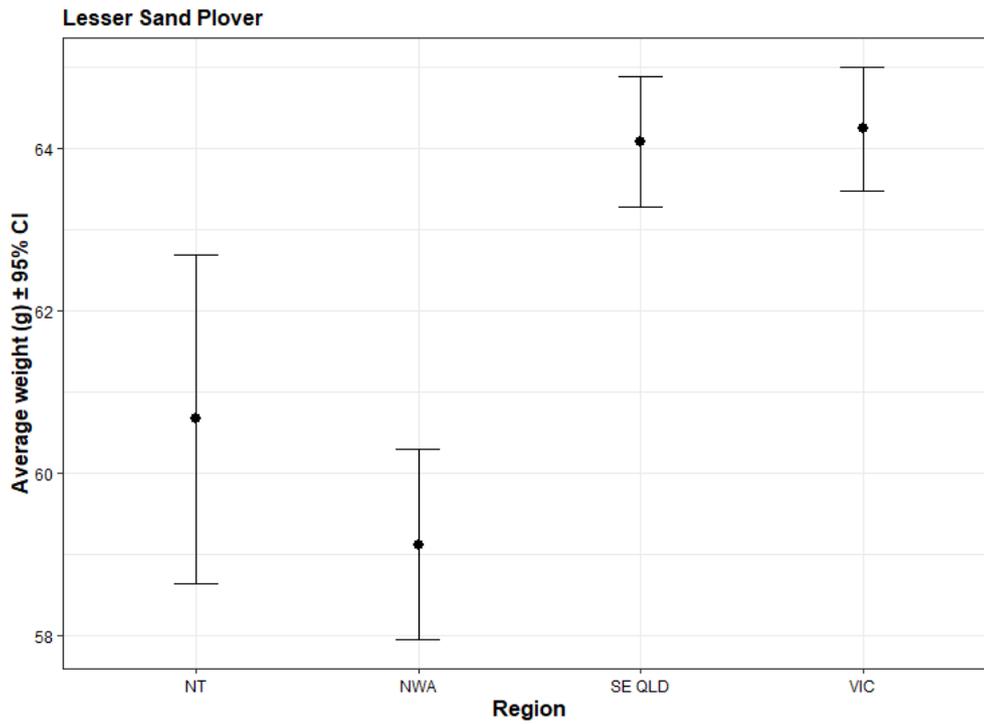Figure S12. Average structural body size (PC1) ± 95% confidence interval of Lesser Sand Plovers by region.

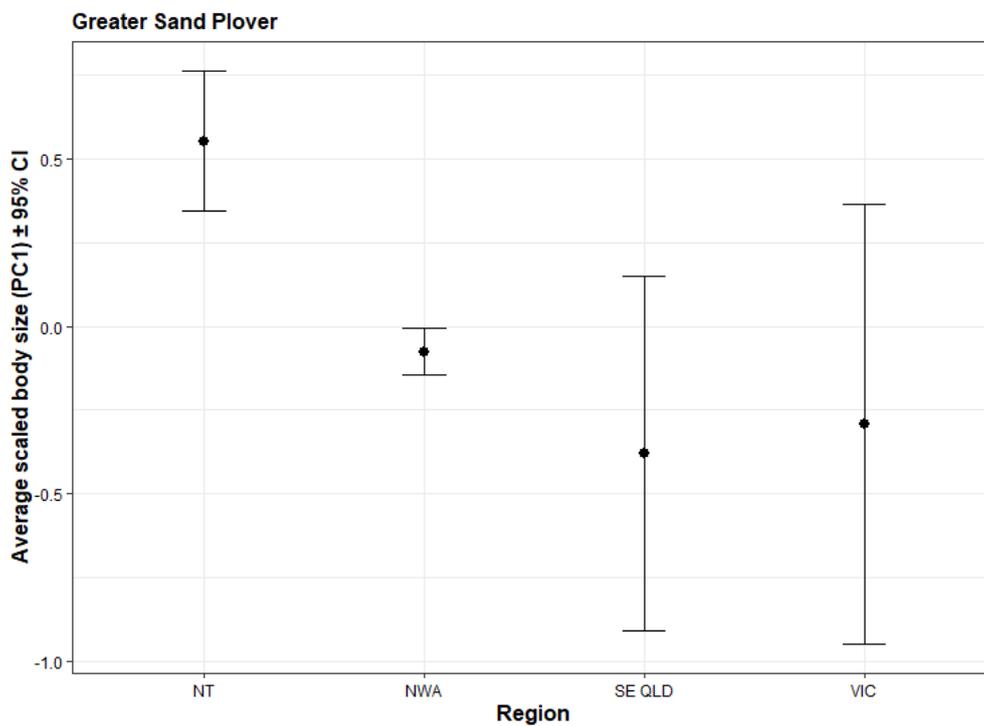Figure S13. Average weight (g) ± 95% confidence interval of Lesser Sand Plovers by region.

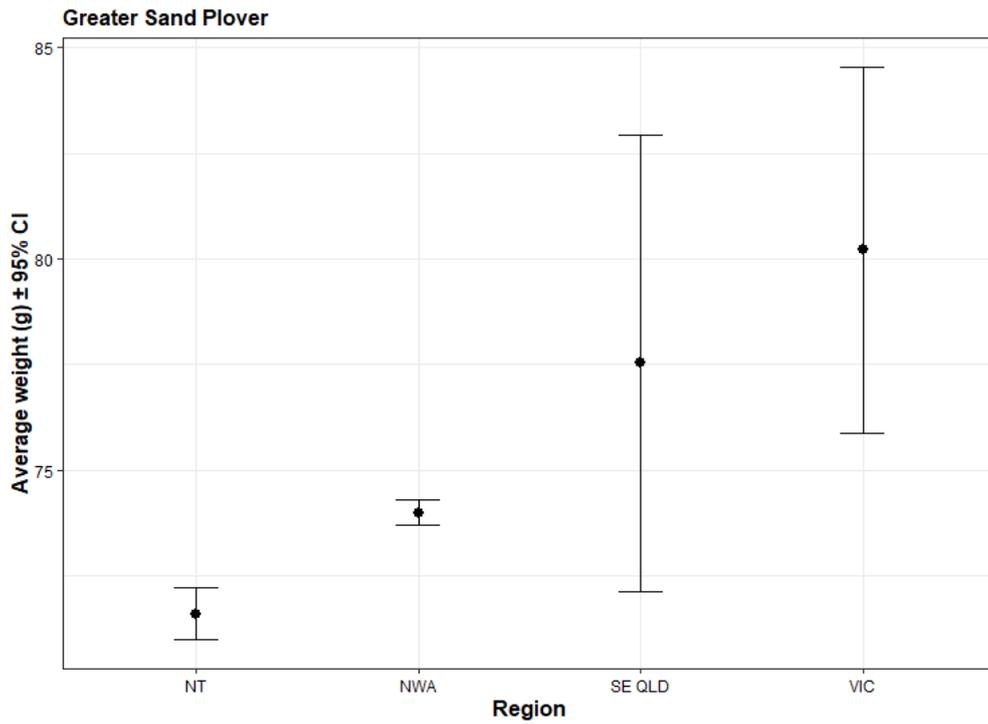Figure S14. Average structural body size (PC1) ± 95% confidence interval of Greater Sand Plovers by region.

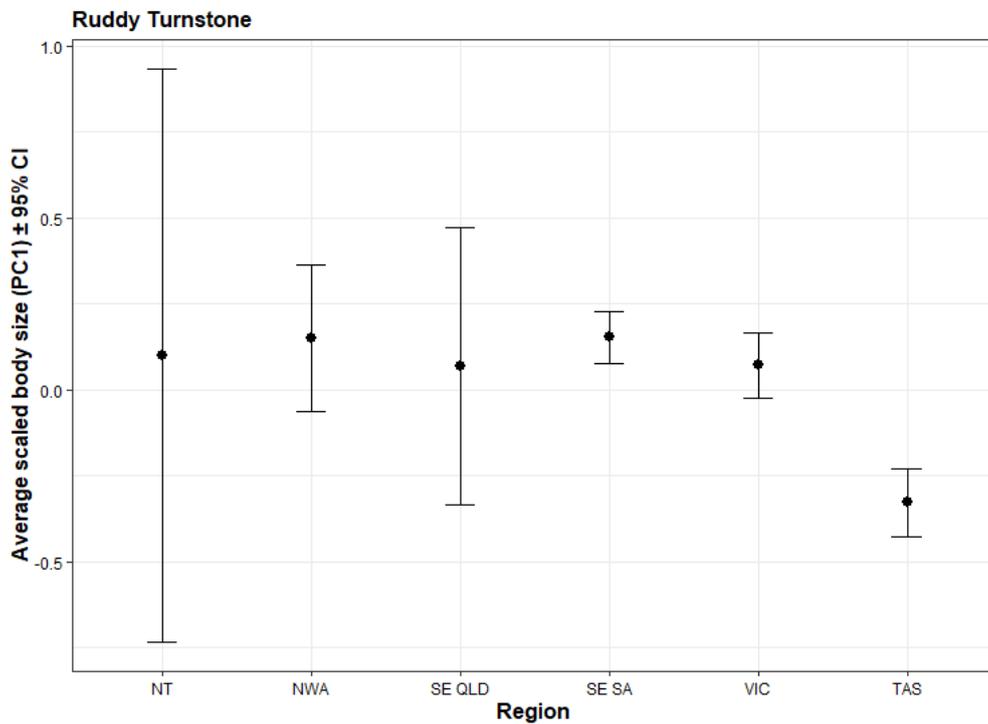Figure S15. Average weight (g) ± 95% confidence interval of Greater Sand Plovers by region.

Figure S16. Average structural body size (PC1) ± 95% confidence interval of Ruddy Turnstone by region.
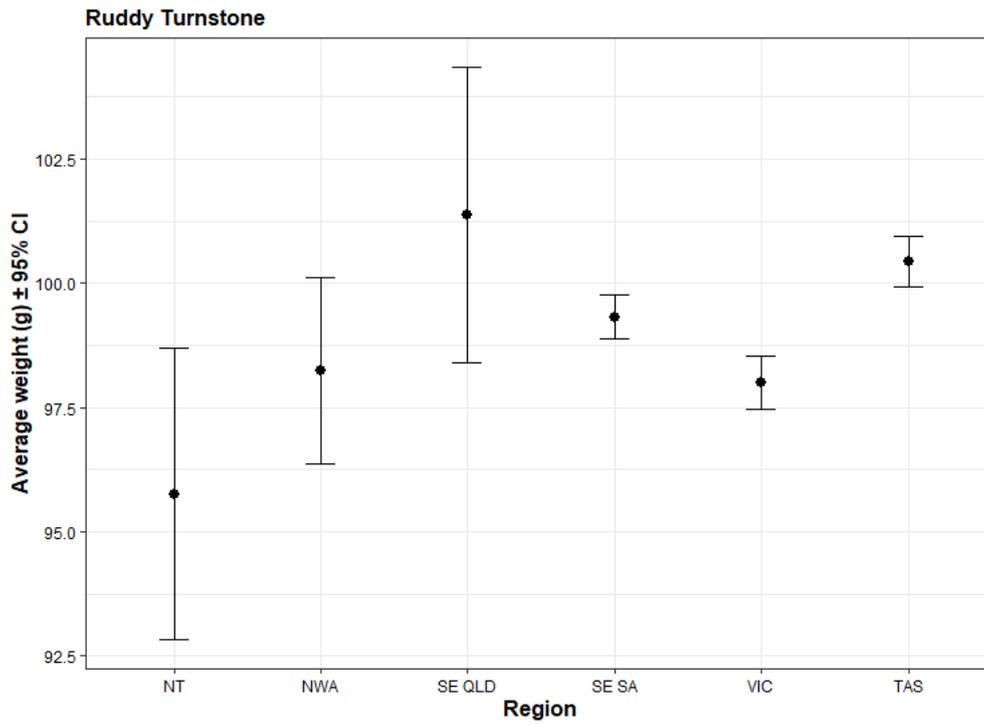
Figure S17. Average weight (g) ± 95% confidence interval of Ruddy Turnstone by region.

Figure S18. Average structural body size (PC1) ± 95% confidence interval of Great Knot by region.

Figure S19. Average weight (g) ± 95% confidence interval of Great Knot by region.
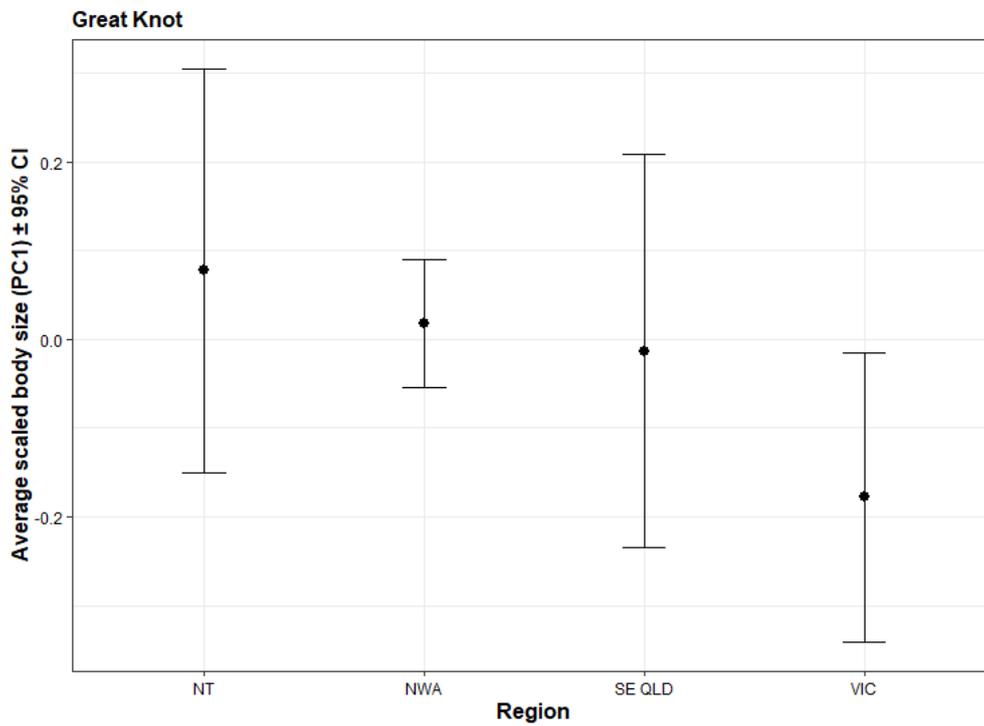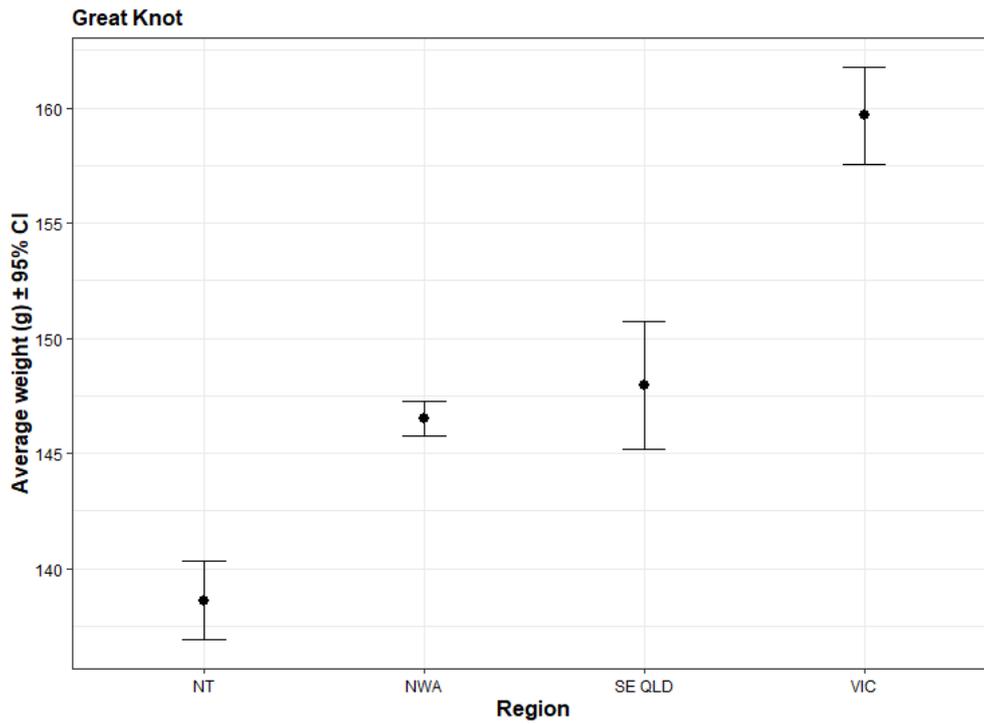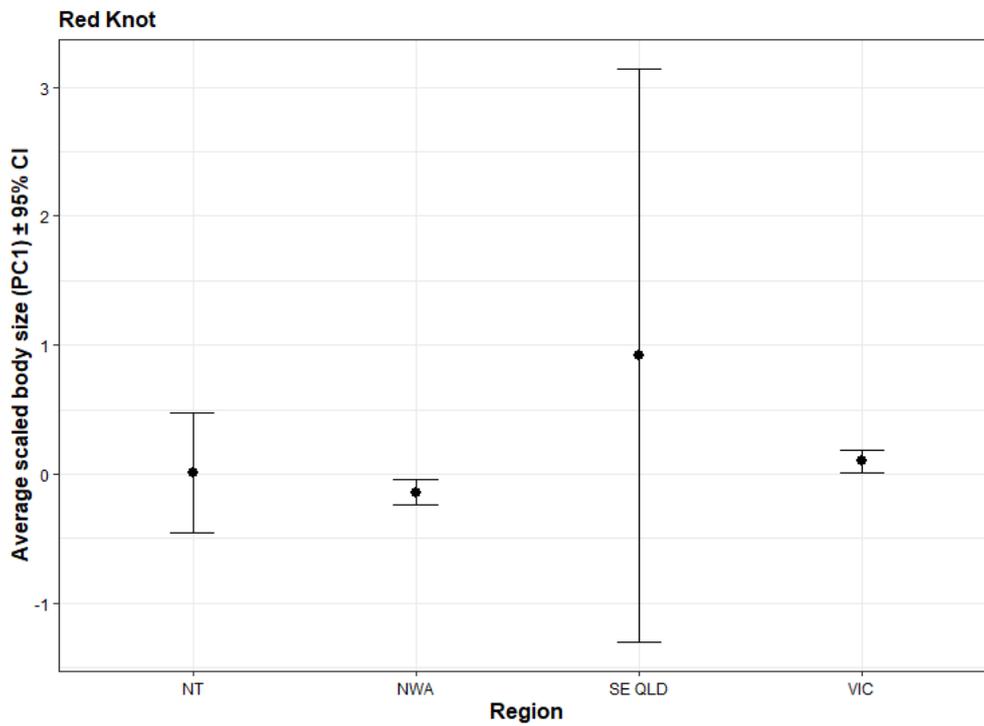

Figure S20. Average structural body size (PC1) ± 95% confidence interval of Red Knot by region.
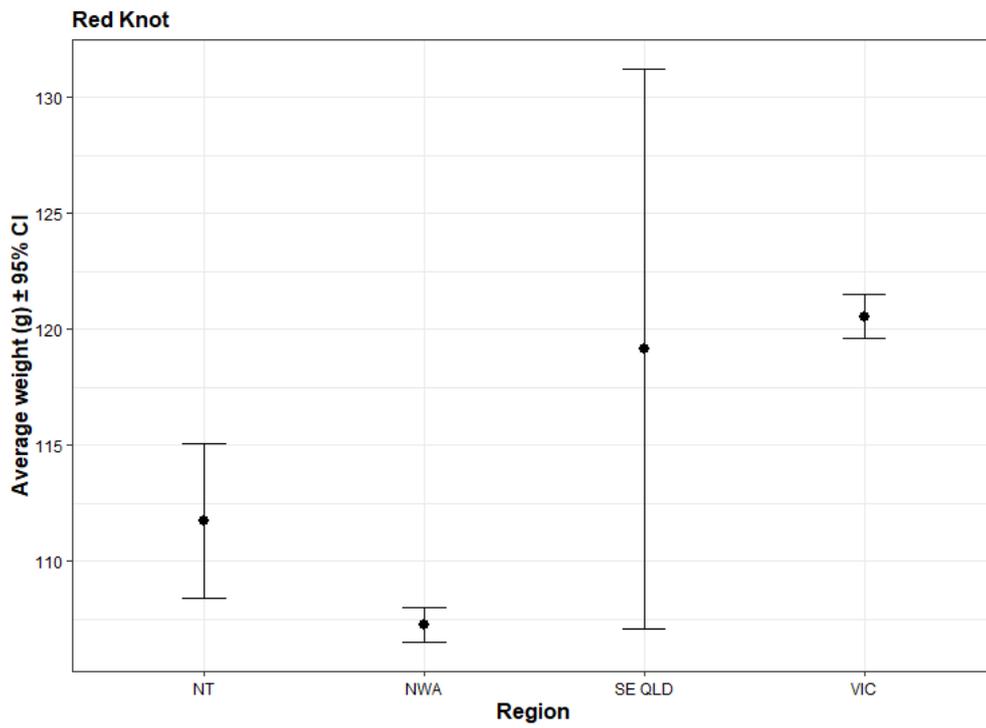
Figure S21. Average weight (g) ± 95% confidence interval of Red Knot by region.

Chapter 3. Supplementary material

Table S1. Number of times the EPBC Act 0.1% (national) and 1% (international) threshold has been met for migratory shorebirds at natural and artificial sites in Darwin, Northern Territory during the study period.

| Threshold | 0.1% | 0.1% | 1% | 1% |
Site class	Natural	Artificial	Natural	Artificial
Bar-tailed Godwit	3	0	0	0
Black-tailed Godwit	28	0	1	0
Common Greenshank	0	6	0	0
Common Sandpiper	0	0	0	0
Curlew Sandpiper	0	0	0	0
Eastern Curlew	4	57	0	0
Great Knot	254	0	33	0
Greater Sand Plover	208	17	1	0
Grey Plover	1	0	0	0
Grey-tailed Tattler	4	17	0	0
Lesser Sand Plover	4	2	0	0
Marsh Sandpiper	0	0	0	0
Oriental Plover	0	0	0	0
Pacific Golden Plover	0	2	0	0
Red Knot	144	2	0	0
Red-necked Stint	1	0	0	0
Ruddy Turnstone	77	0	0	0
Sanderling	154	0	0	0
Sharp-tailed Sandpiper	1	12	0	0
Terek Sandpiper	6	28	0	0
Whimbrel	48	28	0	0

Table S2. Site characteristics of the natural and artificial sites in Darwin Harbour for migratory shorebirds. Area is the available suitable roosting area for shorebirds at tides >6m.

Site class	Site	Habitat type	Area (km^2)
Artificial	East Arm Wharf	dredge ponds	0.117
Natural	Lee Point	sandy beach	0.047
Natural	Spot on Marine	saltpan	0.021
Natural	Nightcliff Rocks	rocky shore	0.013
Natural	East Point	rocky shore	0.018
Natural	Sandy Creek	sandy beach	0.051

Table S3. Count of responses of migratory shorebirds to various disturbance stimuli at four sites from 2014 – 2016 austral summer months. BOP = bird of prey.

Response type => Site	Flight						Non-flight	No response		Total
	Aircraft	BOP	Dog	Human	Human + dog	Unknown	Human	Human	Human + dog	Total
Lee Point		3		8	9		1	4	17	42
Nightcliff Rocks		3		3	1					7
Sandy Creek	2	3	3	6	3	1	4		2	24
Spot on Marine					1		1			2
East Arm Wharf		4				2				6
Total	2	13	3	17	14	3	6	4	19	81
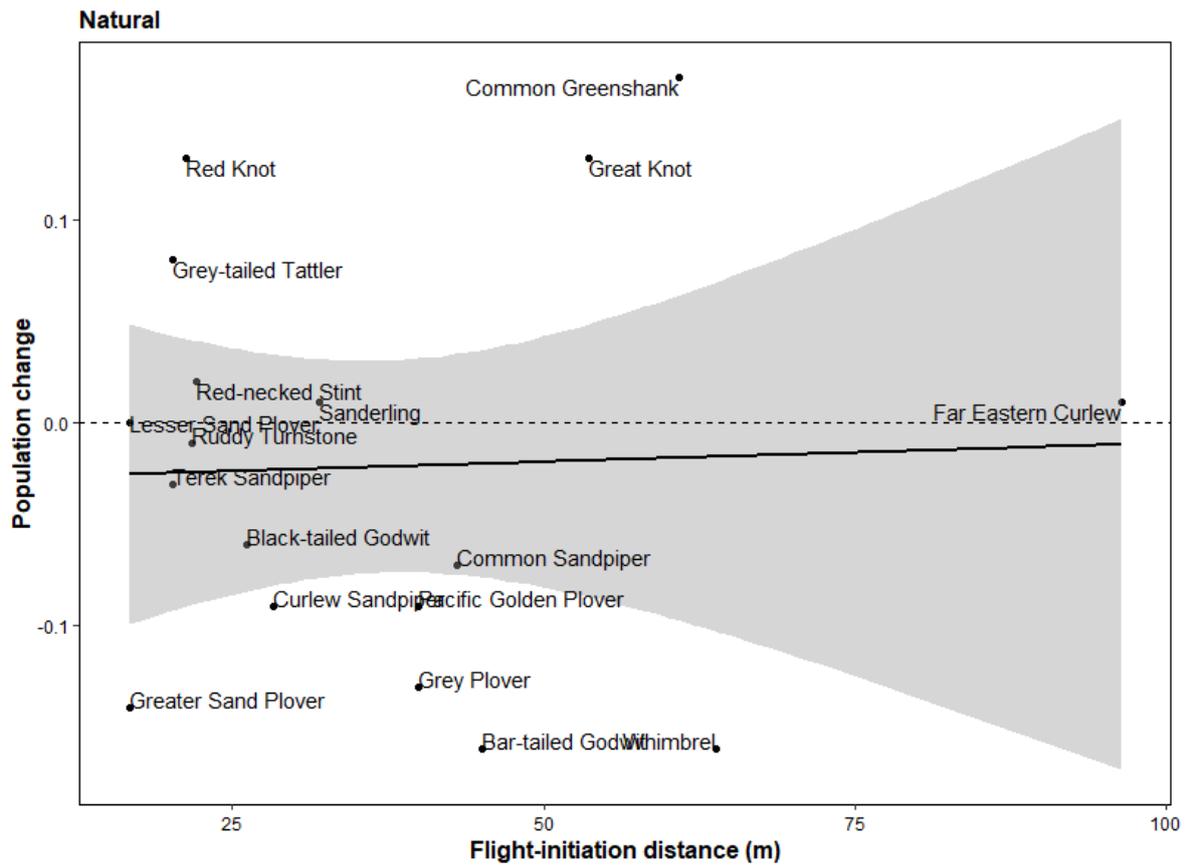
Figure S1. Relationship between population change of each species and flight-initiation distance at natural sites in Darwin Harbour. Dashed line shows a stable population change rate, values above or below indicate the species population increase or decrease, respectively.
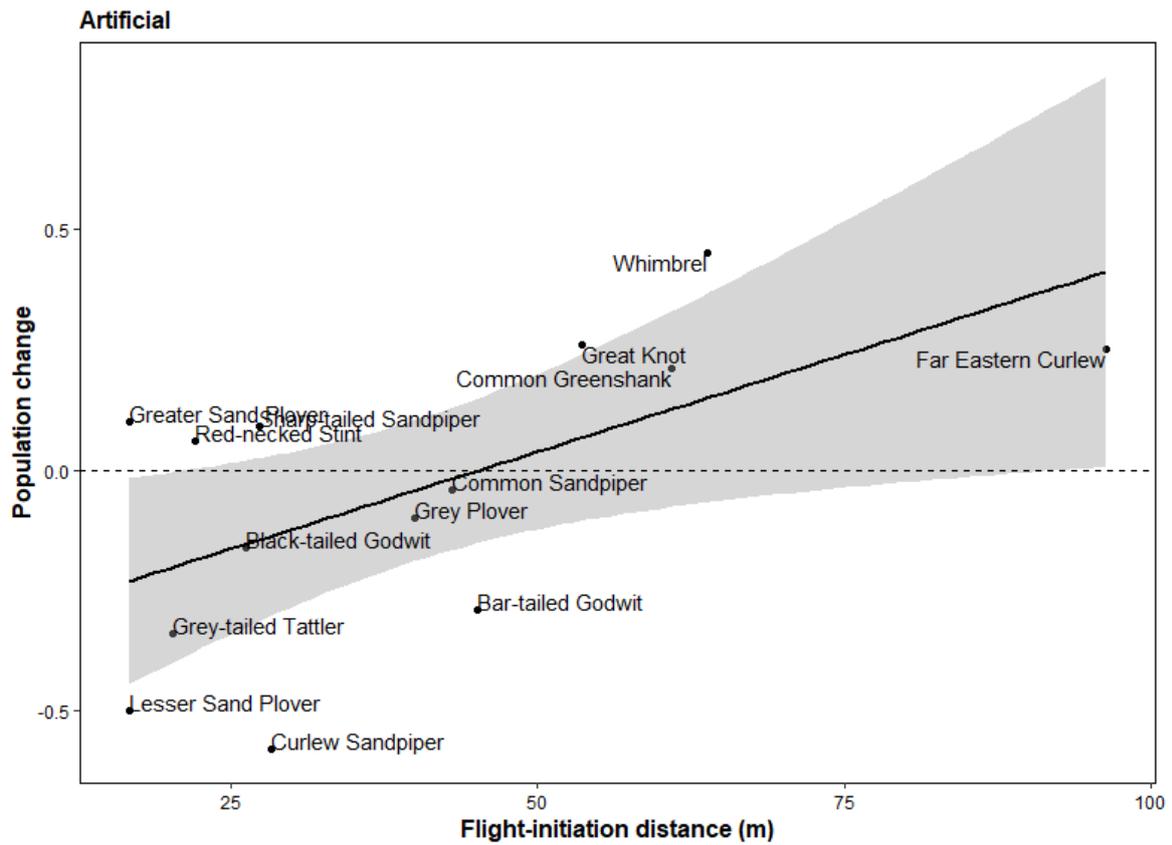
Figure S2. Relationship between population change of each species and flight-initiation distance at the artificial site in Darwin Harbour. Dashed line shows a stable population change rate, values above or below indicate the species population increase or decrease, respectively.

Figures S3 – 31. Shorebird species trends graphs (presented by site class and then by alphabetical order).

Natural sites:

Bar-tailed Godwit

Black-tailed Godwit

Common Greenshank

Common Sandpiper

Curlew Sandpiper

Far Eastern Curlew

189

Great Knot

Greater Sand Plover

Grey Plover

Grey-tailed Tattler

191

Lesser Sand Plover

Pacific Golden Plover
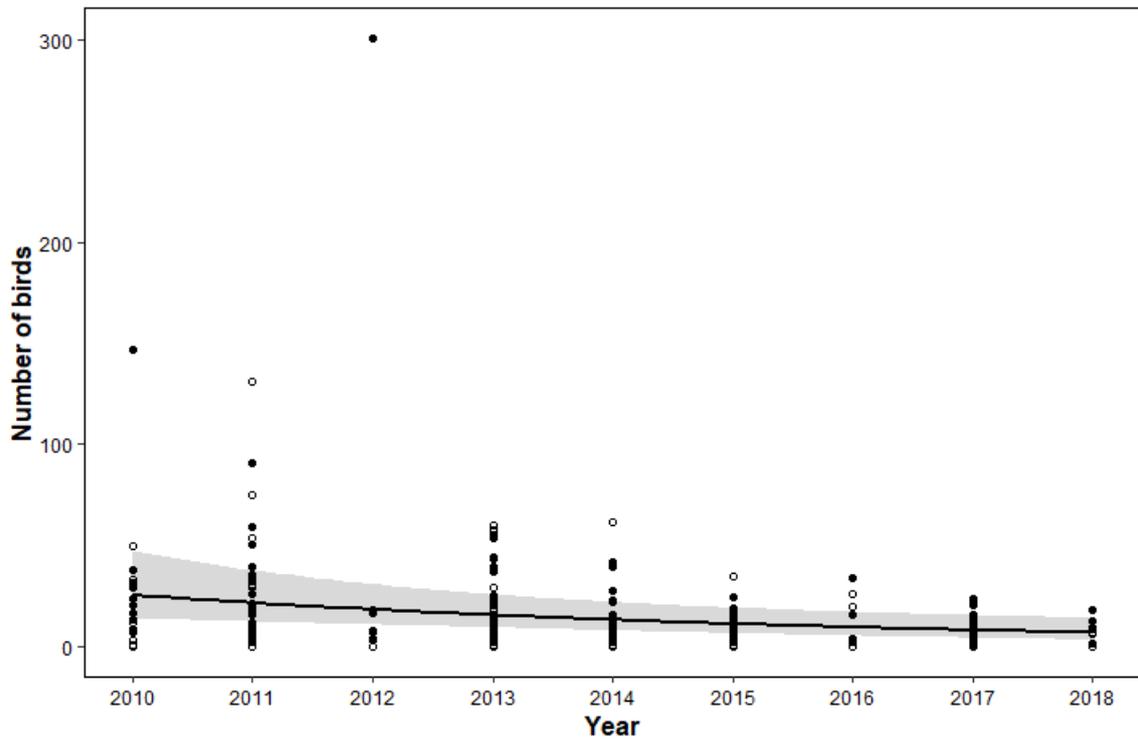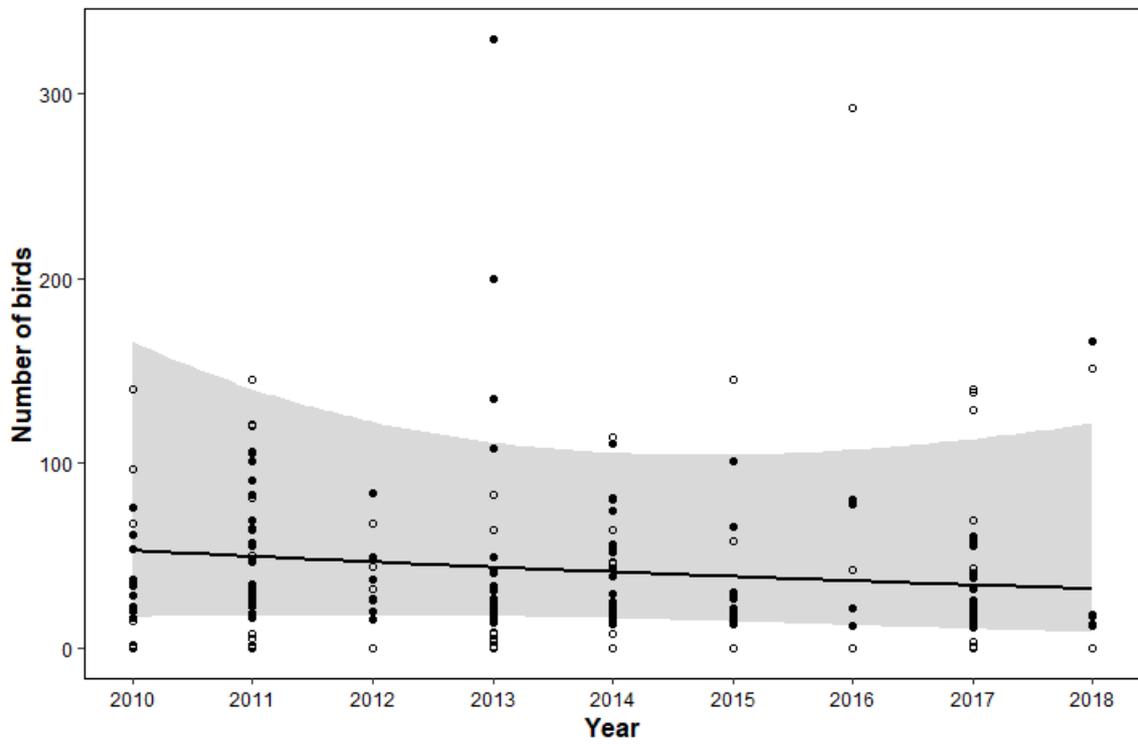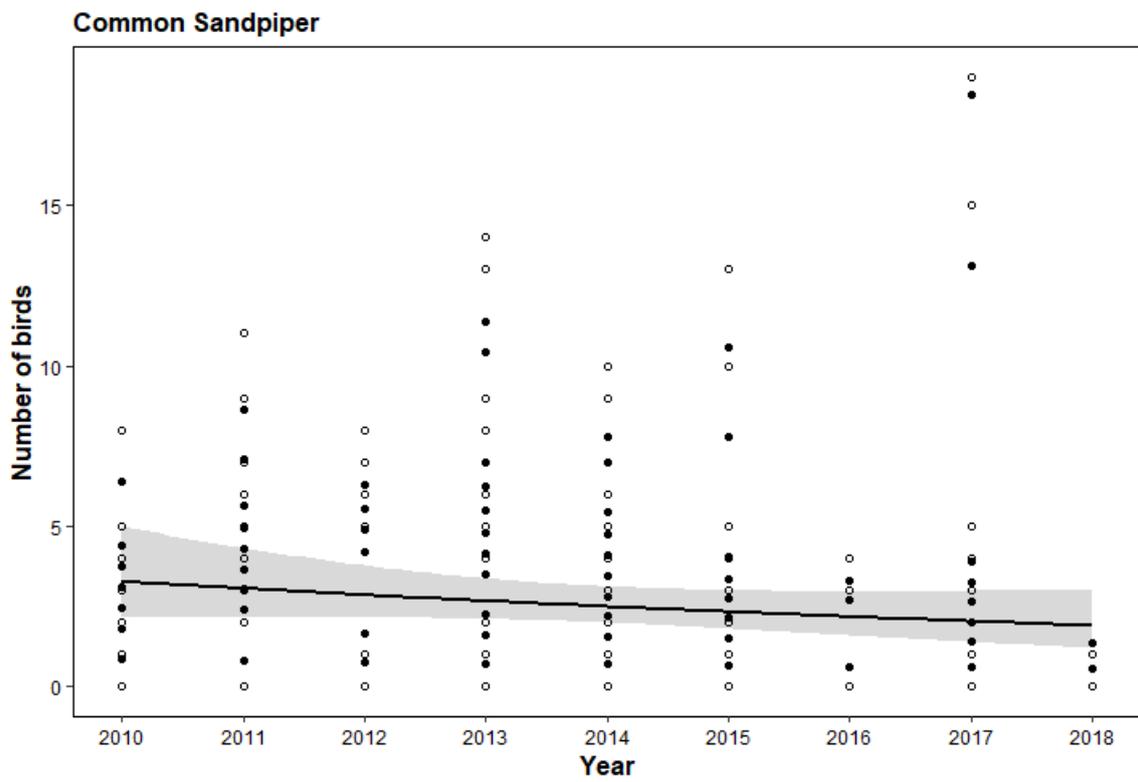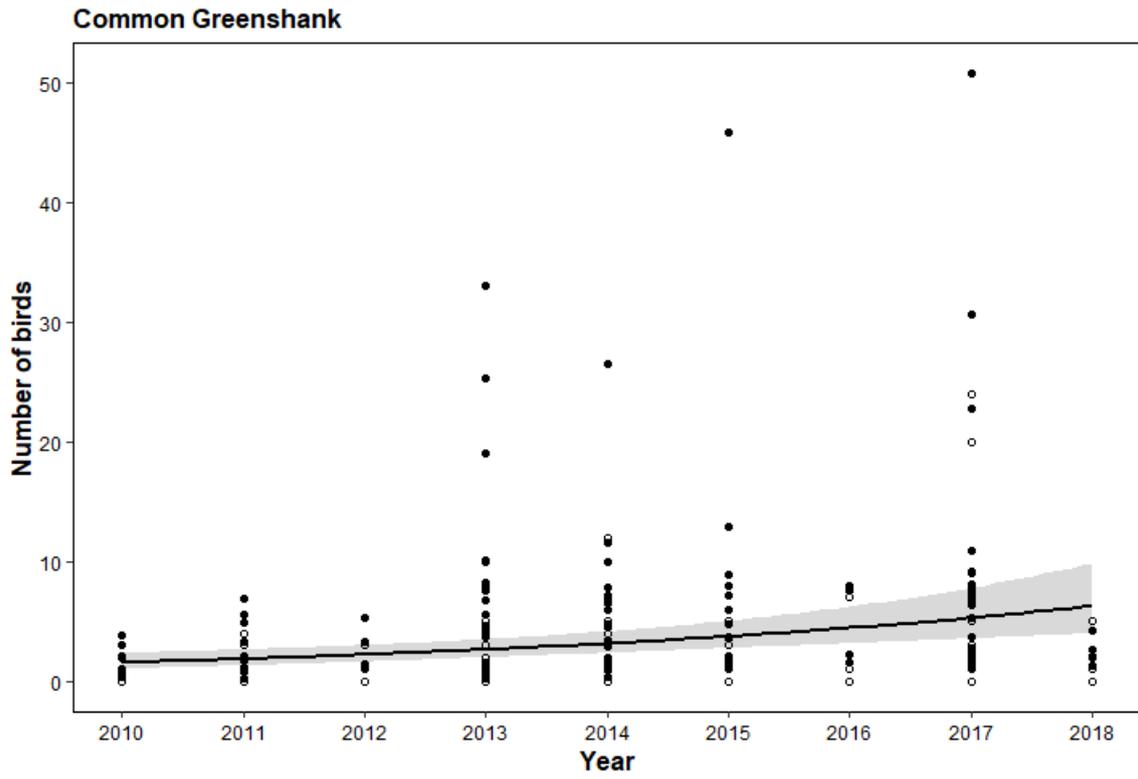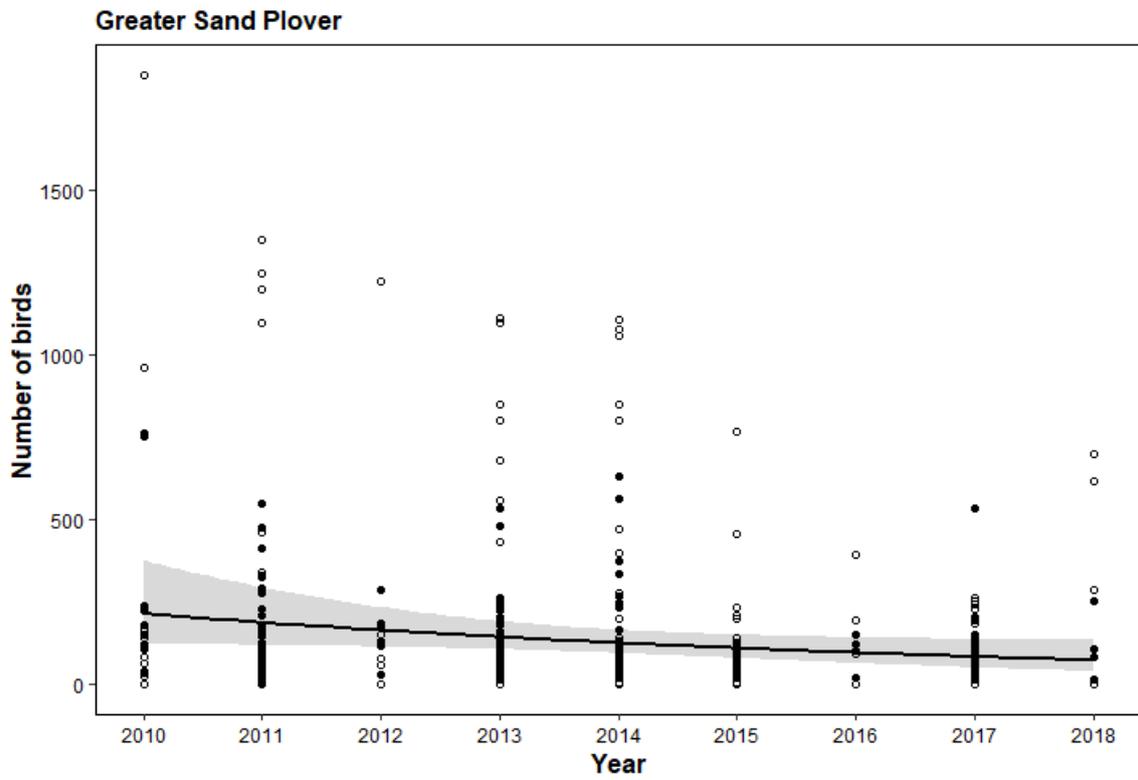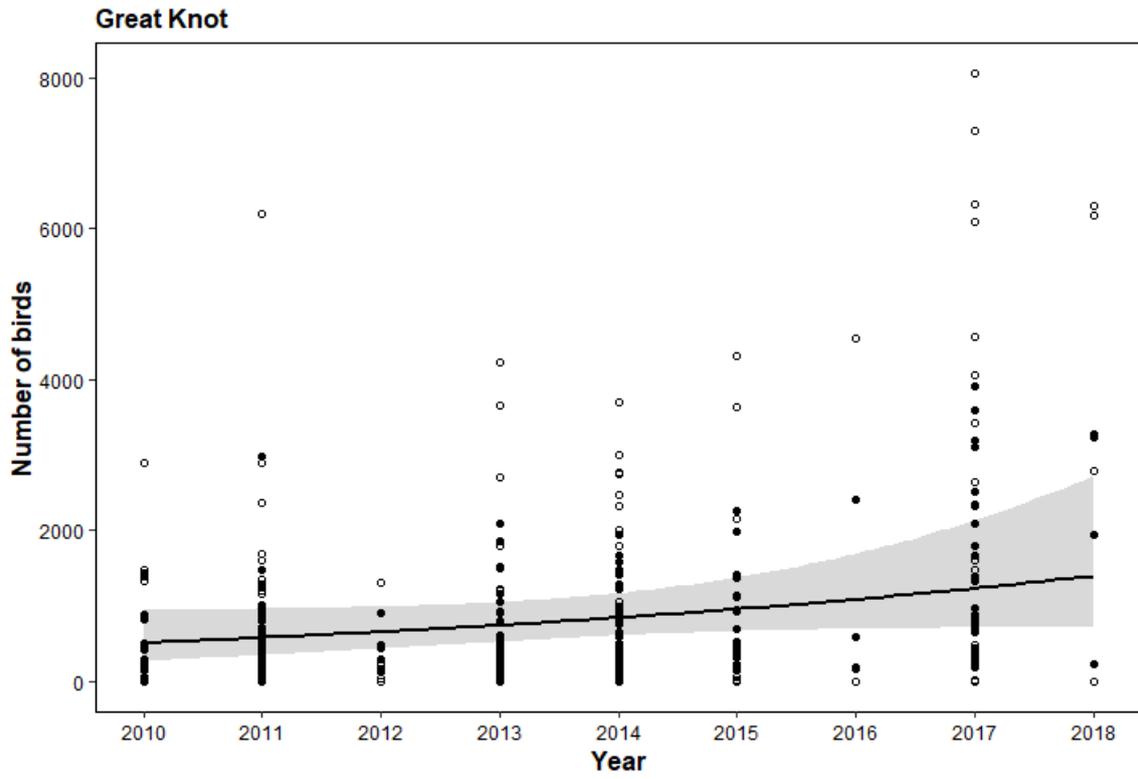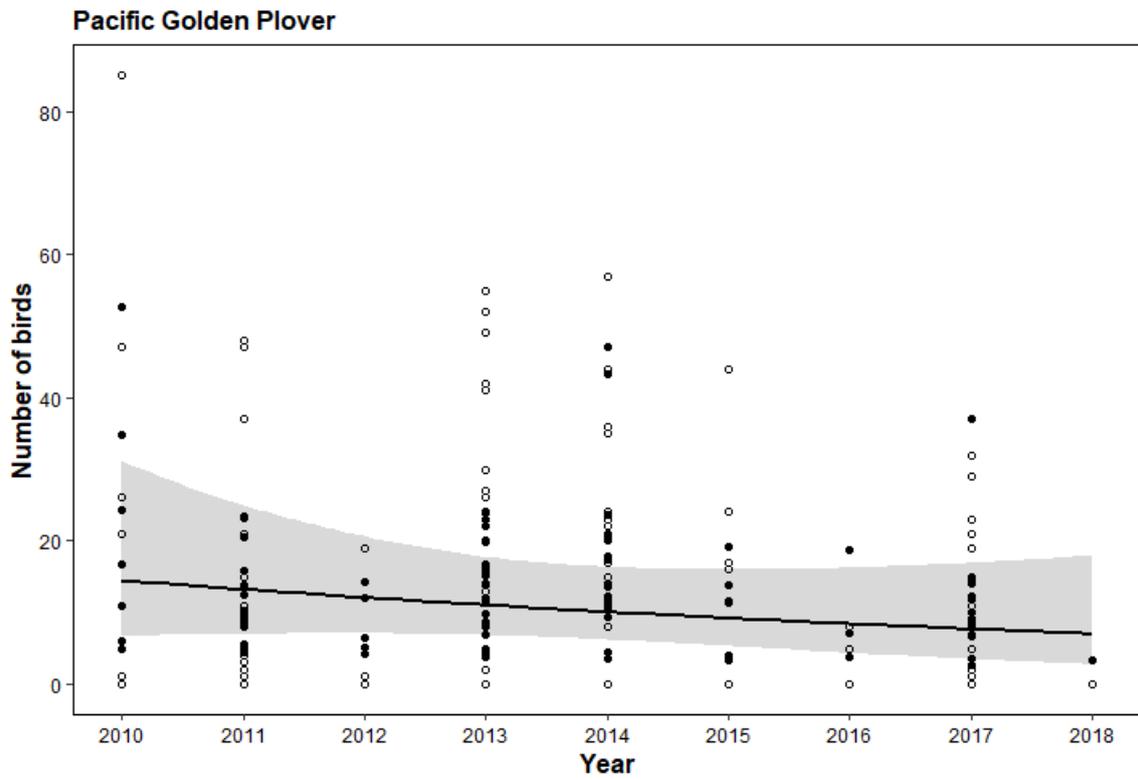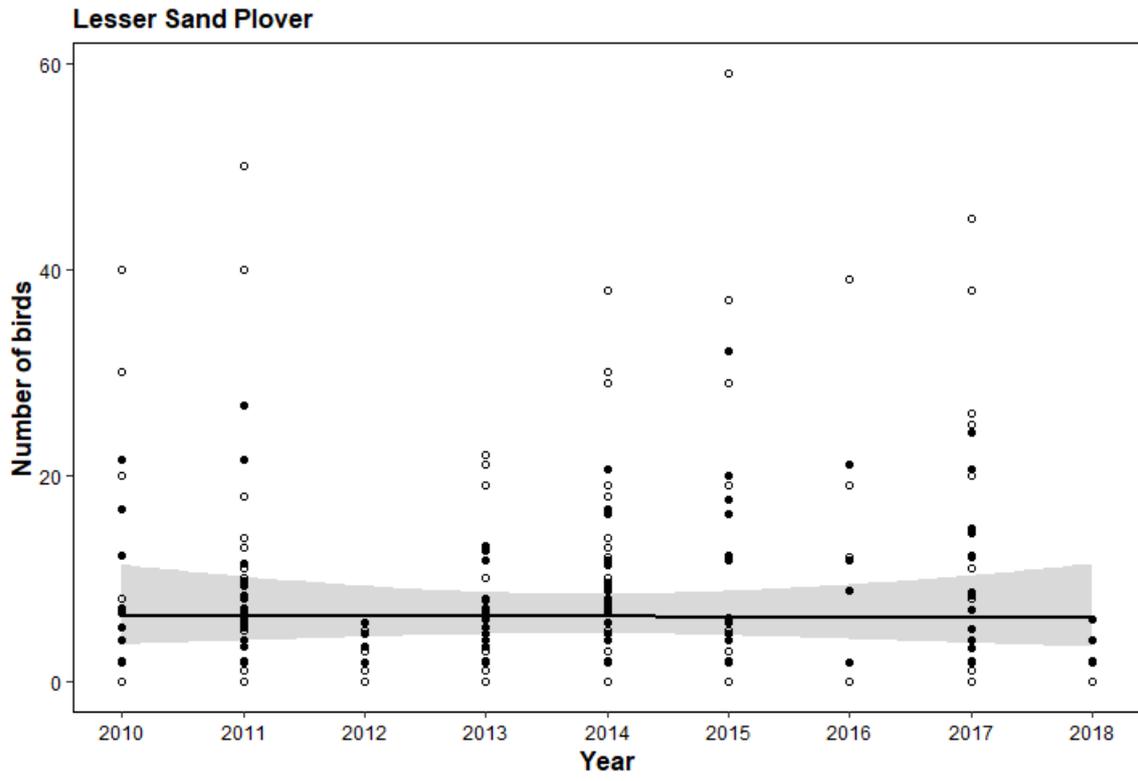
Red-necked Stint

Ruddy Turnstone

Sanderling

Terek Sandpiper

Whimbrel

Artificial site:

Bar-tailed Godwit

Black-tailed Godwit

Common Greenshank

Common Sandpiper

Curlew Sandpiper

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Far Eastern Curlew

Great Knot

Grey Plover
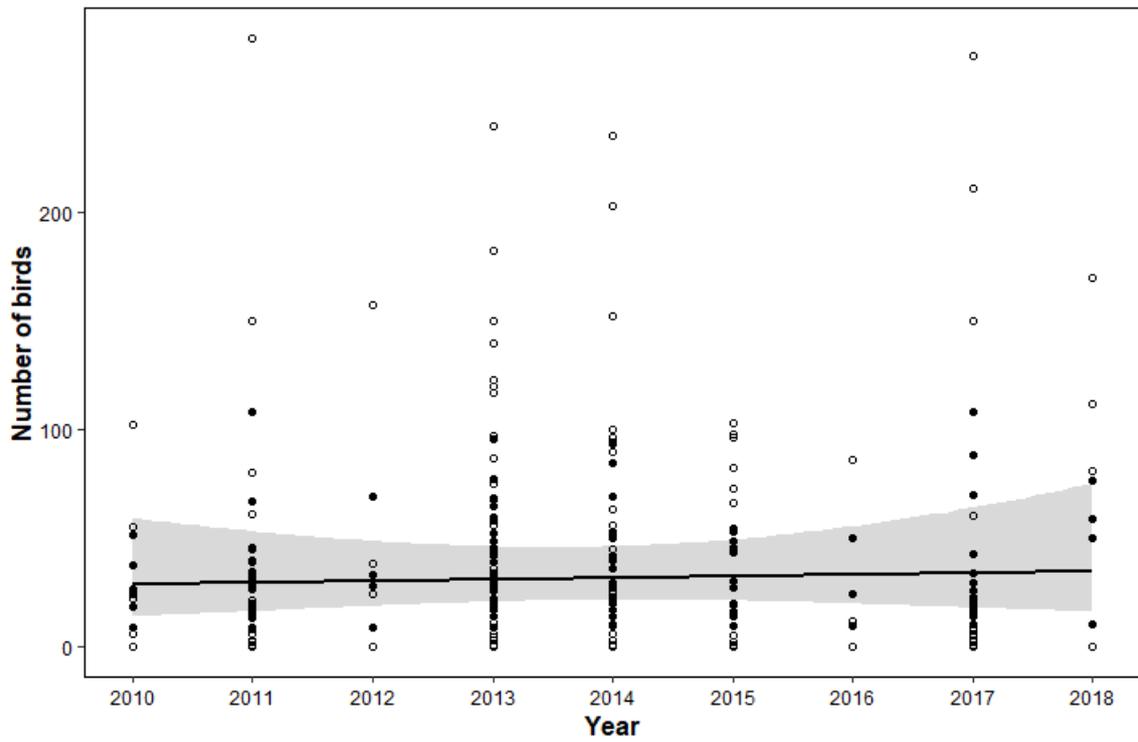
Greater Sand Plover
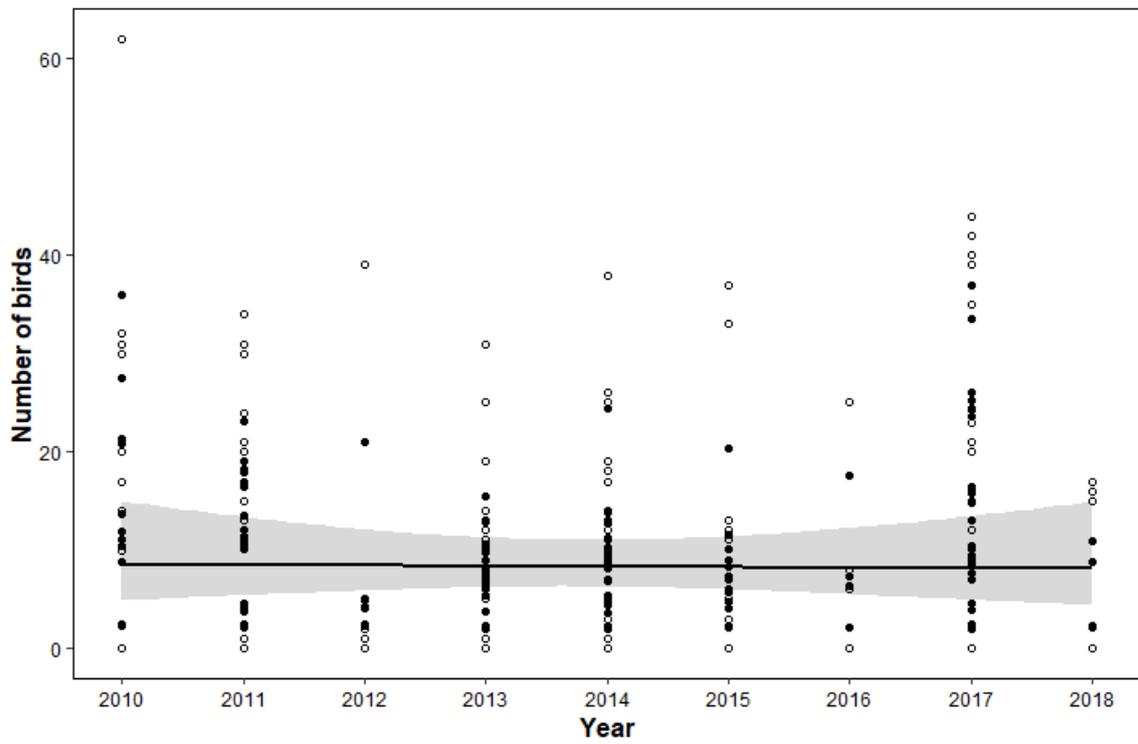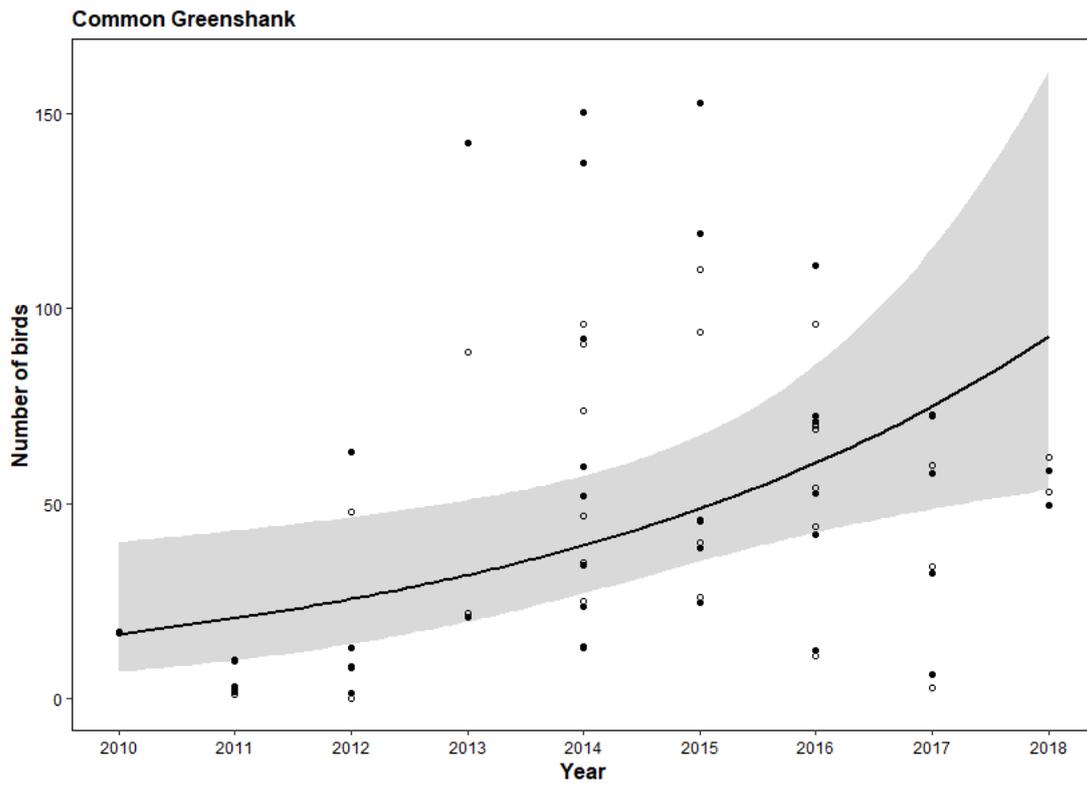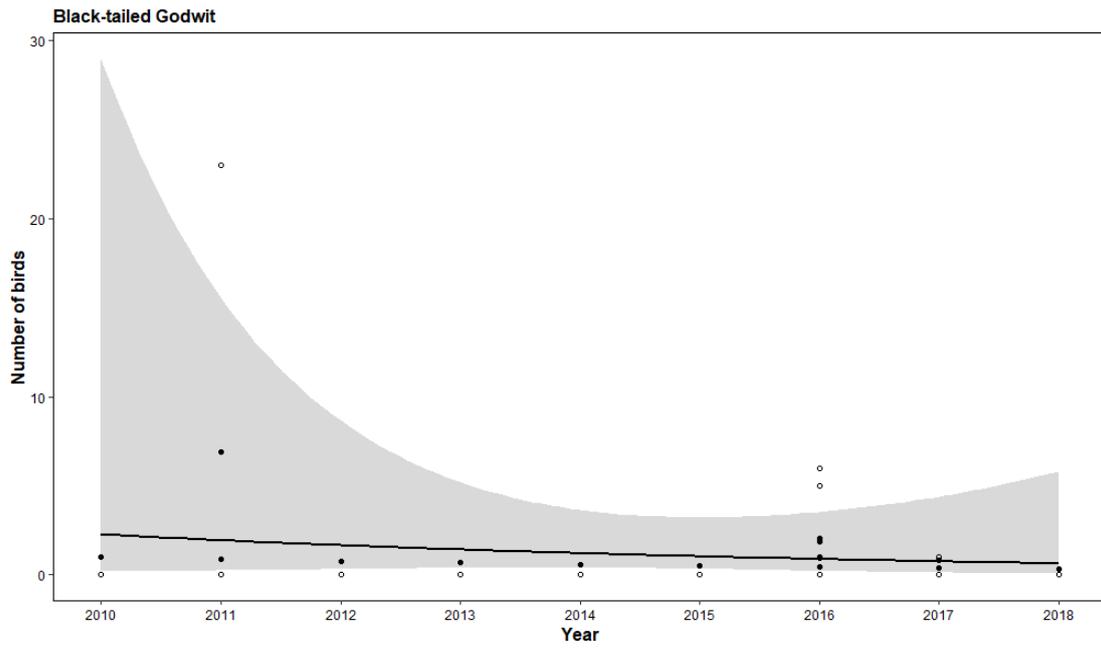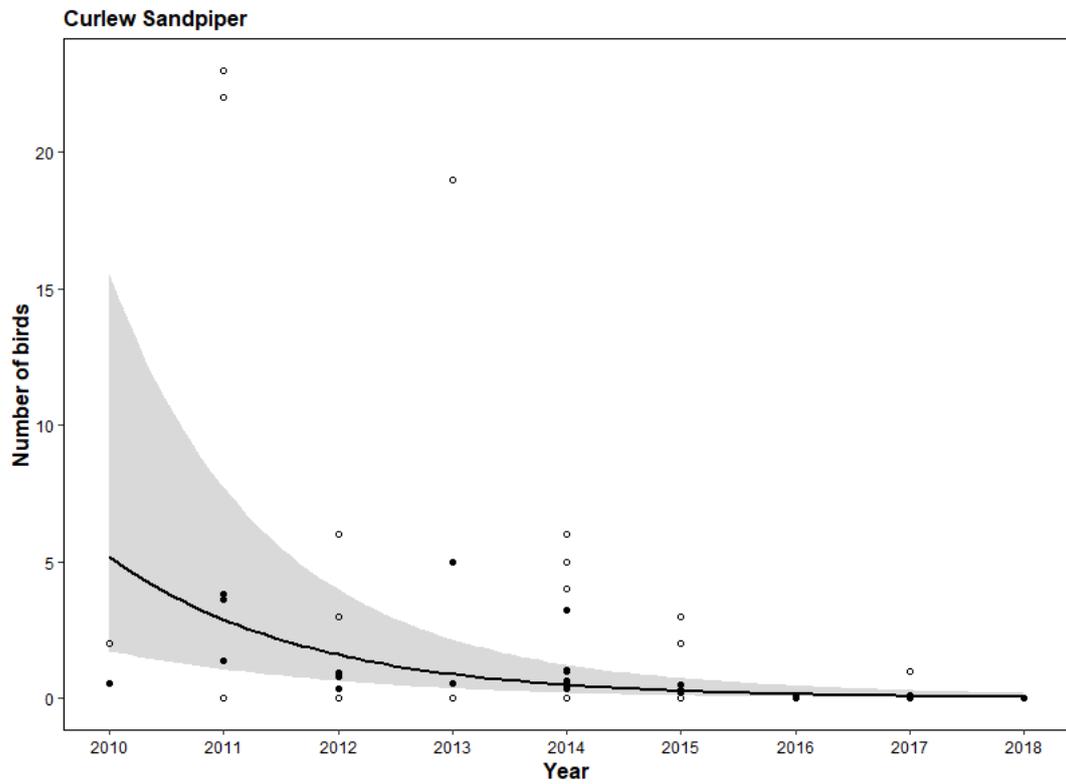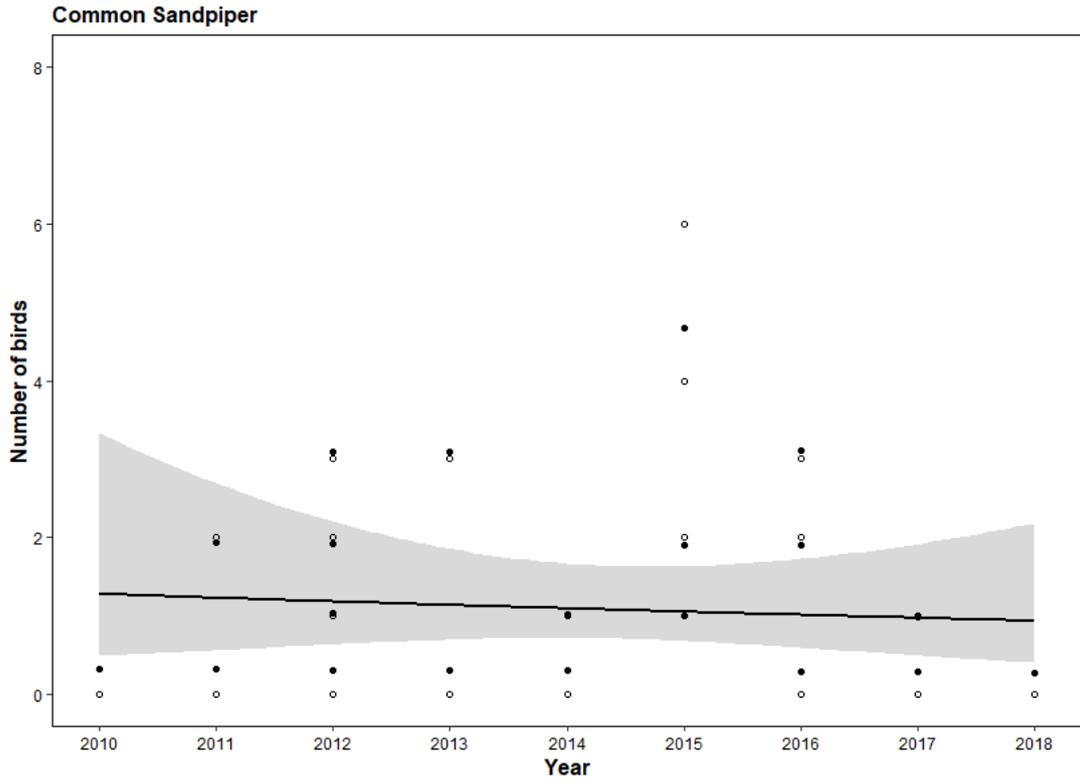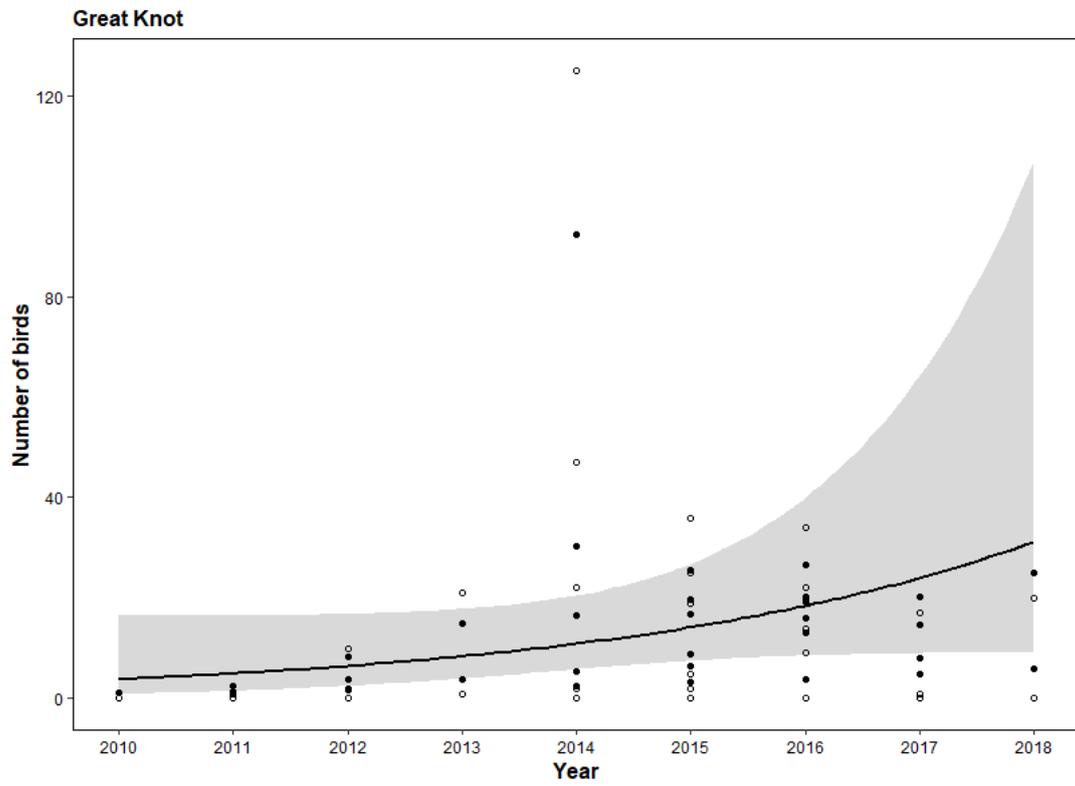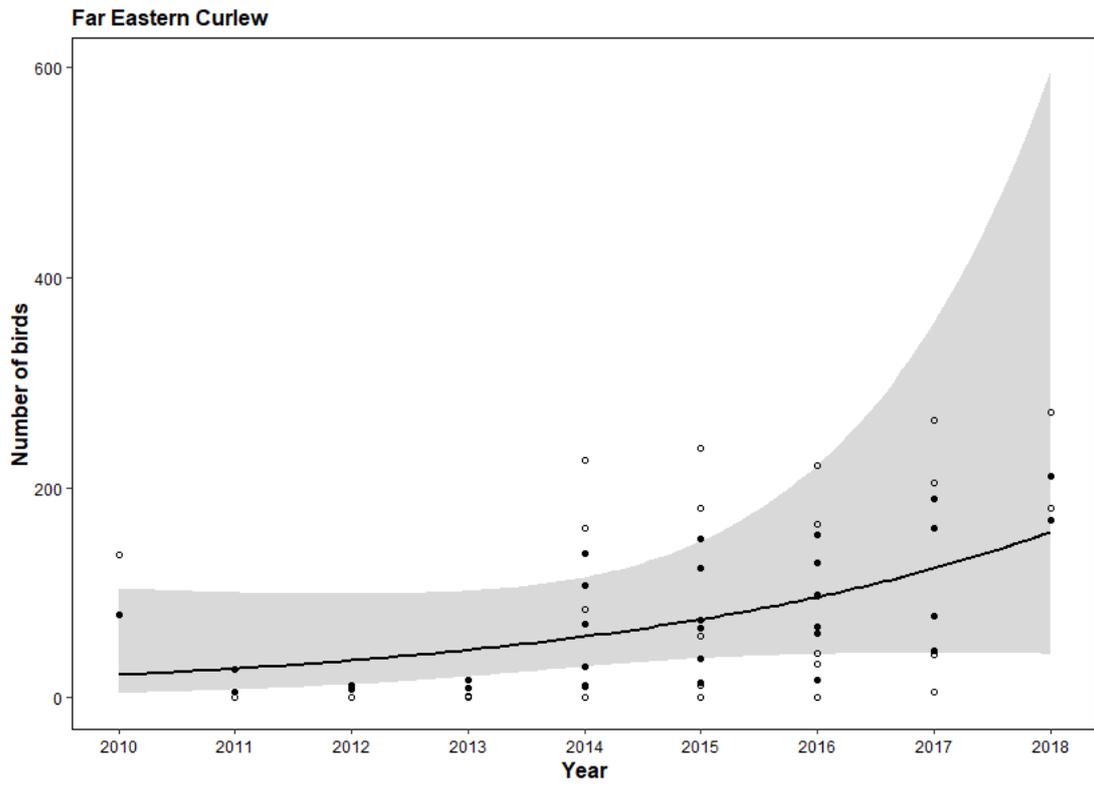
Grey-tailed Tattler

Lesser Sand Plover

Red-necked Stint
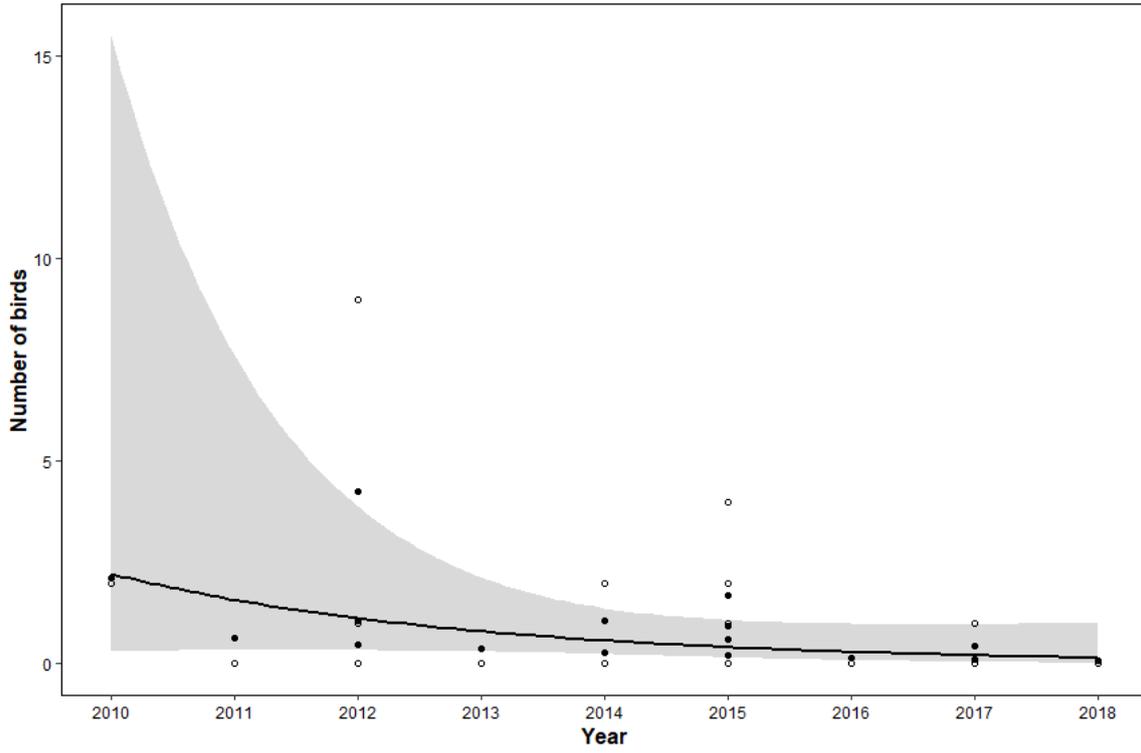
Sharp-tailed Sandpiper
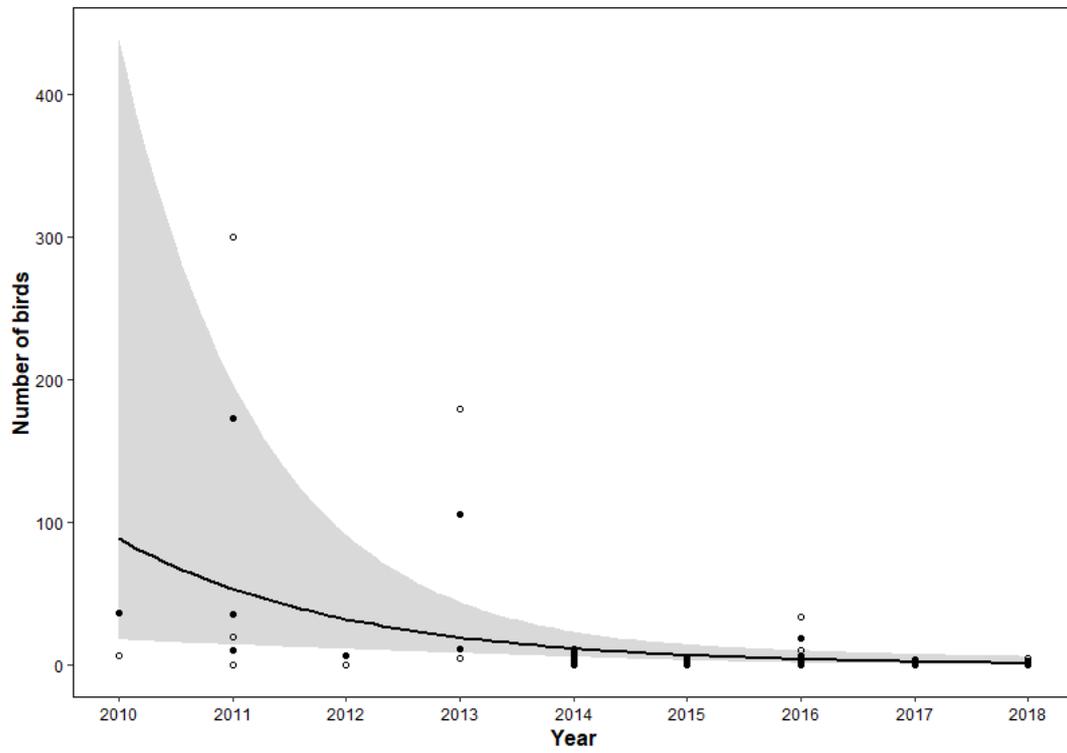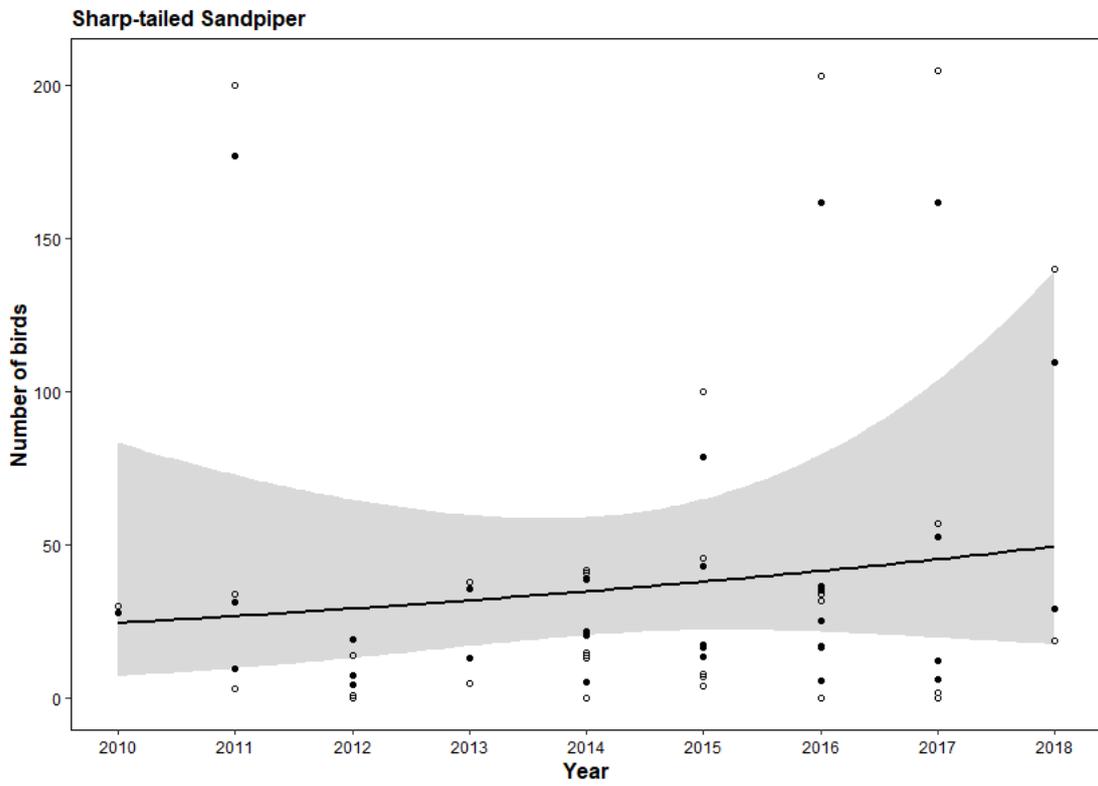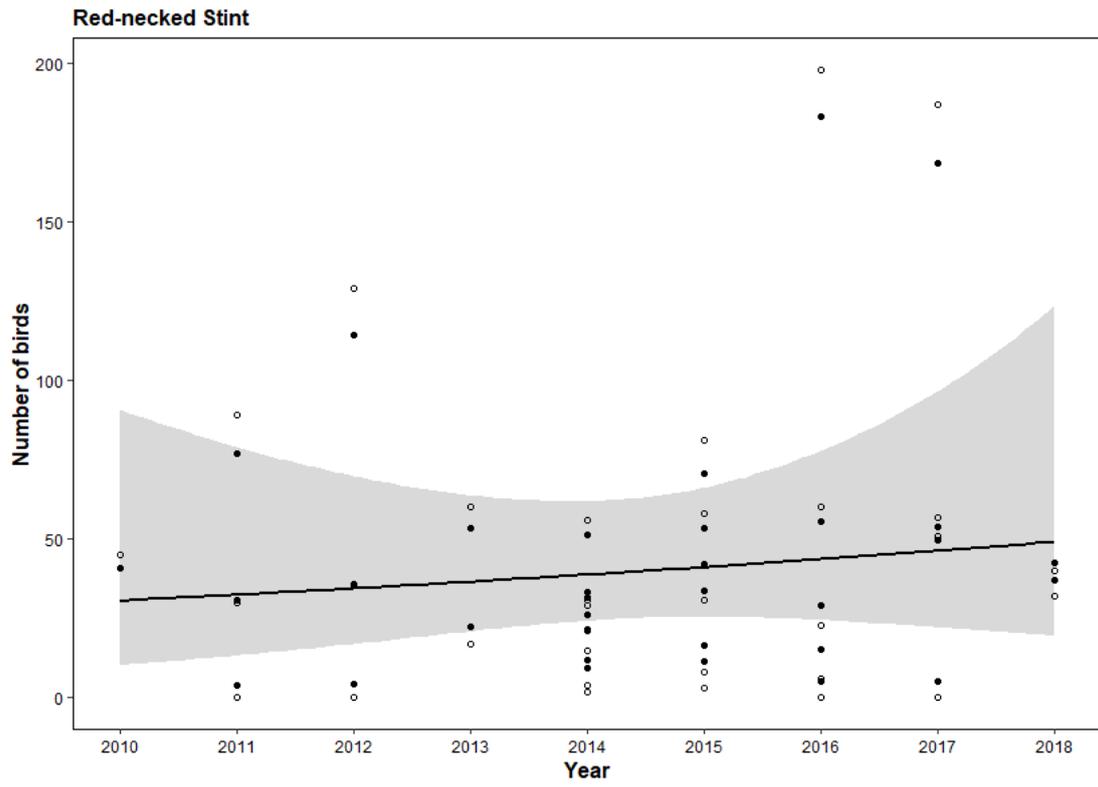
Whimbrel
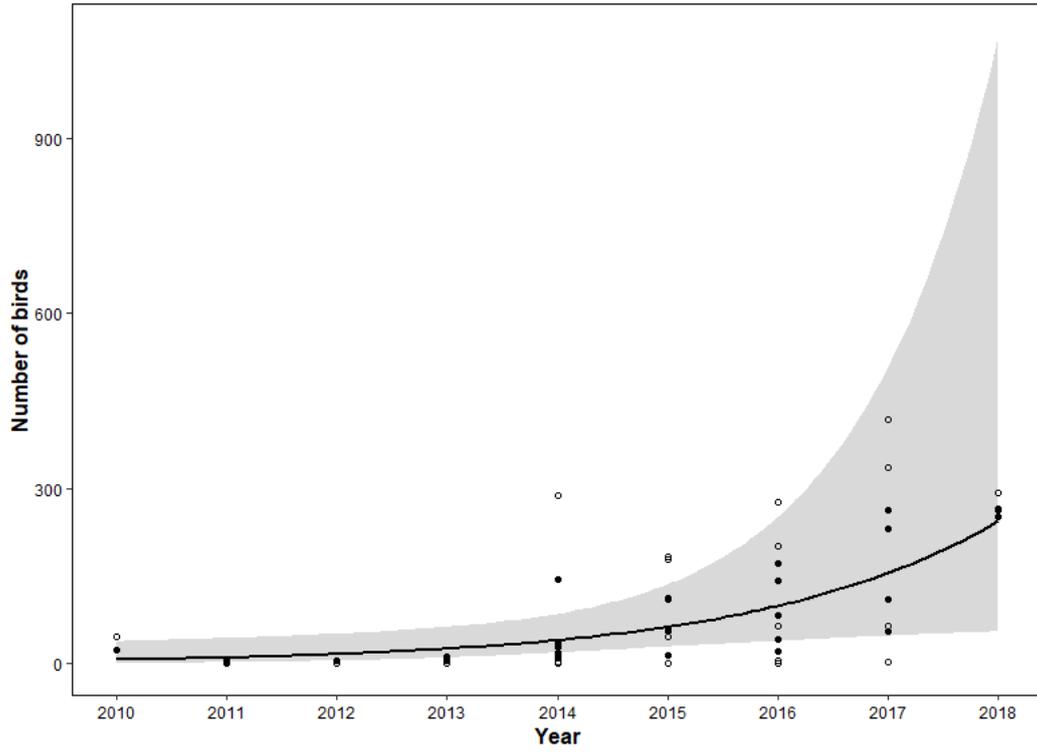
Chapter 4. Supplementary material

Table S1. Table of all individually marked Great Knots in Darwin Harbour from catching sessions in 2014 and 2015, and the maximum and average distance moved (km) with standard deviation.
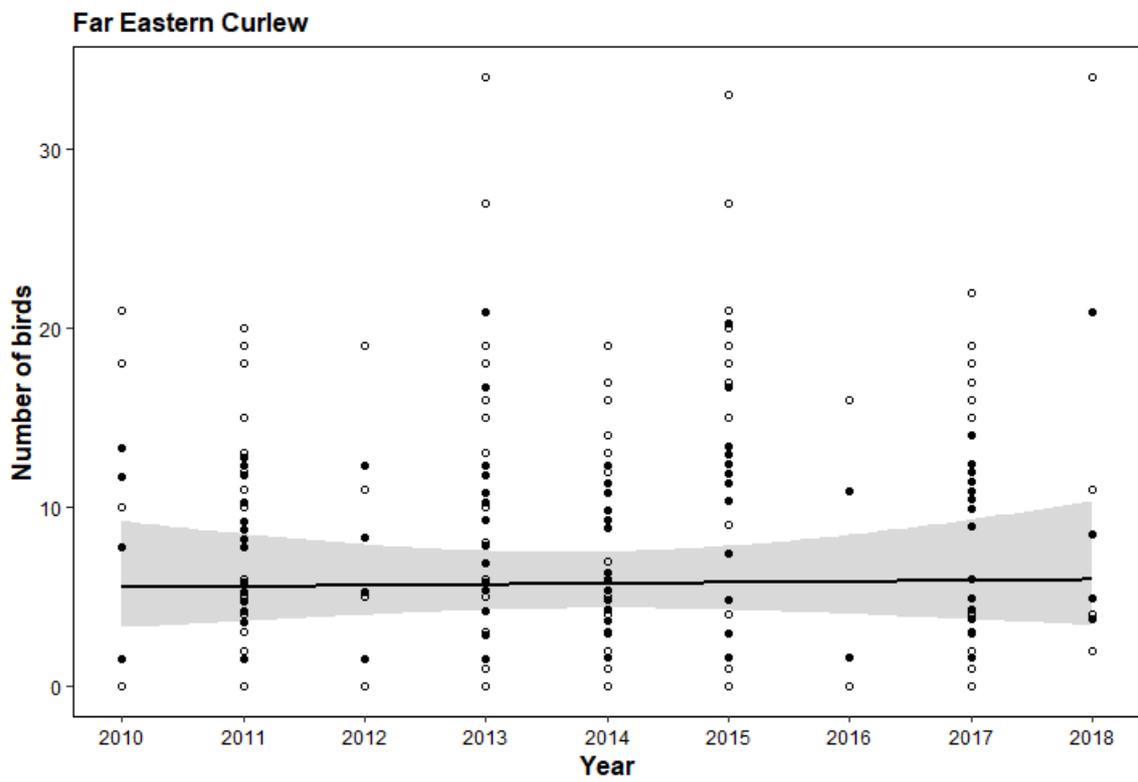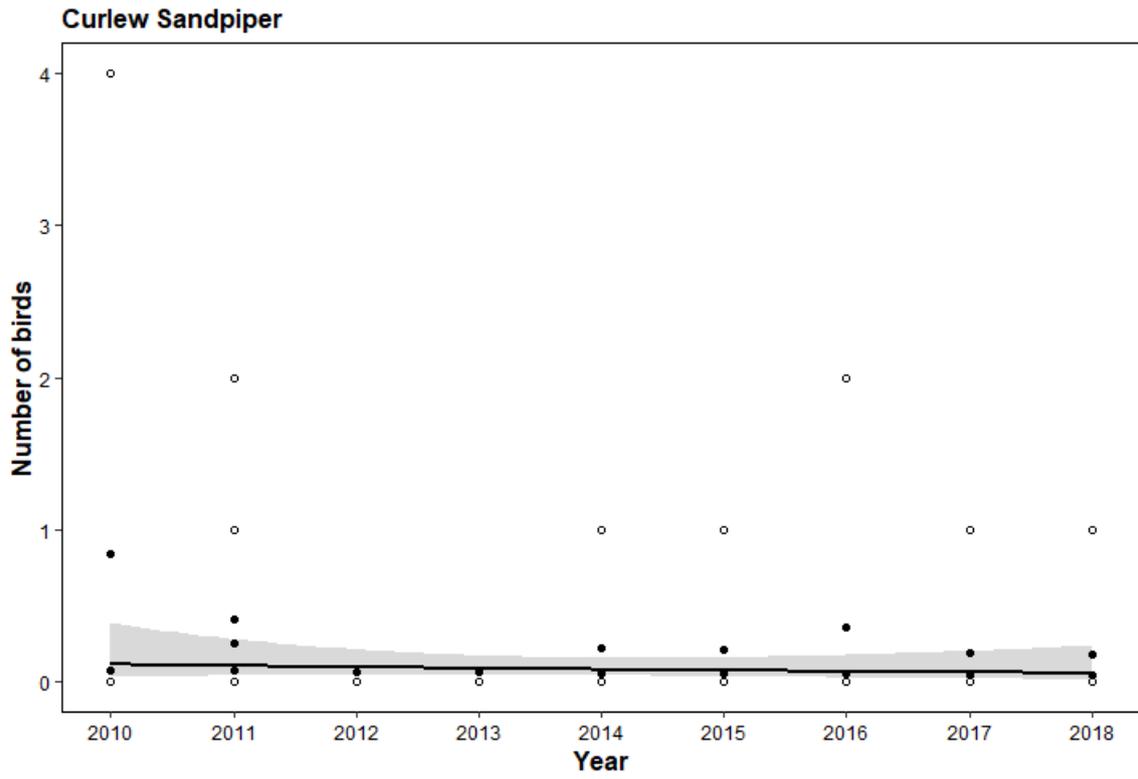
Engraved leg flag	Maximum distance moved (km)	Average distance moved (km)	Standard deviation distance moved (km)
12	12.6	4.2	5.1
13	9.7	3.5	3.5
14	8.5	2.7	2.9
15	8.5	3.3	3.6
16	8.5	1.9	1.9
17	8.5	2.4	2.7
20	12.6	3.6	5.1
21	1	1.0	0.0
22	12.6	5.7	5.3
23	2.2	1.9	0.6
24	12.6	3.0	3.5
25	2.2	1.5	0.7
26	12.6	6.0	5.5
27	8.5	4.5	3.7
28	12.6	6.3	4.7
29	12.6	3.5	4.3
30	8.5	3.8	3.5
31	12.6	12.6	NA
32	12.6	4.0	4.4
33	8.5	2.1	2.8
34	8.5	1.9	2.0
39	8.5	8.5	NA
40	1	1.0	0.0
41	1	1.0	0.0
42	1	1.0	0.0
43	1	1.0	0.0
44	1	1.0	0.0
45	1	1.0	NA
46	2.2	2.2	NA
51	12.6	8.4	5.3
58	12.6	6.1	5.6
59	12.6	3.8	4.4
60	8.5	3.0	3.4
63	12.6	3.7	4.4
64	2.2	1.3	0.6
65	12.6	4.8	4.3
66	12.6	3.5	4.0

67	12.6	4.5	4.2
68	12.6	3.1	3.9
69	12.6	4.1	4.7
70	12.6	7.5	4.9
72	8.5	3.2	3.6
73	12.6	6.3	5.6
74	12.6	6.2	4.5
75	12.6	3.9	5.8
76	17.2	6.0	6.1
77	12.6	3.3	3.8
78	8.5	4.7	3.5
79	2.2	1.5	0.6
80	2.2	1.8	0.7
81	8.5	2.8	2.7
82	1	1.0	NA
83	12.6	4.2	4.4
84	12.6	4.3	4.3
85	2.2	1.6	0.6
86	9.7	3.5	3.4
88	8.5	1.9	1.8
89	8.5	3.6	3.2
90	1	1.0	0.0
91	2.2	1.6	0.7
92	12.6	4.1	4.1
93	8.5	2.6	2.7
94	2.2	1.6	0.8
95	1	1.0	0.0
97	2.2	1.7	0.6
98	2.2	1.9	0.6
99	8.5	2.7	2.9
A0	8.5	8.5	NA
A1	12.6	4.1	3.9
A2	1	1.0	0.0
A3	2.2	2.2	NA
A4	1	1.0	NA
A5	2.2	1.6	0.8
A6	1	1.0	NA
A7	1	1.0	NA
A9	1	1.0	NA
AA	2.2	1.5	0.6
AB	12.6	6.0	4.6
AC	1	1.0	NA
AD	12.6	2.3	3.3
AE	12.6	5.7	4.6
AH	8.5	4.5	3.7

AJ	2.2	1.2	0.5
AK	8.5	5.2	3.7
AL	8.5	2.9	3.8
AM	8.5	2.9	2.8
AN	1	1.0	NA
AP	12.6	2.7	3.8
AR	12.6	5.7	6.0
AT	9.7	3.6	3.7
AU	12.6	5.3	5.0
AV	12.6	4.2	4.0
AW	12.6	5.3	6.4
AX	12.6	6.0	5.2
AY	1	1.0	0.0
AZ	2.2	1.4	0.7
B1	1	1.0	0.0
B2	2.2	1.3	0.6
B3	2.2	1.2	0.5
B4	1	1.0	NA
B6	1	1.0	0.0
B8	1	1.0	NA
B9	12.6	5.3	6.4
BA	1	1.0	0.0
BB	2.2	1.3	0.6
BC	2.2	1.4	0.7
BD	2.2	1.4	0.7
BE	1	1.0	0.0
BH	2.2	1.6	0.8
BJ	1	1.0	NA
BK	12.6	2.9	4.7
BM	1	1.0	0.0
BN	1	1.0	NA
BP	1	1.0	0.0
BR	1	1.0	0.0
BS	1	1.0	NA
BT	1	1.0	0.0
BU	1	1.0	0.0
BW	1	1.0	0.0
BX	2.2	1.6	0.8
C0	1	1.0	NA
C1	1	1.0	0.0
C2	8.5	4.8	5.3
C3	1	1.0	0.0
C4	1	1.0	0.0
C5	1	1.0	NA
C6	12.6	6.1	5.9

C7	1	1.0	NA
C8	1	1.0	0.0
C9	1	1.0	0.0
CA	1	1.0	0.0
CC	1	1.0	NA
CD	1	1.0	0.0
CE	1	1.0	NA
CH	1	1.0	0.0
CJ	2.2	1.3	0.6
CK	1	1.0	0.0
CN	2.2	1.4	0.7
CP	2.2	1.2	0.5
CR	8.5	2.9	3.0
CS	2.2	1.5	0.6
CT	8.5	3.7	3.4
CU	2.2	1.4	0.6
CV	2.2	1.8	0.7
CW	1	1.0	0.0
CX	12.6	2.5	3.2
CY	2.2	1.3	0.6
CZ	12.6	9.7	4.6
D0	1	1.0	NA
D1	1	1.0	0.0
D2	1	1.0	0.0
D3	2.2	1.6	0.8
D4	1	1.0	0.0
D5	1	1.0	NA
D6	1	1.0	NA
D7	1	1.0	0.0
DB	2.2	2.2	NA
DD	1	1.0	NA
DE	1	1.0	NA
DH	1	1.0	NA
DJ	1	1.0	NA
DK	2.2	1.4	0.7
DM	2.2	1.6	0.8
DN	1	1.0	0.0
DR	12.6	12.6	NA
DS	1	1.0	0.0
DU	1	1.0	NA
DW	1	1.0	0.0
DX	1	1.0	0.0
DY	1	1.0	0.0
DZ	1	1.0	0.0
E0	1	1.0	0.0

E1	1	1.0	NA
E2	1	1.0	NA
E3	1	1.0	NA
E4	1	1.0	NA
E8	12.6	7.1	6.4
EA	1	1.0	0.0
EB	1	1.0	0.0
EC	1	1.0	0.0
ED	2.2	1.6	0.8
EE	1	1.0	0.0
EH	1	1.0	0.0
EJ	1	1.0	0.0
EK	2.2	1.4	0.7
EL	12.6	12.6	NA
EP	1	1.0	0.0
H0	1	1.0	0.0
H1	1	1.0	0.0
H3	1	1.0	0.0
H4	1	1.0	0.0
H5	1	1.0	0.0
H6	1	1.0	0.0
H7	1	1.0	NA
H8	1	1.0	NA
H9	1	1.0	NA
J0	1	1.0	0.0
J1	1	1.0	NA
J2	1	1.0	0.0
J3	1	1.0	NA
J4	2.2	1.2	0.5
J5	1	1.0	NA
J7	1	1.0	NA
J8	1	1.0	NA
J9	1	1.0	NA
K0	1	1.0	0.0
K1	1	1.0	0.0
K2	1	1.0	NA
K3	1	1.0	0.0
K4	1	1.0	0.0
K6	1	1.0	NA
K7	1	1.0	0.0
K8	12.6	3.6	5.1
K9	1	1.0	0.0
L1	2.2	1.4	0.7
L2	1	1.0	NA
L3	1	1.0	NA

L4	1	1.0	NA
L5	1	1.0	NA
L6	1	1.0	0.0
L7	1	1.0	0.0
L8	1	1.0	NA
L9	1	1.0	NA
M2	1	1.0	NA
M4	2.2	1.2	0.5
M5	1	1.0	NA
M6	2.2	1.2	0.5
M8	1	1.0	0.0
M9	1	1.0	0.0
N3	1	1.0	NA
N4	1	1.0	NA
N5	1	1.0	0.0
N6	1	1.0	NA
N8	1	1.0	0.0
N9	2.2	1.4	0.7
P0	1	1.0	NA
P1	1	1.0	0.0
P2	1	1.0	0.0
P3	1	1.0	0.0
P4	1	1.0	NA
P5	1	1.0	0.0
P6	1	1.0	NA
P7	1	1.0	NA
P8	1	1.0	0.0
P9	1	1.0	0.0
R0	1	1.0	0.0
R1	2.2	2.2	NA
R2	2.2	1.4	0.7
R3	1	1.0	0.0
T0	1	1.0	0.0

Chapter 5. Supplementary material

Table S1. List of all invertebrate species collected in this study across three sites in the Darwin Harbour region and their most morphologically similar species from Rogers (2006) and equations used to calculate AFDM.

Classification	Species	Similar Species	AFDM equation (L = length in mm)	Equation
Arthopoda	*Anthuridae*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Arthopoda	*Arthropod*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Arthopoda	*Insect*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Arthopoda	*Spider*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Bivalvia	*Bivalve*	*Unidentified bivalve sp*	log AFDM = 0.0092*(log L)^2.369	$\text{Log AFDM} = 0.0092\,(\log L)^{2.369}$
Bivalvia	*Divaricella irpex*	*Anodontia omissa*	=0.013*(L^2.876)	$0.013\,L^{2.876}$
Bivalvia	*Donax faba*	*Tellina piratica*	=0.056*(L^2.193)	$0.056\,L^{2.193}$
Bivalvia	*Dosinia laminata*	*Anomalocardia squamosa*	=0.067*(L^2.319)	$0.067\,L^{2.319}$
Bivalvia	*Jitlada philippinarum*	*Tellina piratica*	=0.056*(L^2.193)	$0.056\,L^{2.193}$
Bivalvia	*Mactra dissimilis*	*Anodontia omissa*	=0.013*(L^2.876)	$0.013\,L^{2.876}$
Bivalvia	*Paphies altenai*	*Anodontia omissa*	=0.013*(L^2.876)	$0.013\,L^{2.876}$
Bivalvia	*Pillucina sp.*	*Anodontia omissa*	=0.013*(L^2.876)	$0.013\,L^{2.876}$
Bivalvia	*Solen sp.*	*Siliqua cf. winteriana*	=0.00199*(L^3.143)	$0.00199\,L^{3.143}$
Bivalvia	*Tellina nucleolus*	*Tellina piratica*	=0.056*(L^2.193)	$0.056\,L^{2.193}$
Chordata	*Fish*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Echinodermata	*Sea urchin*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Echinoidea	*Arachnoides placenta*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Gastropoda	*Nassarius dorsartus*	*Gastropods*	=0.013*(L^3.225)	$0.013\,L^{3.225}$
Gastropoda	*Neverita didyma*	*Gastropods*	=0.013*(L^3.225)	$0.013\,L^{3.225}$
Hemichordata	*Hemichordata?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Holothuroidea	*Cerianatharia*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Holothuroidea	*Holothuria*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Holothuroidea	*Holothuria/Cerianatharia*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Isopoda	*Isopoda*	*Corophium volutator*	=0.0058(L^2.8)	$0.005\,L^{2.8}$
Lesser deuterostome	*Lesser deuterostome*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}\ 996\,(\log L)^{2.1299}$
Malacostraca	*Amphipoda*	*Corophium volutator*	=0.0058(L^2.8)	$0.005\,L^{2.8}$
Malacostraca	*Cumacea*	*Corophium volutator*	=0.0058(L^2.8)	$0.005\,L^{2.8}$
Malacostraca	*Hermit crab*	*Hermit Crabs*	=0.049*(SL^2.318)	$0.049\,SL^{2.318}$
Malacostraca	*Macrophthalmus*	*Other crabs*	=0.067*L^2.65	$0.067\,L^{2.65}$
Malacostraca	*Matuta ?*	*Other crabs*	=0.067*L^2.65	
Malacostraca	*Matuta planipes*	*Other crabs*	=0.067*L^2.65	
Malacostraca	*Mictyris darwinensis*	*Other crabs*	=0.067*L^2.65	
Malacostraca	*Sand Bubbler Crab*	*Other crabs*	=0.067*L^2.65	
Mollusc	*Unknown shell*	*Unidentified bivalve sp*	log AFDM = 0.0092*(log L)^2.369	$\text{Log AFDM} = 0.0092\,(\log L)^{2.369}$
Nemertea	*Cerebratulus*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Nemertea	*Nemertea*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Nemertea	*nemertea*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Nemertea	*Nemertea?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Ostracoda	*Ostracod*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Polychaeta	*Armandia sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Polychaeta	*Capitellid?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Capitellidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Capitellidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Chaetozone sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Chaetozone sp. 2*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Eunicidae/Onuphidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera ?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera brevicirrus*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera macintoshi*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Glycera sp. 3*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Goniadella sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Goniadid ?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Goniadidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Heteromastus*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Leitoscoloplos cf. latibranchus*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Leitoscoloplos sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Leodamas australiensis*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Leodamas sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Leodamas sp. 2*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Lumbrineridae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Lumbrineridae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Magelonidae sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Maldanid sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Maldanid?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Maldanidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Nephtys sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Nephtys sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Nereididae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Notomastus sp*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Notomastus sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Ondontosyllis*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Onuphid sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Onuphid?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Orbiniid sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Orbiniid sp. 2*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Orbiniidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Orbiniidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Owenia sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Paraonidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Phyllodocid sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Phyllodocid sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Polychaeta undetermined*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Polynoid sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Scolelepis*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Scolelepis ?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Scolelepis sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalion sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalionid sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalionid sp. 2*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalionid sp. 3*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalionidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Sigalionidae?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Simplisetia sp.*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Simplisetia sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Spionidae*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Spionidae sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Spionidae?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Tharyx sp. 1*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Polychaeta	*Worm*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
Scaphopoda	*Tusk Shell*	*Laevidentalium lubricatum*	=0.009*(L^2.314)	$0.009\,L^{2.314}$
Turbellarian	*Turbellarian*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Turbellarian	*Marphysa ?*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	$2.455\,(0.1\,L)^{2.208}$
Turbellarian	*Unknown*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Turbellarian	*Unknown phyla*	*Unidentified*	log AFDM = 0.9996*(log L)^2.1299	$\text{Log AFDM} = 0.9996\,(\log L)^{2.1299}$
Turbellarian	*Worm-like unid*	*Nereis diversicolor*	=2.455*(0.1*L)^2.208	
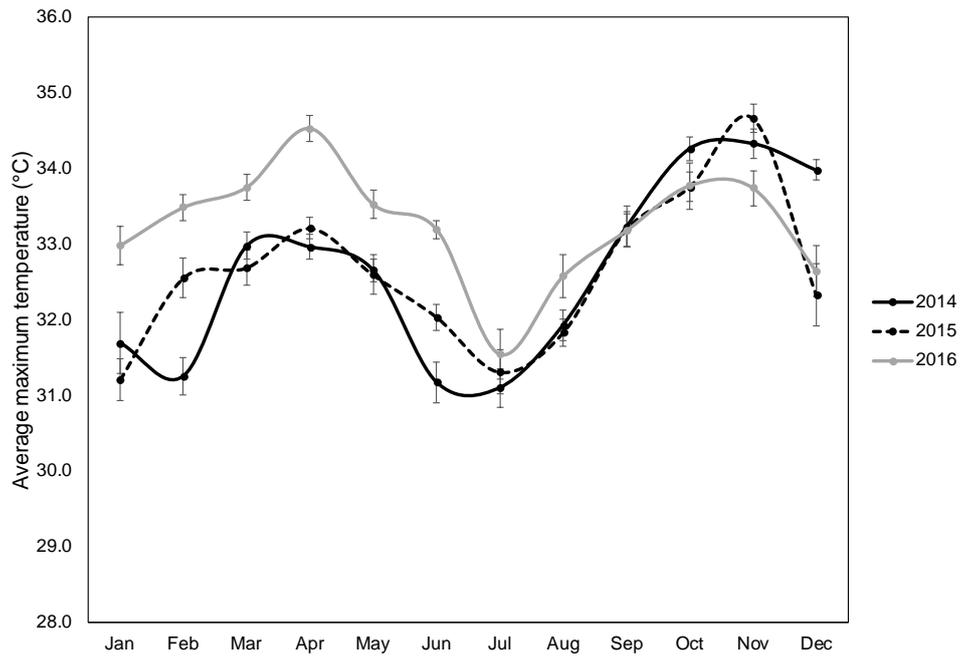
Fig. S1. Average monthly temperature for the Darwin region in the Northern Territory for the years 2014 – 2016.
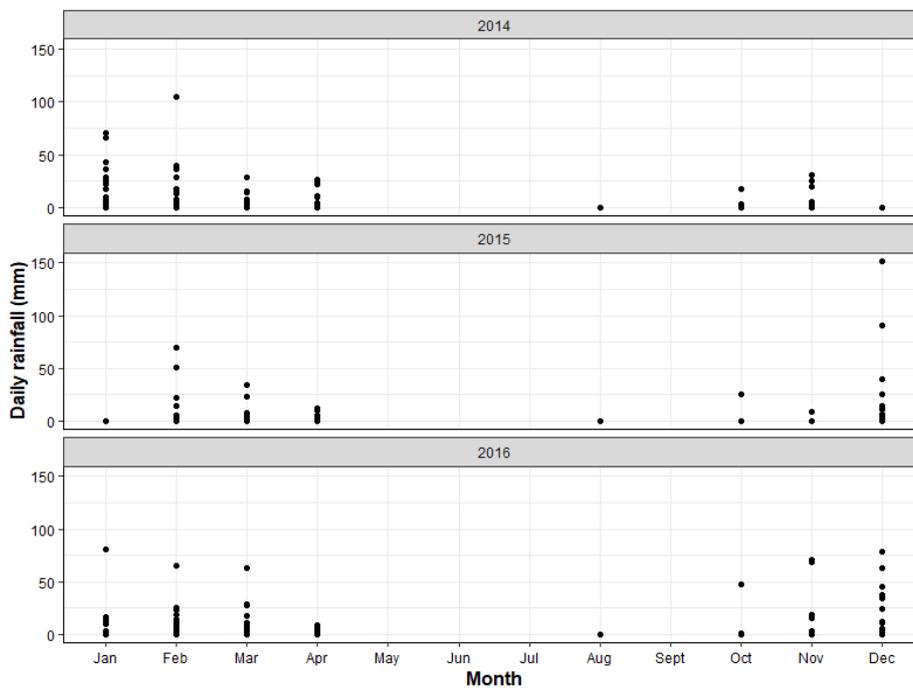
Fig. S2. Daily rainfall (mm) for the Darwin region in the Northern Territory for the years 2014 – 2016.
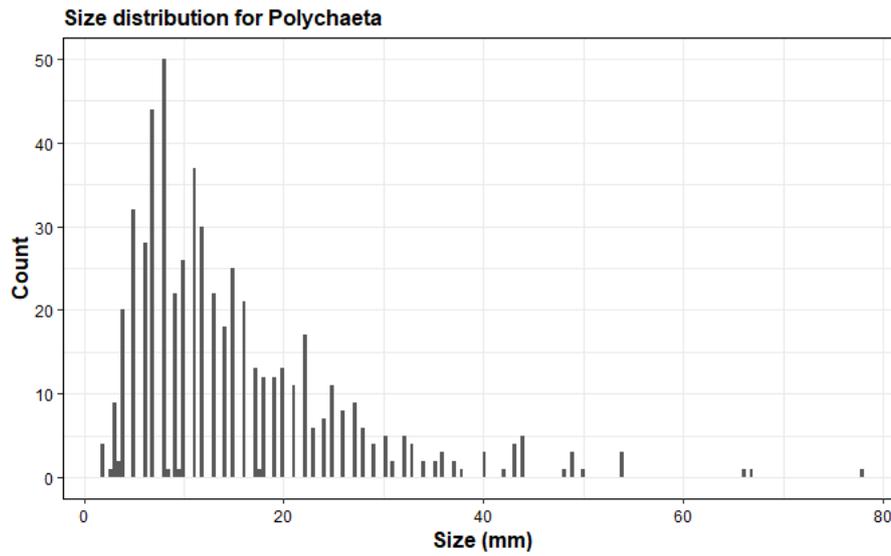
Fig. S3. Size distribution (mm) for invertebrate class Polychaeta in the Darwin region.
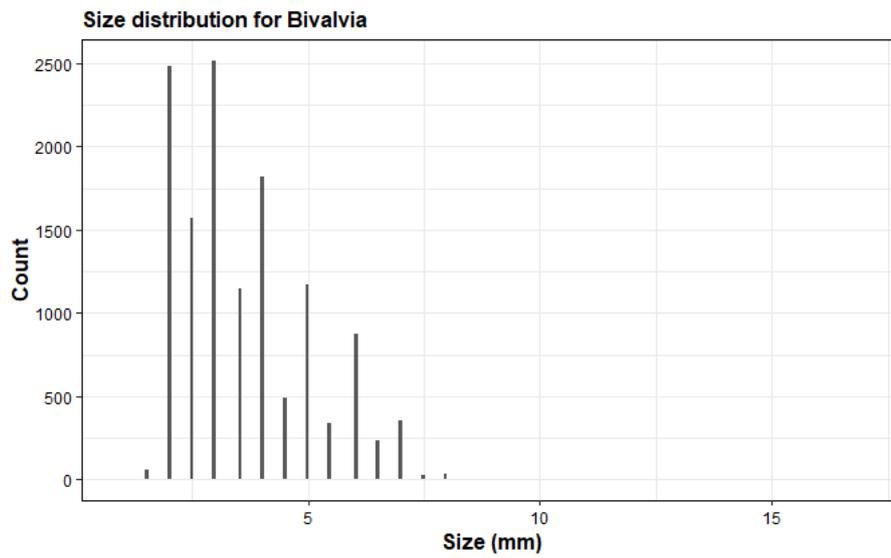
Fig. S4. Size distribution (mm) for invertebrate class Bivalvia in the Darwin region.
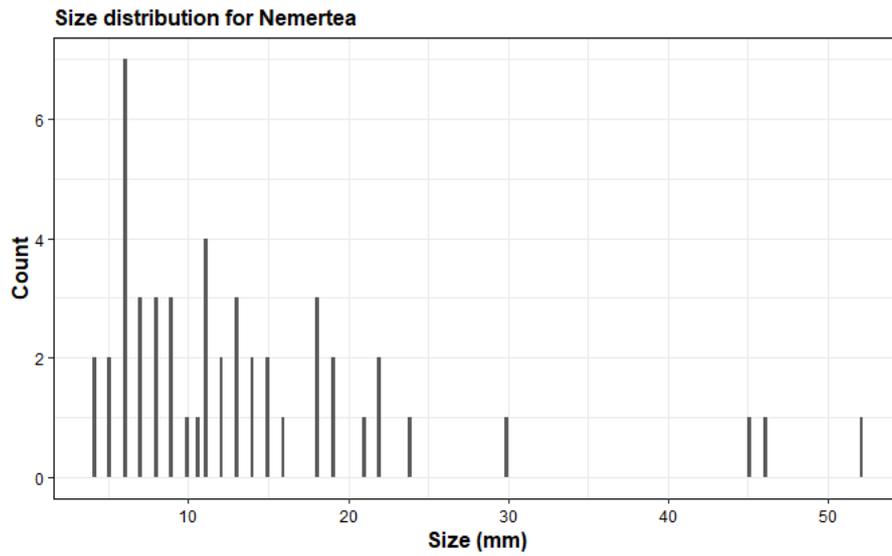
Fig. S5. Size distribution (mm) for invertebrate class Nemertea in the Darwin region.
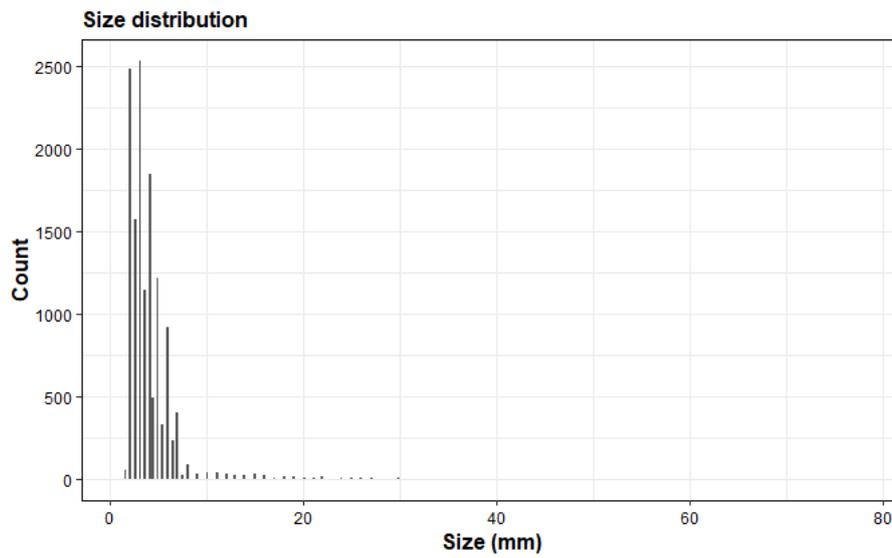
Fig. S6. Size distribution (mm) for all invertebrates in the Darwin region.
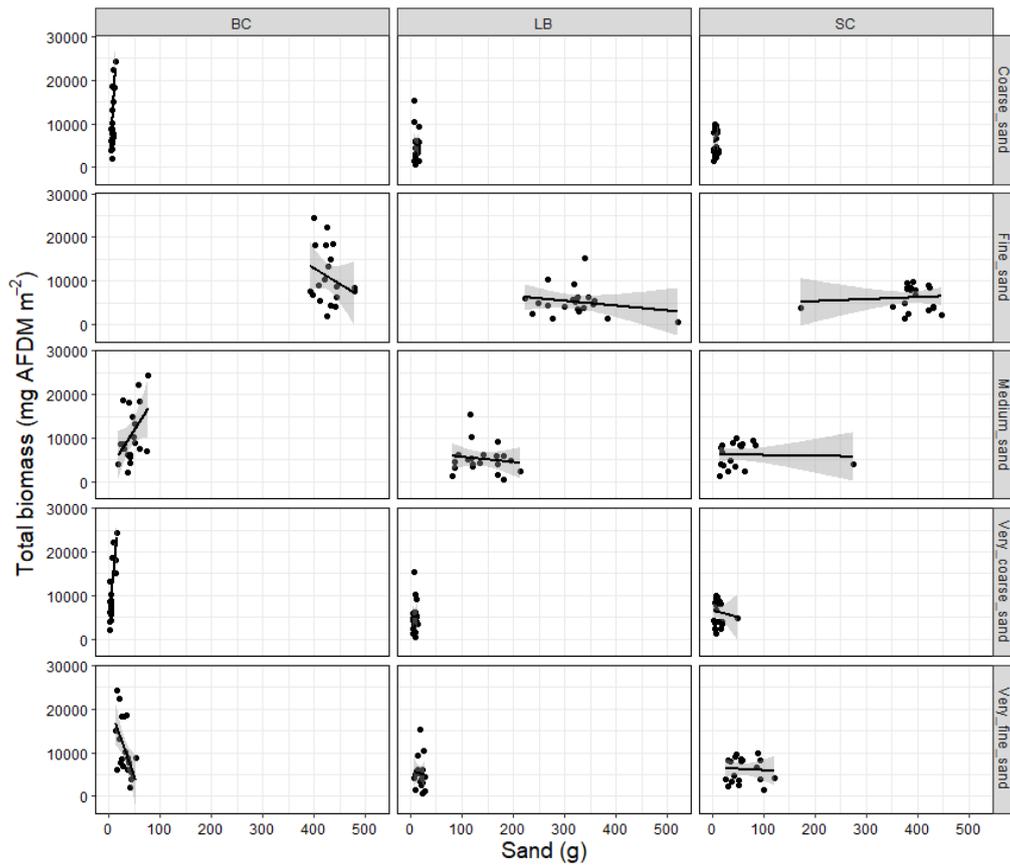
Fig. S7. Modelled results from generalised linear model between the relationship of biomass density and sediment grain size by site in the Darwin region.
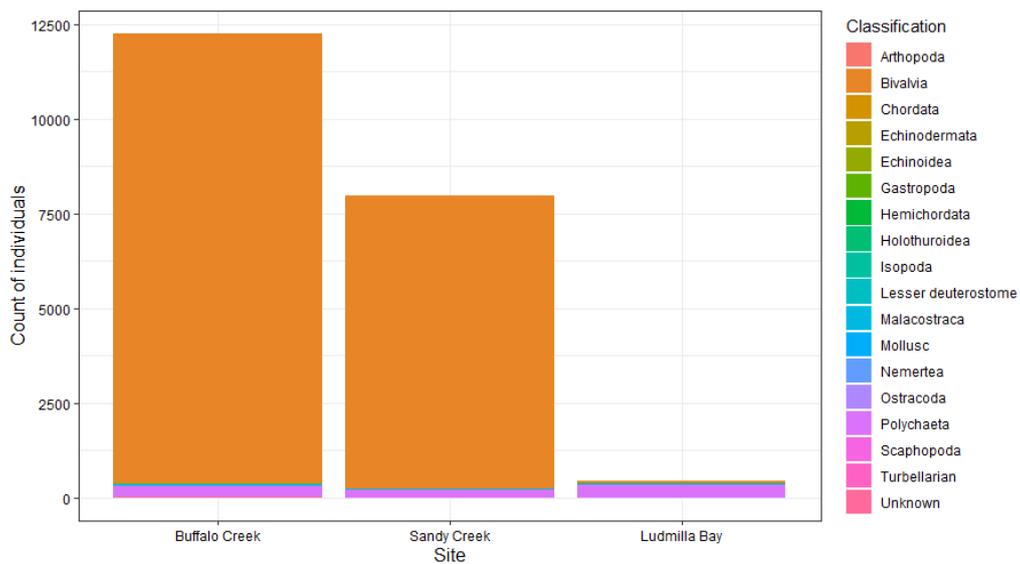
Fig S8. Count of invertebrate individuals of all classifications by site.

Appendix 1

Supplementary Appendix 1. Records of waterbirds and other water-associated birds from the 2014/15 migratory season in the Darwin region

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Records of waterbirds and other water-associated birds from the 2014/15 migratory season in the Darwin region

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Abstract

Records of waterbirds, waterfowl, terns, gulls, egrets and herons, raptors, and resident shorebirds in the Darwin region, Northern Territory, were collected during fortnightly migratory shorebird monitoring. Eight study sites were monitored from August 2014 through to April 2015, which is considered the migratory season for most non-passerine birds in the Top End. Species abundance across the sites, breeding records, and new information on habitat use at an artificial habitat (East Arm Wharf) are presented. Across the eight study sites there were 39 species recorded, representing 15 taxonomic families.

Darwin Harbour in the Northern Territory has a rich coastal waterbird assemblage, owing to its diverse range of habitats. The coastal region supports resident and nomadic Australian waterbirds, waterfowl, resident and migratory terns and gulls and various raptors that inhabit coastlines (McCrie & Watson 2003). A number of terns that breed in the northern hemisphere visit northern Australian coastlines during the austral summer season where they feed over the ocean and along tidelines and then roost at beaches, rocky reefs, dykes and on manmade buoys. The macro-tidal nature of tides in the Darwin region creates extensive mud and sand flats, available for foraging birds. Mangroves, saltpans and saltmarsh provide roosts during high tides.

Studies of waterbirds in the Top End have mainly focused on freshwater wetlands and floodplains in the Fogg Dam and Alligator River regions, east of Darwin (see Crawford 1979; Morton *et al.* 1993). The waterbirds in Darwin Harbour prefer coastal saline habitats, including fringing mangroves, brackish wastewater ponds and dredge ponds nearby, and creeks and rivers. Extensive aerial and ground survey results for waterbirds along the Northern Territory coastline indicate that the region supports a variety of waterbirds (Chatto 2006).

During regular monitoring of migratory shorebirds I collected count data for all birds across eight study sites from August 2014 through to April 2015, which is when most migratory shorebirds and other water-associated migrant birds visit Australian shores. Birds were surveyed at each site most fortnights during spring tide cycles, which were selected to target when migratory shorebirds would be roosting. There were 184 surveys performed over the nine survey months. The sites were: East Arm Wharf, Lee Point-Buffalo Creek, Ludmilla Bay, Spot on Marine, Nightcliff Rocks, East Point, Sandy Creek and East Arm Wharf Railway Mud, all within the Darwin region. This note summarises the results of all birds present at the study sites, excluding migratory shorebirds. Thirty-nine species of birds were recorded within the study period, including 5 species of heron and egret, 2 gull, 8 tern, 3 raptor, 8 resident shorebird, 8 waterbird and 5 waterfowl species. The maximum count for each species and the corresponding site and date are shown in Table 1.

Table 1. Results from waterbird monitoring in the Darwin region from August 2014 – April 2015. Bird species are grouped and presented in taxonomic order following Christidis and Boles (2008).

Family and grouping	Common name	Scientific name	Max count	Site of max count	Site coordinates	Date of max count
Waterfowl						
Anatidae	Wandering Whistling Duck	*Dendrocygna arcuata*	149	East Arm Wharf	-12.29.177 S, 130.53.650 E	4/01/2015
Anatidae	Radjah Shelduck	*Tadorna radjah*	200	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	21/11/2014
Anatidae	Pacific Black Duck	*Anas superciliosa*	17	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014
Anatidae	Hardhead	*Aythya australis*	12	East Arm Wharf	-12.29.177 S, 130.53.650 E	6/04/2015
Podicipedidae	Australasian Grebe	*Tachybaptus novaehollandiae*	12	East Arm Wharf	-12.29.177 S, 130.53.650 E	20/04/2015
Waterbirds						
Anhingidae	Australasian Darter	*Anhinga novaehollandiae*	1	East Arm Wharf	-12.29.177 S, 130.53.650 E	7/09/2014
Phalacrocoracidae	Little Pied Cormorant	*Microcarbo melanoleucos*	17	East Arm Wharf	-12.29.177 S, 130.53.650 E	21/01/2015
Phalacrocoracidae	Little Black Cormorant	*Phalacrocorax sulcirostris*	5	East Arm Wharf Railway Mud	-12.28.775 S, 130.53.348 E	7/10/2014
Phalacrocoracidae	Pied Cormorant	*Phalacrocorax varius*	3	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	21/11/2014
Pelecanidae	Australian Pelican	*Pelecanus conspicillatus*	44	East Arm Wharf	-12.29.177 S, 130.53.650 E	4/01/2015

Ciconiidae	Black-necked Stork	*Ephippiorhynchus asiaticus*	2	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014

Egrets and Herons

Ardeidae	Great Egret	*Ardea modesta*	11	East Arm Wharf Railway Mud	-12.28.775 S, 130.53.348 E	7/10/2014
Ardeidae	Striated Heron	*Butorides striata*	5	East Arm Wharf Railway Mud	-12.28.775 S, 130.53.348 E	7/10/2014
Ardeidae	Pied Heron	*Egretta picata*	1	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	18/03/2015
Ardeidae	Little Egret	*Egretta garzetta*	10	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	12/08/2014
Ardeidae	Eastern Reef Egret	*Egretta sacra*	12	East Arm Wharf Railway Mud	-12.28.775 S, 130.53.348 E	7/10/2014

Waterbirds

Threskiornithidae	Australian White Ibis	*Threskiornis molucca*	11	East Arm Wharf Railway Mud	-12.28.775 S, 130.53.348 E	7/10/2014
Threskiornithidae	Royal Spoonbill	*Platalea regia*	13	East Arm Wharf	-12.29.177 S, 130.53.650 E	22/11/2014

Birds of Prey

Accipitridae	White-bellied Sea-Eagle	*Haliaeetus leucogaster*	4	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014
Accipitridae	Whistling Kite	*Haliastur sphenurus*	1	East Arm Wharf	-12.29.177 S, 130.53.650 E	20/04/2015
Accipitridae	Brahminy Kite	*Haliastur indus*	2	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014

Resident shorebirds

Burhinidae	Beach Stone-curlew	*Esacus magnirostris*	3	Sandy Creek	-12.20.580 S, 130.53.026 E	23/03/2015
Haematopodidae	Australian Pied Oystercatcher	*Haematopus longirostris*	5	East Arm Wharf	-12.29.177 S, 130.53.650 E	13/08/2014

Haematopodidae	Sooty Oystercatcher	*Haematopus fuliginosus*	5	East Point	-12.24.42 S, 130.48.933 E	4/02/2015
Recurvirostridae	Black-winged Stilt	*Himantopus himantopus*	74	East Arm Wharf	-12.29.177 S, 130.53.650 E	20/04/2015
Charadriidae	Red-capped Plover	*Charadrius ruficapillus*	16	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	19/12/2014
Charadriidae	Red-kneed Dotterel	*Erythrogonys cinctus*	2	East Arm Wharf	-12.29.177 S, 130.53.650 E	20/04/2015
Charadriidae	Masked Lapwing	*Vanellus miles*	20	Spot on Marine	-12.24.868 S, 130.50.191 E	8/03/2015
Glareolidae	Australian Pratincole	*Stiltia isabella*	2	East Arm Wharf	-12.29.177 S, 130.53.650 E	20/04/2015
Terns and Gulls						
Laridae	Little Tern	*Sternula albifrons*	29	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	24/03/2015
Laridae	Gull-billed Tern (*macrotarsa*)[1]	*Gelochelidon nilotica macrotarsa*	234	East Arm Wharf	-12.29.177 S, 130.53.650 E	7/09/2014
Laridae	Gull-billed Tern (*affinis*)[1]	*Gelochelidon nilotica affinis*	6	East Arm Wharf	-12.29.177 S, 130.53.650 E	2/11/2014
Laridae	Caspian Tern	*Hydroprogne caspia*	6	Sandy Creek	-12.20.580 S, 130.53.026 E	23/03/2015
Laridae	Whiskered Tern	*Chlidonias hybrida*	351	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014
Laridae	White-winged Black Tern	*Chlidonias leucopterus*	274	East Arm Wharf	-12.29.177 S, 130.53.650 E	23/12/2014
Laridae	Common Tern	*Sterna hirundo*	1	East Point	-12.24.42 S, 130.48.933 E	12/10/2014
Laridae	Lesser Crested Tern	*Thalasseus bengalensis*	35	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	23/11/2014

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Laridae	Crested Tern	*Thalasseus bergii*	192	Nightcliff Rocks	-12.22.833 S, 130.50.431 E	9/11/2014
Laridae	Franklin's Gull	*Leucophaeus pipixcan*	1	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	18/03/2015
Laridae	Silver Gull	*Chroicocephalus novaehollandiae*	480	Lee Point-Buffalo Creek	-12.20.043 S, 130.54.297 E	18/03/2015

[1]Two subspecies of Gull-billed Tern occur in northern Australia, *affinis* being a migrant that visits Australia during the summer season. These subspecies can be separated in the field using morphological features; see Lilleyman and Hensen (2014).

East Arm Wharf, an artificial site made up of dredge ponds, situated within Darwin Harbour, consistently supported the most species of all the sites. The site attracts a diverse range of species because the ponds represent a mix of freshwater and marine/saline habitats, with input from the harbour. The ponds are in open terrain with good visibility for birds to detect predators, and situated next to the coastline. The site is also protected from human disturbance as public access is restricted, and the site excludes feral terrestrial predators like dogs and cats through trapping and fencing. East Arm Wharf supported the most species (18) of water-associated bird compared to the other sites during the monitoring period. Sixteen species were recorded at the East Arm Wharf Railway Mud (adjacent to the dredge ponds at east Arm Wharf), but the assemblages between these two close sites varied. Twelve species of waterbird were recorded at Lee Point-Buffalo Creek during the monitoring period.

Across the sites, November was the best month with the highest total count of birds, mostly weighted by terns, followed by March and then December, both weighted by gulls and terns. A vagrant gull, Franklin's Gull – recognised from the more common Silver Gull by its black head markings or prominent hood and dark grey back and upperwings contrasting with white underparts – was recorded in March, first at Buffalo Creek and then it was sighted at Stokes Hill Wharf (pers. com. Mark de Kretser 18th April 2015), and then at East Arm Wharf (by the author) (see Plate 1). This species breeds in North America and spends the non-breeding season in South America (Handbook of the Birds of the World Alive 2015). This is the 19th record for Australia and the second time the species has been recorded in the Northern Territory (BirdLife Australia 2015). First arrival and last departure records for migratory terns and one vagrant gull are shown in Table 2.

Plate 1. Franklin's Gull (right) and a Silver Gull (left) in a dredge pond at East Arm Wharf in Darwin, 20th April 2015. Photo credit: Amanda Lilleyman

Table 2. First arrival and last departure records for migratory terns and one vagrant gull. Bird species are presented by their first arrival month.

Species	First arrival	Last departure
Gull-billed Tern (*affinis*)	early October	February
Common Tern	mid-October	March
White-winged Black Tern	late October	late April
Little Tern	late December	early April
Franklin's Gull	March	April

Crawford (1980) reported mean counts for Whiskered Terns with peaks in September at Fogg Dam and in Darwin (100 and 50 individuals, respectively) and Lesser Crested Terns (40 individuals) along the coastline of Darwin, but noted January for the highest mean counts of Crested Terns (100 individuals). The maximum count of Crested Terns from the current study was 192 individuals in November from

Nightcliff, which was a site not surveyed in the Crawford (1980) paper. The maximum count of Whiskered Terns from the current study is certainly an increase from the mean counts recorded by (Crawford 1980).

Outside of the monitoring period, in June, July and August there were up to ten Red-necked Avocets using the freshwater dredge ponds at East Arm Wharf. Records from eBird and a local online forum (NT Birds Yahoo group) show this species is recorded in the Top End every year or so, but mostly further south and east of Darwin city (i.e.: South Alligator River, Mamukala, Shark Billabong, Adelaide River). This record at East Arm Wharf is the first record close to Darwin since 20th August 2013 when the species was recorded at Leanyer Sewage Treatment Ponds. Resident shorebirds were recorded nesting and raising young at East Arm Wharf, including Black-winged Stilts, with a maximum count of 74 individuals in April, after the nesting period. Red-capped Plovers, Masked Lapwings and Pied Oystercatchers were also recorded breeding along the muddy edge of one of the dredge ponds. Red-capped Plover also regularly breeds along the sandy beach at Lee Point.

Plate 2. Red-necked Avocets in a dredge pond at East Arm Wharf in Darwin, 19th July 2015. Photo credit: Amanda Lilleyman

Other localities around Darwin provide quality habitat for waterbirds, shorebirds and other water-associated birds, including Holmes Jungle, Knuckeys Lagoon, McMinns Lagoons, Leanyer and Palmerston Sewage Treatment Ponds. These sites were not surveyed in the study period as they were not included in the migratory shorebird monitoring program; however, future monitoring of these sites would improve our knowledge on birds in the region.

The Darwin region coastline and associated freshwater ponds support a diverse range of water-associated bird species and high abundances throughout the austral summer season. Of the sites surveyed for this study, East Arm Wharf is the most important site (based on species diversity and number of individuals recorded) for a range of waterbirds, terns and gulls, waterfowl and breeding resident shorebirds.

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Appendix 2
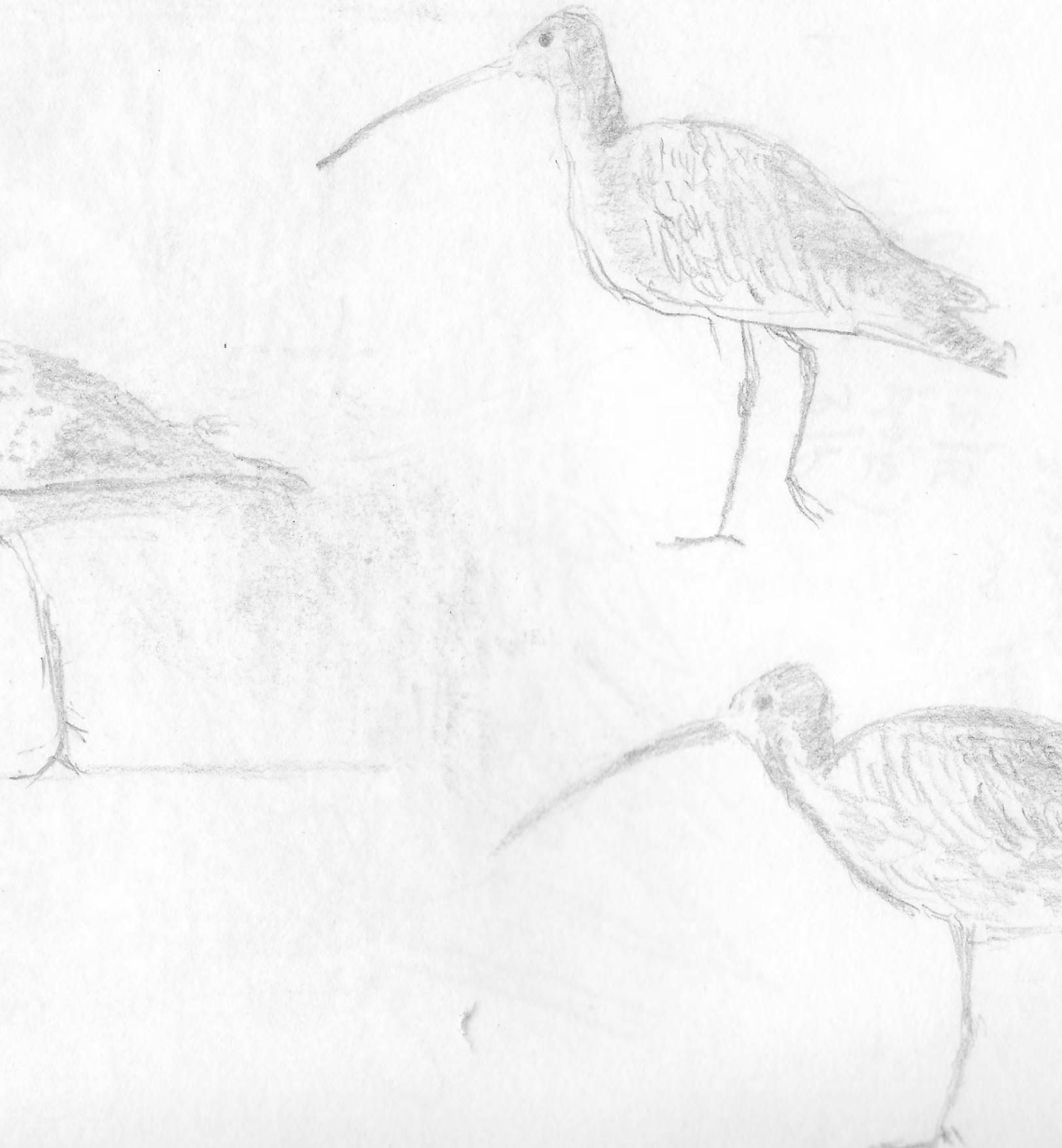
Supplementary Appendix 2. Trends in relative abundance of the Eastern Curlew (*Numenius madagascariensis*) in Darwin, Northern Territory

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TRENDS IN RELATIVE ABUNDANCE OF THE EASTERN CURLEW (*NUMENIUS MADAGASCARIENSIS*) IN DARWIN, NORTHERN TERRITORY

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The Eastern Curlew (*Numenius madagascariensis*) has recently been uplisted to Critically Endangered under Australian Government legislation due to an ongoing decline of the species population on its non-breeding grounds. Declines have been reported from nearly all monitored sites along the coastline of Australia and at some, local extinction is predicted within the next thirty years. In contrast, numbers recorded at two sites in the Darwin region appear to have increased in the same period. Since 1980 numbers at Lee Point have increased by 9 % per year (SE = 2%); at East Arm Wharf in Darwin Harbour, the annual population increase was 17 % per year (SE = 9%) for the period of 2009-2015. This local increase over time may reflect changes in bird roosting behaviour and an increase in suitable high tide roosting habitat. The consistent use of an artificial site at East Arm Wharf is promising for adaptive management of the species and other shorebirds that are threatened by the effects of habitat loss along coastlines.

INTRODUCTION

The Eastern Curlew (*Numenius madagascariensis*) is the largest of the annual migrant shorebirds that travel along the East Asian-Australasian Flyway (hereafter the Flyway), to which it is endemic (Higgins and Davies 1996). After breeding in eastern Russia, Mongolia or north-eastern China, most Eastern Curlew stage (stop-over) in the Yellow Sea region for three to eight weeks where they rely heavily on

invertebrate prey for refuelling (Choi *et al.* in revision). Modelled estimates of passage dates and results from satellite tracking suggest that Eastern Curlew travel from the Yellow Sea to Australia in one non-stop flight or by rapid movement between continents (Choi *et al.* in revision; Driscoll and Ueta 2002). Eastern Curlew also undertake their northward migration in one non-stop flight from their non-breeding grounds in Australia (Minton *et al.* 2013). They spend the non-breeding season along coastlines and sheltered bays in Australia feeding on intertidal invertebrates at low tide and retreating to roosts on beaches, mangroves, dykes and ponds at high tide (Higgins and Davies 1996).

Currently listed as Vulnerable on the IUCN Red List (under review; the species has been assessed as Critically Endangered in Australia using the IUCN Red List criteria by BirdLife Australia), the Eastern Curlew is highly threatened within its range. Habitat destruction and reclamation of tidal mudflats in the Yellow Sea region are the biggest threats to this and many other migrant species dependent on these staging grounds, but the species is also threatened by hunting, pollution, changes to water regimes, disturbance, and climate change impacts on breeding grounds (Harding *et al.* 2007). The cumulative interaction of these threats within the Flyway and the dramatic decline in Eastern Curlew numbers has led to the uplisting of Eastern Curlew from Endangered to Critically Endangered in Australia under the Commonwealth Government's *Environment Protection and Biodiversity Conservation Act 1999.* Eastern Curlew and the habitat they depend upon are protected under several international agreements; the Convention on the Conservation of Migratory Species of Wild Animals, Japan-Australia Migratory Bird Agreement, China-Australia Migratory Bird Agreement and Republic of Korea-Australia Migratory Bird Agreement. These agreements recognise the need to protect shorebirds by cooperating across jurisdictions. However, despite these agreements, there is currently a lack of environmental protection of intertidal wetlands in the Flyway (MacKinnon *et al.* 2012). Rates of decline in shorebird numbers in the Flyway are greater than the rates of decline in other regions, when compared using an extinction risk metric derived from the Red List (Szabo *et al.* 2012). The plight of Eastern Curlew has spurred the East Asian-Australasian Flyway Partnership to establish a task force that will develop an international action plan to support the survival of the species across its distribution (East Asian-Australasian Flyway Partnership 2015).

The last thirty years has seen an increase in the reported decline of the Flyway population of Eastern Curlew with projections that the species will continue declining at 30-49 % over the next thirty years (Garnett *et al.* 2011). Once a common visitor to Tasmania, the Eastern Curlew has declined by 65% since the 1950s and a continuing decline at this reported rate will see the species extirpated from the area within the next 30 years (Reid and Park 2003). This trend has also been reported for areas in South Australia, Victoria, New South Wales, north-Western Australia and Queensland (Close and Newman 1984; Gosbell and Clemens 2006; Hansen *et al.* 2015; Minton *et al.* 2012; Rogers *et al.* 2009; Wilson *et al.* 2011). The common theme among the potential causes leading to the species declines were habitat loss and reclamation of tidal flats in the core staging sites in the Yellow Sea region.

In Darwin, seasonal patterns of abundance and inter-annual trends in numbers have not been documented, in spite of declines elsewhere and plans in Darwin Harbour for ongoing development of coastal environments used by the species. The species has been recorded in low numbers for all months of the year in Darwin (Crawford 1972; Crawford 1997), with a peak in the mean number of individuals during February (Shurcliff 1993). Chatto (2003) reported that Eastern Curlews were distributed widely along the mangrove-fringed coastline of the Northern Territory with flocks of up to 500 in Chambers Bay to the east of Darwin and at Buckingham Bay to the west. The estimated Northern Territory population of Eastern Curlew for the survey period of 1990 through to 2001 was reported to be at least 6800 individuals (Chatto 2003) with peak counts for the species in June and July. A repeat survey of shorebirds along the Northern Territory coastline conducted in December and March during 2010-2012 did not detect large numbers of Eastern Curlew in Chambers Bay, and it was suggested that future surveys be performed during September (Chatto 2012). Despite the relatively lower numbers of Eastern Curlew detected between counts conducted in 1990-2001 and those in 2010-2012, Chatto (2012) argued that the species was consistently abundant in the Northern Territory. The main difference between these survey periods is that Eastern Curlew were detected in the hundreds in earlier surveys in bays away from Darwin Harbour, whereas in more recent surveys the species counts were larger at sites close to Darwin Harbour.

More recently, evidence that Eastern Curlew repeatedly occurs at a port site in Darwin Harbour at nationally important numbers (0.1% of the Flyway population) has meant that targeted surveys for the species have been conducted. Here, we discuss the population trends for Eastern Curlew at two sites in the Darwin region using data from 1980 to the austral summer season of 2014/15 and comment on the local population trends.

METHODS

Study area and count data

We used data collated by the Shorebirds 2020 national program for the period of 1980-2015 and combined these data with unpublished counts conducted by Arthur and Sheryl Keates, Gavin O'Brien, and Amanda Lilleyman from 2009 – 2015 (that were not available from the Shorebirds 2020 database). Surveys were conducted by experienced shorebird counters and vetted by the Shorebirds 2020 scientific committee and local ornithologists. Counts were performed at low and high tides every fortnight in most months over the survey years using point counts and walking transects (along a beach) for an average of 75 minutes at Lee Point and 100 minutes at East Arm Wharf. The Darwin area is macrotidal with a tidal range of 0.7 - 8.0 m. During spring tide cycles the high tides coincide closely with sunrise and sunset. The region is tropical with an average temperature of ≥30°C in all months of the year (Bureau of Meteorology 2015).

Count data were from two sites: Lee Point on the northern beaches and East Arm Wharf in Darwin Harbour, Northern Territory, Australia (Figure 1). Lee Point is a 1.5 km-long sandy beach connected to an extensive intertidal sandflat. It is open to the public who often use it for walking, jogging, or dog-walking. The beach is part of the Casuarina Coastal Reserve and is managed by the Northern Territory Parks and Wildlife Commission. Since 2002 this management has included sign-posting to discourage people from unleashing their dogs, though compliance with this regulation is poor (A. Lilleyman, pers. obs.). East Arm Wharf is the main exporting port in Darwin and surrounded by industrial infrastructure. The site contains several artificial ponds used to store dredge spoil from Darwin Harbour. Human access is only allowed by permit, and the site is rarely disturbed by people. Lee Point and East Arm Wharf

differ in physical characteristics and support different assemblages of shorebird species at different times of the year.
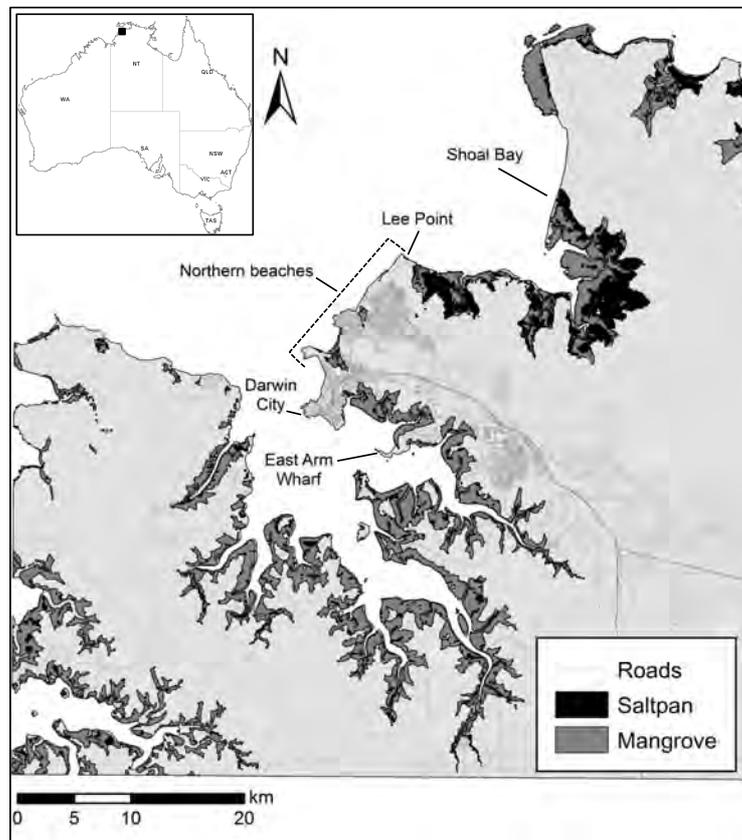
Figure 1. Map of survey sites in the Darwin region, Northern Territory and inset of Australia. Darwin city, roads and mangrove and saltpan habitat types are also shown on the map. Note that most saltpans and mangroves are not accessible by road outside of the Darwin city region and suburbia. The northern beaches are marked by a dashed line and the vicinity of Shoal Bay is indicated.

Statistical analyses

East Arm Wharf data were analysed separately to the Lee Point dataset as survey data were not available for East Arm Wharf until 2009 and because the sites are in a different habitat and >20 km apart. The city of Darwin lies between the two sites, and we are not aware of any observations (by the authors and other counters) of Eastern Curlew moving between the two sites regularly. We used the maximum abundance count over a year as our measure of Eastern Curlew abundance for any one year. Maximum

counts were preferred to mean counts, as Eastern Curlew are notoriously wary and on some surveys, low numbers were probably caused by disturbed birds relocating to alternate roosts that were not surveyed. The maximum counts were considered accurate (curlew are conspicuous and easy to identify and count when present) and in the absence of marked individuals maximum counts provide the most reliable estimate of population size at a site (Kearney *et al.* 2008). Both sites were large enough that the upper limit to the maximum abundance was not constrained by space. Sampling effort (defined as the sum of survey durations for a given year in minutes) varied from year to year and was thus included in the models of population growth rate. Eastern Curlew numbers were greater at higher tides. In this macro-tidal environment the amount of habitat available for roosting at high tide can vary greatly. Accordingly, we included tide height at the time of observation of the maximum count to account for any variation among counts caused by tide height. The relationships between sampling effort and maximum counts and tide height and maximum counts were plotted and described by the non-linear model that best fit the data. Accordingly, for Lee Point data, sampling effort (in minutes) was modelled as a power function and tide conditions i.e. tide height, as an exponential function. At East Arm Wharf, sampling effort and tide conditions were both modelled as linear functions. Data were checked for outliers and homoscedasticity. The count in 2015 at Lee Point was an obvious outlier because only a few months of data had been collected at the time of writing. Therefore the 2015 count datum for Lee Point was excluded from the analyses. Population growth at both sites was modelled using the exponential growth equation of the form $N_{(T)} = N_0 e^{rT}$, where $N_{(T)}$ is population size at any arbitrary time T in the future, N_0 is the initial population size, and r is the intrinsic (or exponential) per capita rate of growth, whose units are per time period (year, in this case). After taking into account sampling effort and tide height the exponential growth rate of the corrected population counts were modelled using the 'nls' procedure in the base package of the R statistical software (R Core Team 2015).

RESULTS

Sampling effort and tide height were significantly correlated with the annual maximum counts at Lee Point (R^2=0.59 and 0.22, respectively) and we controlled for their effect by including these two

covariates in the population growth model. The adjusted population increase for Eastern Curlew at Lee Point for the period 1980-2014 indicates a significant increase in population size of 9 % (SE = 2%) per annum (t= 0.09, P<0.001; Table 1, Figure 2).

[Insert Table 1]

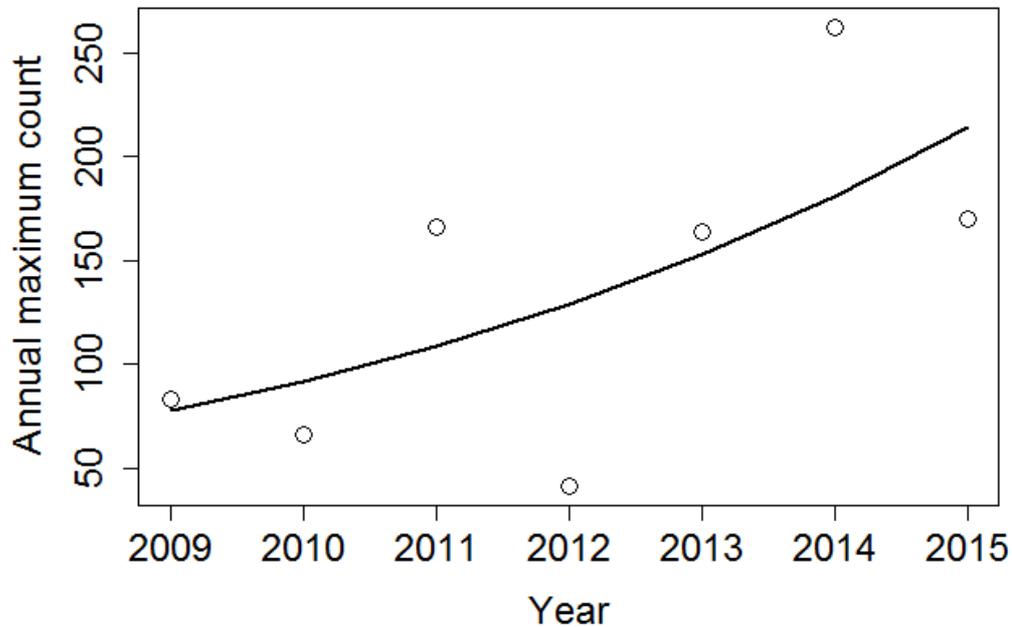**Table 1.** Adjusted population increase for Eastern Curlew at Lee Point and at East Arm Wharf.

Site/Parameter	Estimate	SE	t	P
Lee Point				
$N_{(0)}$	1.8	1.35	1.34	0.19
r	0.090	0.02	3.75	0.001
East Arm Wharf				
$N_{(0)}$	65.7	34.69	1.89	0.12
r	0.169	0.09	1.77	0.14
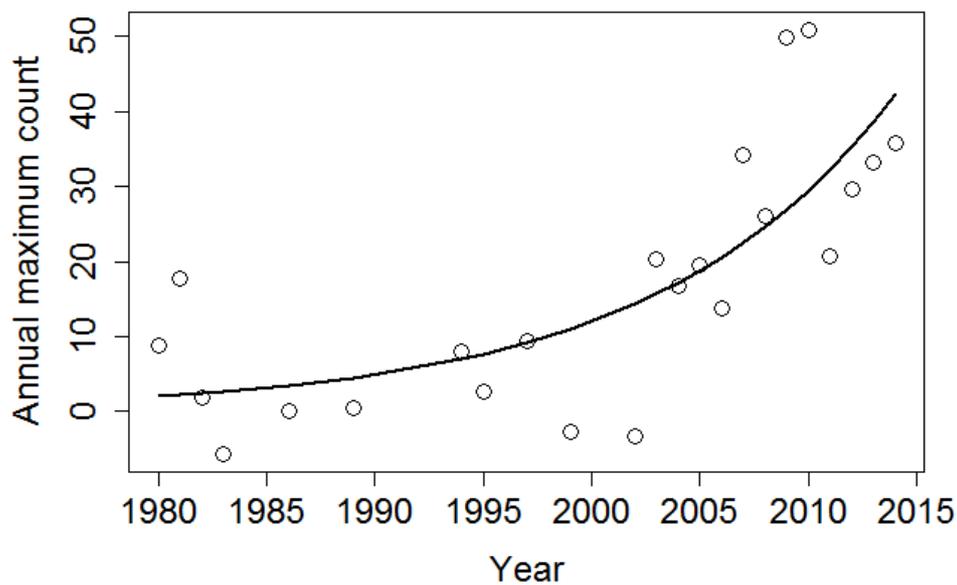
Figure 2. Population increase of Eastern Curlew for the period 1980-2014 at Lee Point. The growth rate r=0.09 is based on annual maximum counts corrected for sampling effort and the effect of tide height.

At East Arm Wharf, sampling effort and tide height were both correlated with annual maximum counts (R^2 = 0.44 and 0.30, respectively). The adjusted population increase for Eastern Curlew was 17 % (SE

= 9%) per annum at this site (Table 1, Figure 3). The model fit was not significant (t= 1.77, P<0. 14) as curlew numbers have fluctuated widely since 2009 (Figure 3) and the sample of seven years is too small to smooth out these trends; consequently the estimate of population increase provided here must be treated with caution, although it is clear that overall, curlew numbers are increasing at East Arm Wharf.

Figure 3. Population increase of Eastern Curlew for the period 2009-2015 at East Arm Wharf. The growth rate r=0.17 is based on annual maximum counts corrected for sampling effort and the effect of tide height (hence some adjusted counts are below zero).

DISCUSSION

Two separate analyses of the population trends of Eastern Curlew in Darwin have revealed a relatively recent local-scale increase in the observed numbers of curlew. Eastern Curlew numbers have increased on a beach despite moderate levels of disturbance, and likewise at East Arm Wharf where an artificial roost is readily used by this species. The increase in the number of Eastern Curlew counted in the Darwin region is in contrast to the general trends reported across much of Australia where Eastern Curlew numbers have declined (Close and Newman 1984; Gosbell and Clemens 2006; Hansen *et al.* 2015; Minton *et al.* 2012; Rogers *et al.* 2009; Wilson *et al.* 2011). The observed population increase of

Eastern Curlew at East Arm Wharf may be due to the fact that this artificial site is available at all tide heights and is relatively undisturbed as site access by people is restricted by the Darwin Port Corporation. Whether the increase at East Arm Wharf is indicative of a general increase in curlew numbers within Darwin Harbour overall or simply a change in roost-site use is unknown, as there is no comprehensive history of roosting sites in the region. Nevertheless, even if the increase at East Arm wharf represents a change in roosting behaviour, rather than an actual local increase in numbers, it must still be beneficial to the birds. The preference for East Arm Wharf might be caused by low disturbance, or because it is closer to preferred low tide foraging areas. The dredge ponds at East Arm Wharf were established in 2001 and have been added to and expanded since then. Prior to their establishment, the area was a mangrove-lined intertidal coast; with supratidal saltpans amongst mangroves as the only suitable roosting option (see black-shaded areas in Figure 1). Eastern Curlew numbers at Lee Point also increased noticeably from 2003 onwards, which coincides with the commencement of dog regulation and zoning of the beach in 2002. Nevertheless, the species is increasing at this beach site that is subject to moderate levels of disturbance.

Habitat preferences

Eastern Curlew are more numerous at East Arm Wharf than at Lee Point. This may be because the East Arm Wharf site is available at all tide heights, being an artificial site above sea level, and provides suitable roosting habitat and few anthropogenic disturbances. East Arm Wharf may also be favoured as it is protected from human disturbance as well as from feral terrestrial predators like dogs and cats. Furthermore, it is close to large areas of soft-sediment intertidal mudflat – an environmental predictor of Eastern Curlew occurrence (Finn *et al.* 2007; Finn *et al.* 2008). Eastern Curlew regularly move directly from the ponds at East Arm Wharf to the exposed intertidal zone of Darwin Harbour to feed (A. Lilleyman pers. obs.). Thus, another reason East Arm Wharf is apparently favoured is that suitable feeding grounds exist close to the roost. Safe high-quality sites are important for successful migration and breeding (Aharon-Rotman 2015), especially if the birds have to build-up enough energy reserves to cope with changed conditions at stop-over sites after their long migration. Given declines at most

other non-breeding sites, East Arm Wharf may thus become increasingly important for this critically endangered species.

Lee Point and neighbouring sites are subject to varying levels of human disturbance, including unrestrained dogs (Lilleyman *et al.* in revision). The increase in Eastern Curlew numbers at Lee Point after the commencement of dog regulation and changed land zoning in 2002 is encouraging and may have contributed to the increase in habitat use by the species. Management intervention often has positive outcomes for shorebirds by increasing overall roosting and foraging habitat use (Burger and Niles 2013). Other factors may influence the presence of Eastern Curlew at a site, including substrate penetrability. The tidal flats adjacent to the northern beaches are much firmer and sandier than in Darwin Harbour. However, a low tide survey conducted in the 2015 austral summer season revealed a high count of 150 Eastern Curlew foraging at the mouth of Buffalo Creek (2 km to the east of Lee Point). This observation suggests that: (1) a large population of Eastern Curlew exists to the east of the Darwin region (and most likely separate to the East Arm Wharf population) with birds choosing to roost away from Lee Point, perhaps in saltpans to the south of Shoal Bay, which is difficult for counters to access (see Figure 1 for potential roosting options in supratidal saltpans and reduced road access); (2) there are sufficient prey available to sustain a large population of foraging Eastern Curlew on the northern beaches of Darwin. The abundance of Soldier Crabs (*Mictyris longicarpus*) on the northern beaches, which Eastern Curlew regularly eat (Zharikov and Skilleter 2004; A. Lilleyman pers. obs) during the core of the non-breeding season (Nov-Dec), suggests that roost sites and disturbance, not food availability, limit the abundance of Eastern Curlews on these beaches.

Maximum counts and seasonal trends

Eastern Curlew numbers are relatively low at Lee Point with small numbers of birds scattered across tidal flats and in creeks during low tide and in loose flocks at the high tide roosts. East Arm Wharf in Darwin Harbour supports a larger population of the species with several hundred birds roosting at the artificial dredge ponds. Numbers exceeding the national threshold of 38 individuals (0.1 % of the total Flyway population) have been counted 39 times out of 101 occasions at East Arm Wharf during the

survey period. The highest count at East Arm Wharf (237) is close to the total estimate of 272 Eastern Curlew for the entire coastline from northern Fog Bay west of Darwin, to Point Stephens further east – surveys that included all of Darwin Harbour (Chatto 2003). The East Arm Wharf maximum count of 237 individuals was recorded in January 2015, whereas the maximum count of Eastern Curlew from the Darwin Harbour survey area reported by Chatto (2003) was recorded in September.

Darwin Harbour is also an important staging site for shorebirds migrating through northern Australia, with many individuals and species using East Arm Wharf and other sites during the southward migration period. East Arm Wharf and Lee Point are important roosts during the wet season months (October-March). Shurcliff (1993) also reported that Eastern Curlew in Darwin Harbour occurred in highest numbers in wet season months. In contrast, Chatto (2003) reported that most Eastern Curlew occur on Northern Territory coasts during the northern hemisphere-breeding months of June and July, a paradoxical result perhaps suggesting that Eastern Curlew may have been overlooked in wet-season surveys or that an unusually large number of birds completed only a partial migration north in the year counted. Highest counts for the species, especially at East Arm Wharf, coincided with high spring tides each month especially when low pressure systems and associated onshore winds raised sea levels higher still. Birds normally roosting in mangroves or supratidal saltpans are likely to be pushed out during these extreme weather conditions. Under the latter conditions, the East Arm Wharf roosting site, with shallow water, good visibility and available at all tide heights, is a particularly suitable roosting site.

Migratory shorebird habitat is increasingly being developed. Currently, many shorebird species occur in Darwin Harbour in nationally and internationally important numbers. Ports and developers are legally obliged to protect these significant populations of shorebirds by providing suitable habitat for them, and by supporting monitoring programs to better understand their population trends. Monitoring of migratory shorebirds at East Arm Wharf in Darwin Harbour has revealed an increase in the numbers of Eastern Curlew and suggests that the artificial roosting habitat provided for them is highly suitable for them and many other shorebird species in the region. The maintenance of dredge ponds in ports to

support migratory shorebirds is a cost-effective conservation action that can help to secure curlew populations and other shorebird species in the Australian part of the East Asian-Australasian Flyway.

Conclusion

Modelled population trends for Eastern Curlew describe a local-scale increase in the numbers roosting at two important sites in the Darwin region. Our findings contrast with declines of Eastern Curlew in other parts of Australia. The most plausible explanations for the increase in Eastern Curlew numbers are (1) improved protection of beach roosting sites from disturbances, and (2) the provision of safe artificial roost sites (East Arm Wharf dredge ponds) that can be accessed year round and independently of the tides. While the apparent increase in Eastern Curlew numbers in the Darwin region is encouraging, these increases must be seen in context; they show an increase in the numbers of Eastern Curlew roosting in sites that are easily surveyed, but it is possible that this increase reflects changes in roost selection rather than a genuine increase in numbers in Darwin Harbour. Nevertheless the increases are indicative of the importance of artificial roost sites close to suitable feeding grounds, an intervention that could be used elsewhere to conserve shorebirds. The increases also suggest that protecting shorebirds from disturbance is important. Given the high rates of disturbance and destruction of habitat elsewhere in the Flyway, secure sites that can be protected are invaluable to the conservation of Eastern Curlew.

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Appendix 3

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Supplementary Appendix 3. Distribution and abundance of migratory shorebirds in Darwin Harbour, Northern Territory, Australia

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Distribution and abundance of migratory shorebirds in Darwin Harbour, Northern Territory, Australia

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Abstract

Here we report the results of an aerial survey of migratory shorebirds in Darwin Harbour, Northern Territory, Australia, as part of a new project on strategic planning for the Far Eastern Curlew (*Numenius madagascarensis*). On one day in January 2017 we surveyed the intertidal zone of a large part of upper and middle Darwin Harbour at low tide and counted all shorebirds and waterbirds present, and then we also surveyed all saltpans and potential roosting areas at high tide. There were 724 birds of 19 species recorded during the low tidal survey and 789 birds from 13 species recorded during the high tidal survey (i.e. a total of 24 species for the day). We found a total of 329 Far Eastern Curlews during the high tide survey, an increase in the Darwin Harbour maximum previously recorded. We will use these results to guide future monitoring work on the Far Eastern Curlew in Darwin Harbour, and to help mitigate the effects of coastal developments on shorebirds.

Introduction

Most shorebirds in Australia are long-distance migrants that breed in Siberia, Alaska or China, and visit Australasian shores during the austral summer. These shorebirds migrate between hemispheres along the East Asian-Australasian Flyway (hereafter the EAAF), but habitat destruction in the Yellow Sea region is driving population decline for many species (Szabo *et al.* 2012; Murray *et al.* 2014; Clemens *et al.* 2016; Conklin *et al.* 2016; Piersma *et al.* 2016). Once in Australia, shorebirds spend the duration of the austral summer seeking out high quality food resources. As most coastal shorebirds feed on benthic invertebrates on exposed mudflats during low tide, foraging and roosting times are dictated by tidal cycles. At high tide, when the foraging grounds are submerged, shorebirds retreat to roosts on sandy beaches, rocky reefs, dykes and ponds, where they preen or rest.

There are 37 species of migratory shorebirds that regularly visit Australia (Commonwealth of Australia 2015), and 25 of them occur along the coastlines of Darwin Harbour in the Northern Territory (A. Lilleyman, unpubl. data). There are seven species of shorebirds classified as Threatened under the *Environmental Protection and Biodiversity Conservation Act* 1999 (EPBC Act); all occur in Darwin Harbour. The focal species of this study is one of them, the the Far Eastern Curlew (*Numenius madagascariensis*) (Figures 1 and 2). In fact its conservation status was recently upgraded to Critically Endangered under the EPBC Act due to reported population declines over the last thirty years from monitoring sites around Australia (Department of the Environment and Energy 2015). Internationally it is listed as Endangered (BirdLife International 2016). It is the largest of the annual migrant shorebirds that travel along the EAAF, to which it is endemic (Higgins & Davies 1996).

Darwin Harbour has a variety of coastal habitats that migratory shorebirds use during the non-breeding season. This includes natural sites such as beaches, rocky reefs, intertidal sand and mud flats, but also an artificial site – the dredge ponds at Darwin Port's East Arm Wharf (Figure 3). This site regularly provides safe roosting habitat for over 1000 shorebirds of 25 species plus 45 species of other waterbirds or water-associated birds (Lilleyman 2016). In contrast to the rest of the species' range (Studds *et al.* 2017; Clemens *et al.* 2016), the Far Eastern Curlew has been counted in increasing numbers in the

Darwin region – at Lee Point in Darwin's northern suburbs – over the last thirty years, and at East Arm Wharf since 2009 (Lilleyman *et al.* 2016b).

In Australia, the key threats to migratory shorebirds are coastal development that destroys habitat and disturbance that disrupts their normal activities (Harding *et al.* 2007). These threats are both present in the Darwin region and the effects of anthropogenic disturbance to shorebirds have been documented (Lilleyman *et al.* 2016a). Safe roosting sites are critically important for shorebirds that feed on coastal intertidal zones that become inundated by the tide twice a day. East Arm Wharf provides secure and safe roosting habitat for shorebirds as human access to the site is restricted. Far Eastern Curlews regularly occur at the site in nationally important numbers (criterion: 0.1 % of the EAAF population) during spring high tides (Lilleyman *et al.* 2016b), suggesting that a large proportion of the population uses this site when other roosting sites are not available. The connectivity and availability of these sites at various tide cycles is crucial for managing the shorebird populations in Darwin Harbour.

Migratory shorebirds select roosting sites that are close to feeding grounds to allow short commutes twice a day. In tropical locations, both roosting and feeding sites need to be in areas where birds can thermoregulate to avoid heat stress (Rogers *et al.* 2006; Rosa *et al.* 2006; Zharikov & Milton 2009). Shorebirds will often use a network of sites in a region for roosting and feeding to ensure that there is always one site available at which they can forage. Far Eastern Curlews are solitary foragers and defend small territories across intertidal mudflats (Jackson 2017). On Stradbroke Island, in southern Queensland, territory size varies from 0.22–0.85 ha, depending on densities of favoured prey (Zharikov & Skilleter 2004) and in Moreton Bay, also in southern Queensland, the Curlews operate daily at scales of 5–10 km (Finn *et al.* 2002). Prey abundance and thus territory size are yet to be measured in Darwin Harbour but will affect both the abundance and dispersion of Curlews across the Darwin Harbour intertidal zone.

Darwin Harbour is likely to undergo substantial development over coming decades. Under the EPBC Act, new developments need to take the needs of protected threatened species into account. This can only be done if there is a greater understanding of how the different species use the available habitat

and the extent to which sites are connected. This project on the Far Eastern Curlew will contribute to this understanding so the deleterious effects of coastal development can be minimised. This preliminary survey builds on an intensive monitoring program for shorebirds at the Port of Darwin. The aim of the aerial survey was to record all migratory shorebirds and other waterbirds observed in the study area. While our main focus was on Far Eastern Curlews, we took the opportunity to survey all other bird species that utilise the intertidal zone. The result is a detailed survey of shorebird abundance and distribution at low and high tide during the core non-breeding period in Darwin Harbour. We also present the first full count of Far Eastern Curlew numbers in the Harbour.

An additional factor in the research of which this survey forms part, is that it is a partnership between researchers at Charles Darwin University and the Larrakia people, the Traditional Owners of the habitat where the Curlew occurs. Far Eastern Curlews and other shorebird species have been recorded at the Larrakia sacred site Yirra (Catalina Island) to the east of East Arm Wharf. There is extensive overlap between the habitat used by Far Eastern Curlews and areas that are culturally important to Larrakia people. Extensive middens around the fringes of Darwin Harbour attest to a long and continuing history of use of the mangroves and mudflats around the edges of the Harbour that are non-breeding habitats for the Far Eastern Curlew. Such resource use, however, can only continue if the environment remains in a healthy and productive state. Larrakia people are already working with university researchers to monitor pollution levels in shellfish around the Harbour. The current project will allow us to understand how the resources are being used by the threatened birds that also use Larrakia's land and sea areas.

Darwin Port, a major stakeholder in the long-term planning of Darwin Harbour and the associated coastline, is a partner in this project and aims to assist in the management of globally-threatened shorebirds through appropriate and sustainable decision-making. The Port of Darwin currently manages the nationally important habitat for the Far Eastern Curlew at East Arm Wharf and will seek to understand how the species uses other feeding and roosting habitat in Darwin Harbour as a contribution to long-term strategic planning.

Methods

We conducted an aerial survey of Darwin Harbour using a helicopter on Thursday 12 January 2017 during low tide (10.15 hr to 12.15 hr) and then again at high tide (17.00 hr to 18.30 hr). Low tide (0.75 m) occurred at 12.09 hr and high tide (7.63 m) occurred at 18.44 hr that day. An aerial survey allowed full coverage of Darwin Harbour during one full tidal cycle and gave us access to saltpan habitat that would otherwise be inaccessible by road.

During the low tidal phase of the survey, we flew over the intertidal zone along the edge of the mangroves starting from Dinah Beach Boat Ramp (12.44°S, 130.85°E) through to Mandorah Wharf (12.44°S, 130.76°E) (Figure 3). We circumnavigated all the small islets and flew over exposed sandbars. During the high tidal phase of the survey, when the intertidal zone was covered, we flew low over mangroves and supratidal saltpans where, from experience, we expected shorebirds to be roosting (Figure 4). This meant that we omitted the southern ends of the three arms of the Harbour because there are no saltpans behind the mangroves where roosting birds were likely to be visible from the air. For surveying, A. Lilleyman and S. Garnett called out counts of all shorebirds and waterbirds, and A. Lilleyman recorded all birds observed and made notes on habitats into a hand-held voice recorder (Sony ICD-PX440). Survey personnel avoided duplicating observations by making counts from different sides of the helicopter. When shorebirds were not easily identified from the air, they were classed as either 'Small' or 'Medium' based on their size. The recording data were later transcribed into a database.

During the high tidal phase of the survey, an experienced shorebird counter (G. O'Brien) was stationed at East Arm Wharf roost to count all birds present at the site, while A. Lilleyman and S. Garnett surveyed additional sites in the region. This on-ground survey was conducted between 16.00 hr and 19.00 hr. Once all high tidal sites had been surveyed, we flew over East Arm Wharf to count shorebirds at the Port's ponds and later ground-truthed this by comparing with the East Arm Wharf on-ground count. The timing of arrival of birds at the Port's ponds was recorded and this was checked against records of birds away from the site to avoid duplication in the final estimate of birds.

Results

Abundance of migratory shorebirds in Darwin Harbour

We recorded 724 individuals of 19 species of bird during the low tidal phase of the survey (Table 1) including 160 Far Eastern Curlews. All the Curlews were feeding on the exposed intertidal mud alone or in loosely associated pairs. At the lowest tide they were commonly feeding in the middle of the mudflat, often along small drainage channels, though this was difficult to quantify.

At high tide we located 789 individual shorebirds belonging to 13 species (i.e. a total of 24 species for the day), including 185 Far Eastern Curlews. Many of the Curlews were roosting in small flocks with a median group size of 2 individuals, a mean group size of 7 and a maximum of 60.

At East Arm Wharf, 388 individuals from 14 species were counted from the ground (Table 2). This included 144 Far Eastern Curlews. These individuals were in addition to the 185 Far Eastern Curlews that we recorded in Darwin Harbour during the high tidal survey. The total population of Far Eastern Curlews in Darwin Harbour on 12 January 2017 was therefore 329 individuals. This is greater than the previously recorded maximum count of Far Eastern Curlews for the East Arm Wharf site (264 individuals recorded during the December monthly high tide count).

Table 1. Total count of migratory shorebirds recorded in Darwin Harbour during low tide and high tide on 12 January 2017.

Species	Low tide	High tide
Grey Plover	0	3
Bar-tailed Godwit	0	30
Whimbrel	104	344
Far Eastern Curlew	160	329
Terek Sandpiper	2	0
Common Sandpiper	42	0
Grey-tailed Tattler	14	0
Common Greenshank	46	16
Small	167	66
Medium	118	13

Note: The 'Small' component of this count comprises Red-necked Stint, Common Sandpiper, Terek Sandpiper, Grey-tailed Tattler, Red Knot, Great Knot, Ruddy Turnstone, Sharp-tailed Sandpiper, Greater Sand Plover, and Lesser Sand Plover. The 'Medium' component of this count comprises Common Greenshank, Grey Plover, and Bar-tailed Godwit.

Table 2. Count of migratory shorebirds from East Arm Wharf (on-ground count) during the high tidal survey of 12 January 2017.

Species	Total count
Grey Plover	6
Bar-tailed Godwit	3
Whimbrel	116
Far Eastern Curlew	144
Common Greenshank	50
Marsh Sandpiper	2
Sharp-tailed Sandpiper	8

Distribution of the Far Eastern Curlew in Darwin Harbour

Far Eastern Curlews were found to be widely distributed throughout Darwin Harbour during the aerial survey conducted at low tide (Figure 5). Most were recorded foraging on the inner section of the mud flats closer to the mangroves than the outer section of the mud flats towards the lowest tide height (see 'Intertidal' layer on map of Figure 5). They were recorded in small flocks during the high tidal period when they were roosting, primarily in supratidal saltpans, above the high-water mark (Figure 6).

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Shorebirds were forced out of these saltpans once the tide had reached its peak height and they flew to roosts on islands, in mangroves, or on beaches. Some shorebirds, including Far Eastern Curlews, roosted at the East Arm Wharf site, and even when perturbed at the site during the aerial survey, they returned to roost in the artificial dredge ponds.

Curlews recorded during the low tidal survey had to fly from different parts of the Harbour to roost at East Arm Wharf. The straight line distance between foraging sites at low tide and the East Arm Wharf roost site varied from 2.5 to 19.6 km, with an average of 9.7 km. Although birds recorded on the intertidal zone at low tide were always close to supratidal saltpans, these are not available during high spring tide heights because they are covered in deep water. At such times we believe that most, if not all, the Curlews around the harbour roost at East Arm Wharf, although other roosting sites may be important on lower high tides or as staging posts while the tide is rising.

Nationally important roosting sites

During the count of high tidal roosts, we recorded two locations where flocks of Far Eastern Curlews had more than 31 individuals (Figures 3, 6). This meets the threshold for protection of threatened shorebirds under the EPBC Act, which is 0.1 % of the flyway population. One flock was recorded at East Arm Wharf, where large congregations of greater than or equal to 31 individuals assemble frequently. The other flock was at the saltpan, south-east of East Arm Wharf, adjacent to the ConocoPhillips LNG Plant, although this roosting site may not be available at the highest tides.

Discussion

Distribution and abundance

Most migratory shorebirds observed in this study were sparsely distributed over the intertidal mudflats of Darwin Harbour during low tide. Some areas were devoid of birds, whilst at others individuals had congregated in small feeding flocks. Most Curlews were feeding on the upper half of the mudflat exposed at low tide during which we surveyed from near the mangroves to half way out to the sea with only a few at the edge of the water. This suggests that Far Eastern Curlews may not strictly follow the tide when foraging. We observed high abundances of crabs in the middle of the exposed area at low

tide and this might influence where Far Eastern Curlews forage, as crustaceans are its preferred prey (Finn *et al.* 2008). Also, if Curlews are defending territories, they may only defend mudflats exposed at most tides and not those exposed only at the lowest spring low tides (the timing of the current survey).

The abundance and distribution data reported from this aerial survey will be used to guide the fieldwork program for the strategic planning project on the Far Eastern Curlew, including the benthic invertebrate monitoring component which will examine the availability of food for Curlews. Understanding the types of prey and how much of it is available to shorebirds will help determine the habitat requirements of these birds in Darwin Harbour. Prey distribution influences shorebird distribution across the intertidal habitat (Ponsero *et al.* 2016), and tidal cycles constrain both the movement of benthic invertebrates and the available time for shorebirds to forage (Kraan *et al.* 2009). Our aerial survey has shown where Far Eastern Curlews forage during low tide, but it has not shown the distances these birds move within the Harbour during a complete tidal (high to low) cycle. Our next project is to examine the movement of individuals in Darwin Harbour to explore the connectivity within the region. Migratory shorebirds require a network of high-quality sites at both a flyway scale and at a local regional scale to migrate and breed successfully each year (Aharon-Rotman *et al.* 2016).

Understanding habitat choice of shorebirds allows informed management of important habitat, which in turn can secure the protection of these birds. Migratory shorebirds will require a range of roosting and feeding sites in Darwin Harbour so they can move between sites if the optimal habitat is disturbed or unavailable due to tidal conditions. It will be important to ensure there is an adequate array of roosting sites for shorebirds as a reduction in these may lead to increased competition for resources (Goss-Custard *et al.* 2002) or, in extreme circumstances, a population crash if suitable habitats are not available (Burton *et al.* 2006).

The use of the East Arm Wharf site by Far Eastern Curlews (and many other species of shorebirds) (Figure 3) documented during the survey reported here suggests an ongoing attraction to this artificial habitat. The high count from the current survey represents a substantial increase in Curlews for the Darwin Harbour area compared to those reported previously (Chatto 2003). The results from this study

coupled with the local-scale increases as reported by Lilleyman *et al.* (2016b) show that this species can adapt to local habitat changes if the alterations to the environment provide a net increase in habitat availability. The East Arm Wharf site is evidently now providing high quality roosting habitat for Far Eastern Curlews and other shorebirds and waterbirds. These birds roost there in preference of all other roosting sites in Darwin Harbour, as evidenced by the large number of birds at the site, relative to the total Darwin Harbour population.

In Darwin Harbour, shorebird numbers may be constrained by the availability of roosting sites. Feeding grounds appear to be widely available with extensive intertidal areas within the region, although the quality of these mudflats is yet to be tested. Although Far Eastern Curlews were always close to potential saltpan roost sites when they were feeding at low tide, the saltpans are inundated at the highest tides. The birds can then roost in mangroves or fly to East Arm Wharf. This latter site is apparently being adopted by increasing numbers of migratory shorebirds, including the Curlews. Indeed, the increasing numbers counted at East Arm Wharf may be because the availability of the roosting site there is allowing more birds to feed in Darwin Harbour. Given the length of time over which the increases have been sustained, this seems a more probable explanation than the alternative explanation, which is that birds traditionally using the Harbour have only gradually come to know the quality of the East Arm Wharf roosting site. However, the distance the Curlews appear to be travelling to East Arm Wharf from feeding areas is longer than is usual among shorebirds (Jackson 2017). This in turn implies that the creation of additional roosting sites could further increase the quality of the Harbour to migratory shorebirds if food is available.

Conclusion

The low tidal survey revealed a high level of usage of mudflats by the Far Eastern Curlew with birds feeding on mudflats around almost all the Harbour, particularly on the broader tidal flats. Roosting occurred on saltpans but, when these were inundated, many birds moved to East Arm Wharf. The survey confirmed that the artificial East Arm Wharf site has become the most important roosting site for the Far Eastern Curlew within Darwin Harbour. The site is also particularly important for other species of

migratory shorebirds throughout the austral summer. The new maximum count for the Far Eastern Curlew of 329 birds is an increase in the population estimate for this species and shows that there are more birds in the Darwin region than previously recorded. This study, along with recent research (Lilleyman *et al.* 2016b), provides an opportunity to further manage an artificial site for positive conservation outcomes for migratory shorebirds. Management of the Far Eastern Curlew in Darwin Harbour requires a holistic approach so that the species, and other migratory shorebirds, are adequately protected against the potential impacts of coastal development.

Acknowledgements

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Figure captions

Figure 1. Far Eastern Curlews (*Numenius madagascariensis*) in flight. (Amanda Lilleyman)
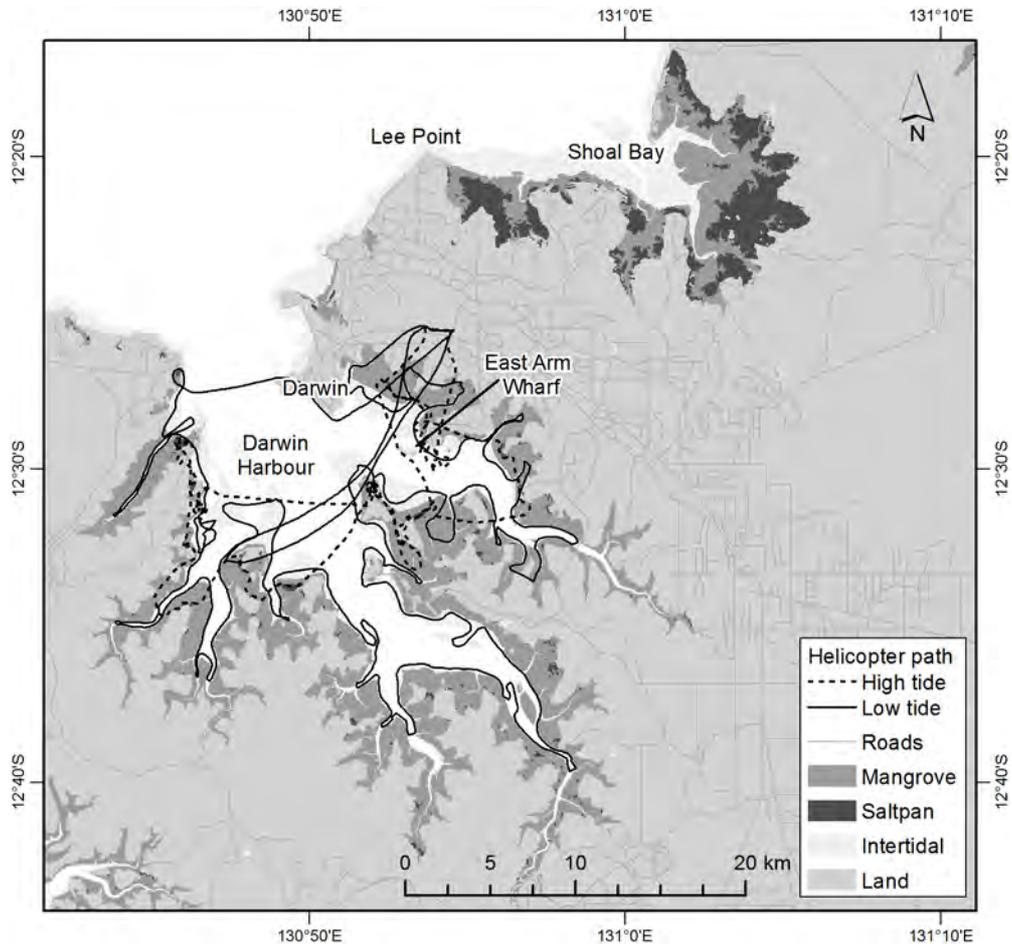
**Figure 2.** A male Far Eastern Curlew (*Numenius madagascariensis*) in flight. (Amanda Lilleyman)

Figure 3. Far Eastern Curlews roosting with other waterbirds in a dredge pond at Darwin Port's East
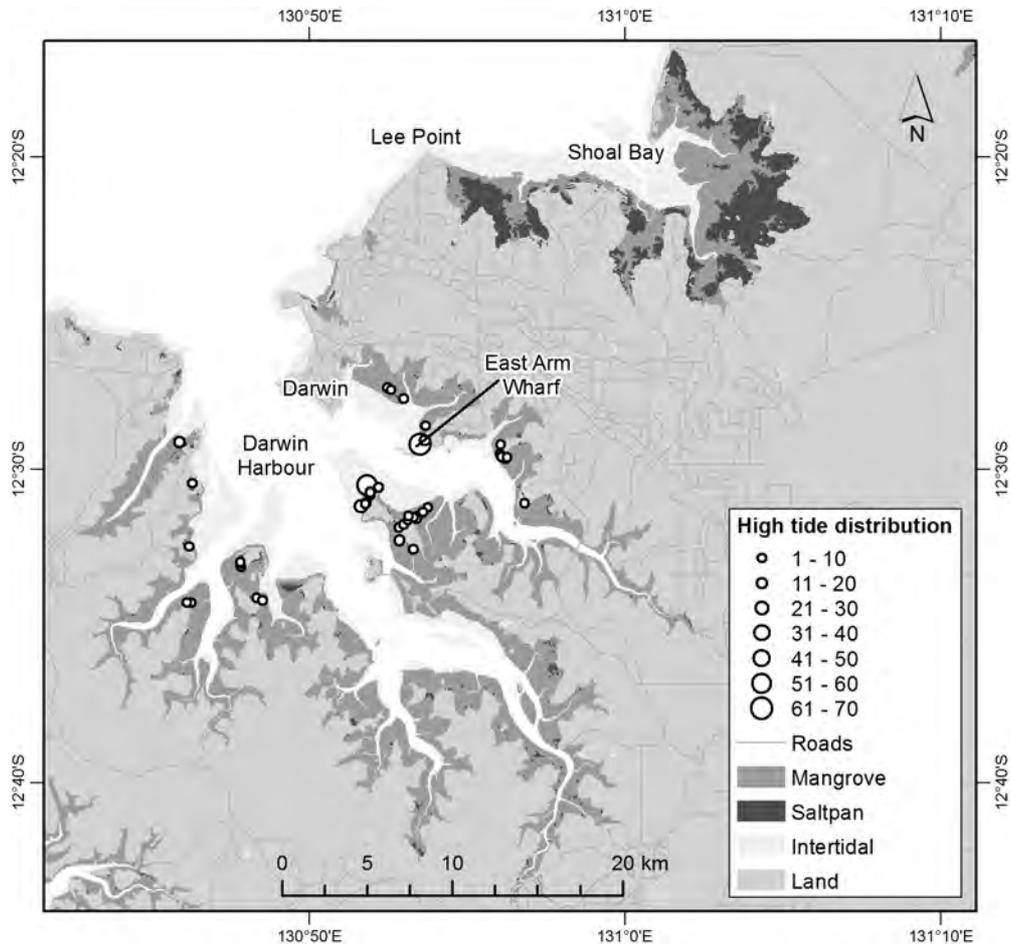
Arm Wharf. This photo alone yields a count of Far Eastern Curlews that exceeds the national threshold for that species of bird. (Amanda Lilleyman)

Figure 4. Map of the survey area in Darwin Harbour and the path flown during high tide and low tide.
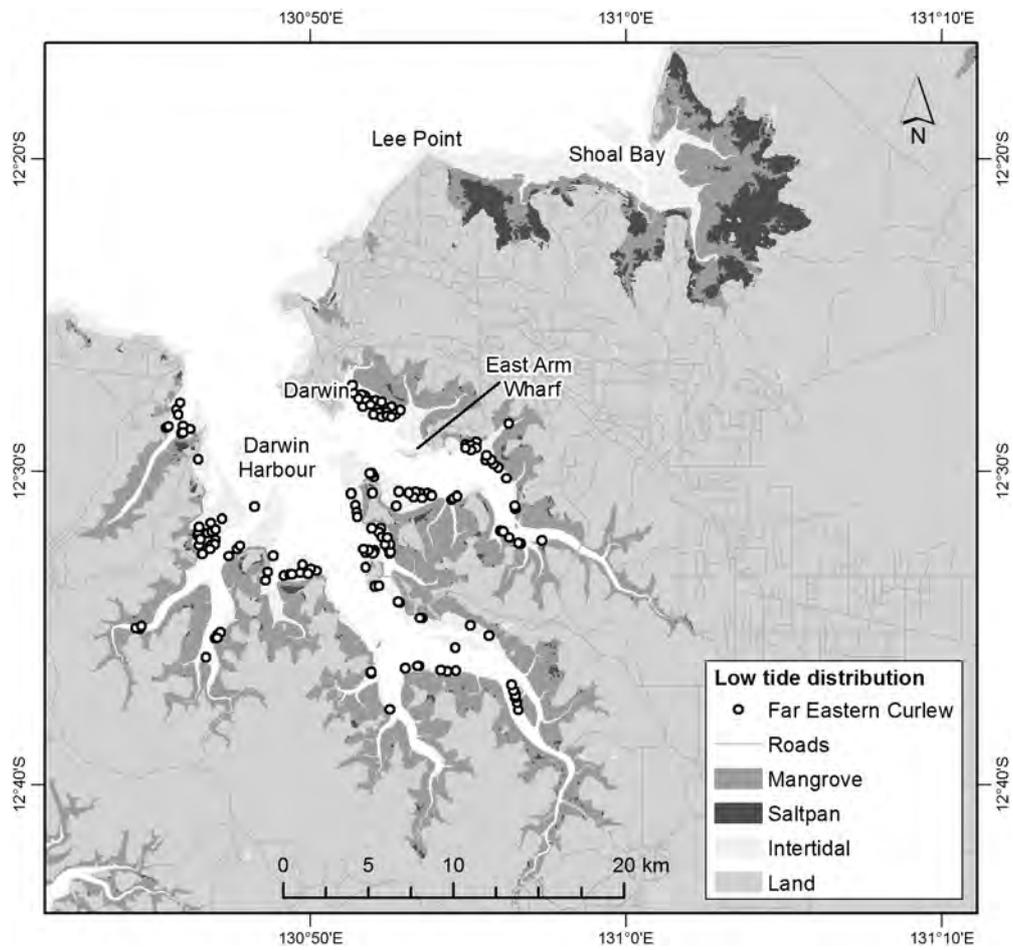
Figure 5. Distribution of Far Eastern Curlews recorded during low tide in Darwin Harbour.

Figure 6. Distribution of Far Eastern Curlews recorded during high tide in Darwin Harbour. Legend shows count size classifications. Flocks of this species greater than or equal to 31 individuals indicate representation at sites considered as nationally important under the EPBC Act.

Appendix 4

Greater & Lesser Sand
Graphite + water col
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Supplementary Appendix 4. Darwin shorebird catching: expedition report 2018

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DARWIN SHOREBIRD CATCHING: EXPEDITION REPORT 2018

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RUNNING TITLE

Darwin shorebird expedition report

ABSTRACT

Shorebird expeditions have been run in the Northern Territory sporadically since 1995 and have focussed on birds from five sites along the Top End coastline. Over the years, there has been 2510 shorebirds caught from 19 species from a combination of cannon netting and mist netting. From 2014 onwards, we applied engraved leg-flags to shorebirds and this has allowed for a more detailed understanding of site fidelity on the non-breeding grounds and migration pathway connectivity. Since that time, there has been more than 3403 leg-flag resightings from six countries in the East Asian-Australasian Flyway. In 2018, the objective of the expedition was to capture the critically endangered Far Eastern Curlew *Numenius madagascariensis* to attach GPS tracking devices to birds to learn about their local movements on the non-breeding grounds of Australia. One GPS tag was deployed on a Curlew during this expedition. Shorebird catching expeditions allow researchers to collect useful data on age demographics within populations, and to target species for more detailed studies such as those on movements of birds.

INTRODUCTION

"*The team started the expedition with the aim of catching the world's largest shorebird, the Far Eastern Curlew, and we finished the week in the field catching the world's smallest shorebird – the Little Stint.*"

<div align="right">Dr Clive DT Minton</div>

A team of researchers from the Australasian Wader Studies Group (AWSG) joined Amanda Lilleyman in Darwin to cannon net Far Eastern Curlew in November 2018. The expedition was timed to maximise the chances of catching curlew and catching in November meant that adult and juvenile birds would be in Darwin for the non-breeding season of the austral summer. November is typically a humid time of the year and is characterised as the 'build-up' period; however, it was unseasonably wet during the catching week with rain during net-setting times and on one occasion the team had to retreat to cars as a severe storm passed over Darwin Harbour.

The main catching site during this expedition was Darwin Port's East Arm Wharf and the secondary catching site was Lee Point beach, in Casuarina Coastal Reserve (Figure 1). In early November the high tides occurred during the mornings and evenings and it was a new moon spring tide period. Most of the equipment preparations occurred in the mornings and net setting occurred during the day. Most catches were made in the evenings on the incoming high tide and the very last catch on the morning high tide.
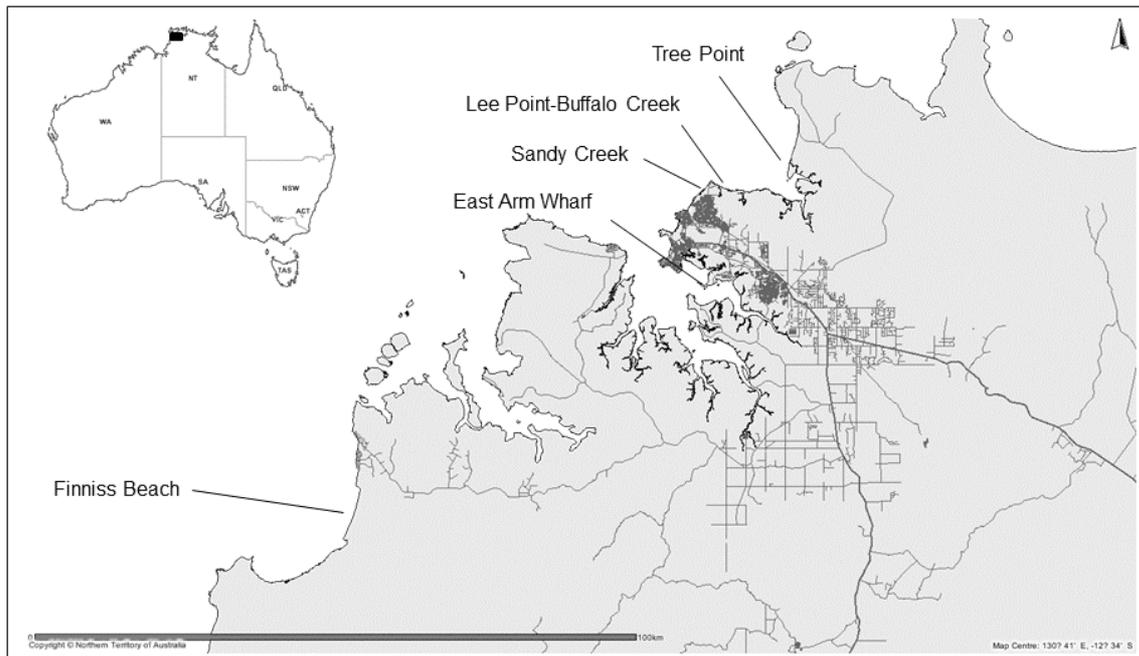
Figure 1. Map of all expedition catching sites in the Northern Territory. Map also shows main roads and housing in the Darwin region.

The team was made up of five interstate experts (3 Vic 1 QLD, 1 WA), one local researcher (AL), accompanied by a team of Indigenous rangers from the local Larrakia Rangers program from Larrakia Nation Aboriginal Corporation and local volunteers. A daily team of 15-25 people were involved.

Darwin – importance of catching and banding

Darwin's geographical position creates an opportunity to explore the mixing of several subspecies of migratory shorebird. Until the 2014 and 2015 catching and flagging, there was no understanding of the proportion of the two Red Knot subspecies that occur in Australia (*rogersi* and *piersmai*). The individual engraved leg-flag marking allowed us to gain resighting data on this species and estimate the subspecies ratio for the region (Global Flyway Network, *Pers. Comm.*).

Darwin is a known staging site in northern Australia and while this concept was once only considered through anecdotal evidence, it has now been confirmed with resighting data from terminal sites in southern Australia and in New Zealand.

Historical background

Researchers first caught shorebirds in the Top End of the Northern Territory in 1995, then again in 1996, 2008, 2014, 2015, 2018. These mini expeditions were led by a local Darwin researcher and team members from the Australasian Wader Studies Group and were undertaken for a range of objectives (Clive Minton, *Pers. Comm.*).

The main aim of the 1995 and 1996 expeditions was to catch shorebirds and waterbirds to collect blood samples to detect avian-borne diseases for the Northern Territory Quarantine and Inspection Services (now known as Northern Australia Quarantine Strategy) and to collaborate with the Conservation Commission of the Northern Territory (now known as Parks and Wildlife). Similarly, the 2008 expedition had the same aims but also set out to flag shorebirds using plain yellow over blue leg flags.

The aim of the 2014 and 2015 expeditions was to catch and flag as many shorebirds as possible to contribute to a PhD study on the movement of shorebirds in the Darwin region (Lilleyman, *in prep*). Data from these expeditions also contributed to continental-wide analysis of body condition in shorebirds. The 2014 and 2015 expeditions had advanced from previous expeditions through the application of engraved yellow over plain blue leg flags. These were placed on all shorebirds, except Red-necked Stint, that had plain yellow over blue leg flags applied.

All shorebirds were caught on beaches or wetlands along the Northern Territory coastline, in Darwin Harbour during all years, and in Fog Bay (Finniss Beach) during 1995-1996 (Figure 1). Darwin Harbour is a mangrove-lined tropical estuary in the Northern Territory that is near-pristine in condition (Munksgaard *et al*. 2018). Darwin Harbour supports more than 10 000 migratory shorebirds during the austral summer (Chatto 2012) is also home to most of the human population in the Northern Territory. Most shorebirds in the Darwin Harbour catching sites occur in the land tenure of Casuarina Coastal Reserve, managed by Parks and Wildlife Commission of the Northern Territory (Parks and Wildlife Commission Northern Territory 2016). This area also has high human pedestrian traffic and consequently, anthropogenic disturbances to shorebirds are common at the site (Lilleyman *et al*. 2016).

Finniss Beach sits within Fog Bay to the west of Darwin Harbour and has historically supported up to 17 000 migratory shorebirds (Chatto 2012). It is at risk of increased disturbance through human visitation and increased housing at the nearby town of Dundee Beach (Chatto 2012).

2018 expedition objectives

The aim of the 2018 expedition was to catch the critically endangered Far Eastern Curlew to attach GPS tags to birds as part of the project 'strategic planning for the Far Eastern Curlew' under the National Environment Science Programme Threatened Species Recovery Hub (http://www.nespthreatenedspecies.edu.au/projects/strategic-planning-for-the-far-eastern-curlew). An additional aim was to band and flag other species of migratory shorebird and to continue taking measurements for morphometric studies.

METHODS

Study sites

In the 2018 expedition we cannon-netted at Lee Point-Buffalo Creek beach (-12.33, 130.90) and at East Arm Wharf (-12.48, 130.89). Catching happened in the first week of November on best available high tides. This month was selected because most adult and juvenile shorebirds have returned to Darwin by November and those in the region would most likely stay, rather than continuing further south.

Field methods

All expeditions involved catching shorebirds using cannon nets, and in 2017 and 2018, the team also used mist nets to catch shorebirds. All cannon nets were set following standard methods (Australasian Wader Studies Group 2018). Mist nets were used when high tides occurred late in the night and it was not practicable to cannon net at night. We used mist nets to catch birds in 2017 and went out every month to either East Arm Wharf or a saltpan next to the EAW. We also used mist nets in 2018 when cannon netting was not practical due to high tides occurring in the night. We always mist-netted during evenings when the tide was rising.

All captured shorebirds had biometrics taken: mass, wing length, head length, head-bill length, moult, age and sex (if known). Captured birds had a metal band, and from 2014 onwards had engraved yellow over plain blue leg flags applied.

RESULTS

In 2018 there were 142 shorebirds from 11 species caught and processed during the expedition (Table 1), including two Far Eastern Curlew, with one GPS tag deployed on a male bird.

Table 1. Darwin 2018 catch totals, method used and percent juveniles for each species.

Date Capture Method	Site	Species	New	Total	Juv	% Juv
6/11/2018 **Cannon netting**	Lee Point-Buffalo Creek	Greater Sand Plover *Charadrius leschenaultii*	19	19	0	0
		Lesser Sand Plover *Charadrius mongolus*	6	6	0	0
		Great Knot *Calidris tenuirostris*	2	2	2	100
		Red-necked Stint *Calidris ruficollis*	1	2	0	0
		Sharp-tailed Sandpiper *Calidris acuminata*	1	1	1	100
		Total	**29**	**30**	**3**	
9/11/2018 **Cannon netting**	East Arm Wharf (Pond E)	Far Eastern Curlew *Numenius madagascariensis*	2	2	0	0
		Total	**2**	**2**	**0**	
10/11/2018 **Mist netting**	East Arm Wharf (Pond K)	Greater Sand Plover *Charadrius leschenaultii*	7	1	1	100
		Sharp-tailed Sandpiper *Calidris acuminata*	7	7	1	14
		Red-necked Stint *Calidris ruficollis*	3	3	0	0
		Grey-tailed Tattler *Tringa brevipes*	2	2	1	50
		Whimbrel *Numenius phaeopus*	2	2	2	100
		Great Knot *Calidris tenuirostris*	1	1	1	100
		Lesser Sand Plover *Charadrius mongolus*	1	1	1	100
		Terek Sandpiper *Xenus cinereus*	1	1	0	0
		Total	**24**	**24**	**7**	
11/11/2018 **Cannon netting**	Lee Point-Buffalo Creek	Great Knot *Calidris tenuirostris*	40	40	4	10
		Red-necked Stint *Calidris ruficollis*	32	34	5	15
		Greater Sand Plover *Charadrius leschenaultii*	7	7	1	14
		Lesser Sand Plover *Charadrius mongolus*	2	3	0	0
		Little Stint *Calidris minuta*	1	1	1	100
		Red Knot *Calidris canutus*	1	1	0	0

		83	86	11
Total				
TOTAL BIRDS	142			

Since 1995, there has been 2510 shorebirds caught from 19 species during expeditions, across five sites in the Northern Territory (Table 2). Since the 2014 expedition and application of engraved leg-flags, there has been approximately 3403 resightings of Darwin birds from across six countries in the East Asian-Australasian Flyway (EAAF) (Table 3). Most (>97%) of the resightings came from the Northern Territory in Australia.

Table 2. Number of species caught during expeditions per year and site in the Northern Territory.

Common name	Scientific name	1995 Lee Point-Buffalo Creek	1995 Finniss Beach	1995 Tree Point	1996 Lee Point-Buffalo Creek	2008 Lee Point-Buffalo Creek	2008 Finniss Beach	2014 East Arm Wharf	2014 Lee Point-Buffalo Creek	2014 East Arm Wharf	2015 Lee Point-Buffalo Creek	2015 Sandy Creek	2017 East Arm Wharf	2017 GWA saltpan (EAW)	2018 Lee Point-Buffalo Creek	2018 East Arm Wharf
Bar-tailed Godwit	*Limosa lapponica*		1					2						7		
Broad-billed Sandpiper	*Calidris falcinellus*						3									
Common Greenshank	*Tringa nebularia*							13		19				7		
Common Sandpiper	*Actitis hypoleucos*															1
Curlew Sandpiper	*Calidris ferruginea*							2		1	1					
Far Eastern Curlew	*Numenius madagascariensis*												1	1		2
Great Knot	*Calidris tenuirostris*		391				40	1	98		229			4	44	1
Greater Sand Plover	*Charadrius leschenaultii*	27	74		13	111	52		189		95	10		3	26	8
Grey Plover	*Pluvialis squatarola*										3					
Grey-tailed Tattler	*Tringa brevipes*			4				6	5	6	1			14		2
Lesser Sand Plover	*Charadrius mongolus*	9			3	21			6		4				8	2
Little Stint	*Calidris minuta*														1	
Red Knot	*Calidris canutus*		272						2		45			1		1
Red-necked Stint	*Calidris ruficollis*	2	16		42	209	37		73		37	2			37	3
Ruddy Turnstone	*Arenaria interpres*	2	2		12	2			11		9					
Sanderling	*Calidris alba*	3			2	1					16	4				
Sharp-tailed Sandpiper	*Calidris acuminata*										6			2	1	7
Terek Sandpiper	*Xenus cinereus*		18	11		1	2	16	13				2	3		7
Whimbrel	*Numenius phaeopus*												1	2		3
TOTAL		43	774	15	72	345	136	38	397	26	446	16	4	44	118	36

Table 3. Count of resightings for each shorebird species across countries in the EAAF from 2014 onwards.

Common Name *Scientific Name*	NT Aust	VIC Aust	WA Aust	China	Japan	New Zealand	Russia	South Korea
Bar-tailed Godwit *Limosa lapponica*	32				2			
Common Greenshank *Tringa nebularia*	38							
Curlew Sandpiper *Calidris ferruginea*	1							
Great Knot *Calidris tenuirostris*	1208		3	31			4	2
Greater Sand Plover *Charadrius leschenaultii*	1478			3				
Grey Plover *Pluvialis squatarola*	20							
Grey-tailed Tattler *Tringa brevipes*	29							
Lesser Sand Plover *Charadrius mongolus*	9							
Red Knot *Calidris canutus*	51	1		36		3		
Red-necked Stint *Calidris ruficollis*	74							
Ruddy Turnstone *Arenaria interpres*	219			5				
Sanderling *Calidris alba*	151			1				
Terek Sandpiper *Xenus cinereus*	2							
TOTAL	**3312**	**1**	**3**	**76**	**2**	**3**	**4**	**2**

The proportion of juvenile birds to adult birds in the total catch has changed over time (Table 4), from <6% juveniles caught in the total flock in 1995 to >22% in the total flock in 2018. In 2014 juveniles made up 11% of the total flock, and then in 2015 when the catching expedition was in October, juveniles made up 28.7% of the total flock.

Table 4. Percentage of juvenile shorebirds and adult shorebirds in the total catch over the expedition years.

Year	Juvenile %	Adult %
1995	5.4	94.6
1996	1.4	98.6
2008	13.9	86.1
2014	11.0	89.0
2015	28.7	71.3
2017	22.9	77.1
2018	22.1	77.9

DISCUSSION

Summary of achievements

The Darwin expeditions have proved to be highly important in improving the understanding of migratory shorebirds in northern Australia, with some leg-flag resightings from a range of sites in the EAAF. With this information we are starting to fill a gap of where birds from the Top End go on migration, and how faithful individual birds are to the Darwin non-breeding grounds. For example, resighting data from Darwin suggests that some shorebirds within the population are site faithful to the region, returning to the site of capture year after year. Additionally, we have also learned that the Darwin region is a steppingstone for some individuals within the population; for example, Red Knot that were banded in Darwin have been resighted in New Zealand, which is most likely their migration terminus.

The use of tracking devices on birds allows a detailed understanding of movement patterns and habitat use – data which are vital to the conservation of migratory shorebirds. Results from the Far Eastern Curlew tracking study have already indicated that curlew depart Darwin late in the northward migration season (April, n=2), and one of the birds nested on the Kamchatka Peninsula, which is considered very far north on their breeding grounds (Lilleyman 2018).

The expeditions have also allowed researchers to collect biometric data on all shorebirds, which will help to describe the condition of Top End shorebirds compared to birds from sites at other locations on the non-breeding grounds.

On review of the conditions and number of birds caught in the Darwin region over the years, we have decided that October is the best month to cannon net shorebirds because 1) most shorebirds (adults and juveniles) have returned to the region, 2) while it is the build-up season, October is not as humid as November, and this may influence the condition of the birds upon release after processing, and 3) October has historically provided the highest percent of juvenile birds in the total catch and this will allow for the best estimate of breeding success, if this measure was to be estimated.

Future of catching and banding shorebirds in the Northern Territory

There is considerable interest in creating a regular shorebird catching program to allow researchers to catch, process and flag birds in the Northern Territory at least once a year. This would allow for a regular addition of marked individuals in the system and would further contribute to understanding the migration and site fidelity of shorebirds that visit or stay in the Northern Territory.

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