Prepared for

Gladstone Ports Corporation Limited (GPC)

Subject

Final Report: Migratory Shorebird Monitoring – Understanding Ecological Impact (CA12000284)

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27 May 2017
UniQuest Project No: C01427

The main commercialisation company of
THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

UNIQUEST

Title

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This report should be cited as:

Choi C.-Y., Coleman, J., Klaassen, M., Moffitt, D.J., Rogers, D., Skilleter, G., & Fuller, R.A. (2017). Final Report: Migratory Shorebird Monitoring – Understanding Ecological Impact (CA12000284). Report produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of GPC's Ecosystem Research and Monitoring Program. 133 pp.

This report has been produced for the Ecosystem Research and Monitoring Program Advisory Panel as part of Gladstone Ports Corporation's Ecosystem Research and Monitoring Program. The study was undertaken through a Consultancy Agreement (CA12000284) between GPC and UniQuest to discover how to integrate migratory species into environmental impact assessment.

This publication has been compiled by UniQuest.

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1. EXECUTIVE SUMMARY

1.1 Research highlights

- We studied migratory shorebird ecology in the ERMP Survey Area, a coastal region in Queensland between the Fitzroy Delta and Rodds Peninsula.
- About 20,000 migratory shorebirds use the ERMP Survey Area, underlining its national and international importance.
- Many migratory shorebirds transit through the area to fly further south, and annual summer surveys miss about 44% of the total number of birds using the area.
- Individual birds show high site fidelity both within and between non-breeding seasons
- Birds also moved between alternate foraging or roosting sites within subregions of the ERMP Survey Area, suggesting that the impact of a development will be felt by more birds than just those using the physical footprint of the precinct.
- Prey items favoured by the birds occur at low density by international standards, show low digestible content, and are notably patchy across space and over the tidal cycle.
- Much of the highest quality intertidal foraging habitat is only available for a limited time, with only 10%–25% of the intertidal habitat exposed at half tide.
- This pattern of exposure time probably explains a dissonance between observed shorebird abundance and predicted shorebird abundance base on food density alone.
- Subject to a number of assumptions in the analysis, the site appears to be operating close to its carrying capacity, because there is only marginally more food available for most species than currently required by the birds.
- This is surprising because shorebird numbers have declined nationally from habitat loss overseas, and it is possible that this low carrying capacity reflects a long term decline in habitat quality in the region.
- Overall, we conclude that this system that is currently ecologically healthy with respect to migratory shorebirds, but is potentially vulnerable to any further reductions in quality or quantity of shorebird habitat.

1.2 Recommendations

- Given the long term declines of Australian shorebirds, and the evidence that the ERMP Survey Area is operating close to carrying capacity, extreme vigilance over shorebirds in the area is needed.
- This vigilance entails:
    - Monitoring emerging threats to migratory shorebirds in the region, and modelling their impact.
    - Monitoring the benthic invertebrate food base periodically to check for changes in migratory shorebird carrying capacity, and to understand the drivers of any changes.
    - Monitoring migratory shorebirds in the ERMP Survey Area beyond 2020, after the ERMP process has concluded.
- We recommend that the ERMP Survey Area is provisionally treated as four management units (Fitzroy Delta, North Curtis, Gladstone Harbour and Rodds Peninsula) until further information suggests otherwise.
- Explore designating part or all of the ERMP Survey Area as a Ramsar site and / or an East Asian–Australasian Flyway Partnership Flyway network site.
- Explore options for recognising the special importance of the Fitzroy Delta and North Curtis Island to migratory shorebird conservation through formal protected area designation, and / or production of a migratory shorebird management plan.
- An additional survey at the end of September or early October would permit transiting birds to be monitored.

1.3 Narrative summary

The large tidal flats around Gladstone support an impressive array of migratory shorebirds, and many species occur in internationally important numbers. Underlining the global significance of the area is its function as both a “stopover” site for birds briefly refuelling during their migrations, and a non-breeding destination in which birds stay for several months to feed on invertebrates found in the intertidal sediments.

In this project, we estimate the capacity of the Ecosystem Research and Monitoring Program (ERMP) Survey Area to support migratory shorebirds, and assess the movements of birds around the area to determine the extent to which the potential impacts of development could affect migratory shorebirds. We discovered that the site is operating close to its carrying capacity, with potentially marginally more food available for most species than currently required by the birds. This signals a system that is currently ecologically healthy, albeit close to carrying capacity and potentially vulnerable to any future threats that may impact on the quality or quantity of shorebird foraging habitat. Birds also moved between various foraging or roosting sites within subregions of the ERMP Survey Area, suggesting that the impact of a development will be felt by more birds than just those using the physical footprint of the precinct.

Part A: What is the carrying capacity of the Port Curtis / Port Alma area to support migratory shorebirds?

We conclude that the ERMP Survey Area is functioning at or near carrying capacity, based on analysing the distribution, abundance and energy content of the shorebirds’ invertebrate prey.

Satellite-based mapping shows that about 216km^2 of intertidal substratum is exposed in the ERMP Survey Area when the tide is in the bottom 10% of its range, representing an enormous foraging opportunity for shorebirds. Yet these tidal flats are highly unevenly distributed across the Survey Area with 39% of this area comprising of rarely inundated claypans, and the extent to which each tidal flat is exposed by the tide varying markedly over daily, lunar and seasonal cycles.

Across the whole ERMP Survey Area, about half of the full extent of intertidal substratum is exposed at half-tide. Yet in key shorebird foraging areas, characterised by large contiguous tidal flats, exposure of most of the potential foraging habitat is very brief, with only 10–25% of the intertidal habitat exposed at half tide. Moreover, several weeks or months can elapse between exposure periods of the intertidal substratum in the lower levels of the tidal range.

Analysis of 1,560 benthic samples from six major tidal flats from the Fitzroy Delta to Rodds Peninsula revealed enormous spatial and temporal variation in benthic prey availability, with dominant benthic taxa broadly transitioning from bivalves in the north to polychaete worms in the south, and digestible energy available to foraging shorebirds increasing toward the lower edge of the tidal flat, which is rarely exposed by the tide. These patterns of benthic invertebrate distribution were reflected in the distributions of shorebirds across the area.

Shorebirds typically need access to between 2 and 7.8 times more food than their physiological requirement to maintain high survival rates during the non-breeding season (from August to April). The six tidal flats surveyed in the ERMP Survey Area contain between two and six times more food than needed by the current number of birds using the sites, and this gap is closed rapidly when considering constraints on prey selection and the costs of foraging on the generally small prey that can only be found at low densities. Indeed, the density of food available to shorebirds in the ERMP Survey Area ranks among the lowest in the world compared with other tidal flat ecosystems such as Roebuck Bay in northwest Australia, Deep Bay in Hong Kong and the Frisian coast in the Netherlands. We therefore conclude that much of the ERMP Survey Area is functioning at or near carrying capacity, which is concerning given the steep declines in many Australian migratory shorebird species.

Suitable management interventions to benefit the birds might include careful planning of future developments to avoid the highest quality shorebird habitats (particularly the upper shore), recreation and disturbance minimisation, water quality control, monitoring of tidal flat extent, and monitoring to ensure major roost sites remain useable by the birds. The Fitzroy Delta and North Curtis Island are especially important areas for migratory shorebirds, given the high abundances of nationally threatened species.

Part B: How large is the shorebird population potentially impacted by development associated with the Port?

We conclude that migratory shorebirds moved between alternate foraging or roosting sites within subregions of the ERMP Survey Area during the austral summer, and also migratory flights further south, suggesting that the impact of a development will be felt by more birds than just those using the physical footprint of the precinct. The ERMP Survey Area supports about 20,000 migratory shorebirds and qualifies as a wetland of international importance and an East Asian–Australasian Flyway Partnership network site.

We have discovered that migratory shorebirds move (i) through the ERMP Survey Area to and from their ultimate destinations, and (ii) among a portfolio of feeding and roosting locations within the ERMP Survey Area. This means that impacts of threats to migratory shorebirds in the ERMP Survey Area will extend well beyond the point location of a development.

We modelled the migratory movements of birds through the ERMP Survey Area, by developing a method to infer total population size calibrated against historical data available from sites across eastern Australia. We also radio tracked 35 birds of four species using hand-held, aircraft-borne and automated receiver systems, and supplemented this with 319 re-sightings of 86 birds marked locally by us, and observations of 61 birds marked elsewhere. We observed marked birds from other states in Australia, as well as Alaska, Russia, Japan, China, and New Zealand.

Although highly site faithful for most of the time, our individually-marked birds made three distinct kinds of movements, comprising (i) local commuting flights of up to 10km between alternative feeding and roosting locations, strongly associated with tidal patterns, (ii) shifts in foraging or roosting sites within subregions of the ERMP Survey Area, and (iii) migratory transitions through the Survey Area. High site fidelity was evident within and between non-breeding seasons. We obtained no direct evidence of longer exploratory movements of shorebirds within or beyond the ERMP Survey Area.

Diurnal and nocturnal movement patterns were strikingly different, such that birds may be depending on more than one roost site even during the course of a single 24-hour period. This suggests that studies, such as on the impact of light spill, must focus on nocturnal roosting and foraging sites, and not necessarily those places where birds are present during the day. Exploratory movements within the ERMP Survey Area did not occur or were too infrequent to be detected, indicating that impact assessments cannot safely assume that shorebirds can relocate to different regions if displaced by local habitat loss.

Combining count data, and modelling of migration phenology, we estimate that at least 19,984 migratory shorebirds currently use the ERMP Survey Area during the non-breeding season. We estimate that a single count in February will miss about 44% of the total number of migratory shorebirds using the area, with most of the missed birds being transiting birds that use the area relatively briefly as a refuelling site during northward or southward migration. Our modelling of the flow of birds through the ERMP Survey Area indicates that five species use the ERMP Survey Area primarily as a stopover site while on migration, and three use the area as both a stopover site and non-breeding destination. This highlights the potential to underestimate the numbers of birds using an area by relying solely on the infrequent midsummer counts that typify migratory shorebird monitoring in Australia.

The highly dynamic nature of the feeding opportunities, the frequent movements of the birds and the existence of transiting individuals strongly suggests that impacts of threats to migratory shorebirds in the ERMP Survey Area will extend well beyond a pinpoint location. This evidence also indicates that management is best regionalised within the ERMP Survey Area rather than applied across the whole system, or applied at point locations.

The ERMP Survey Area is an internationally important location for migratory shorebirds, including many threatened and declining species. Its continued ecological health is of paramount importance for the maintenance and recovery of nationally threatened migratory shorebird populations. Proper quantitative estimation of the impact of any future developments in the region is now possible, using the data and findings presented in this report.

1.4 List of terms

Assimilation: The incorporation of new digested materials into an animal’s body.

East Asian–Australasian Flyway: a boundary encompassing the overlapping distributions of many migratory bird species, which move between Arctic breeding grounds in Russia and Alaska to non-breeding grounds in East and South East Asia, Australia and New Zealand.

ERMP: The Ecosystem Research and Monitoring Program, a compliance requirement under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) approval for the Western Basin Dredging and Disposal Project. It is designed to provide high level information on the health of Port Curtis and Port Alma ecosystems and observe and provide advice on any potential impacts caused by the Western Basin Dredging and Disposal Project.

ERMP Survey Area: Coastal region in Queensland covered by the ERMP, between the Fitzroy Delta and Rodds Peninsula, encompassing Curtis Island, and the Port of Gladstone. See Figure 3.1 for a map.

Foraging area: places where shorebirds search for or obtain food; these are mostly intertidal habitats which are available to shorebirds for only a certain period of time each day when the sea level is low enough to allow the habitats to be exposed.

High tide roost: areas where shorebirds rest during high tide.

Home range: an area in which a shorebird normally lives when not migrating, often comprising foraging and roosting locations on intertidal wetlands.

Intertidal habitat: coastal area between the highest and lowest tidal levels.

Staging area: stopover sites used by migratory shorebirds while on migration to prepare for a long flight over a geographic barrier that requires substantial fuel stores.

Basal metabolic rate: the minimal rate of energy expenditure when the shorebirds are at rest.

Non-breeding season: the period during which birds are stationary and not breeding typically from August to April; this is the time when most migratory shorebirds settle without making any movements beyond tidal commuting flights or local exploratory movements.

Nektonic organisms: marine and freshwater organisms that can swim freely and are generally independent of currents such as fish, prawns, or crabs.

Ramsar convention: an international treaty for the conservation and sustainable use of wetlands.

Ramsar site: a wetland site designated of international importance under the Ramsar Convention.

2. BACKGROUND AND CONTEXT

The conservation outlook for migratory shorebirds in Australia is poor and worsening rapidly. These migratory shorebirds belong to the East Asian–Australasian Flyway, which includes Australia and New Zealand, extends northwards through South-east and East Asia, and stretches beyond the Arctic Circle in Russia and Alaska (USA) in the north, encompasses the entire range that many migratory bird species move on an annual basis. Since the beginning of this project, eight migratory shorebird taxa from seven species, all of which occur in the ERMP Survey Area, were listed on the EPBC Act List of Threatened Fauna, with eastern curlew *Numenius madagascariensis*, curlew sandpiper *Calidris ferruginea*, great knot *Calidris tenuirostris* and *Limosa lapponica menzbieri* bar-tailed godwit as Critically Endangered, red knot *Calidris canutus* and lesser sand plover *Charadrius mongolus* as Endangered, *L. l. baueri* bar-tailed godwit and greater sand plover *Charadrius veredus* as Vulnerable. Meanwhile, two shorebird species were up-listed from Vulnerable to Endangered on the global IUCN Red List (eastern curlew and great knot) and four from Least Concern to Near Threatened (bar-tailed godwit, red knot, curlew sandpiper and red-necked stint *Calidris ruficollis*; (BirdLife International 2016). Some of these species have declined by more than 80% in three generations (Studds et al. 2017), and all occur in the ERMP Survey Area.

Analysis of shorebird count data has clearly shown that many migratory shorebird populations are in severe decline across Australia (Creed & Bailey 1998; Wilson 2001; Minton et al. 2002; Reid & Park 2003; Olsen & Weston 2004; Gosbell & Clemens 2006; Rohweder 2007; Close 2008; Wainwright & Christie 2008; Rogers et al. 2009; Herrod 2010; Cooper et al. 2012; Dawes 2012; Milton & Harding 2012; Minton et al. 2012; Szabo et al. 2012; Clemens et al. 2016; Studds et al. 2017), and habitat loss, especially on Asian staging grounds, is considered the most serious threat (e.g., Amano et al. 2010; Piersma et al. 2016; Studds et al. 2017). Shorebird habitat loss is very often direct, with reclamation projects or other coastal developments converting shorebird habitat to agricultural or industrial land uses that shorebirds are unable to exploit. In addition, declines in the amount of infauna accessible to shorebirds can arise from a variety of causes, including weed invasion, pollution and over-harvesting. Such declines can cause local or even global declines in shorebird numbers (e.g., Baker et al. 2004; van Gils et al. 2006).

The main tidal flat habitat for migratory shorebirds is rather restricted in area, and coastal shorebird populations are not numerically large. Moreover, migratory shorebirds depend on an international network of breeding regions, non-breeding grounds and stopover sites, and are acutely vulnerable to global population decline should any of these essential habitats deteriorate (e.g., Runge et al. 2014; Iwamura et al. 2013; Studds et al. 2017). All migratory shorebirds that regularly visit Australia are listed as Matters of National Environmental Significance (MNES) under the EPBC Act, and are also protected under a number of international treaties.

Shorebird numbers at non-breeding sites may also be limited by the availability of high tide roosts – typically very open and undisturbed areas at the water's edge where shorebirds loaf (resting, sleeping and preening) in flocks when the tide is too high for foraging to occur. Moreover, shorebirds must frequently move between foraging areas and roosting areas, and can show different patterns of site selection at night compared with during the day, depending on the lunar cycle, so a portfolio of sites is usually needed to sustain an individual bird. Thus, even a small development can have implications for a much broader area than the development precinct itself. Roosts can be lost to shorebirds through construction, weed invasion or frequent disturbance. Loss of roosts can force shorebirds to abandon productive foraging areas if there are no suitable roost sites within commuting range (Rogers et al. 2006c).

Coastal developments frequently result in loss, or at least modification of shorebird habitat, with resultant obligations on government or developers to manage shorebird habitats so that shorebird populations do not decline. The concept of carrying capacity has become a baseline for management or offsets in such cases, that is, the concept that in any particular shorebird site, population size will be limited by the available food supply. In theory, if the size of an area, the prey density and the rate at which the shorebirds are able to catch prey successfully within it, are known, one can calculate how many shorebirds the area can support. This might give clues as to whether a particular development could cause population decline. However, great care is needed in assessing impacts based on carrying capacity estimates. For example, birds might often emigrate or starve well before carrying capacity is reached (Goss-Custard et al. 2002), and thus predictions based on traditional carrying capacity estimates could under-estimate the effect of development on shorebirds. Moreover, the number of migratory shorebirds present in an area depends not only on local conditions at the site, but also other sites along the migratory route or that displaced birds could occupy.

In practice, measurement of carrying capacity of shorebird habitat is difficult. A traditional approach is to analyse population trends, the underlying concept being that if habitats are fully occupied, counts will be similar from year to year, while if there are substantial annual fluctuations, then they cannot be at capacity (at least in years of low numbers). This may indeed be a scenario that applies to many Australian sites, given mounting evidence that Australian shorebird populations are declining as a result of habitat loss overseas (Wilson et al. 2011; Clemens et al. 2016; Studds et al. 2017). However, to be confident in conclusions drawn from this approach, it is necessary to demonstrate no concurrent decline in habitat quality. This would be challenging in the ERMP Survey Area, given the scantiness of previous data on benthos and shorebird abundance, although counts over the last five years as part of the ERMP do indeed suggest some variations in shorebird numbers (GHD 2011a, 2011b, 2011c, 2011d; Sandpiper Ecological Surveys 2012a, 2012b, 2012c; Wildlife Unlimited 2012, 2013, 2014, 2015, 2016), potentially indicating that the area could support more birds than are often present.

Estimates of carrying capacity require knowledge of the number of birds that occur on a site. Shorebirds lend themselves well to direct counts, as they congregate in relatively small roosts at high tide. However, the number of shorebirds present at a site at any one time can be considerably smaller than the numbers that use the site year-round; Queensland Wader Study Group (QWSG) datasets suggest that many shorebirds only use the eastern Queensland coast as a stopover area, migrating to non-breeding regions further south. We have used a modelling method to estimate passage dates and total number of migrants transiting an area (Thompson 1993). In addition to birds captured locally as part of this study, marked birds in the ERMP Survey Area include individuals that have been colour-banded or flagged elsewhere in the flyway; regular systematic scans for such birds were made at a few accessible roosts to determine their movement through the study area.

Radio-telemetry may be a helpful tool in assessing migration dates of the shorebirds. However, in this study it was used mainly to develop an improved understanding of local movements on non-breeding birds, identifying the scale of movements undertaken by individuals when moving between foraging and roosting sites (Rogers 2003), and hence the limits of the area in which shorebirds might be affected by port and regional development. Mark-recapture studies in Europe (Rehfisch et al. 1996; Rehfisch et al. 2003) have suggested that some species have very high site fidelity and others do not; for example, red knots often move between relatively distant roosts, perhaps because they feed on small bivalves which are patchily distributed.

3. PROJECT ELEMENTS

We have carried out the most comprehensive field study of shorebirds that has ever been undertaken in the ERMP Survey Area, combining bird counts, sampling of benthic prey availability, and tracking the movements of birds. We have mapped intertidal substrata across the whole ERMP Survey Area, and empirically linked their patterns of exposure with the tidal cycle and benthic prey availability. This has allowed us to:

(i) build models that estimate the tidal flat extent at any point in time;
(ii) understand the temporal dynamics of food availability for the birds in relation to daily, lunar and seasonal cycles; and
(iii) determine the number of birds the ERMP Survey Area can support.

During the project, in which about 1,000 person-days were spent in the field, we collected and processed 1,865 benthic core samples (over 2 seasons), recorded ~200 videos of foraging birds, conducted 10 shorebird surveys, caught and banded 101 birds, and radio-tracked 35 birds via handheld receivers, an automated receiver array, and from aircraft transects over the Survey Area.

3.1 Summary of aims

The project is divided into Part A and Part B, with four aims in each part respectively (see the annual reports from this project, Choi et al. 2015, 2016a, for full details). We list the aims here, along with a brief summary of the activities completed against each aim (Table 1). We then go on in Sections 4 and 5 to outline in detail the discoveries made by this project under Parts A and B respectively.

The project is primarily focused on the ERMP Survey Area (Figure 3.1), although given the mobile nature of migratory species, and the need to understand their movements and habitat linkages in a wider context, the spatial scope of some analyses in this report reaches beyond the ERMP Survey Area. For example, we analysed information on the migratory movements of shorebirds around Australia and beyond Australia’s borders to enable us to quantify the flow of birds to and from the Survey Area (Section 5.1). We further divided the Survey Area into 4 subregions during analysis, namely the Fitzroy Delta, North Curtis Island, Gladstone Harbour and Rodds Peninsula (Figure 3.2), approximating the local scale that data from other regions suggested the birds might restrict their movements during the non-breeding season (see Section 5.2).

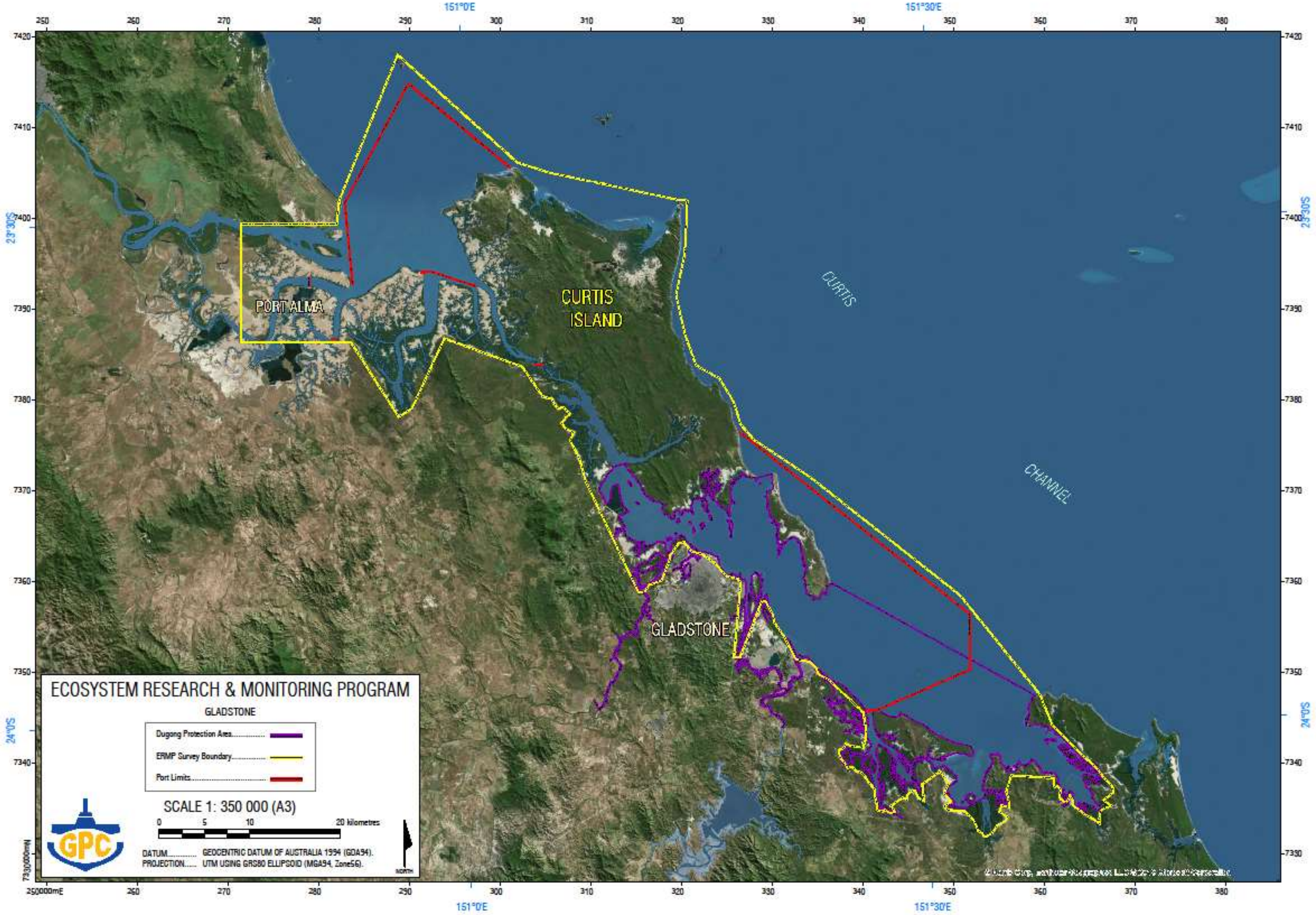


Figure 3.1 Extent of the ERMP Survey Area (yellow boundary).

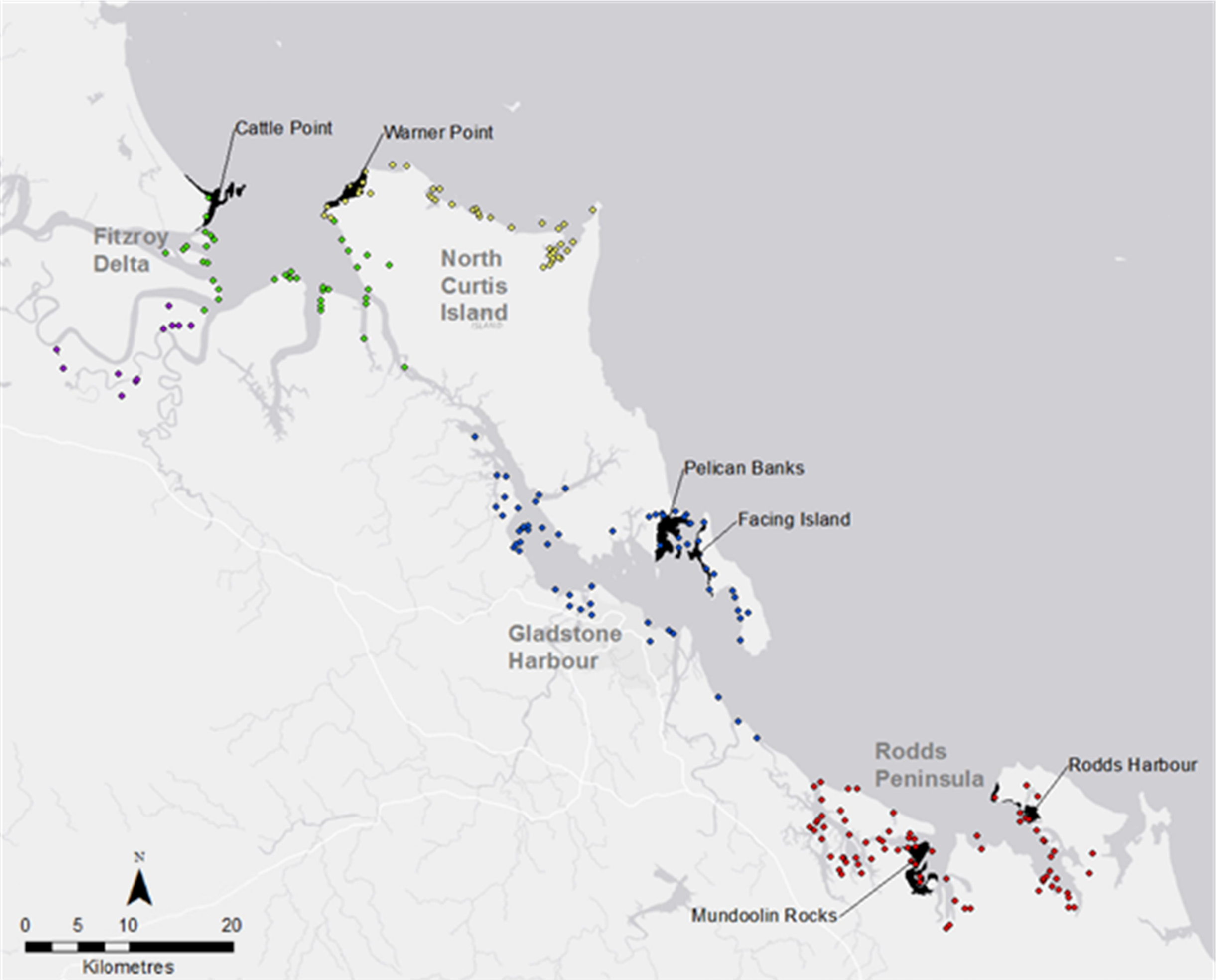


Figure 3.2 The four subregions and six benthic sampling locations (labelled tidal flats, black shading) within the ERMP Survey Area. Coloured points represent locations where shorebird surveying has been conducted since 2011 (green – Fitzroy Delta, yellow – North Curtis Island, blue – Gladstone Harbour, red – Rodds Peninsula, purple – salt works).

Table 3.1 Activities carried out for each project aim.

PART A: ESTIMATE CARRYING CAPACITY	**Activities completed**
Aim A1: Map tidal flat distribution and exposure	We mapped tidal flats using Landsat data, and combined this with a bathymetry map to stratify the flats into height bands. After our benthic sampling was already completed (see Aim A2), Geoscience Australia produced a much higher vertical resolution product that we have subsequently used for our tidal flat exposure analyses.
Aim A2: Measure benthic prey availability	We collected 305 benthic samples in the first year, and used a cost/benefit analysis to design a sampling strategy for 1,560 samples in the 2015/2016 field season. We sampled six major accessible tidal flats with reasonably large number of shorebirds and area of tidal flats across the ERMP Survey Area, and analysed the distribution and density of shorebird prey geographically, and in relation to tidal cycles.
Aim A3: Estimate how many birds the area can support	We took 200 videos of foraging birds to describe diet, and combined dietary information with prey density information to estimate the carrying capacity of the Survey Area (i.e., how many migratory shorebirds the area can support).
Aim A4: Identify priority areas for management	We combined the historical shorebird count data with our carrying capacity estimates in various subregions of the Survey Area to identify priority areas for management.

PART B: DETERMINE THE SIZE OF THE IMPACTED POPULATION	Activities completed
Aim B1: Describe the patterns of flow of birds into the study area, in relation to impacts	We reviewed past count data from the ERMP Survey Area, and the migration routes used by the birds through the East Asian–Australasian Flyway, and estimated the timing of migration movements through the Survey Area, as well as the total numbers of birds using the Survey Area on migration, and during the non-breeding season. The method is published (Choi et al. 2016b).
Aim B2: Discover how birds move around the study area	Over the two seasons, we captured and marked 101 birds, 35 of which were radio tagged. Through a combination of direct field observations and radio tracking (manual, aerial and on-ground fixed automatic tracking stations), we discovered the movement of the migratory shorebirds in in the Survey Area.
Aim B3: Determine how many birds currently use the study area	Combining count data, and modelling of migration phenology, we estimate that about 18,000 migratory shorebirds currently use the ERMP Survey Area during the non-breeding season. Crucially, this work shows that some species (such as red knot) use the Area mainly as a stopover site and not a non-breeding destination.
Aim B4: Identify size of management units	We conclude that the ERMP Survey Area can be treated as four subregional management units, and that assessing the impact of any developments within those subregions should start with the assumption that it could potentially impact all birds occupying that subregion.

4. PART A: ESTIMATE CARRYING CAPACITY

4.1 Tidal flat distribution and exposure (Aim A1)

4.1.1. Summary

Intertidal substrata are crucial for foraging migratory shorebirds, which usually feed by probing soft sediment to extract invertebrate prey. Using updated Landsat-based mapping produced in June 2016 by Geoscience Australia, we determined that a maximum of 216km^2 of exposed intertidal substratum occurs in the ERMP Survey Area during spring low tides, but that the daily mean amount of exposed tidal flat varies between 89km^2 and 124km^2, depending on the time of year and weather conditions. Of this area, 82.9 km^2 comprises claypans which are infrequently inundated, have depauperate benthos and are seldom used by foraging shorebirds; excluding these areas, daily mean tidal flat area suitable for foraging shorebirds varies between 39.2 km^2 and only 4.2km^2. Inundated tidal flat is of course inaccessible to birds, and so the dynamics of exposure are crucial to understanding carrying capacity. Much of the intertidal area in the ERMP Survey Area is only exposed and available to foraging shorebirds at the lower half of the tidal range. Overall across the Survey Area, about half of the full extent of intertidal substratum is exposed at half-tide. Yet in the key shorebird foraging areas, which are characterised by large contiguous tidal flats, often with very shallowly sloping lower regions, exposure of much of the potential foraging habitat is very brief, with only 10%–25% of the intertidal habitat exposed at half tide. We integrate these tidal exposure dynamics into our consideration of carrying capacity.

4.1.2. Tidal flat mapping

We completed *de novo* mapping of the distribution of tidal flats in the ERMP Survey Area (Dhanjal-Adams et al. 2016). Since the publication of this work, and after the design and execution of the benthic sampling programme outlined in this report, Geoscience Australia released a 25m Landsat-based intertidal mapping product building on our previously published method (Murray et al. 2012) with several key innovations, including:

(i) using pixel stacks to increase the quantity of data that could be used, and thus the quality of the land/water estimate, and
(ii) overlaying modelled tidal data to estimate how frequently each pixel is exposed (see Geoscience Australia 2016 for full details).

In brief, the Geoscience Australia process for creating the Relative Extents Model began by forming deciles of observed tidal ranges from a series of modelled tide heights at the time of each Landsat image observation acquisition (using the Oregon State University model http://volkov.oce.orst.edu/tides/tpxo8_atlas.html), applied to a manually chosen representative location within each one degree cell around the coastline of Australia. A pixel-based median

Normalised Difference Water Index (NDWI; McFeeters 1996) was then calculated for each Landsat tile, for each decile interval of each one degree cell's observed tidal range. The 10 NDWI composites derived for each cell were used to estimate the extent of exposed substratum at each decile interval of the observed tidal range. These deciles were grouped into bands for mapping (see Table 4.1).

Table 4.1 Duration and area of exposed intertidal substratum in 2015. Definitions of the bands are 0 Always water; 1 Exposed at lowest 0–10% of the observed tidal range; 2 Exposed at 10–20% of the observed tidal range; 3 Exposed at 20–30% of the observed tidal range; 4 Exposed at 30–40% of the observed tidal range; 5 Exposed at 40–50% of the observed tidal range; 6 Exposed at 50–60% of the observed tidal range; 7 Exposed at 60–70% of the observed tidal range; 8 Exposed at 70–80% of the observed tidal range; 9 Exposed at highest 80–100% of the observed tidal range.

Band	**Corresponding colour in Figure 4.1, 4.4**	**Total area of the band (km^2)**	**Mean hours per day exposed in 2015**	**Cumulative area (km^2)**
9 land	⬜			
8 mostly claypans	🟩	84.8	22.7	84.8
7	🟩	11.3	19.8	96.0
6	🟩	4.6	15.9	100.6
5	🟨	8.1	12.4	108.7
4	🟧	12.3	9.0	121.0
3	🟧	31.9	5.1	152.9
2	🟧	37.9	1.9	190.8
1	🟥	25.0	0.3	215.8
0 sea				

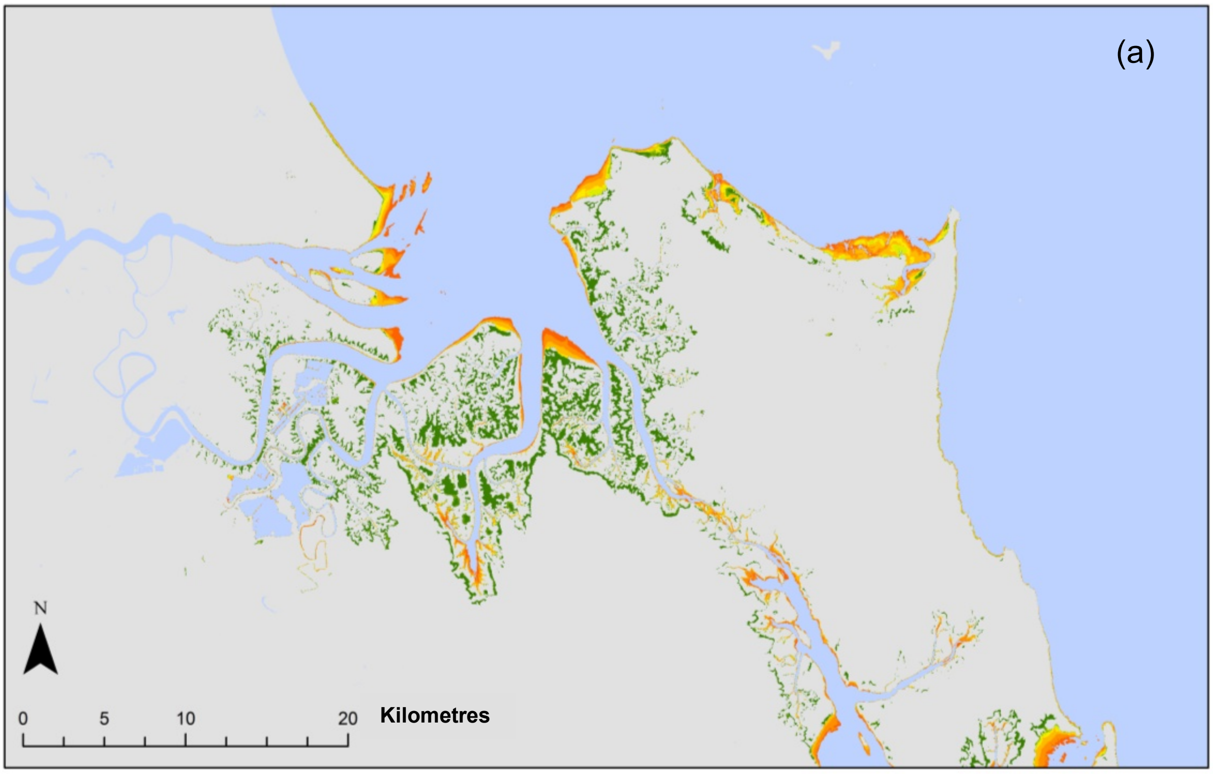
Geoscience Australia's Relative Extents Model has yielded significant improvements in mapping quality for areas that had proven difficult to map accurately in the past (e.g., Rodds Peninsula), and allows inferences to be made about the exposure dynamics of each 25m pixel of intertidal substratum, by virtue of each pixel being classified as exposed at a certain proportion of the observed tidal range. These mapping data form the basis of the tidal flat exposure analyses developed below.

Within the ERMP Survey Area, a minimum of 216 km^2 of intertidal substratum is exposed when the tide is in the bottom 10% of its range, representing a considerable amount of potential foraging habitat for migratory shorebirds (Figure 4.1). However, 84.8km^2 (39.3%) of the intertidal area consists of rarely inundated claypans or mangroves where shorebirds seldom forage, such that there is probably only 131.1km^2 of regularly inundated intertidal substratum in the ERMP Survey Area (Figure 4.2; Table 4.1). Many claypans are classified as land by the Australian Geoscience dataset, reflecting their extremely rare inundation. During our observations, only 8.7% of shorebirds (from five species: whimbrel *Numenius phaeopus*, grey-tailed tattler *Tringa brevipes*, eastern curlew, red-necked stint and ruddy turnstone *Arenaria interpres*) recorded during high tide were foraging while the remaining 91.3% (from

15 shorebird species) were resting (n = 4,943). There are three major concentrations of intertidal substrata:

(i) the Fitzroy Delta;
(ii) Gladstone Harbour, and;
(iii) Rodds Peninsula.

Specifically, large intertidal areas occur in the Fitzroy Delta, Balaclava Island, the northern coast of Curtis Island (Figure 4.1a), Western Basin, the southern coast of Curtis Island, the western coast of Facing Island, South Trees Island (Figure 4.1b), and the sheltered waters of Rodds Peninsula (Figure 4.1c). Claypans that are rarely inundated by the tide (shown in green on Figure 4.1) are a dominant feature of the intertidal substrata in the region, but are incompletely mapped by the satellite method because the sun-synchronous passes of the Landsat satellites result in images being unavailable at the extreme upper and lower end of the tidal range (Geoscience Australia 2016). Claypans are very rarely used as foraging habitat by migratory shorebirds in the region, although they are frequently used for roosting (GHD 2011a).



[caption below]

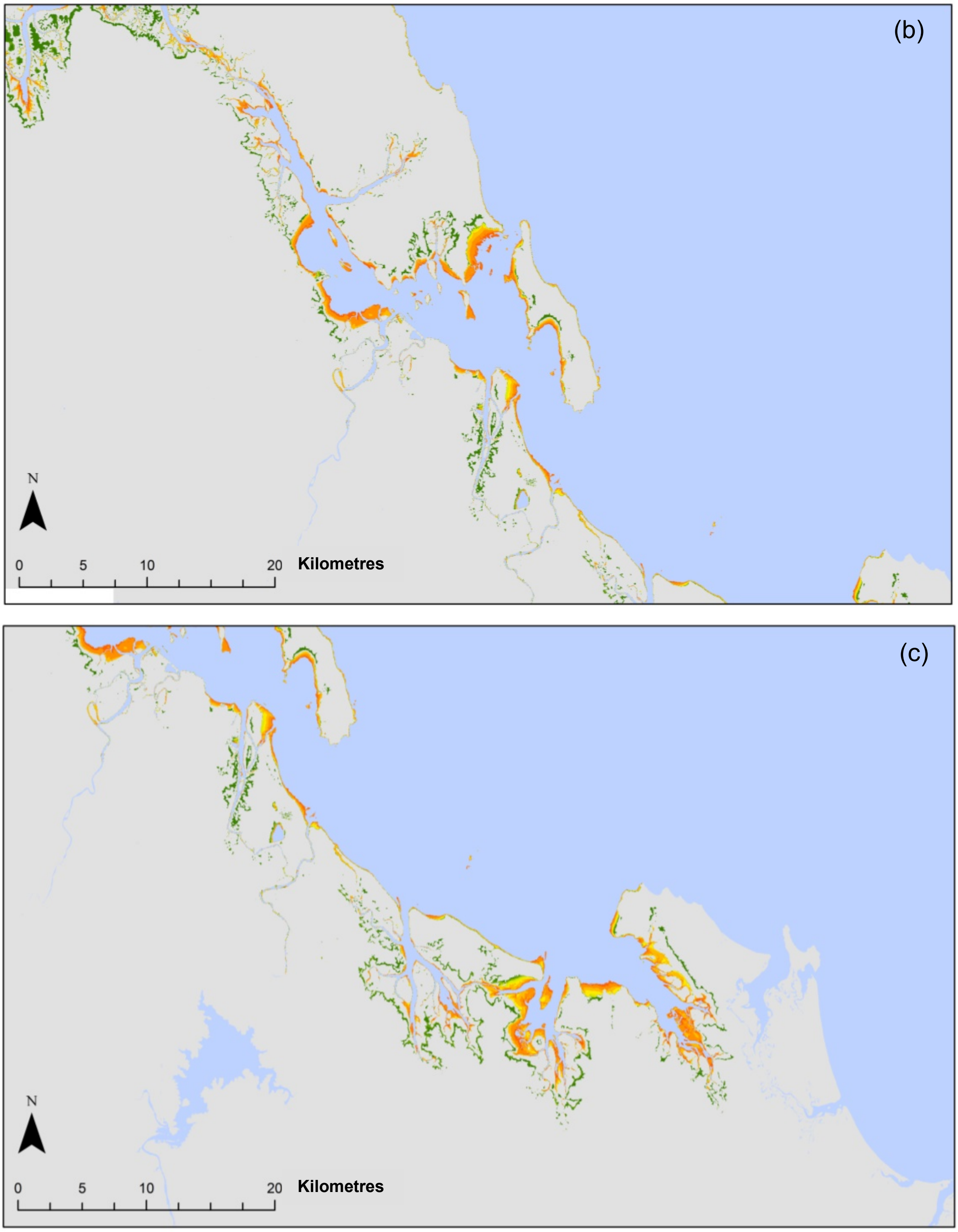


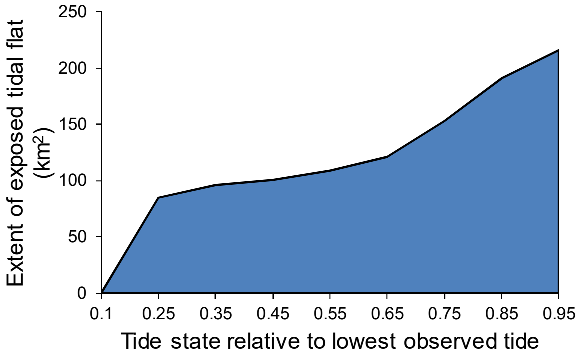
Figure 4.1 Distribution of intertidal substrata in the (a) north, (b) centre, and (c) south of the ERMP Survey Area, based on Landsat data at a 25m spatial resolution. Areas exposed at the highest 80–100% of the tidal range are interpreted as land (grey), and areas never exposed are interpreted as sea (blue). The dark green areas represent rarely-inundated claypans that are exposed at 70–80% of the observed tidal range, and the subsequent colour ramp through pale green, yellow and orange indicates pixels only exposed at decreasing bands of the observed tidal range, culminating in the red areas, that are exposed only at the lowest 0–10% of the observed tidal range. See (Geoscience Australia 2016) for a full description of the methods used to produce this dataset.

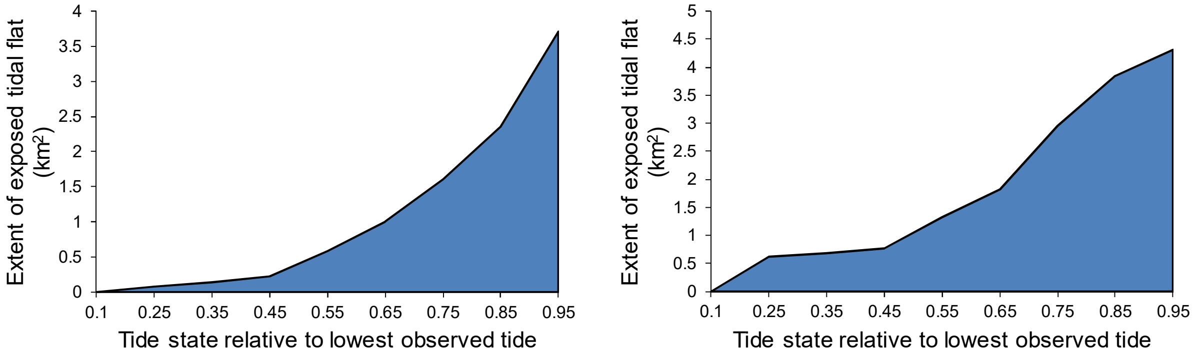
4.1.3. Intertidal substratum exposure relative to water level

To estimate how much intertidal area is exposed at different stages of the tide, we produced cumulative plots of the total area of intertidal pixels exposed at each band of the observed tidal range (Figure 4.1). Across the whole study area, exposure was relatively linear with respect to water level, with approximately half of the full extent of the intertidal area exposed at half tide (Figure 4.2a). However, in the six relatively large tidal flats selected for benthic analysis (Figure 4.2b–f), exposure patterns were non-linear, with most of the intertidal substratum being exposed only at the lowest water levels. For example, at Cattle Point, only about 15% of the intertidal substratum was exposed at half-tide, and half the intertidal substratum was only exposed when the tide was at about 80% of its lowest extent (Figure 4.2b).

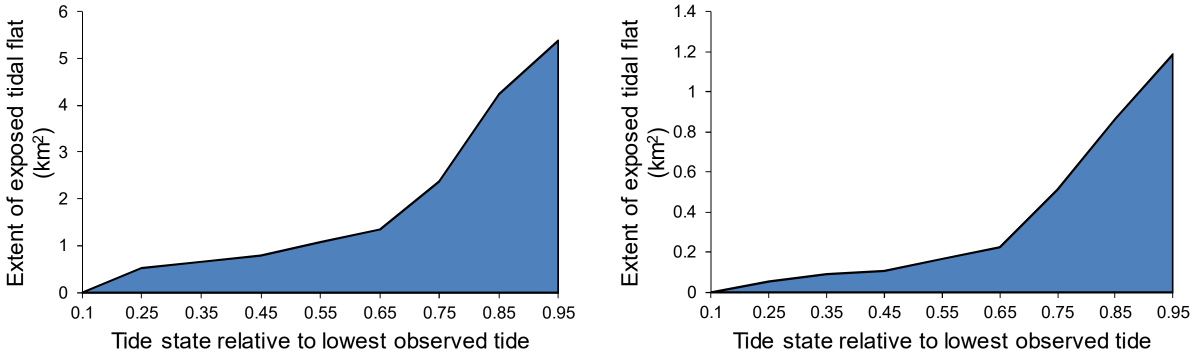
4.1.4. Diurnal, lunar and seasonal variation in intertidal substratum exposure

Tides are highly dynamic, with much local variation caused by, for example, topography and weather conditions superimposed onto combinations of astronomical factors occurring on scales from days to years. We explored the consequences of this variability for patterns of exposure of intertidal substratum, and hence foraging opportunities for shorebirds in the ERMP Survey Area. We linked the Relative Extents Model with water level data at 10-minute intervals from the Auckland Point tidal gauge (Gladstone; -23.83°, 151.26°). From the outset, it must be borne in mind that while the observed tidal range data used to construct the bands in the Relative Extents Model are known broadly to reflect actual tidal variation, the sun-synchrony of Landsat passes means that the observed tidal range from the Relative Extents Model will underestimate the actual tidal range (Geoscience Australia 2016). Even with this caveat in mind, it is clear that there is wide variation in intertidal substratum exposure over time (Figure A1). We estimated daily exposure by calculating the mean of the extent of exposed intertidal substratum across the 144 10-minute tide gauge readings on each day of 2015 (there are 1,440 minutes in each 24 hour period, so each day was represented by 144 readings spaced 10 minutes apart). Against a backdrop of 216km^2 of tidal flat exposed at the lowest spring tides (see Section 4.1.2), estimated daily mean tidal flat exposure varied from 89km^2 (16th May 2015) to 124km^2 (2nd September 2015), and showed rather erratic variation with the lunar cycle reflecting a similar pattern in the tidal data, and also a slight seasonal increase in exposure between July and October 2015 associated with slightly lower daily mean water levels at the tide gauge during this period.

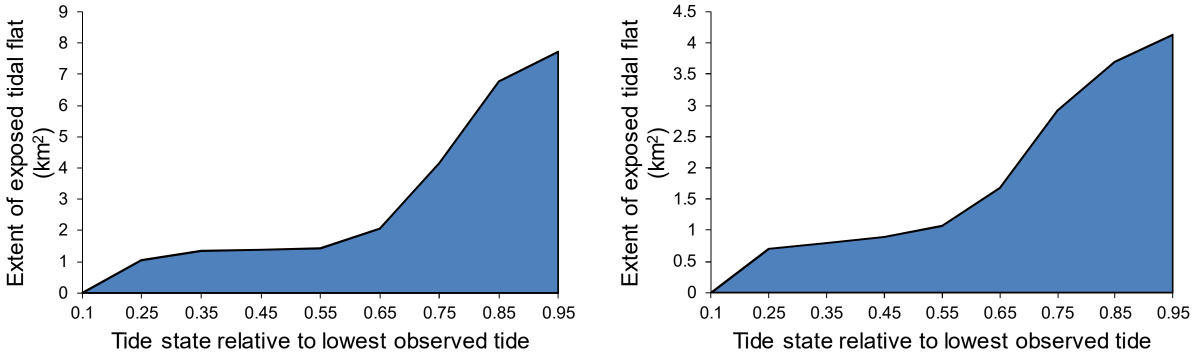

(a) Entire study area


(b) Cattle Point

(b) Warner Point


(c) Pelican Banks

(d) Facing Island


(e) Mundoolin Rocks

(f) Rodds Harbour

Figure 4.2 Area of intertidal substratum exposed at the midpoint of each decile of the observed tidal range, from the highest observed tide on the left to the lowest observed tide on the right, for (a) the entire ERMP Survey Area, and (b) – (f) for each of the six benthic sampling sites (see Section 4.2).

4.1.5. Duration of availability of intertidal substrata

The duration of exposure among different bands of the observed tidal range also showed marked variation (Figure 4.3). This is important for foraging shorebirds, because the abundance and composition of benthic invertebrates vary substantially downshore. For example, the lowest intertidal band was only exposed on spring tides in 2015, and did not get exposed at all in May, June or July, which means 12% (Table 4.1) of the total intertidal substratum was not available for shorebirds to feed on during this entire period. The lowest four bands of the observed tidal range, comprising about 50% of the total intertidal substratum, were exposed for a short period of time (about four hours per day), in contrast to the 15 hours per day of exposure in the highest four bands (Figure 4.3, Table 4.1). For shorebird species whose prey is mostly found on the intertidal substratum in the lowest four bands, they only have four hours to look for food, with half of this time occurring during darkness. This would mean a potential lack of time to find enough food to maintain a positive energy balance for species such as eastern curlews, which could spend 7.5 hours per day foraging (Zharikov & Skilleter 2003, 2004b). It is likely that upper bands of tidal flat (consistently exposed at low water in both spring and neap tide series) are therefore of disproportionate importance to foraging shorebirds, something that is worth considering from a management perspective.

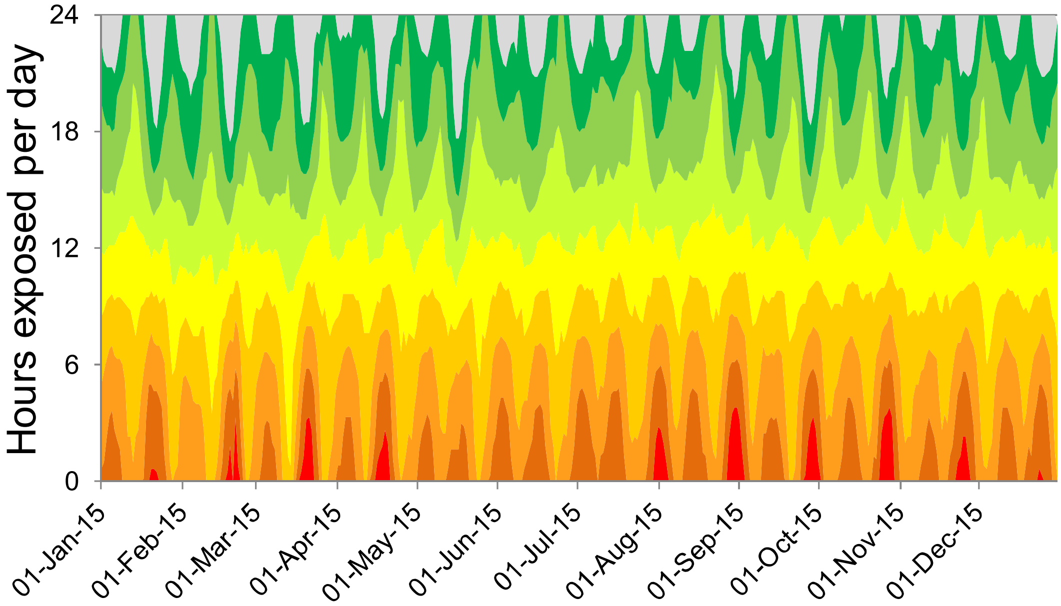


Figure 4.3 Hours per day of exposure for tidal substratum at each band of observed tide heights (colours as per **Figure 4.1**). The seaward bands (red, dark orange) are infrequently exposed, while the upper bands are consistently and lengthily exposed every day. This plot can be read cumulatively, for example band 5 (yellow) is exposed for about 10–12 hours per day, while band 3 (mid-orange) is exposed between zero and seven hours per day.

In the key intertidal foraging areas, much of the potential foraging habitat for shorebirds is available for a limited time only, with only 10%–25% of the intertidal habitat exposed half-way between low and high tide.

4.2 Benthic prey availability (Aim A2)

4.2.1. Summary

We deployed a program of benthic sampling, in which we identified the invertebrates living within the top 5cm of the sediment (accessible to probing shorebirds) and estimated the densities of prey potentially available to foragers. We first conducted a detailed pilot study in December 2014 (305 core samples) to determine the spatial scale at which variation in benthic prey numbers needed to be sampled. Using this information, we designed a sampling program stratified across six tidal flat height bands covering six of the shorebird foraging sites across the ERMP Survey Area. We collected 1,560 benthic samples between October 2015 and February 2016, and processed 1,200 (November and December 2015) of these, discovering enormous variation in the density and composition of the benthic invertebrate fauna with respect to height on the shore and among sites.

Detailed analysis of patterns of abundance and community structure in the benthic organisms collected showed that total abundance of all invertebrates on the top 5cm varied considerably across the six sites at all heights down the shore, with a much higher abundance of invertebrates at Cattle Point (density: 11,429 ± 14,424m^2) than other sites (range of mean density: 384 – 2,212m^2). The latter was particularly true for the upper shore, and it was caused primarily by the overwhelming dominance of small bivalves at Cattle Point (bivalve density: 5,648 ± 7,153m^2; other invertebrates: 5,782 ± 10,423m^2). Overall, bivalves (1,062 ± 3,573m^2), copepods (1,021 ± 4,660m^2), polychaetes (592 ± 1,392m^2) and amphipods (99 ± 308m^2) were the invertebrate groups with the highest overall density and their relative contribution to the benthic community differed between locations, in particular with an increase in the abundance of polychaetes and amphipods from north to south. The significant impact of height implies that exposure and inundation time will play a crucial role in determining the benthic community available to foraging migratory shorebirds on the intertidal flats.

The overall composition of the intertidal benthic communities in the six sites separated into four main groupings. The community at Cattle Point was different from all the other sites. A second group was characterised by the community at Facing Island, and the third was at Pelican Banks. The community at the two most southern sites, Rodds Harbour and Mundoolin Rocks were not different from each other and also overlapped with that in Warner Point, one of the most northerly sites.

4.2.2. Introduction

To estimate how many shorebirds the ERMP Survey Area could support (see Section 4.3), we first needed to understand how much prey is available to foraging shorebirds that could potentially use the area. Resolving the abundance and distribution of benthic invertebrates (shorebird prey) is a critical component in the estimation of shorebird carrying capacity. Grid-based approaches are typically used to estimate benthic invertebrate abundance in which a large grid with 0.5km or 0.25km intersects is imposed over the area of interest – often a single tidal flat (e.g., Gill et al. 2001). Samples of benthic invertebrates are taken at each intersection of the grid and the prey densities at unsampled locations within the grid are spatially interpolated. The advantage of such a coarse grid-based approach is that broad spatial coverage can be achieved, but it makes several key assumptions about the spatial scale of variation in prey abundance. Our initial visits to sites within the ERMP Survey Area suggested to us that variation in prey abundance was occurring at much finer scales than would be captured by the typically-used coarse grid. Indeed, benthic communities in soft sediments can be patchily distributed at a range of spatial scales from less than a metre to several kilometres (Morrisey et al. 1992). Given that the only previous benthic sampling in the study area was primarily subtidal (see Currie & Small 2005, 2006), we needed to measure the pattern of spatial variation in shorebird-relevant intertidal benthos *de novo*.

We therefore conducted a pilot study incorporating four different spatial scales ranging from 2m between replicate cores to 50km between tidal flats. The aims of the pilot study were (i) to identify the spatial scales at which variation in shorebird prey communities is significant for the study area, (ii) to estimate the contribution of different spatial scales to the total variation in shorebird prey abundance between regions in the study area, and (iii) to perform a cost-benefit analysis to determine the optimal allocation of sampling effort in the second field season for estimating prey abundance and distribution.

We used the results of the pilot study to design and implement a full benthic sampling program across the Survey Area, covering six major tidal flat systems that are accessible, span across the full length of the Survey Area with reasonably large size and high shorebird abundance (Cattle Point, Warner Point, Pelican Banks, Facing Island, Rodds Harbour and Mundoolin Rocks). Our aims were to (i) document the size, identity and density of benthic invertebrates across the six study sites for use in carrying capacity estimates, and (ii) discover how benthic invertebrate densities and community structure varied with respect to height in the littoral zone and among sites.

4.2.3. Methods

4.2.3.1 Benthic Sampling Pilot Study

Cattle Point and Pelican Banks were selected for the pilot study, being two of the largest tidal flats within their subregions, providing broad spatial coverage of the study area and representing independent estuarine settings. The roosts near to the tidal flats that were selected have been found to support consistently greater numbers of shorebirds than more distant roosts each year during the summer and are thought to be important foraging habitat for migratory shorebirds in the ERMP Survey Area (GHD 2011a, 2011b, 2011c, 2011d; Sandpiper Ecological Surveys 2012a, 2012b, 2012c; Wildlife Unlimited 2012, 2013, 2014, 2015, 2016). As noted previously (Section 4.1), shorebirds rarely or never foraged on claypans or in mangroves. Therefore, the benthic sampling work focused exclusively on open intertidal habitats, typically exposed for no more than ~12 hours per day.

A large grid with 0.5km intersects was imposed over each tidal flat. Two grid squares were selected at random in each tidal flat. Each grid square was then further sub-divided so that it consisted of 25 equidistant sampling stations (Figure 4.4). The distance between adjacent stations was 125m. Where sample stations intersected with a channel or another obstacle that prevented sampling, the samples were taken from the nearest possible location at which it was feasible to sample.

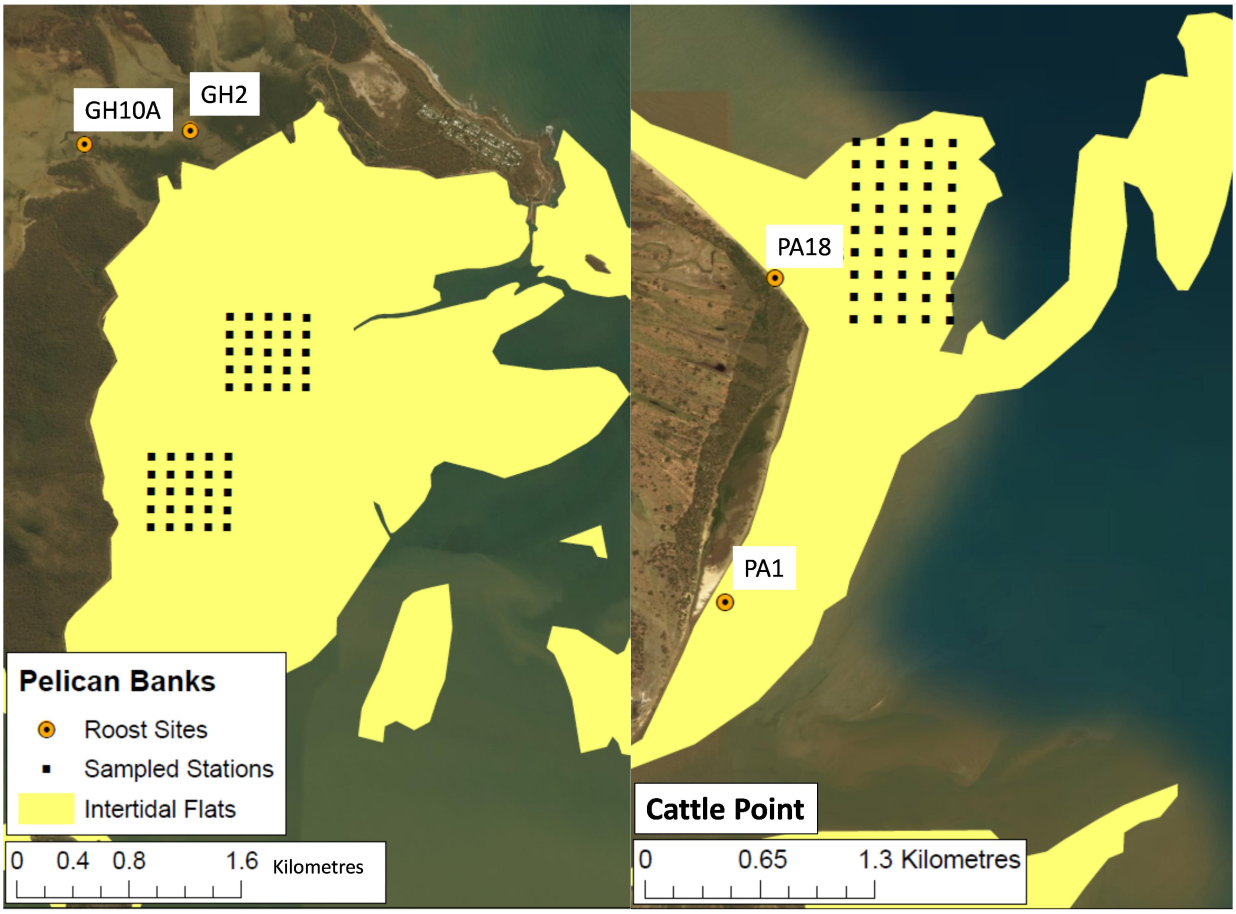


Figure 4.4 Pilot benthic sampling locations at (a) Pelican Banks in the Gladstone Harbour and (b) Cattle Point in the Fitzroy Delta. At each location, two 500m x 500m rectangles were located, and sampling stations were spaced 125m apart in a grid, with three replicate cores 2m apart taken at each station.

Pilot sampling was carried out during daylight hours at low tide on 2, 4 and 11 December 2014 at the Fitzroy Delta site (Cattle Point) and on 3, 5, 7, and 12 December 2014 at the Gladstone Harbour site (Pelican Banks). Three replicate core samples spaced 2m apart were collected at each station. The coring device consisted of a PVC tube 20cm deep and 18cm in diameter. Soon after collection and retrieval from the tidal flat, each core sample was fixed in a 7% buffered formalin solution to minimise deterioration of soft-bodied organisms during the sieving process. After at least two days, samples were transferred to 70% ethanol solution to await sieving and sorting in the laboratory.

The samples were passed through a 0.5mm mesh sieve. A 1mm sieve is often used in shorebird carrying capacity studies, but because we are calculating carrying capacity for multiple shorebird species ranging in size and feeding habits we elected for the smaller size. For example, some smaller shorebird species such as red-necked stints are known to feed on prey smaller than 1mm (Dann 1999). It was therefore important to use the smaller mesh size to ensure that the prey community for smaller shorebirds species was not under-estimated. Samples were then sorted to a coarse taxonomic level appropriate to the taxon in question (typically class or order level). Finer level identifications were not performed because (i) this would have been extremely time consuming, and (ii) there is little value in sorting to finer taxonomic resolution as prey selection by shorebirds is unlikely to be influenced by subtle morphological characters that can only be detected with a microscope (Gerwing et al. 2016).

The final component of the pilot study was to perform a cost-benefit analysis. Here, the “cost” of sampling at a particular spatial level is taken to be the total time required to complete sampling at that level while the “benefit” of sampling at each level is considered to be the contribution that level makes to the total variance across all the spatial scales (Underwood 1981). At each spatial scale, all the costs (time) required to complete tasks was recorded. In the final cost-benefit analysis, an average of these costs was then used for each spatial scale based on all sampling on the two tidal flats.

By chance, the two grids selected at random on Cattle Point were adjacent with some sampling stations co-occurring. For the cost-benefit analyses, we were interested in estimating how to allocate sampling effort optimally across all the appropriate spatial scales, so it was important that we included analysis of data from grids that were separated at least by 400–500m. We achieved this by sub-sampling the two grids, to create three smaller grids, each ten stations in area (five stations across x two stations deep; each station separated by ~125m). The data from these three smaller grids were then analysed with a nested (hierarchical) analysis of variance that incorporated the three critical spatial scales (1–2m, among replicate cores; 100–125m, among replicate stations; 400–500m, among replicate grids). The relevant variance components were extracted from the results of an Analysis of Variance (ANOVA; see Underwood, 1981 for appropriate Mean Square estimates and the calculation of the variance components).

We found that despite the relatively large spatial separation of the grids that were laid out across Cattle Point (400–500m), the total abundance of all benthic organisms did not differ significantly among the grids (Table 5 in Choi et al. 2015b; grids, P=0.113). The abundance of the benthic organisms was, however, extremely patchy at the spatial scale of hundreds of metres, i.e., among stations across the grid (Table 5 in Choi et al. 2015b; stations (grids), P<0.001).

Approximately 59% of the variation in the abundance of prey items at Cattle Point was associated with the smallest spatial scale (about 2m), among the replicate cores collected at each station (Table 6 in Choi et al. 2015b). A further ~34% of the variation in the prey abundance was among the replicate stations (about 125m apart) within each of the grids. Therefore nearly 94% of the variation in the abundance of the prey resource for the shorebirds occurs at the smallest spatial scales on even large tidal flats. This indicates that the benthic organisms are very patchy at a fine scale, suggesting that shorebirds will have to move frequently in order to access food as rapidly as possible.

While we expected variation to be relatively fine scale, we were surprised by the important amount of variation at the station level, and without this carefully constructed pilot study there would have been considerable risk of under-sampling at these fine and meso scales, weakening inference about carrying capacity. The results of the pilot study were used to inform the design of our full sampling programme in the second season (summer 2015/16). A comparison of cost (time) and benefit (variance of the mean number of prey items per core) indicated that we should collect 1600 samples from eight sites in four different regions. However, after taking logistical and safety considerations into account, we had to exclude the Yellow Patch and Deception Point because the former was inaccessible using our vessel while the latter comprises soft sediments that made wading too dangerous. For these reasons, we treated Warner Point on the North Curtis Island as a site within the Fitzroy Delta given its close proximity to the delta (Figure 3.2). See Choi et al. (2015b, 2016a) for full details of the results of the pilot study, and how it was used to inform the design of the full benthic sampling program.

4.2.3.2 Benthic Sampling Full Program

We collected, processed and sorted 100 core samples from each of six different sites across the ERMP Survey Area (Figure 4.5, 4.7). Each 20cm depth core sample was split into two, yielding one sample of the top 5cm of sediment, and a second sample of the sediment from 5–20cm depth, giving a final total of 1,200 samples. From north to south the six sites were Cattle Point, Warner Point, Pelican Banks, Facing Island, Rodds Harbour and Mundoolin Rocks. This ensured we representatively sampled the full length of the Survey Area. We used a stratified random sampling approach to identify quadrats from which we collected samples (Figure 4.5). Inundation time (a function of the tidal flat height) strongly influences benthic community composition, and to ensure we sampled effectively across the height gradient down shore, we sampled equally across *a priori*-estimated quartiles of tidal flat height (Figure 4.6), as derived from intertidal mapping in Dhanjal-Adams (2016), combined with bathymetry data (see Choi et al. 2015b for full methods). In each height quartile, five quadrats (3m x 3m each) were randomly located, enforcing the criterion that each one was at least 200m from the nearest neighbouring quadrat within the same height quartile. We could not use the 10-band Geoscience Australia mapping because it was not yet available at the time of the implementation of our full benthic survey program. Our *a priori* stratification method was approximate, as there is much fine scale subpixel variation in the exact height of the tidal flat (runnels, creeks, local deposition around vegetation etc.), but we were able to reclassify each sampling station into one of six height bands for analysis, based on a combination of field observations, inspection of surface plots, and multivariate analysis.

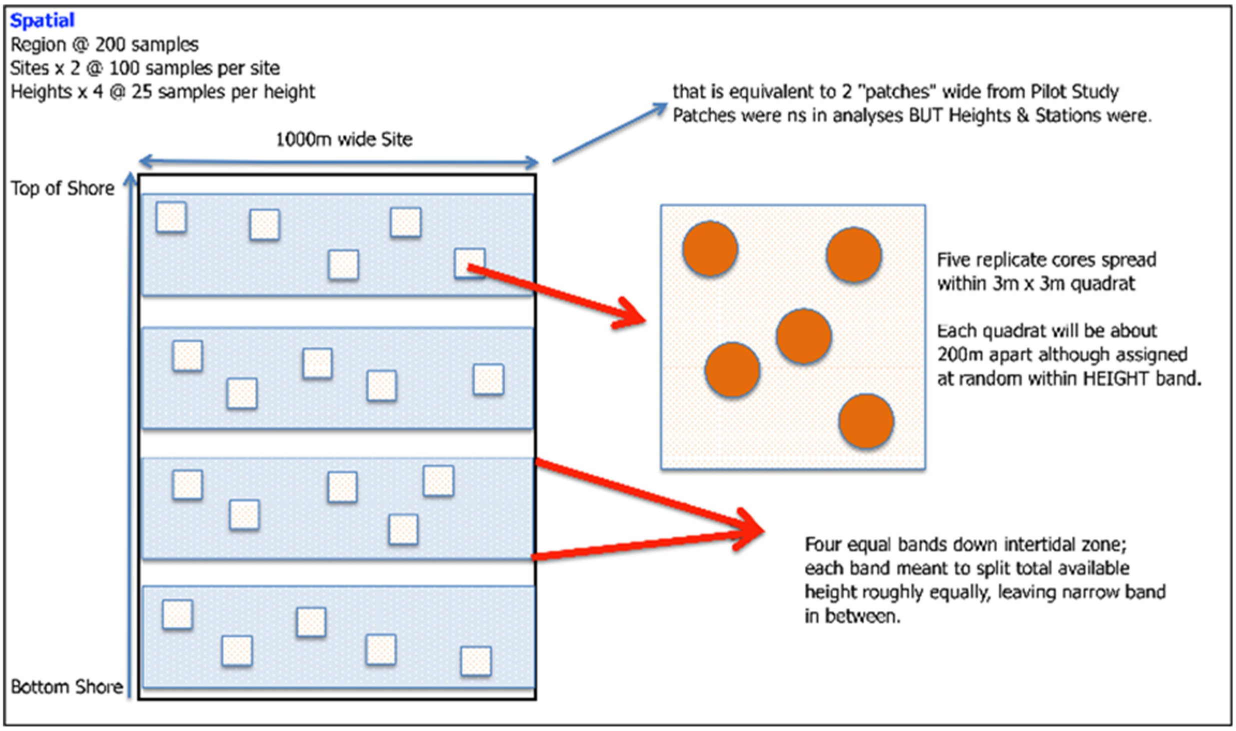


Figure 4.5 Sampling design to quantify the distribution, density and diversity of the benthic prey community.

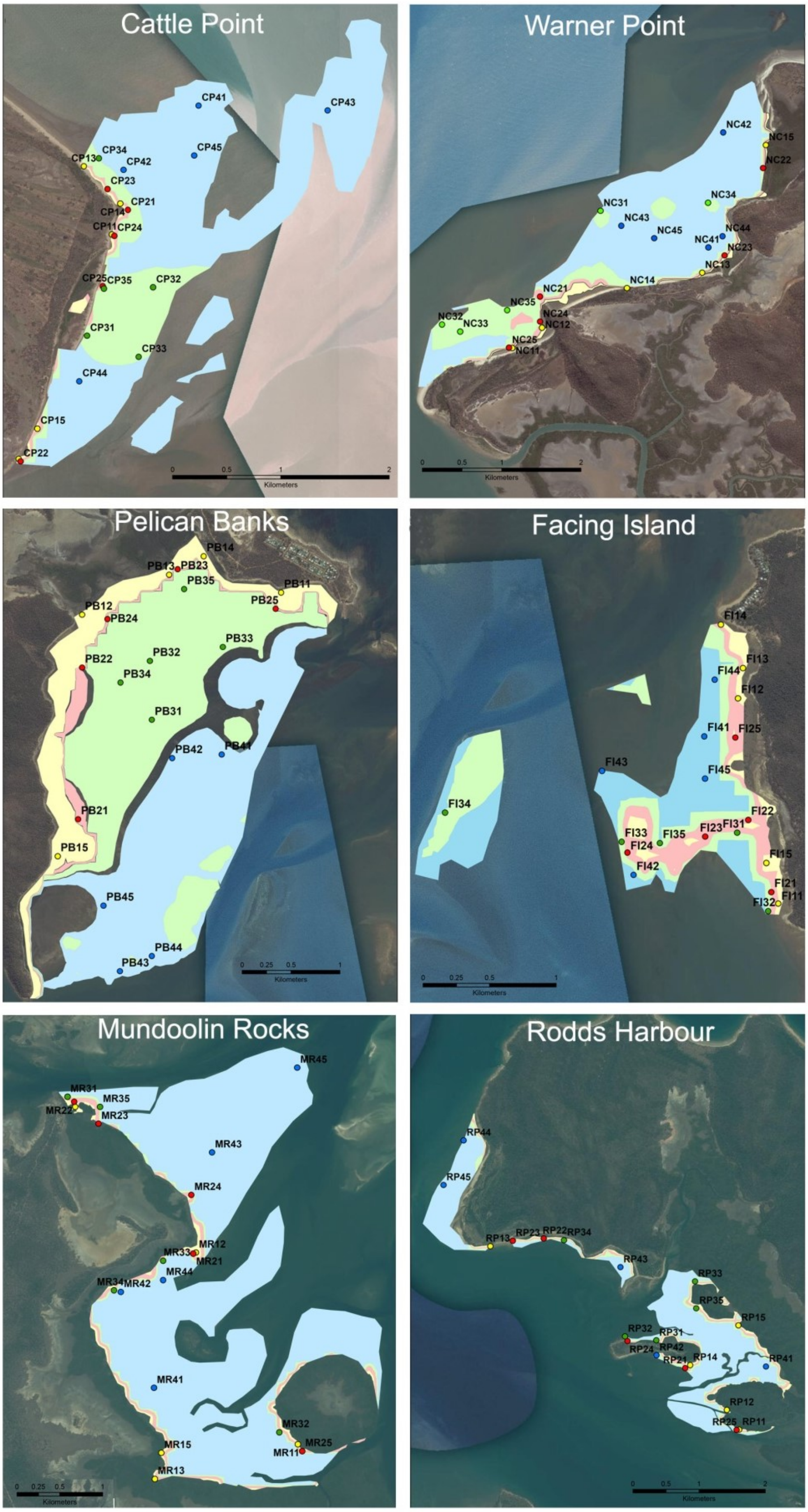


Figure 4.6 Maps of the six study sites, showing the four vertical sampling quartiles (yellow, pink, green, blue descending down shore).

4.2.3.3 Sampling Methods

At each sampling quadrat, we collected infaunal cores from five random locations within the quadrat using a cylindrical coring device (dimensions: overall length = 25cm; diameter = 12.5cm). The device was driven into the sediment to a depth of 20cm and the core was then retrieved and the top 5cm separated from the rest of the core. The two samples were placed in separately labelled sample containers. Dividing core samples by core depth in this fashion allowed prey availability to be independently assessed for shorebirds that employ vastly different feeding strategies (i.e., tactile vs visual feeders) or have different bill lengths. The samples were then sealed and taken back to a storage facility. Any excess water was decanted through a fine 10µm sieve and transferred into a 10% buffered formalin solution containing a red stain (Rose Bengal) facilitating visual separation of infaunal organisms. Samples were left in formalin for at least two days. During this time, the samples were periodically agitated so that the formalin was able to permeate the whole sample and bind to all the infaunal organisms held within. After two days, the formalin was removed and replaced with a 70% ethanol solution to preserve the samples until sorting of the infauna. After passing the core samples through a 0.5mm sieve, infauna were retrieved and identified to an appropriate taxonomic level, depending on the type of organism. A subsample of each major type of organism in each sample was assessed subsequently to provide an estimation of energy content (Section 4.3.3).

We compared the composition of the prey community in the top 5cm of the core samples across the study area (i) among the six height bands, and (ii) among the six sites, using multivariate analytical techniques. We used non-metric multidimensional scaling (NMDS) to assess the pairwise dissimilarity in abundance of each taxon across height bands and sites. Essentially, this tells us whether the community composition differs between any two sets of samples being compared.

4.2.4. Results

4.2.4.1 Effect of height on benthic community composition

A total of 30,763 benthic organisms was sorted. There was a highly significant effect of height on benthic community composition at all sites except Mundoolin Rocks (Table 4.2), where the community compositions of samples from different heights were as similar to each other as they were to samples from within the same height band. At Rodds Harbour, although the global analysis indicated a significant effect of height band on community composition, the pair-wise tests were ambiguous in interpretation, and there appeared to be very weak or no vertical structuring of the benthic community at this site (Table 4.2).

There was a clear directional change in community composition with increasing height on the shore for Cattle Point, Warner Point, Pelican Banks and Facing Island, as reflected by the clear segregation of the upper and lower height bands (Figure 4.7), but much less clear progression in community composition for the two southern sites of Rodds Harbour and Mundoolin Rocks (Table 4.2; Figure 4.7). We confirmed this by statistically testing the hypothesis that if height was influencing the composition of the benthic community, then height bands that are adjacent to each other should have communities more similar to each other than to those from bands that are further apart. We plotted the R statistic (an index of dissimilarity) for combinations of bands of increasing distance apart against the number of height bands separating them (i.e., adjacent bands = 1; bands 2 apart = 2; Figure 4.8). The hypothesis of a progressive serial change in the benthic community composition with increasing height on the shore was indeed strongly supported for Warner Point and Pelican Banks, weakly supported for Cattle Point and Facing Island, but rejected for Rodds Harbour and Mundoolin Rocks (Figure 4.8). This suggests strong structuring of benthic communities according to height for most sites, but that other factors might also be at play at Cattle Point, and that the two southern sites of Rodds Harbour and Mundoolin Rocks are responding very differently from other sites.

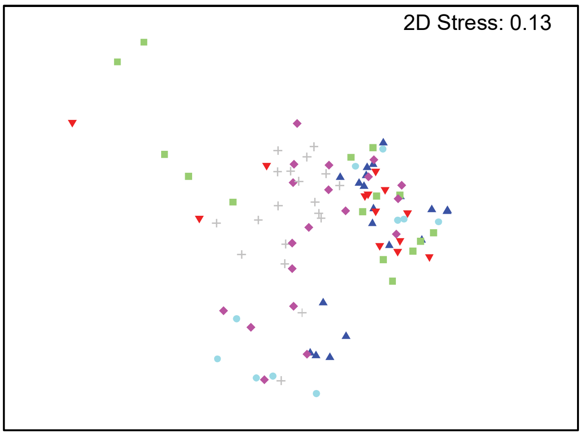
We examined which of the main invertebrate groups contributed to the changes in benthic composition with increasing height on the shore using an analysis of similarity percentages (SIMPER; Clarke, 1993). We present the results for adjacent height bands, as we are looking for serial directional changes in benthic composition with height across the littoral zone.

Different benthic taxa were markers of change in height down the shore across the four sites for which significant vertical structuring was discovered (Table A1). At Cattle Point, the abundance of bivalves and copepods (primarily harpacticoids) consistently contributed the most to the change in composition of the prey community with decreasing height across the littoral zone (Table A1). The pattern of change in abundance of bivalves (primarily small donacid bivalves) was very clear, showing a steadily decreasing density with decreasing height in the littoral zone, although the pattern was less clear for copepods, which possibly increased downshore (Figure 4.9).

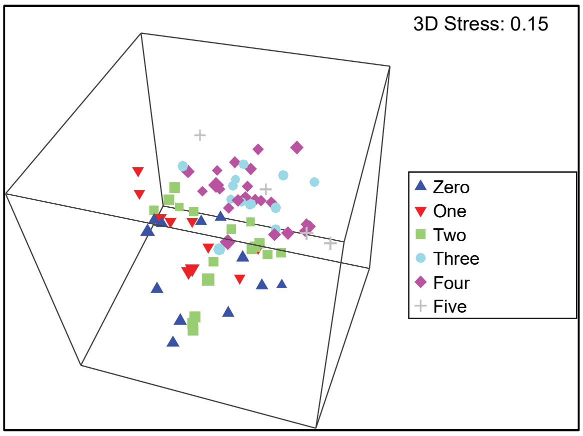
Table 4.2 Results of ordered analysis of similarities (ANOSIM) using Bray-Curtis similarity measure on square-root transformed abundance data, testing for differences in benthic community composition among six height bands down the shore (0 = top of littoral zone; 5 = bottom of littoral zone). For direct comparisons across all six regions, heights were scaled against a common mean low water level. Height band 5 was not present at Rodds Harbour.

	Cattle Point	**Warner Point**	**Pelican Banks**	**Facing Island**	**Rodds Harbour**	**Mundoolin Rocks**
Heights	**P (R)**	**P (R)**	**P (R)**	**P (R)**	**P (R)**	**P (R)**
0,1	0.196 (0.045)	0.222 (0.041)	0.878 (-0.174)	0.181 (0.058)	0.878 (0.052)	0.092 (0.103)
0,2	0.028 (0.112)*	0.052 (0.092)	0.400 (0.02)	0.002 (0.239)*	0.400 (0.164)	0.097 (0.097)
0,3	0.027 (0.188)*	0.001 (0.452)*	0.056 (0.118)	0.003 (0.303)*	0.056 (0.022)	0.584 (-0.022)
0,4	0.010 (0.109)*	0.001 (0.441)*	0.002 (0.304)*	0.003 (0.286)*	0.002 (0.083)*	0.029 (0.159)*
0,5	0.001 (0.36)*	0.001 (0.532)*	0.001 (0.59)*	0.001 (0.359)*	N/A	0.734 (-0.098)
1,2	0.398 (0)	0.132 (0.073)	0.200 (0.296)	0.001 (0.334)*	0.200 (0.118)	0.002 (0.463)*
1,3	0.034 (0.151)*	0.001 (0.453)*	0.166 (0.16)	0.002 (0.395)*	0.166 (0.062)	0.012 (0.096)*
1,4	0.019 (0.136)*	0.001 (0.408)*	0.061 (0.302)	0.001 (0.234)*	0.061 (0.017)	0.045 (0.062)*
1,5	0.001 (0.355)*	0.003 (0.541)*	0.002 (0.684)*	0.001 (0.379)*	N/A	0.213 (0.097)
2,3	0.056 (0.126)	0.004 (0.176)*	0.532 (-0.05)	0.818 (-0.059)	0.532 (0.153)	0.204 (0.057)
2,4	0.003 (0.185)*	0.001 (0.248)*	0.194 (0.177)	0.502 (-0.008)	0.194 (0.008)	0.001 (0.488)*
2,5	0.001 (0.381)*	0.021 (0.326)*	0.002 (0.485)*	0.468 (-0.002)	N/A	0.533 (-0.033)
3,4	0.025 (0.133)*	0.399 (0.007)	0.109 (0.145)	0.773 (-0.047)	0.109 (0.039)	0.001 (0.182)*
3,5	0.001 (0.482)*	0.038 (0.401)*	0.001 (0.384)*	0.813 (-0.068)	N/A	0.496 (-0.006)
4,5	0.026 (0.079)*	0.252 (0.095)	0.015 (0.069)*	0.037 (0.116)*	N/A	0.114 (0.142)
Global	0.001 (0.099)*	0.001 (0.303)*	0.001 (0.348)*	0.001 (0.099)*	0.001 (0.348)*	0.693 (-0.016)

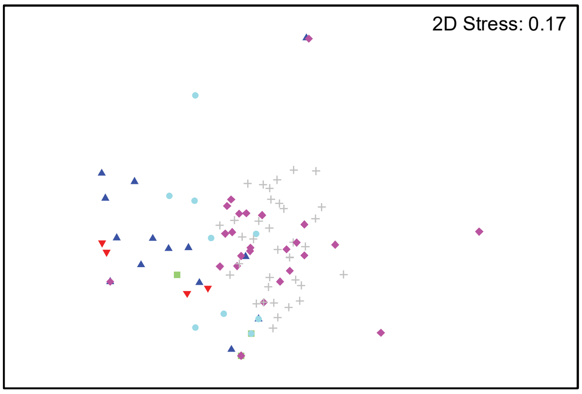
(a) Cattle Point



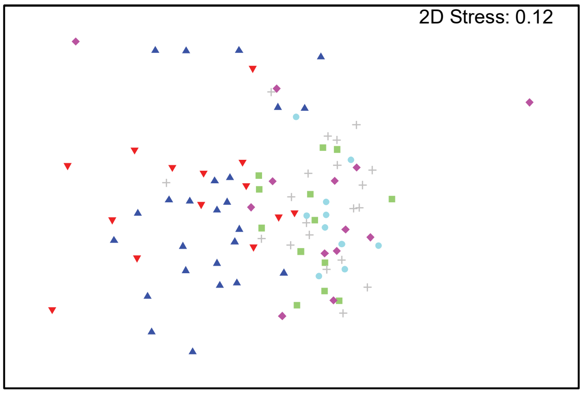
(b) Warner Point



(c) Pelican Banks



(d) Facing Island



(e) Rodds Harbour

(f) Mundoolin Rocks

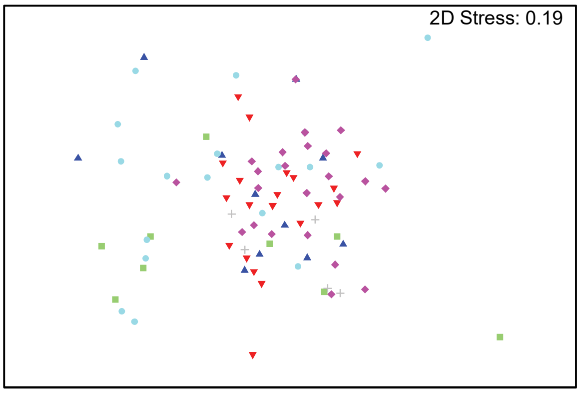
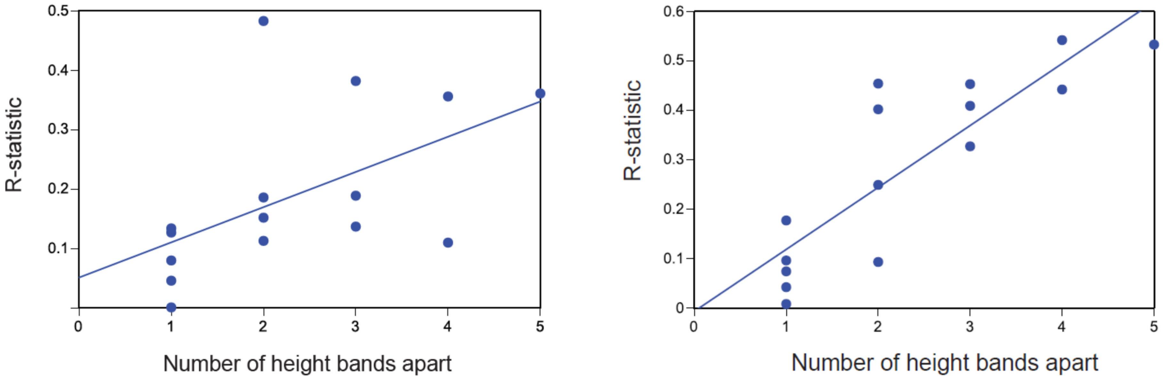
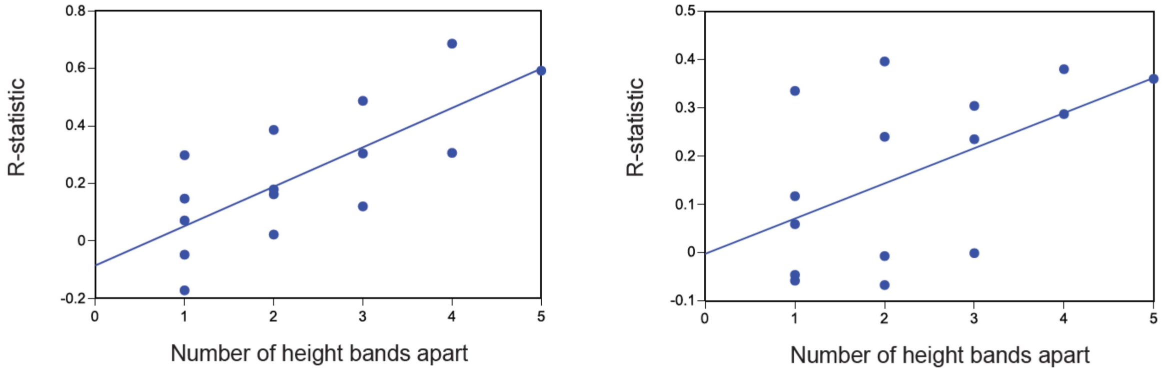


Figure 4.7 Non-metric multidimensional scaling ordinations showing the effects of height above sea level on the composition of the benthic prey community in six height bands above mean low water spring (each height band represented by a differently coloured dot) at six sites in the ERMP Survey Area (0 = top of littoral zone; 5 = bottom of littoral zone). Data are square-root transformed abundances. The ordination for Warner Point is three-dimensional because three important axes were identified by the model; for all other sites, only two axes of variation were important. The axes are arbitrary in scale and orientation, and are therefore unlabelled. Points closer to each other have a more similar community composition. Stress values indicate moderate, but not excellent fit.



(a) Cattle Point ($R^2 = 0.30$, $P < 0.034$)

(b) Warner Point ($R^2 = 0.73$, $P < 0.0001$)



(c) Pelican Banks ($R^2 = 0.56$, $P < 0.0013$)

(d) Facing Island ($R^2 = 0.29$, $P < 0.039$)

Figure 4.8 Scatterplot of the dissimilarity in community composition between different height bands (measured by the R statistic) and the number of height bands apart for four sites in the ERMP Survey Area where there was a significant effect. Lines of prediction from the linear regressions are shown, with a significantly increasing R statistic indicating that benthic community composition is more different the greater the difference in height upshore. There was a weak positive trend for Rodds Harbour ($R^2 = 0.087$, $P > 0.41$), and a weak negative trend for Mundoolin Rocks ($R^2 = 0.20$, $P > 0.096$) indicating no clear progression in community composition with height upshore for those two sites.

At Warner Point, polychaete worms, bivalves and isopods contributed the most to separation of the height bands for the upper three bands, while lower in the littoral zone, isopods were rare but polychaetes and bivalves continued to differentiate between the adjacent heights on the shore. Plots of the changes in abundance of polychaetes and bivalves (Figure 4.9) did not show any simple pattern of change with height suggesting neither group alone would be a useful indicator for the broader patterns of community change.

At Pelican Banks, polychaete worms and bivalves consistently contributed the most to separation of different adjacent height bands across the littoral zone (Table A1). None of the other invertebrate groups was sufficiently abundant across the entire shore profile to provide any meaningful distinction between the height bands. There was a general trend of increasing abundance of polychaetes with decreasing height in the littoral zone and the opposition pattern for the bivalves (Figure 4.9), although abundances were generally low.

At Facing Island, polychaete worms, small bivalves and nemertean worms provided the largest consistent contribution to the vertical change in benthic community composition (Table A1). Again, there were no simple patterns in terms of the general changes in the abundance of these three groups, and any indicators of the effects of height on the shore on the abundance of prey would need to be developed on the basis of changes in multiple groups of animals (Figure 4.9).

4.2.4.1.1 Differences Among Regions

Total abundance of all invertebrates varied considerably across the six sites at all heights down the shore, with a much higher abundance of invertebrates at Cattle Point than other sites (Figure 4.10). This was particularly true for the upper shore, and it was caused primarily by the overwhelming dominance of small bivalves at Cattle Point (Figure A2). There were also other important differences in the relative contribution of the different invertebrate groups to the benthic community, in particular with an increase in the abundance of polychaetes and amphipods from north to south (Figure A2).

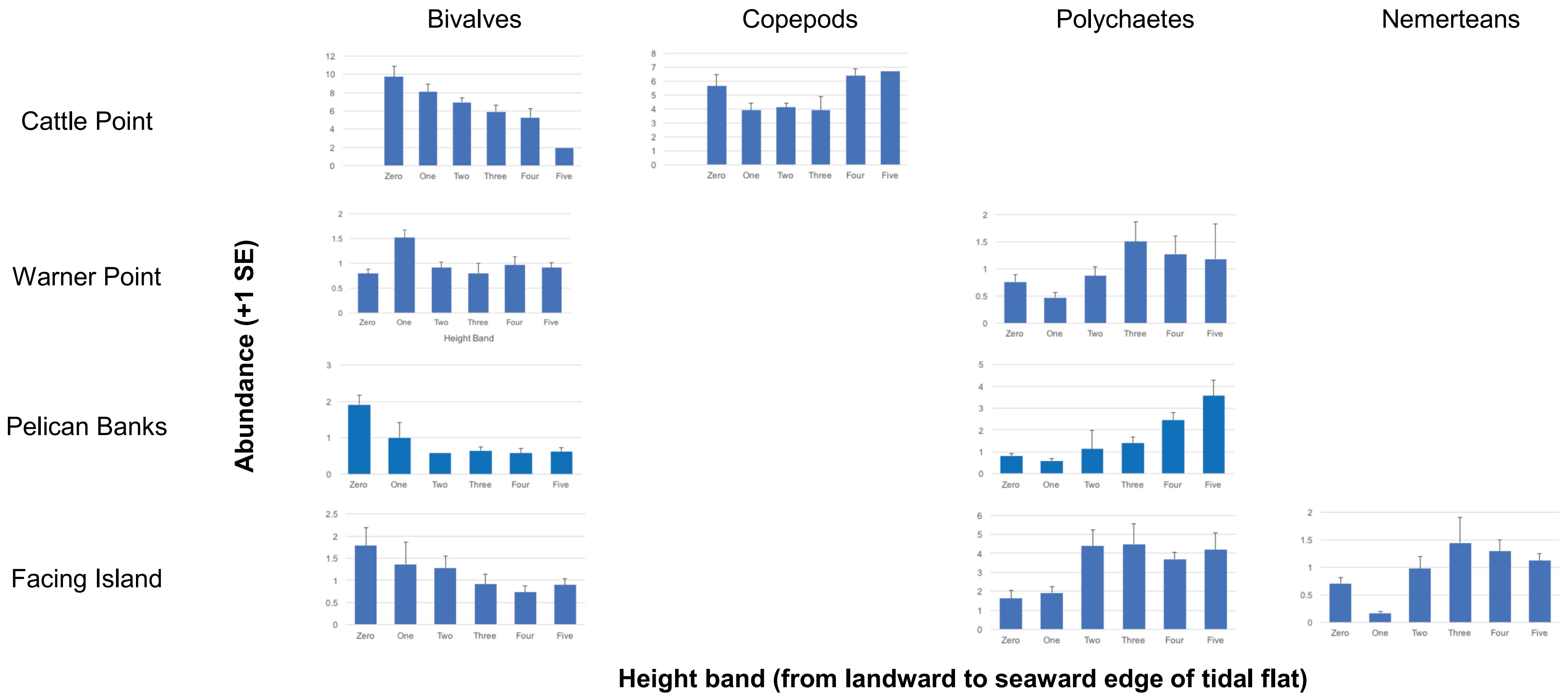


Figure 4.9 Mean abundance (±1 SE) of major benthic taxa with decreasing height on the shore (0 = top of littoral zone; 5 = bottom of littoral zone). For clarity, only taxa useful for distinguishing among all height bands at each site (see Table A1) are shown.

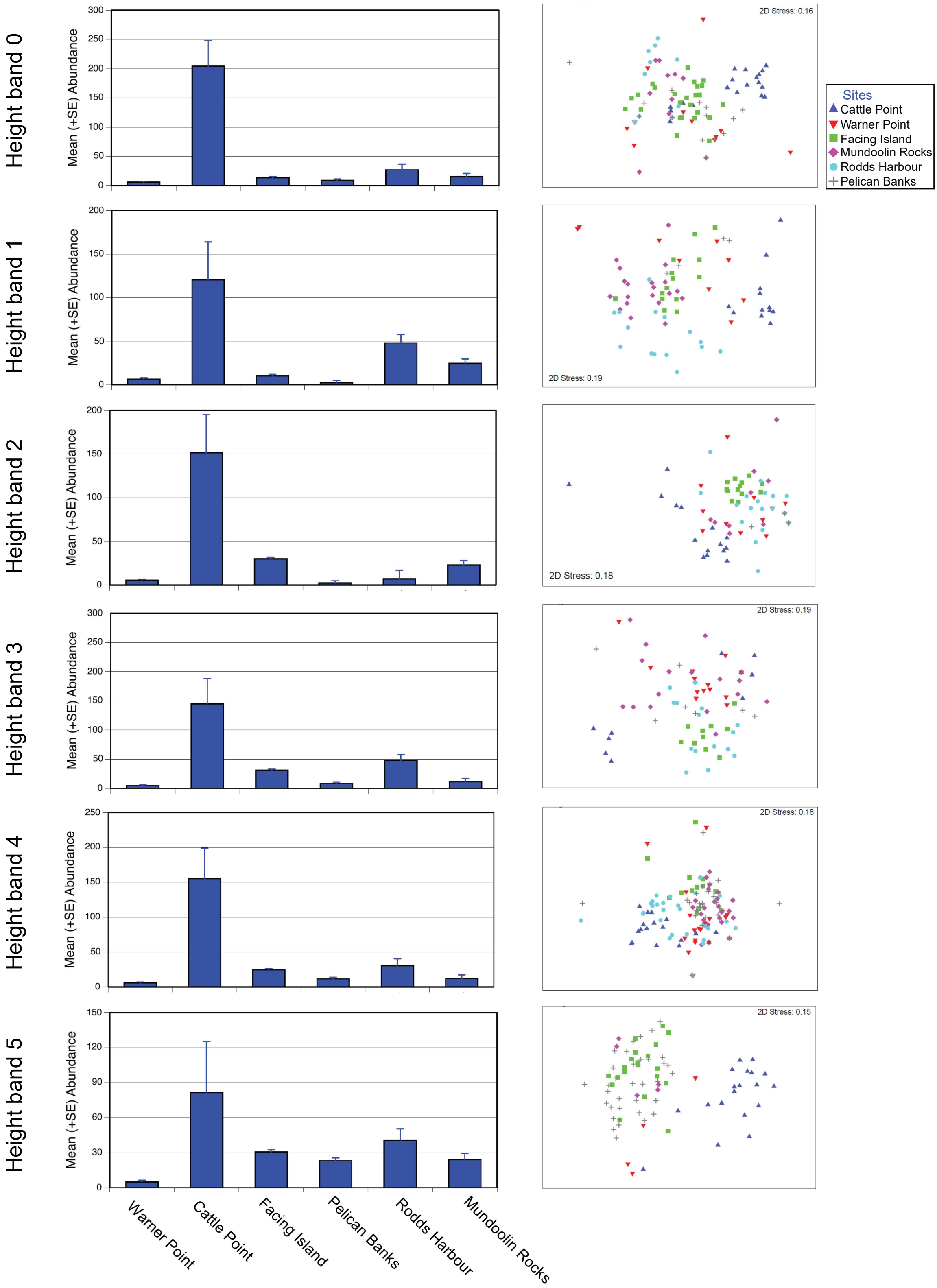


Figure 4.10 Mean abundance (+1 SE) of benthic invertebrates across the six sampling sites (left column), and non-metric multidimensional scaling 2D ordinations comparing the benthic community composition using square-root transformed abundances (right column).

Table 4.3 Results of unordered analysis of similarities and associated pair-wise tests, using the Bray-Curtis similarity measure on square-root transformed data, testing for differences in benthic community composition among the six sites, for each of the six height bands (0 = top of littoral zone; 5 = bottom of littoral zone).

Comparison	**0**	**1**	**2**	**3**	**4**	**5**
Cattle Point vs Warner Point	< 0.001	< 0.001	< 0.001	< 0.004	< 0.001	< 0.001
Cattle Point vs Facing Island	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cattle Point vs Pelican Banks	< 0.001	< 0.001	< 0.009	> 0.065	< 0.001	< 0.001
Cattle Point vs Rodds Harbour	< 0.001	< 0.001	< 0.001	< 0.001	< 0.031	N/A
Cattle Point vs Mundoolin Rocks	< 0.001	< 0.001	< 0.006	< 0.018	< 0.018	< 0.001
Warner Point vs Facing Island	< 0.001	< 0.004	< 0.004	< 0.001	< 0.001	< 0.001
Warner Point vs Pelican Banks	> 0.512	> 0.822	> 0.981	< 0.014	< 0.014	< 0.001
Warner Point vs Rodds Harbour	< 0.064	< 0.064	< 0.007	< 0.007	< 0.007	N/A
Warner Point vs Mundoolin Rocks	> 0.161	< 0.003	> 0.142	> 0.407	< 0.001	< 0.008
Facing Island vs Pelican Banks	< 0.007	> 0.534	< 0.002	< 0.200	> 0.262	> 0.391
Facing Island vs Rodds Harbour	< 0.001	< 0.001	< 0.001	> 0.303	< 0.006	N/A
Facing Island vs Mundoolin Rocks	< 0.010	< 0.003	< 0.004	< 0.012	< 0.001	> 0.704
Pelican Banks vs Rodds Harbour	< 0.001	< 0.001	> 0.393	< 0.003	< 0.001	N/A
Pelican Banks vs Mundoolin Rocks	< 0.014	< 0.002	> 0.355	> 0.309	< 0.050	> 0.865
Rodds Harbour vs Mundoolin Rocks	> 0.642	< 0.001	< 0.009	< 0.009	< 0.001	N/A
Global test	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

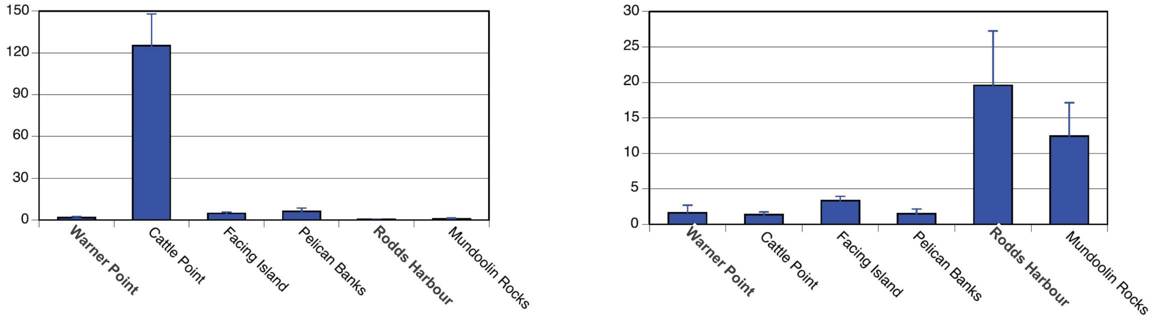
Because community composition varied markedly with both height up the littoral zone, and across the six sites, we briefly discuss in detail these differences, in progressive order from the upper shore to lower shore.

Height band 0

The overall composition of the upper shore prey communities in the six sites separated into four main groupings (Figure 4.10 NMDS plots; Table 4.3). The community at Cattle Point was different from all the other sites, even after data were square root transformed to reduce the effects of especially abundant taxa (i.e., bivalves at Cattle Point). A second group comprised the community at Facing Island, and the third was at Pelican Banks. The community at the two most southern sites, Rodds Harbour and Mundoolin Rocks were not different from each other and also overlapped with that in Warner Point, the most northern site.

Four main invertebrate groups contributed consistently to the separation of the benthic community across the sites: bivalves, polychaete worms, harpacticoid copepods and crabs (Table A2). The abundances of these four groups across the six sites for the Zero height band (top of the shore) are shown (Figure 4.11). Bivalves and copepods (the most abundant groups) were significantly more abundant at Cattle Point than elsewhere in the study region. In contrast, polychaetes were more abundant in the south (Rodds Harbour and Mundoolin Rocks) than elsewhere, while crabs were marginally more abundant at Facing Island and Mundoolin Rocks, although it should be noted that the abundance of crabs was generally small everywhere sampled.

(a) Bivalves (b) Polychaete worms



(c) Copepods (d) Crabs

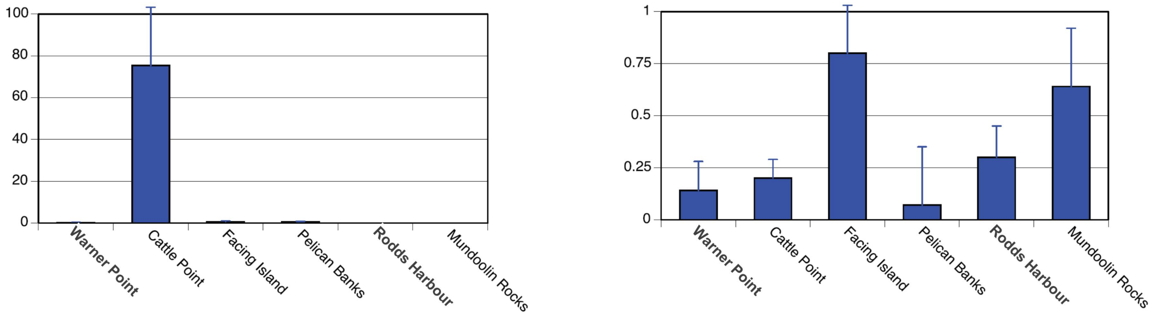


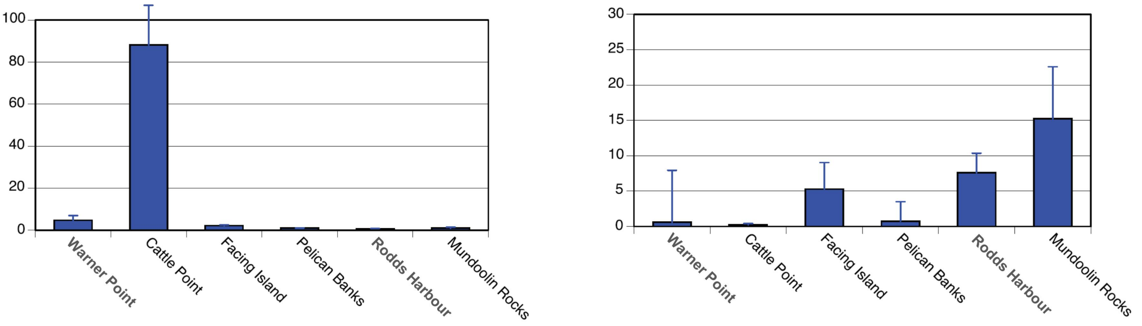
Figure 4.11 Mean (+1 SE) abundance of the four invertebrate groups that were important in explaining overall variation in community structure among the six sites in height band 0 (top of the shore).

Height band 1

In the next height band, down from the top of the littoral zone, total abundance of all invertebrates across the six sites was still dominated by the much greater numbers of animals at Cattle Point compared with elsewhere, although the other sites were not as obviously depauperate as was evident at the very top of the littoral zone (Figure 4.10). Small bivalves dominated the sediments in height band 1 in the northern region (Warner Point and Cattle Point), with an increasing relative importance of polychaetes moving south (Figure A2, Figure 4.12). Amphipods were also relatively abundant in the sediments at Rodds Harbour. The six sites begin to separate more clearly from each other at height band 1 with only

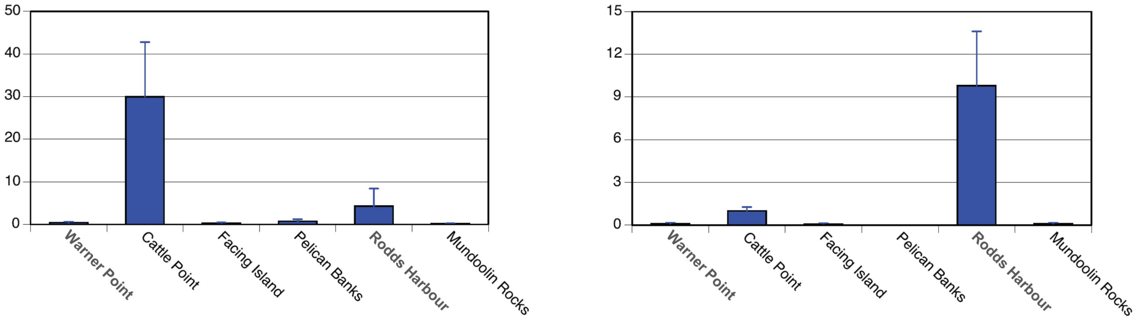
Pelican Banks showing any obvious overlap with the other sites (NMDS plot in Figure A2; Table 4.3) and this was primarily due to the very small numbers of animals present at this height in the sediments at Pelican Banks.

Four taxa provided the most consistent contributions to the separation of the sites in terms of the composition of the benthic prey community (Table A3) for height band 1. As for the top of the littoral zone, bivalves, copepods and polychaetes were included, but now amphipods replaced crabs as the fourth group. There were no clear patterns of changing abundance within these four taxa along the gradient from north to south (Figure 4.12), despite the increase in the relative importance of some taxa with the sites (e.g., increasing dominance of polychaetes – Figure A2 – from north to south). These results suggest regional patchiness in the distribution of each of the major invertebrate groups.



(a) Bivalves

(b) Polychaete worms



(c) Copepods

(d) Amphipods

Figure 4.12 Mean (+1 SE) abundance of the four invertebrate groups that were important in explain overall variation in community structure among the six sites in height band 1.

Height bands 2–5

The remaining height bands showed similar patterns in total abundance of invertebrates across the six sites, with total abundance much greater at Cattle Point than the other five sites (Figure 4.10). It was only at the very bottom of the littoral zone (height band 5), that large numbers of invertebrates were found at sites other than Cattle Point (Figure 4.9, Figure 4.10).

The composition of the prey community at height band 2 (NMDS plot in Figure 4.10) varied significantly among the six sites (Table A4), but there was no clear north-to-south pattern evident. The community at Warner Point grouped together with that at Pelican Banks and Mundoolin Rocks which were much further south. The other sites were all significantly different from each other (pair-wise tests, Table A4).

Only two taxa provided any consistent contribution to the separation of the benthic prey community among the six sites at height band 2: bivalves and polychaetes (Table 4.4). The other prey taxa each contributed variously to specific pair-wise comparisons between sites, in different rank orders of importance. The relative importance of the different prey group at height band 2 no longer showed the pattern of increasing dominance of polychaetes from north to south that had been evident higher up the shore (Figure A2). Instead, the introduction of amphipods and some nemertean worms became evident in the southern sites (Rodds Harbour and Mundoolin Rocks), providing a more diverse diet for the shorebirds. The northern four sites were still primarily dominated by bivalves and polychaetes.

On the lower half of the littoral zone (height bands 3–5), the composition of the prey community was rather less distinct among the six sites. The prey communities in the middle section of the study region (Sites at Facing Island and Pelican Banks) were not significantly different from each other at any of these three heights (NMDS plots on Figure A2; Table A5, Table A6, Table A7). At the bottom of the littoral zone (height band 5), this merging of the prey communities was extended further with no difference evident among any of the sites south of Facing Island (i.e., Facing Island = Pelican Banks = Mundoolin Rocks).

Table 4.4 Results of analysis of similarity percentages analysis to determine which of the invertebrate groups contributed most to the changes in the benthic composition among the six sites for height band 2. The two taxa that appeared consistently across all pair-wise comparisons are shown, although for any specific comparison other taxa may have contributed as much or more than some of these.

	% contribution	
Site	**Bivalves**	**Polychaetes**
Cattle Point vs Warner Point	41.96	-
Cattle Point vs Facing Island	28.51	22.08
Cattle Point vs Pelican Banks	44.04	10.01
Cattle Point vs Rodds Harbour	39.15	12.09
Cattle Point vs Mundoolin Rocks	36.30	13.15
Facing Island vs Pelican Banks	11.63	33.34
Facing Island vs Rodds Harbour	10.98	28.19
Facing Island vs Mundoolin Rocks	14.83	28.75
Facing Island vs Warner Point	12.48	32.48
Pelican Banks vs Rodds Harbour	17.87	27.99
Pelican Banks vs Mundoolin Rocks	28.09	26.00
Warner Point vs Pelican Banks	40.83	26.65
Warner Point vs Rodds Harbour	20.54	25.49
Warner Point vs Mundoolin Rocks	24.90	25.00
Rodds Harbour vs Mundoolin Rocks	22.18	24.90

The abundance of all benthic invertebrates varied considerably across the six sampled sites and elevations on the tidal flat, with bivalves, copepods, polychaetes and amphipods being the numerically dominant benthic organisms in the Survey Area.

4.3 Estimate how many birds the area can support (Aim A3)

4.3.1. Summary

We combined results from the benthic sampling with information about the diet and energy requirements of birds to estimate the number of shorebirds that the ERMP Survey Area could support. Studies in Europe indicated that shorebirds typically need access to between 2 and 7.8 times more food than their physiological requirement to maintain high survival rates during the non-breeding season (usually from August to April). Our analysis suggests that the six tidal flats surveyed in the ERMP Survey Area contain between two and six times more food than needed by the current number of birds using the sites, and this gap closes rapidly when considering constraints on prey selection and the costs of foraging on the generally small prey that can only be found at low densities. Indeed, the density of food available to shorebirds in the ERMP Survey Area ranks among the lowest in the world compared with other tidal flat ecosystems such as, e.g., Roebuck Bay in northwest Australia, Deep Bay in Hong Kong and the Frisian coast in the Netherlands. Reasons for the low density of food available to shorebirds are unclear, and this would be a good subject for a careful comparative study. We therefore conclude that much of the ERMP Survey Area is functioning at or near carrying capacity, which is concerning given the steep declines in many Australian migratory shorebird species. We therefore conclude the region is vulnerable to future impacts.

We also showed that the numbers of birds present relative to carrying capacity varied markedly across the ERMP Survey Area, and Gladstone Harbour had the fewest shorebirds relative to carrying capacity. This could be a result of (i) high benthic biomass density distributed mostly in areas that are exposed the least, (ii) local pressures such as disturbance causing shorebirds to be present at lower numbers than the site could support, or (iii) declines caused elsewhere being reflected in lower numbers present, or some combination of these processes.

Cattle Point is highly attractive for migratory shorebirds that are specialised on bivalves, providing these species with a higher predicted intake rate than energy expenditure. This site is particularly important in supporting red knots, which transit through the ERMP Survey Area on their way to non-breeding sites further south. In short, the density and type of benthic invertebrates present had a clear effect on the numbers and type of shorebirds present in a site, with predicted energy intake rates strongly related to the distribution of different shorebird species.

4.3.2. Introduction

Fundamental to estimating the consequences of an environmental impact, or to implementing an effective offset, is determining the size of the migratory shorebird population that can potentially be supported by an area. The concept of 'carrying capacity' has become important in migratory shorebird management, in which population size in any particular site is considered to be limited by the available food supply. In theory, if the size of an area and the prey density within it are known, one can calculate how many shorebirds the area can support. Next, one can in principle also assess whether a particular development will cause population decline or whether provision of additional habitat nearby could be sufficient to offset any local losses. In this section, we estimate carrying capacity for six tidal flat systems across the ERMP Survey Area, and compare this with estimates of the numbers of birds actually using those sites.

Carrying capacity is a concept that has been employed in a wide range of disciplines including population ecology, wildlife management, anthropology and mechanical engineering. Coined as early as 1845 within the field of mechanical engineering to determine the amount of duties that could be imposed on a ship (Sayre 2008), the term was subsequently introduced in the field of ecology and applied to grazing livestock (Hadwen & Palmer 1922) and herbivorous wildlife (Leopold & Brooks 1933). It was not until Odum (1971) defined it in the context of population limitation as the upper asymptote of a logistic population growth trajectory (also known as K, or equilibrium level) that its popularity increased dramatically within the field of ecology (Dhondt 1988; Odum 1971).

Over the years the concept of carrying capacity has led to considerable confusion and uncertainty in definitions and measurement methods, possibly caused by its use across a range of disciplines, and has also received considerable criticism (Sutherland & Parker 1985; Sutherland 1996). Part of this criticism relates to difficulties in substantiating the natural limit to population growth (Price 1999) and whether this limit is a dynamic quantity that may vary in time (e.g., amount of food in a pasture) or a fixed constraint (Sayre 2008). Moreover, in an ecological context, carrying capacity depends not only on habitat features, but also on the behaviour of the animals living there (Newton 1998). For instance, the carrying capacity of an area could vary in relation to the extent of territoriality and gregarious behaviours and (at least partially) independently of resource availability. A complication in the case of highly mobile animals, such as migrants, may arise from the fact that carrying capacity at one place could be influenced by events at other locations (Goss-Custard 1993).

The definition of the term 'carrying capacity’ has itself been somewhat ambiguous. One of the more complex definitions is “the user-specified quality biomass of a particular species, under the influence of social or behavioural constraints, for which a particular area, having user-specified objectives, will supply all energetic and physiological requirements over a long (but specified) period” (Giles 1978). Conversely, it has also been simply defined as “the maximum population of a given organism that a particular environment can sustain” (Allaby 2014). In the study of migratory organisms, it has been defined as the “maximum numbers of migratory animals that can be supported in a particular locality at a particular time of year” (Goss-Custard et al. 2002).

Carrying capacity estimates could inform prioritisation processes, shed light on factors affecting population size and assist in predicting the effects of environmental change on species. The applied values of the carrying capacity concept may be particularly relevant to the conservation of migratory shorebirds along the East Asian–Australasian Flyway given their alarming population declines (Moores et al. 2016), which have been linked to the rapid disappearance of their coastal habitats (Murray et al. 2014; Studds et al. 2017). There is thus an urgent need for rapid assessment protocols that can quickly assess habitat change at impacted sites along the flyway. Therefore, we retain and recommend the carrying capacity concept as a highly valuable paradigm, under the condition that a clear definition is provided and results are interpreted with care. In this study, we follow the approach of Goss-Custard et al. (2002), and define carrying capacity as the maximum number of migratory shorebirds that can be supported in the ERMP Survey Area during the non-breeding season.

For the measurement of carrying capacity both demographic (Dasmann 1964) and energetic approaches (de Leeuw 1997) have been considered. The former is a numerical approach focusing on the demographic analyses of the number of organisms using an area but the outcome from such approach is often inconclusive because concurrent measurement of local habitat quality and potential influences beyond the study area are often unfeasible or neglected. The alternative, energetic carrying capacity is a more deterministic, functional approach that examines the biological mechanisms limiting the utilisation of food resources (de Leeuw 1997). Models that have been employed to estimate energetic carrying capacity include, in order of increasing complexity, Daily Ration Models, Spatial Depletion Models and Spatially-explicit Individual-based Models (Stillman & Goss-Custard 2010).

Daily Ration Models estimate the total number of bird-days an area can support based on the total amount of food available and the requirement of an average individual animal (Alonso et al. 1994; Stillman & Goss-Custard 2010). In some cases, critical prey density, below which food intake rate rapidly diminishes or ceases, is also taken into consideration (Gill et al. 2001). Despite its successful application in a number of cases (e.g., Alonso et al. 1994; Gill et al. 2001), it has been criticised for its simplicity. Adding complexity, the Spatial Depletion Models consider spatial variation in food abundance and track how identical foragers utilise the different food patches using game theoretical approaches (Stillman & Goss-Custard 2010). Spatial Depletion Models consider fixed critical prey densities and, like Daily Ration Models, assume all individuals in the population to be identical. However, it has been shown that assuming a fixed critical prey density may not be appropriate in spatially heterogeneous environments with varying costs in different patches (van Gils et al. 2004), while individual organisms are unlikely to be identical in competitive ability and foraging efficiency (Ens & Goss-Custard 1984). As a result, a population does not instantly disappear if prey abundance declines below a fixed critical prey density; instead, some individuals will have the foraging or competitive skills to remain in preferred patches while others do not, resulting in patchy and gradual declines in abundance rather than an instant (and easily interpreted) exodus. Therefore, more sophisticated approaches have been developed based on individual-based models, which assume individuals are usually different and behave in ways that maximise their fitness (Railsback et al. 2012). These Spatially-explicit Individual-based Models tend to be far more complex, tracking large numbers of individuals with different entities rather than identical individuals. Often these models are data hungry, requiring a lot of data for model parameterisation and calibration (Stillman & Goss-Custard 2010).

In the current project, given its short timeframe and lack of previous information on foraging shorebirds in the area, we adopt a Daily Ration Model to estimate carrying capacity. We do this both with and without taking critical prey densities into account. The fundamental data required for models of this kind are measures of prey abundance and availability (i.e., considering tidal exposure of the potential foraging areas and burrowing depths of potential prey species; (see Sections 4.1 and 4.2)), shorebird abundance and daily food requirements of the shorebirds. For the case where we also take critical prey densities into account, which we will coin “Site quality from a shorebird’s perspective”, we also need to know the functional response, or how intake rate varies with prey density. Instead of merely providing an estimate of number of birds the study area can potentially support, we compare this number (availability) to the current number of birds present (physiological requirement) and this will give us an idea of which sites in the ERMP Survey Area are close to their carrying capacity and might therefore (i) be impacted most by further environmental degradation, or (ii) benefit most from habitat management measures such as disturbance control in the surrounding tidal flats to encourage shorebirds to explore underused areas.

4.3.3. Methods

Food requirements

Total food requirements (in terms of digestible energy requirements) by migratory shorebirds during the non-breeding season were estimated based on the daily digestible energy requirements for each species, then multiplied by the abundance and number of days birds spend in the ERMP Survey Area. The latter were obtained from the passage date estimates and peak counts reported in Sections 5.1 and 5.3. We only included the counts from roosts within 5km of the six benthic sampling sites and that were conducted during the non-breeding season (from August 2015 to February 2016). Thus, the number of birds assessed is more likely to correspond with benthic food availability. We considered that the birds operated under thermal neutral conditions (i.e., that they expend no energy in thermoregulation; Kersten et al. 1998) and that their daily Digestible Energy Requirements (DER) are twice their Basal Metabolic Rate (BMR), increasing to four to five times BMR during the fuel deposition period prior to migration (Piersma 2002). We also assumed that fuel-deposition in preparation for migration, requiring elevated intake rates, takes place during the final one-third of the birds' stay. For species that only transit through the ERMP Survey Area, this elevated intake rate applies to their entire stay. The monthly mean body mass of shorebirds was obtained from averaging the body mass data for birds caught in Queensland (Coleman unpubl. data). We estimated BMR using the allometric relationship between BMR and body mass as measured in non-breeding migratory shorebirds in tropical Africa (Kersten et al. 1998). Using the results from these calculations and the passage date estimates and peak counts reported in Sections 5.1 and 5.3, we could then work out the total DER for all shorebirds in each benthic sampling site during the non-breeding season.

Food availability

Food availability was derived from benthic samples collected in the six different benthic-sampling sites (see Section 4.2 for full details). Unless specified otherwise, we used the data from the entire core sample (20cm deep) for this analysis since some of the shorebirds considered are capable of reaching beyond the top 5cm of the substratum. For ease of calculation, we assumed that no net production of benthos took place during the non-breeding season and that all benthos depletion was due to consumption by shorebirds only. Violations would underestimate shorebird carrying capacity if net production of benthos takes place or overestimate it if other predators also contribute to benthos depletion. We also excluded prey size or types that are not ingestible by shorebirds (Table 4.5). To convert count data of benthic organisms into prey digestible energy content, we took these steps:

1. We randomly selected one out of the five replicates collected in each sampling station, and measured the size (in mm, mostly length but sometimes width) of individual organisms within the replicate. Ten individuals were randomly chosen for measurement if the replicate contained more than ten individuals of the same taxon. Most benthic organisms were measured to the nearest 0.001mm, using Tucsen ISCapture software that allows the viewing and measurement from the computer screen after connecting a digital camera (Tucsen ISH500 camera) to a dissecting microscope (Olympus SZX9). Larger organisms were measured to the nearest 0.1mm using callipers. This yielded the size distribution of 24 benthic taxa based on the measurements taken from 3,041 benthic organisms.

2. We used published benthic size-biomass (ash-free dry mass, hereafter AFDM) relationships of the focal or closely related taxa (Choi 2015; Rogers 2006; Zwarts & Wanink 1993) to work out the AFDM (mg) of all measured individuals in step 1, while excluding taxa unlikely to be consumed by shorebirds (Table 4.5). We then took the mean AFDM (mg) of all individuals within a taxon to represent the typical AFDM (mg) for an individual of that taxon.

3. We converted AFDM (mg) to gross energy content (kilojoules: kJ) using 22kJ / g AFDM for bivalves and 21.48kJ / g AFDM for all other taxa. Next we converted these values to digestible energy content through multiplication with the assimilation efficiency for which 0.8 was assumed (Castro et al. 2008; Kersten & Piersma 1987; Zwarts & Wanink 1993).

4. For each height quartile within each site (see Section 4.2 for details), we calculated the mean density (count per km^2) of individual animals within a benthic taxon across all replicate samples. This value was subsequently multiplied by the area (km^2) of the corresponding height quartile, yielding the total abundance of the various benthic taxa for each height band in each site (count).

5. Finally, for each benthic taxon we multiplied the total abundance for each height quartile in each site (step 4) with the digestible energy content (kJ, step 3), yielding the total digestible energy content of each benthic taxon available in each height quartile in each site. The digestible energy content of various taxa in different height quartiles within the same site was then summed, yielding the total digestible energy content available to shorebirds at that site.

Table 4.5 References to equations used to calculate AFDM from individual lengths of different benthic taxa. Sources listed are: (1) Zwarts & Wanink (1993); (2) Rogers (2006); (3) Choi (2015). Species that were considered not to be consumed by shorebirds in the ERMP Survey Area due to large proportion of indigestible material are listed as "Excluded[1]", those due to their relatively low abundance in the Survey Area as "Excluded[2]", those are likely to be too big for shorebirds to swallow as "Excluded[3]".

Benthic taxon	**Example animals**	**Data source**	**Size range (in mm) used in this analysis (L=length, W=width)**
Amphipoda	Amphipod	1	0.37–4.28 L
Arachnida	Spider, tick, mite, scorpion	Excluded[2]	na
Araneae	Spider	Excluded[2]	na
Cirriedia	Barnacle	Excluded[1]	na
Bivalvia	Bivalve	2	0.81–18.6 L
Brachiopod	*Lingula*	3	na
Brachyura	Crab	2	0.92–19 W
Chironomid larvae	Fly larvae	1	2.03–5.26 L
Copepoda	Copepod	1	0.4–4.25 L
Cumacea	Cumacea	1	1.29–1.99 L
Echiura	Spoon worm	1	3.02–5.24 L
Egg	Egg	Excluded[1]	Na
Fish	Fish	Excluded[3]	Na
Gastropoda	Gastropod	2	0.62–4.69 W
Callianassidae	Ghost shrimp	3	7.32–28.34 L
Goby fish	Goby fish	Excluded[3]	na
Insect	Insect	Excluded[2]	na
Isopod	Isopod	1	1.99–5.32 L
Nemertea	Nemertea	1	1.21–28.09 L
Oligochaete	A kind of Annelid	1	2.96–18.93 L
Ophiuroidea	Brittle star	Excluded[1]	na
Ostracoda	Seed shrimp	1	0.59–0.99 L
Paguroidea	Hermit crab	Excluded[1]	na
Penaeidae	Penaeid shrimp / prawn	Excluded[1]	Na
Platyhelminthes	Flatworm	1	3.47–6.53 L
Polychaeta	Polychaete worm	1	0.14–47.4 L
Polyplacophora	Chiton	Excluded[1]	Na
Sea anemone	Sea anemone	3	2.15–4.53 L
Sipuncula	Sipuncula	1	1.27–37.37 L
Tanaidea	Tanaid	1	1.89–9.68 L
Unknown	Unknown	2	1.02–8.66 L

The carrying capacity of each of the six sites was calculated as the ratio of availability to requirement, for which we divided the total digestible energy content available to shorebirds by the current digestible energy requirement of those shorebirds at that site. A value of 1 thus indicates the area is used at carrying capacity whereas values exceeding 1 indicate that more birds could potentially use the site.

Site quality from a shorebird's perspective

In addition to the carrying capacity estimate, we provided another way to understand how the ERMP Survey Area is supporting migratory shorebirds. We used the benthos data collected in this project (Section 4.2) to predict shorebird energy intake rate, by applying the information to the published equation generated from analysing 30 empirically-derived functional responses (food intake rate as a function of food density) in free-living shorebirds (Goss-Custard et al. 2006). This equation predicted the functional response asymptote successfully in 93% of cases (Goss-Custard et al. 2006) and required only the means and standard deviations of the density and ash-free dry mass of benthic prey and the staging body mass of the shorebird. In this exercise, it is straightforward to obtain the necessary data for shorebird species that rely mostly on one prey type. For generalist, rather than specialist shorebirds which take multiple prey types, the mean prey density per height band per site was calculated as the sum of the mean prey density of all possible prey types. Prey ash-free dry mass for birds foraging on multiple prey types was calculated as a weighted mean (by prey type and density) per height band per site. The predicted intake rate from this exercise provides a "shorebird's view" of site quality. The site is unprofitable for the shorebird to forage if the predicted intake rate is less than the estimated energy requirement, while the site is profitable if the predicted intake rate is higher.

We selected seven shorebird species that are relatively common in the ERMP Survey Area and for which dietary information was available for this analysis (great knot, red knot, whimbrel, Terek sandpiper, eastern curlew, bar-tailed godwit, grey-tailed tattler). We assumed great knot and red knot to feed only on bivalves that burrow to 5cm below surface and whimbrel and Terek sandpiper to feed only on crabs that burrow to 20cm below surface, based on field observations and published records (Choi et al. 2017; Rogers 2006; Tulp & de Goeij 1994). We also assumed that eastern curlew has a mixed diet comprising both crabs and ghost shrimps that burrow to 20cm (Zharikov & Skilleter 2004b), and bar-tailed godwit and grey-tailed tattler feed on everything listed as edible in Table 4.2, with the former reaching to 20cm while only to 5cm for the latter (Rogers 2006). For body mass of the shorebirds we took their average monthly body mass during their stay (from August to April next year) based the body mass data for birds caught in Queensland (Coleman unpubl. data). We assumed their energy requirements to equate to twice their BMR, and calculated intake rate and energy requirements in units of Watts (i.e., J/s) using the appropriate AFDM and digestibility conversions presented above. All the key assumptions made and the potential consequences to our capacity estimates when violated are given in Table A8.

4.3.4. Results and Discussion

Carrying capacity

Benthic organisms mostly fell within the ingestible size range for shorebirds (Choi et al. 2017; Goss-Custard et al. 2006; Rogers 2006). Even the smallest shorebird species in this study could ingest most, if not all, of the amphipods, bivalves and polychaete worms, except for a few gastropods, which were excluded from our carrying capacity analysis (Figure 4.13). The size of the benthic organisms in our study sites did not impose a strong ingestion constraint to shorebirds as found in other areas (Tulp & de Goeij 1994; Zwarts & Blomert 1992). Following the steps in Section 4.3.3, we calculated the digestible energy requirement of shorebirds in each of the six benthic sampling sites based on the number of shorebirds currently using the area and their length of stay during the non-breeding season (Table 4.6).

On a broad scale, bar-tailed godwit, eastern curlew, whimbrel, great knot and red knot are the shorebird species with the highest energy requirement in the survey area, due to their relatively high abundance, large body size and long length of stay. Shorebirds using the Rodds Peninsula subregion (Mundoolin Rocks and Rodds Harbour) have the largest collective digestible energy requirement due to the large number of birds recorded in the area (Table 4.7). Nevertheless, the Rodds Peninsula subregion (Mundoolin Rocks and Rodds Harbour) ranks only second after the Gladstone Harbour subregion (Pelican Banks and Facing Island) in benthic prey availability for shorebirds, next followed by the Fitzroy Delta (Cattle Point and Warner Point). This remained the same when taking the size of the different intertidal areas into account, which varied only slightly (Figure 4.13).

The seagrass habitats in the Gladstone Harbour subregion (Pelican Banks and Facing Island) may have importantly contributed to the high benthic biomass available in this subregion. Compared to bare sand, seagrass habitats are generally known to support considerably higher densities of benthic organisms (Barnes & Barnes 2012; Barnes & Hamylton 2016). Given the high food availability of the area, it was surprising that we did not find more shorebirds using it, with an apparent use amounting to only 15% of its capacity. Possibly, the close proximity to human settlements and lack of suitable night time roosts may have discouraged more shorebirds from using the area (C.-Y. Choi and D. Rogers personal observation). However, as outlined below, much of the available biomass in this area may have been unsuitable for many of the shorebird species in the ERMP Survey Area due to tidal influences and low density.

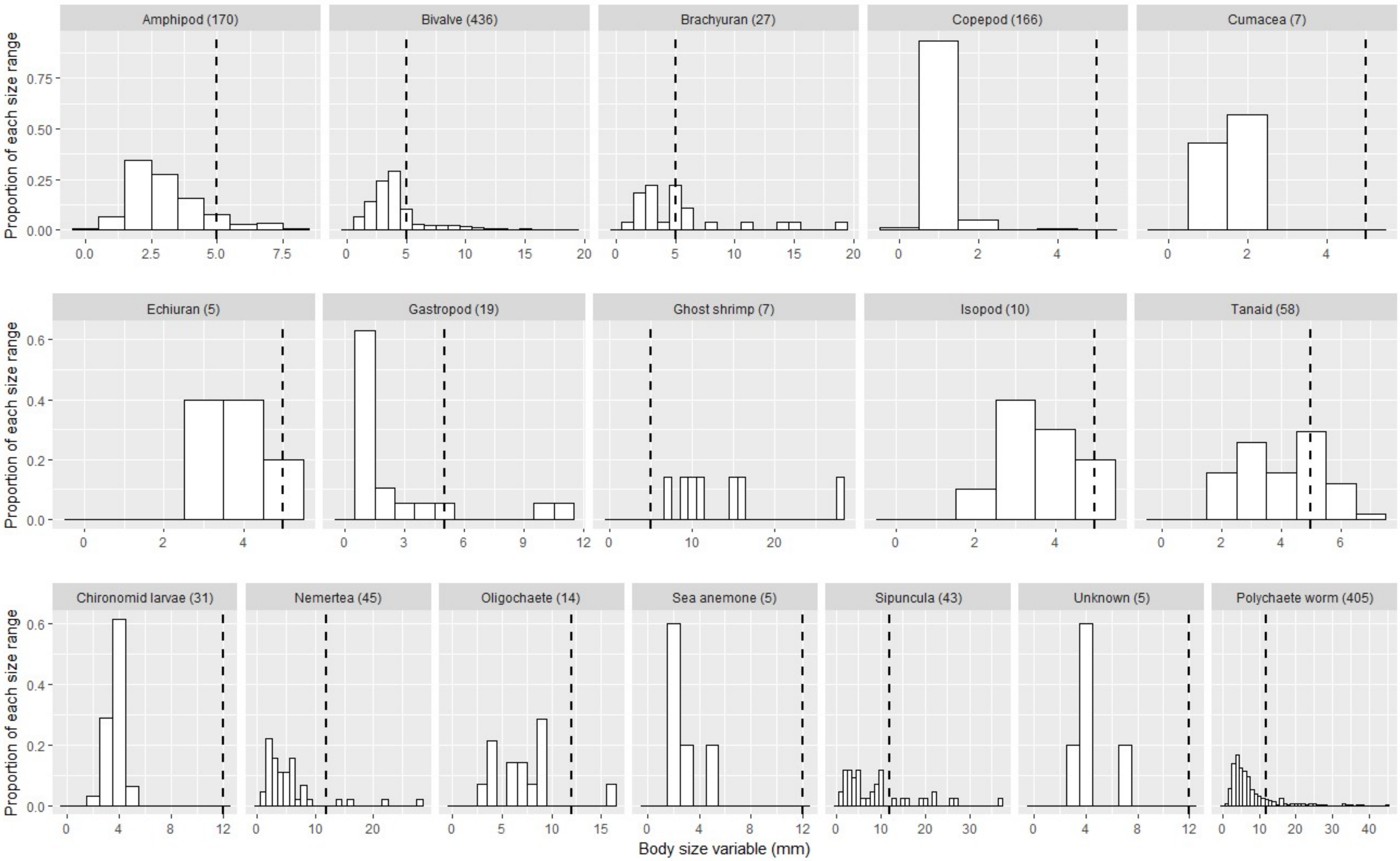


Figure 4.13 Size distributions of different benthic taxa in the ERMP Survey Area. Body length was the body size variable used for all taxa except Brachyurans and Gastropods where width was used (Table 4.5). Sample sizes are given in parentheses. Size classes towards the left of the black vertical dash lines indicate prey sizes ingestible by the smallest shorebird species in our study (red-necked stint; Rogers 2006).

Table 4.6 Per capita digestible energy requirement for each shorebird species and the total requirement for each species in each site based on local bird counts (including average staging duration). The percentage of total energy required by the species relative to all migratory shorebirds for each site is presented in parentheses. Data from species with the three largest digestible energy requirements in each site are presented in bold and are underlined. Abbreviations: NB = non-breeding, CP = Cattle Point, WP = Warner Point, PB = Pelican Banks, FI = Facing Island, MR = Mundoolin Rocks, RH = Rodds Harbour. Data from Pelican Banks and Facing Island were combined due to the regular movement of shorebirds between two sites (See Section 5.2 for details).

	Highest counts from roosts within 5km of benthic sampling area in 2015–2016's NB season							**Total digestible energy required in MJ (Percentage of total requirement in all migratory shorebirds in the site)**				
Species	**CP**	**WP**	**PB, FI**	**MR**	**RP**	**Duration (days)**	**Per capita requirement for non-breeding season (MJ)**	**CP**	**WP**	**PB, FI**	**MR**	**RH**
Bar-tailed godwit (*L. l. baueri*)	195	79	863	537	1,195	194	85.6	**16,684(14)**	**6,759 (25)**	**73,839 (41)**	**45,946 (33)**	**102,245 (53)**
Broad-billed sandpiper	0	0	2	1	0	56	10.6	0 (0)	0 (0)	21 (0)	11 (0)	0 (0)
Common greenshank	18	0	8	36	0	170	48.5	873 (1)	0 (0)	388 (0)	1,745 (1)	0 (0)
Curlew sandpiper	201	0	7	6	2	160	32.8	6,587 (5)	0 (0)	229 (0)	197 (0)	66 (0)
Eastern curlew	23	41	334	210	188	193	162.4	3,736 (3)	**6,660(25)**	**54,257(30)**	**34,114(24)**	**30,540(16)**
Great knot	568	0	99	315	409	188	51.7	**29,388(24)**	0 (0)	5,122 (3)	**16,299(12)**	**21,162(11)**
Greater sand plover	474	0	125	132	201	199	28.4	13,475(11)	0 (0)	3,554 (2)	3,753 (3)	5,714 (3)
Grey plover	36	0	1	63	62	220	84.2	3,033 (3)	0 (0)	84 (0)	5,307 (4)	5,223 (3)
Grey-tailed tattler	21	25	316	265	174	246	51.1	1,072 (1)	1,277 (5)	16,138 (9)	13,533(10)	8,886 (5)
Lesser sand plover	283	0	69	268	270	92	12.8	3,635 (3)	0 (0)	886 (0)	3,443 (2)	3,468 (2)
Marsh sandpiper	0	0	0	2	0	213	30.4	0 (0)	0 (0)	0 (0)	61 (0)	0 (0)
Pacific golden plover	3	0	0	31	0	198	45.8	137 (0)	0 (0)	0 (0)	1,421 (1)	0 (0)
Red knot	835	0	3	15	15	102	33.6	**28,065(23)**	0 (0)	101 (0)	504 (0)	504 (0)
Red-necked stint	763	0	17	612	778	98	5.5	4,220 (3)	0 (0)	94 (0)	3,385 (2)	4,303 (2)
Ruddy turnstone	0	0	6	3	1	55	18.3	0 (0)	0 (0)	110 (0)	55 (0)	18 (0)
Sharp-tailed sandpiper	354	0	0	2	0	87	19.8	6,998 (6)	0 (0)	0 (0)	40 (0)	0 (0)
Terek sandpiper	22	4	141	288	131	44	6.6	146 (0)	27 (0)	938 (1)	1,915 (1)	871 (0)
Whimbrel	23	99	185	77	75	229	120.7	2,777 (2)	**11,955(45)**	**22,340(13)**	9,298 (7)	9,056 (5)

Not considering prey specialisation and suitability for the various species of shorebird, our results indicate that the Fitzroy Delta (Cattle Point and Warner Point) and Rodds Peninsula (Mundoolin Rocks and Rodds Harbour) subregions have a potential shorebird carrying capacity, defined as “maximum number of migratory shorebirds that can be supported during the non-breeding season”, two times the number of migratory shorebirds currently using these subregions. For Gladstone Harbour (Pelican Banks and Facing Island) a ratio exceeding 6 was found, potentially suggesting the area has a much higher capacity than current usage (Table 4.7, Figure 4.14).

Table 4.7 The estimated digestible energy (MJ) required by the current number of migratory shorebirds and the digestible energy content available based on the benthic prey sampled in the subregions during the non-breeding season from August 2015 to April 2016. Samples collected from Cattle Point and Warner Point were combined as Fitzroy Delta; Pelican Banks and Facing Island combined as Gladstone Harbour; Mundoolin Rocks and Rodds Harbour as Rodds Peninsula.

Subregions	Area (km^2)	Digestible energy (MJ) required	Digestible energy (MJ) content available	Ratio of availability to requirement
Gladstone Harbour	10.82	178,100	1,211,051	6.8
Fitzroy Delta	9.11	147,506	363,314	2.5
Rodds Peninsula	12.22	333,080	919,156	2.8

However, the various shorebird species tend to have clear preferences and adaptations to forage on specific prey species and the dominant benthic groups, in terms of digestible energy content, differed substantially between sites. In Gladstone Harbour (Pelican Banks and Facing Island), polychaete worms contributed 78% to the total digestible energy content of the sites, followed by sea anemones, sipunculids and nemerteans. Polychaete worms again dominated further south in Rodds Peninsula (Mundoolin Rocks and Rodds Harbour), contributing 63–73% of total digestible energy content to the sites. However, unlike at Gladstone Harbour, this was followed by Brachyurans (crabs) and ghost shrimps. Interestingly, in Fitzroy Delta (Cattle Point and Warner Point) in the north, bivalves and amphipods contributed substantially more to the total digestible energy content than in other regions, making up 21–75% and 1–4% of the total digestible energy content in these sites, respectively (Table 4.8).

Table 4.8 The estimated digestible energy density (kJ per m^2) and the contribution (%, in parentheses) of different benthic groups to the total digestible energy content (kJ) of the benthic sampling sites in the ERMP Survey Area. The three benthic groups with the largest contribution in each site are presented in bold and are underlined.

Benthic taxon	**Sampling site**						
	Cattle Point	**Warner Point**	**Pelican Banks**	**Facing Island**	**Mundoolin Rocks**	**Rodds Harbour**	**All sites**
Amphipod	**2.34 (3.74)**	0.15 (0.71)	0.25 (0.23)	0.38 (0.3)	0.16 (0.2)	1.33 (2.09)	0.6 (0.77)
Bivalve	**47.26 (75.44)**	**4.64 (21.3)**	3.1 (2.86)	4.48 (3.49)	3.31 (4.15)	3.11 (4.88)	**9.03 (11.64)**
Brachyuran	1.72 (2.74)	0.71 (3.28)	5.1 (4.71)	3.11 (2.42)	**4.44 (5.55)**	**12.88 (20.23)**	**4.53 (5.84)**
Chironomid larvae	0	0	0.01 (0.01)	0.13 (0.1)	0.05 (0.06)	0.03 (0.04)	0.03 (0.03)
Copepod	0.81 (1.29)	0 (0.01)	0.01 (0.01)	0.01 (0.01)	0	0.29 (0.46)	0.14 (0.18)
Cumacea	0	0	0	0.01 (0.01)	0	0	0
Echiuran	0	0	0.02 (0.02)	0.14 (0.11)	0.08 (0.11)	0.06 (0.1)	0.04 (0.06)
Gastropod	0.43 (0.69)	0.1 (0.47)	0.09 (0.08)	0.13 (0.1)	0.01 (0.02)	0.01 (0.02)	0.11 (0.14)
Ghost shrimp	0.15 (0.23)	0	0.91 (0.84)	0.56 (0.44)	**6.33 (7.93)**	0.31 (0.49)	2.05 (2.64)
Isopod	0.01 (0.01)	0.02 (0.1)	0.01 (0.01)	0.01 (0.01)	0	0.02 (0.03)	0.01 (0.01)
Nemertea	2.07 (3.3)	0.62 (2.85)	2.71 (2.51)	**5.94 (4.63)**	1.93 (2.42)	1.86 (2.93)	2.2 (2.84)
Oligochaete	0.09 (0.14)	0.11 (0.5)	0.02 (0.01)	0.03 (0.02)	1.48 (1.85)	0	0.43 (0.56)
Platyhelminthe	0	0	0	0	0	0.15 (0.23)	0.02 (0.02)
Sea anemone	0	0.13 (0.58)	**6.55 (6.05)**	5.22 (4.07)	0	0	2.14 (2.76)
Sipuncula	1.35 (2.15)	**1.26 (5.77)**	**5.14 (4.75)**	**7.66 (5.97)**	3.59 (4.5)	**3.49 (5.47)**	3.61 (4.65)
Tanaid	0	0 (0.02)	0.48 (0.44)	0.85 (0.66)	0.15 (0.19)	0.02 (0.04)	0.23 (0.29)
Unknown	0.03 (0.06)	0.73 (3.33)	0.02 (0.02)	0.39 (0.3)	0.01 (0.02)	0.02 (0.02)	0.16 (0.2)
Polychaete worm	**6.39 (10.2)**	**13.3 (61.06)**	**83.84 (77.44)**	**99.19 (77.34)**	**58.33 (73)**	**40.1 (62.97)**	**52.24 (67.35)**

Although we found that the current apparent food availability for shorebirds is generally higher, and in some places (Gladstone Harbour) much higher than the amount needed by the current number of shorebirds, it is critically important to evaluate the assumptions made in that assessment. Although we assumed that all benthic prey items would be available to all shorebird species, irrespective of the size of the prey and that of the shorebird (and notably its beak's gape size), some prey may be too large for consumption by at least some shorebirds, or too small to make their pursuit profitable (see e.g., Figure 4.13). Benthic organisms also have defence or predator avoidance mechanisms in place (Piersma 1986), potentially again making their pursuit unprofitable (Choi et al. 2017). The high bivalve availability compared to the shorebirds' requirement in Cattle Point is a case in point (Figure 4.14). Great knot and red knot have significantly heavier gizzards for their body mass than other shorebird species, allowing them to crush the shells in a diet dominated by hard-shelled molluscs (Battley & Piersma 2005). Thus, the abundance of red knots at Cattle Point is not surprising, as this site had abundant bivalve prey (Figure 4.14). However, by the same token, it is surprising that there were fewer bivalves available than required for the number of great knot in the southern, Rodds Peninsula subregion (Mundoolin Rocks and Rodds Harbour). We suspect that the main bivalve patch may have been located outside our sampling areas in this subregion and perhaps overlooked. This possibility is supported by the sporadic movement of individually-marked shorebirds between high tide roost 67 near the Mundoolin Rocks sampling site and roost 71 where no benthic sample was collected (Figure 5.1). In addition, there were fewer crabs available than required by eastern curlew, whimbrel and Terek sandpipers at Gladstone Harbour (Pelican Banks and Facing Island) and Mundoolin Rocks. The requirement in Mundoolin Rocks was met after ghost shrimp, which is another food source often used by eastern curlews (Zharikov & Skilleter 2004b), was taken into account. It is also likely that the availability of crabs in the study area was underestimated, partly due to our exclusion of mangrove forests, where some whimbrels were seen foraging, and partly due to the escape behaviour of crabs (Backwell et al. 1998) when observers sampled the area (Figure A3). Finally, in the absence of comprehensive foraging studies from the ERMP Survey Area, we cannot exclude the possibility that some shorebird species consumed prey types (e.g., large polychaetes) that have not been found in their diet in other parts of the world. However, in our field observations and videos we did not observe any foraging behaviour that we considered atypical; indeed we almost invariably recorded these species feeding on soldier crabs.

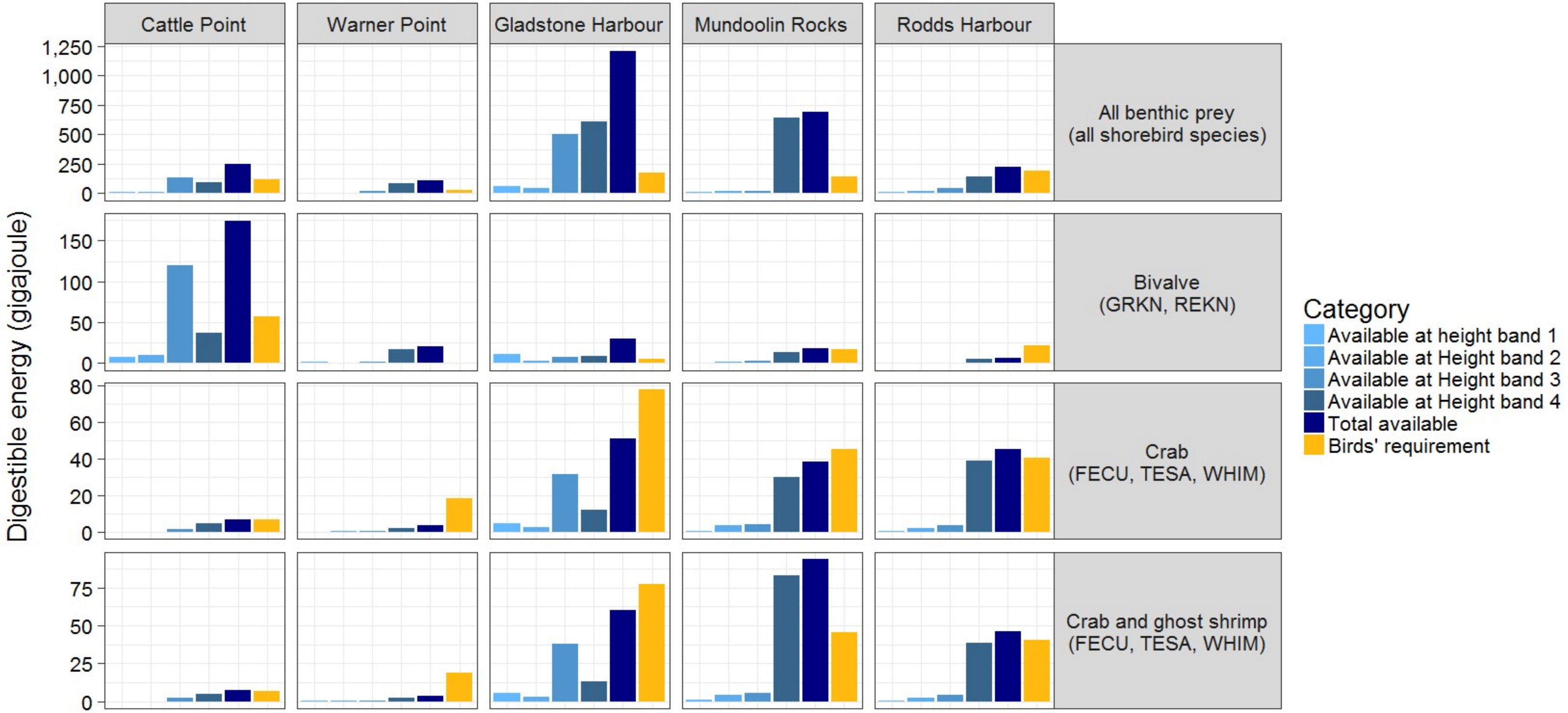


Figure 4.14 The availability of different types of digestible prey energy and requirement of different shorebird groups. "All benthic prey" refers to the digestible prey energy made available by all ingestible benthic prey items within 20cm to the surface. "Bivalve" refers to the digestible energy from bivalves. "Crab" refers to the digestible energy from crabs (excluding hermit crabs). "Crab and ghost shrimp" refers the digestible energy from crabs and ghost shrimps (excluding hermit crabs). Shorebird species corresponding to the particular benthic group are presented in parentheses. Abbreviations: FECU = eastern curlew; GRKN = great knot; REKN = red knot; TESA = Terek sandpiper; WHIM = whimbrel.

That all food is not necessarily available to all of the birds at any one time may not only be due to the behavioural and morphological characteristics of the prey but also to certain traits of individual shorebirds (Goss-Custard 2014). For instance, dominance hierarchies and territorial behaviour in some shorebird species may exclude some individuals and may reduce the number of birds profiting from a resource (e.g., eastern curlew; Zharikov & Skilleter 2004a). More importantly, the availability of prey can also change with different tidal stages, as illustrated below (Goss-Custard 2014; Rogers 2006).

We assumed that migratory shorebirds would be the only predators of benthic prey, whereas the food considered is also taken by resident shorebirds (e.g., pied oystercatcher *Haematopus longirostris*, red-capped plover *Charadrius ruficapillus*), migratory terns and gulls, as well as other nektonic organisms such as fish, prawns, crabs and estuary stingray (Pardo et al. 2015). On the other hand, if our assumption that food consumed by shorebirds is replenished over the shorebird non-breeding season is not met, then the actual amount of food available to the shorebirds will be lower than our estimates presented here. Both of these potential violations would mean our shorebird carrying capacity was an overestimate, and that in reality the amount of resources available to migratory shorebirds is lower than calculated.

Tidal influences on prey availability

To illustrate the influence of tides on benthic prey availability, we used the results from the tidal exposure dynamics calculation in Section 4.1 to estimate the average proportion of each benthic sampling height band (Figure 4.6) that was exposed each day from August 2015 to April 2016, coinciding with the non-breeding season of the migratory shorebirds and the timing of our benthic sampling work. The average area of exposure was calculated across all 10-minute time slices in each 24-h period.

We found that the tidal exposure pattern in all of the benthic sampling sites followed the same general pattern. The areas near shore (height bands 1 and 2) had a relatively large average proportion of area exposed per day than those further away from shore (height bands 3 and 4; Table A9). However, substantial differences were found between sites, with Cattle Point having a larger proportion of upper tidal areas exposed than other sites while Pelican Banks and Facing Island had a substantially smaller proportion of lower tidal areas exposed than other sites (Table A9).

Taking the benthic biomass density (based on full core samples and all shorebird ingestible prey) into account, it is clear that the biomass density tends to increase down the littoral zone. Thus, the further away from the shore, the higher benthic biomass densities occurred (Warner Point, Pelican Banks, Facing Island and Rodds Harbour, Figure 4.15). However, the opposite pattern was found at Cattle Point, where benthic biomass density decreased downshore. In addition, Cattle Point also had a substantially higher weighted average proportion of exposed area per day (0.18) than other sites such as Pelican Banks and Facing Island (0.09 and 0.06, Table A9). This high benthic biomass density concentrated in areas exposed for longer by the tide probably explains the high number of shorebirds found in Cattle Point and the close proximity to carrying capacity (Table 4.6, Table 4.7). In contrast, the high benthic biomass density areas in the Gladstone Harbour sites (Pelican Banks and Facing Island) were located in the bottom two height bands, with only an average of 5% of these areas exposed per day, leaving shorebirds with very limited foraging opportunities in comparison with Cattle Point. It is very likely that some of these high benthos density areas in Gladstone Harbour are only exposed, thus available to shorebirds, erratically during spring tides and totally unavailable for days during neap tides (Figure 4.3). This could potentially explain the low number of shorebirds and low occupancy relative to capacity in the Gladstone Harbour subregion, and the high biomass of potential prey that can only be accessed for a limited period (Table 4.6, Table 4.7).

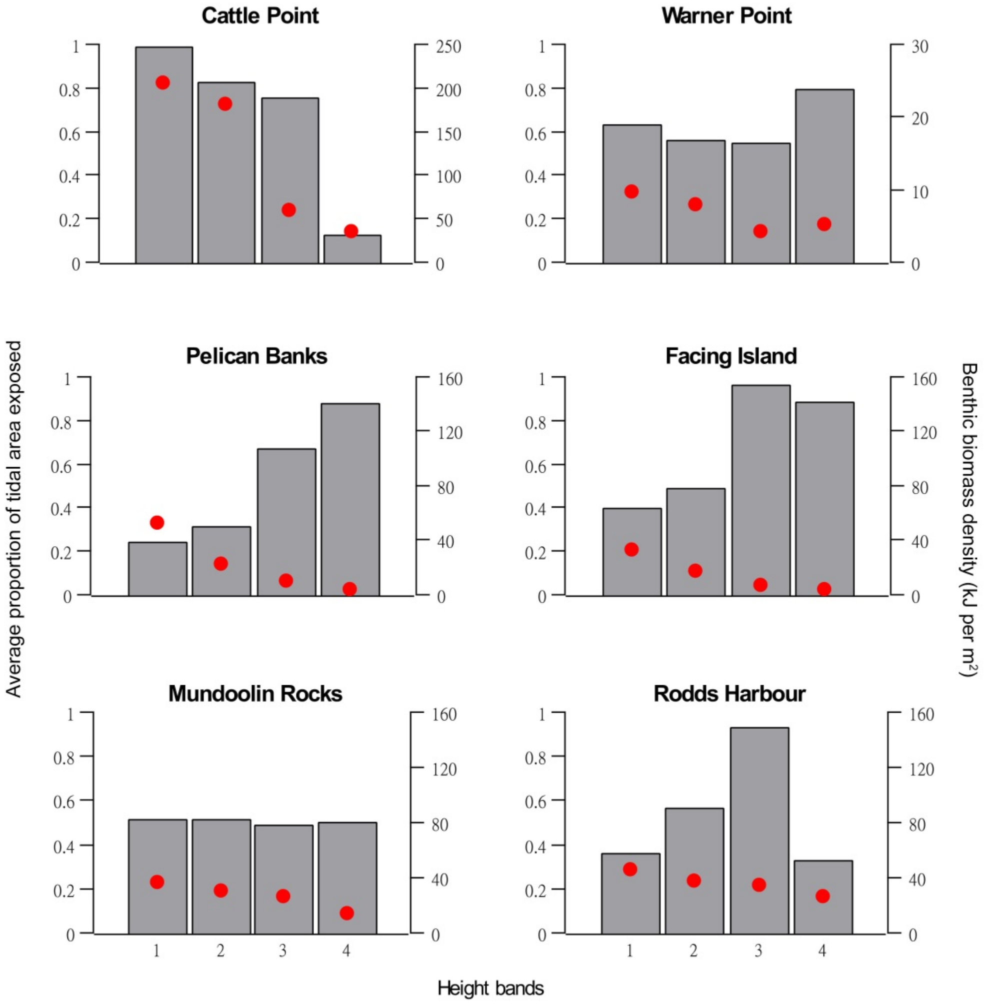


Figure 4.15 The change in average proportion of tidal area exposed per day (red dots against the left y-axis) and benthic biomass density (bars against the right y-axis) across different benthic sampling height bands and sites from August 2015 to April 2016.

Site quality from a shorebird's perspective

So far we have ignored the consequences of prey density on intake rates and the consequences this may have on the suitability and carrying capacity of potential foraging sites for the different species of shorebird. The comparison between predicted intake rates with estimated energy requirements in the seven key shorebird species for which we estimated their functional responses, indicated that the quality of sites (i.e., intake rate divided by energy requirements; Table 4.9) were far lower (range 0.3–2.7) than might have been expected from carrying capacity estimates that did not take prey selection and functional response into account (Table 4.7). For some of the species the quality of sites also varied greatly, rendering some sites unsuitable for foraging (i.e., quality ratio < 1; Table 4.9). Another observation was the differences in the profitability of foraging in the various height bands within areas, which were sometimes marginal and at other times quite substantial.

For the medium- to large-sized shorebirds with a specialised crab diet (whimbrel and eastern curlew) the site quality estimates suggest they might have difficulties in finding sites where they can maintain positive energy balance. Estimated energy requirements were always higher than the predicted intake rate regardless of height band and site (Figure 4.16, Table 4.9). As mentioned earlier some of these specialised feeders could feed on other benthic organisms or other prey types that they were not particularly specialised on, such as the abundant polychaete worms, in order to meet their daily energetic requirement (Skagen & Oman 1996; van Gils et al. 2005; Zwarts & Wanink 1993). Irrespectively, the variations in estimated quality of sites for eastern curlew (Table A9) and the distribution of eastern curlews across these six sites (Table 4.6; splitting numbers evenly across Pelican Banks and Facing Island) showed a suggestively high rank correlation (Spearman's correlation coefficient rho = 0.52). For whimbrel, there was no such correlation, but this species is also relatively evenly distributed, with the exception of Cattle Point (23 birds compared to 75–99 in the other areas), which indeed also had the lowest quality score (Table 4.9). The small-sized crab feeder (Terek sandpiper) should find Facing Island, Mundoolin Rocks and Rodds Harbour attractive (Figure 4.16, Table 4.9) and its abundance in these three sites was indeed higher than at other sites (Table 4.6; rho = 0.70 for rank correlation between site quality and bird numbers). Our current sampling regime may underestimate the actual number of crabs, partly due to our exclusion of mangrove forests in benthic sampling, where some whimbrels were seen foraging, and partly due to escape behaviour (Backwell et al. 1998). This underestimation of crab availability may explain the apparent unprofitability of the area for eastern curlew and whimbrel as indicated by our calculations (Table 4.9).

In contrast to the crab specialists, generalist shorebirds, such as the bar-tailed godwit and grey-tailed tattler, should do well in most of the sites (Figure 4.16, Table 4.9). For these species there was a correlation between site quality and number of birds observed at these sites (rho = 0.70 and rho = 0.84, respectively). The site quality estimates (Figure 4.16, Table 4.9) also indicated that bivalve-specialists (great knot and red knot) should show a strong preference for foraging at Cattle Point, which was indeed substantiated by observations, notably for red knot (Table 4.6). This site provided the bivalve-specialists with a substantially higher predicted intake rate than the estimated energy requirements for non-breeding birds.

As discussed earlier, there are many confounding factors that determine the distribution of shorebirds, such as disturbance, interference and predation risk. Nonetheless, food availability is undoubtedly one of the most important factors, and one can take energy requirements and functional responses into account, as we have done here for seven prominent shorebird species.

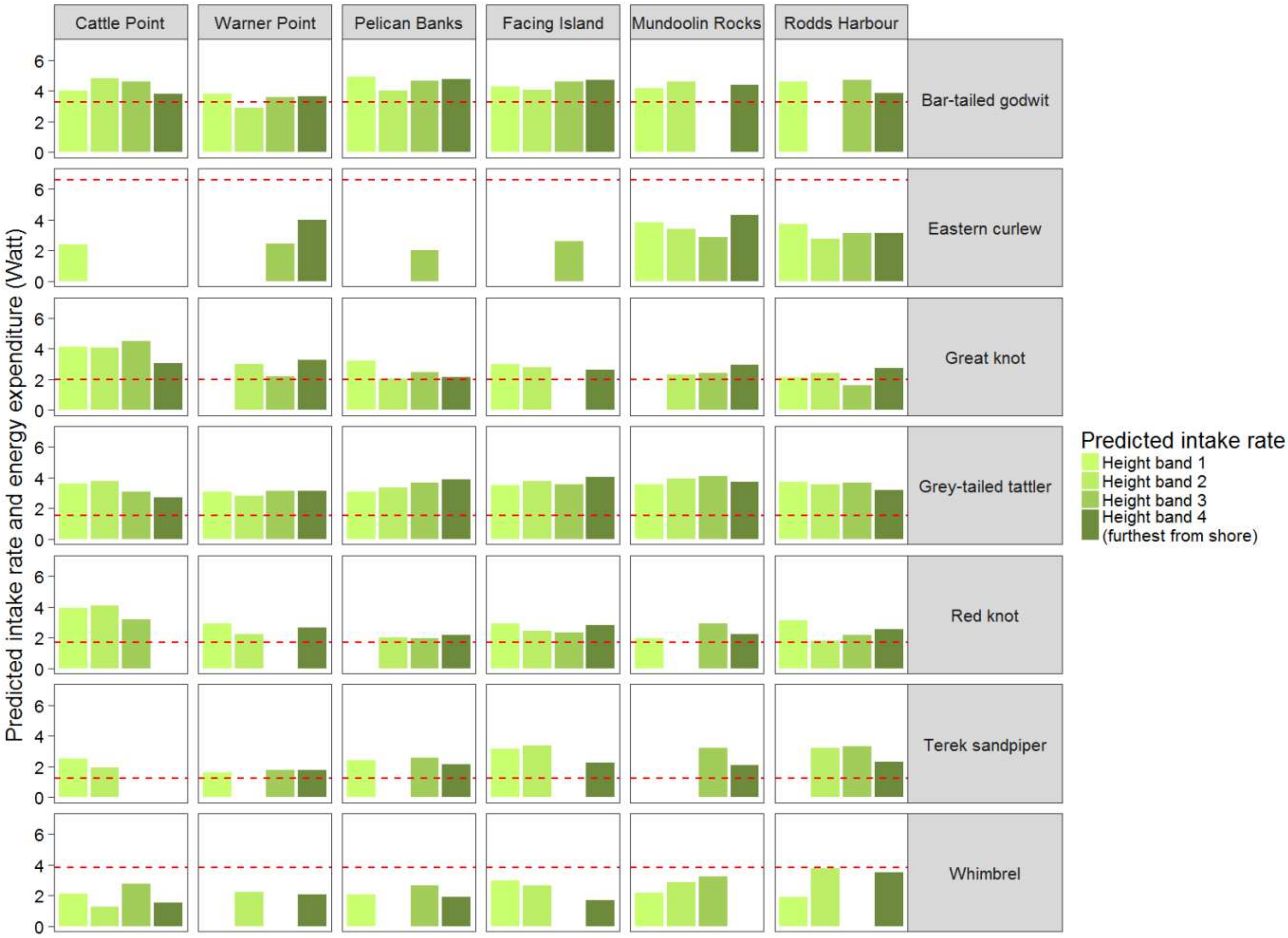


Figure 4.16 The profitability of foraging in different areas for seven different shorebird species. The area is unprofitable to forage for the corresponding shorebird species if the predicted intake rate (green bars; colours representing height band) is below the energy requirements (red dashed line). No predicted intake rate was presented in cases where the error margin around the intake rate estimate was extremely large and no reliable intake rate could thus be estimated.

Table 4.9 The quality of different sites to seven different shorebird species as based on the quotient of predicted intake rate divided by energy expenditure (in Watts). A quotient less than 1 indicates that the energy expenditure is higher than the predicted intake rate, which means the area is not profitable while a quotient higher than 1 indicates that the area is profitable for birds to forage. HB = height band, with height band 1 is the upper littoral zone while height band 4 is the lower littoral zone. "Mean" gives the mean across 4 height bands. "na" are cases where the error margin around the intake rate estimate was extremely large and was therefore excluded.

Species	Site	HB1	HB2	HB3	HB4	Mean
Bar-tailed godwit	Cattle Point	1.2	1.5	1.4	1.2	1.33
	Warner Point	1.2	0.9	1.1	1.1	1.08
	Pelican Banks	1.5	1.2	1.4	1.5	1.40
	Facing Island	1.3	1.2	1.4	1.4	1.33
	Mundoolin Rocks	1.3	1.4	na	1.3	1.33
	Rodds Harbour	1.4	na	1.4	1.2	1.33
Eastern curlew	Cattle Point	0.4	na	na	na	0.40
	Warner Point	na	na	0.4	0.6	0.50
	Pelican Banks	na	na	0.3	na	0.30
	Facing Island	na	na	0.4	na	0.40
	Mundoolin Rocks	0.6	0.5	0.4	0.7	0.55
	Rodds Harbour	0.6	0.4	0.5	0.5	0.50
Great knot	Cattle Point	2.1	2	2.3	1.5	1.98
	Warner Point	na	1.5	1.1	1.6	1.40
	Pelican Banks	1.6	1	1.2	1.1	1.23
	Facing Island	1.5	1.4	na	1.3	1.40
	Mundoolin Rocks	na	1.2	1.2	1.5	1.30
	Rodds Harbour	1.1	1.2	0.8	1.4	1.13
Grey-tailed tattler	Cattle Point	2.3	2.4	2	1.8	2.13
	Warner Point	2	1.8	2	2	1.95
	Pelican Banks	2	2.2	2.4	2.5	2.28
	Facing Island	2.3	2.4	2.3	2.6	2.40
	Mundoolin Rocks	2.3	2.5	2.6	2.4	2.45
	Rodds Harbour	2.4	2.3	2.4	2.1	2.30
Red knot	Cattle Point	2.3	2.4	1.9	na	2.20
	Warner Point	1.7	1.3	na	1.6	1.53
	Pelican Banks	na	1.2	1.2	1.3	1.23
	Facing Island	1.7	1.4	1.4	1.7	1.55
	Mundoolin Rocks	1.1	na	1.7	1.3	1.37
	Rodds Harbour	1.9	1.1	1.3	1.5	1.45
Terek sandpiper	Cattle Point	2.1	1.6	na	na	1.85
	Warner Point	1.3	na	1.4	1.5	1.40
	Pelican Banks	2	na	2.1	1.8	1.97
	Facing Island	2.6	2.8	na	1.9	2.43
	Mundoolin Rocks	na	na	2.6	1.7	2.15
	Rodds Harbour	na	2.6	2.7	1.9	2.40

Species	Site	HB1	HB2	HB3	HB4	Mean
Whimbrel	Cattle Point	0.6	0.3	0.7	0.4	0.50
	Warner Point	na	0.6	na	0.5	0.55
	Pelican Banks	0.5	na	0.7	0.5	0.57
	Facing Island	0.8	0.7	na	0.4	0.63
	Mundoolin Rocks	0.6	0.7	0.8	na	0.70
	Rodds Harbour	0.5	1	na	0.9	0.80

Taking functional responses and prey selection into account, the initial carrying capacity estimates that did not consider these seem to be overestimates. If we next consider that energy requirements may be considerably increased when birds are preparing for migration (i.e., four to five times BMR instead of two times BMR), there may not be too much margin left for more birds to occupy the area. Indeed, the density of food available to shorebirds based on our benthic samples was substantially lower than that found in many other tidal flats around the world (Piersma et al. 1993) such as Roebuck Bay in northwest Australia, Deep Bay in Hong Kong and the Frisian coast in the Netherlands (Figure 4.17). Birds need to forage longer or more effectively to obtain the same amount of energy in comparison with most tidal flats studied globally. Finally, the possibility that more food may be available than the current number of birds using the ERMP Survey Area does not justify further degradation of the intertidal wetlands. Indeed, it has been estimated that some shorebirds in Europe needed access to between 2 and 7.8 times more food than their physiological requirement (i.e., our requirement calculation) to maintain high survival rates during the non-breeding season, as a result of the various additional factors mentioned above (Stillman et al. 2016).

Careful monitoring of shorebird numbers seems crucial because significant collapse in benthic invertebrate numbers has been noted in several shorebird sites along the Flyway (e.g., Moreton bay and the Yalu Jiang coastal area) even without clear evidence of habitat area loss. In addition, the ERMP Survey Area also holds internationally important numbers of several species that are not in severe population decline, such as the grey-tailed tattler, *baueri* bar-tailed godwit, red-necked stint and Terek sandpiper (Studds et al. 2017). Therefore, for some species there is no clear argument that feeding areas will be under less pressure in the future because of declines in bird numbers driven from overseas. Additionally, areas such as the ERMP Survey Area, may be critical in the future if bird populations decline in other feeding areas in Australia through habitat loss, degradation or sea-level rise. The last is especially relevant because intertidal shorebird habitats in northeast Australia have a relatively lower estimated threat of loss through sea-level rise (50–200cm rise) than southeast Australia, Southeast Asia or New Zealand (Iwamura et al. 2013). The loss of feeding habitats has a negative impact on shorebirds not only because of the loss of feeding areas, but also a decrease in feeding time (CPSL 2001). Despite low prey densities compared with other regions globally, the ERMP Survey Area is able to sustain large populations of birds allowing for the possibility that birds will be able to forage here when these other areas are no longer sustainable. With links disappearing in the chain of wetlands on which migratory shorebirds rely, the demands on other links is also increasing in terms of quality of the site; birds may need to fuel up more because of the longer migratory legs between stopover sites.

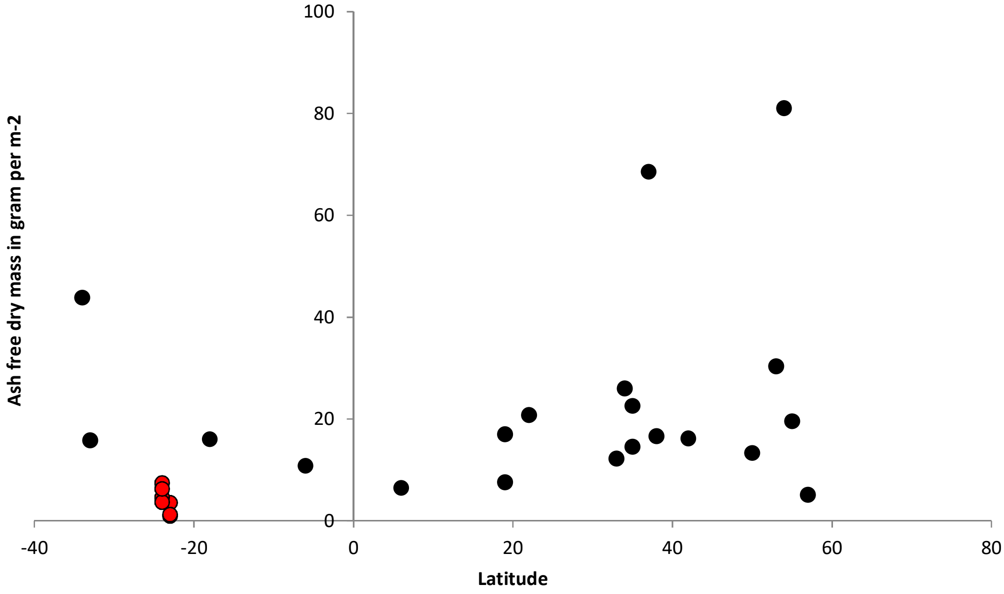


Figure 4.17 The biomass (ash free dry mass in grams per m^2) of intertidal benthic organisms in the ERMP Survey Area (in red) in comparison to those of similar studies around the world (in black; Piersma et al. 1993) as a function of latitude. Note that relatively few studies have been conducted in the southern hemisphere and in Australia (only one study from Roebuck Bay) before our study.

Much of the ERMP Survey Area is functioning at or near carrying capacity.

The density of food available to shorebirds in the ERMP Survey Area ranks among the lowest in the world.

High food density patches are often exposed for only a brief time by the tide.

The spatial variation in benthic invertebrate availability and the exposure time of the tidal flats have a clear effect on the abundance and composition of shorebirds.

4.4 Identify priority areas for management (Aim A4)

Based on roost site data available from surveys since 2011 (GHD 2011a, 2011b, 2011c, 2011d; Sandpiper Ecological Surveys 2012a, 2012b, 2012c; Wildlife Unlimited 2012, 2013, 2014, 2015, 2016), the Fitzroy Delta and North Curtis Island support the highest overall abundance of northern hemisphere-breeding shorebirds while the lowest was recorded in the Gladstone Harbour region (Table 4.10, Figure 4.18). All three subregions were used by all seven threatened migratory shorebird species listed on the EPBC Act and the two species on the IUCN Red List (BirdLife International 2016), albeit to different extents. Among the 18 species that used the survey area regularly (>10 individuals recorded since 2011), eight were most abundant in the Fitzroy Delta of which half are threatened species listed on the EPBC Act (curlew sandpiper, greater sand plover, lesser sand plover and red knot; Table 4.10). Of the remaining ten species five were most abundant on north Curtis Island and the five others in Rodds Peninsula. Three of the north Curtis Island species are threatened species listed on the EPBC Act (bar-tailed godwit, eastern curlew and great knot; Table 4.10). In terms of numerical presence of nationally threatened species, the Fitzroy Delta is the most important subregion, followed by north Curtis Island, supporting the highest overall abundance of migratory shorebirds and the highest abundance of those threatened species listed on the EPBC Act.

According to the results from the previous section, notably after considering site quality from a shorebird's perspective and a global comparison of infaunal biomass, it seems prudent to conclude that the area may be used to capacity or close to capacity. Priority areas are perhaps those supporting the highest shorebird abundances, such as the Fitzroy Delta, which seems to be an area warranting priority monitoring and management actions for shorebird conservation. Despite the relatively small area, the ERMP Survey Area supports about 5% of the eastern curlew and whimbrel flyway population (Table 5.8) and the north Curtis Island is the stronghold of these species, as well as bar-tailed godwit and great knot (Table 4.10). It is important that the high quality intertidal areas in the north Curtis Island are maintained to provide suitable habitats for migratory shorebirds.

On a more local scale, we have shown that high benthic biomass densities are often found at the lower tidal flats which are inaccessible for most of the time during neap tide cycle (Figure 4.15). The shorebirds would therefore need to forage in areas with lower benthic biomass density, which may limit their intake rate and result in an overall negative energy balance that can only be replenished in spring tides when the more profitable feeding grounds are exposed. Efforts to lower unnecessary human disturbance on nearshore tidal flats, especially during neap tide cycles, could potentially benefit the shorebirds.

Table 4.10 The highest number of birds recorded in different subregions based on all the high tide count data since 2011. The percentage of the highest count in a subregion relative to the total from the entire survey area is presented in parentheses. Abbreviations: NT = Near Threatened; VU = Vulnerable; EN = Endangered; CR = Critically Endangered.

Species	**EPBC Status**	**IUCN Status**	**Fitzroy Delta**	**North Curtis Island**	**Gladstone Harbour**	**Rodds Peninsula**
Asian dowitcher		NT	0 (0)	1 (100)	0 (0)	0 (0)
Bar-tailed godwit	VU (*L. l. baueri*)	NT	813 (18)	1,407 (31)	934 (21)	1,337 (30)
Black-tailed godwit		NT	1 (20)	2 (40)	0 (0)	2 (40)
Broad-billed sandpiper			369 (98)	7 (2)	1 (0)	1 (0)
Common greenshank			20 (18)	33 (30)	22 (20)	36 (32)
Common sandpiper			1 (20)	1 (20)	2 (40)	1 (20)
Curlew sandpiper	CR	NT	337 (74)	80 (18)	7 (2)	32 (7)
Eastern curlew	CR	EN	521 (22)	806 (34)	520 (22)	547 (23)
Great knot	CR	EN	707 (25)	979 (34)	264 (9)	892 (31)
Greater sand plover	VU		814 (44)	615 (33)	125 (7)	303 (16)
Grey plover			101 (36)	100 (35)	8 (3)	75 (26)
Grey-tailed tattler		NT	243 (17)	326 (23)	402 (29)	439 (31)
Latham's snipe			0 (0)	0 (0)	1 (50)	1 (50)
Lesser sand plover	EN		1,047 (41)	966 (38)	224 (9)	300 (12)
Little curlew			0 (0)	0 (0)	0 (0)	1 (100)
Marsh sandpiper			1 (10)	4 (40)	1 (10)	4 (40)
Pacific golden plover			51 (35)	31 (21)	9 (6)	56 (38)
Red knot	EN	NT	835 (84)	92 (9)	12 (1)	55 (6)
Red-necked stint		NT	6,013 (66)	1,497 (16)	513 (6)	1,085 (12)
Ruddy turnstone			1 (1)	11 (13)	12 (15)	58 (71)
Sanderling			0 (0)	72 (92)	0 (0)	6 (8)
Sharp-tailed sandpiper			355 (81)	34 (8)	42 (10)	9 (2)
Terek sandpiper			334 (24)	192 (14)	338 (24)	528 (38)
Wandering tattler			0 (0)	0 (0)	2 (67)	1 (33)
Whimbrel			283 (9)	1,842 (60)	484 (16)	469 (15)
Total			12,847	9,098	3,923	6,238

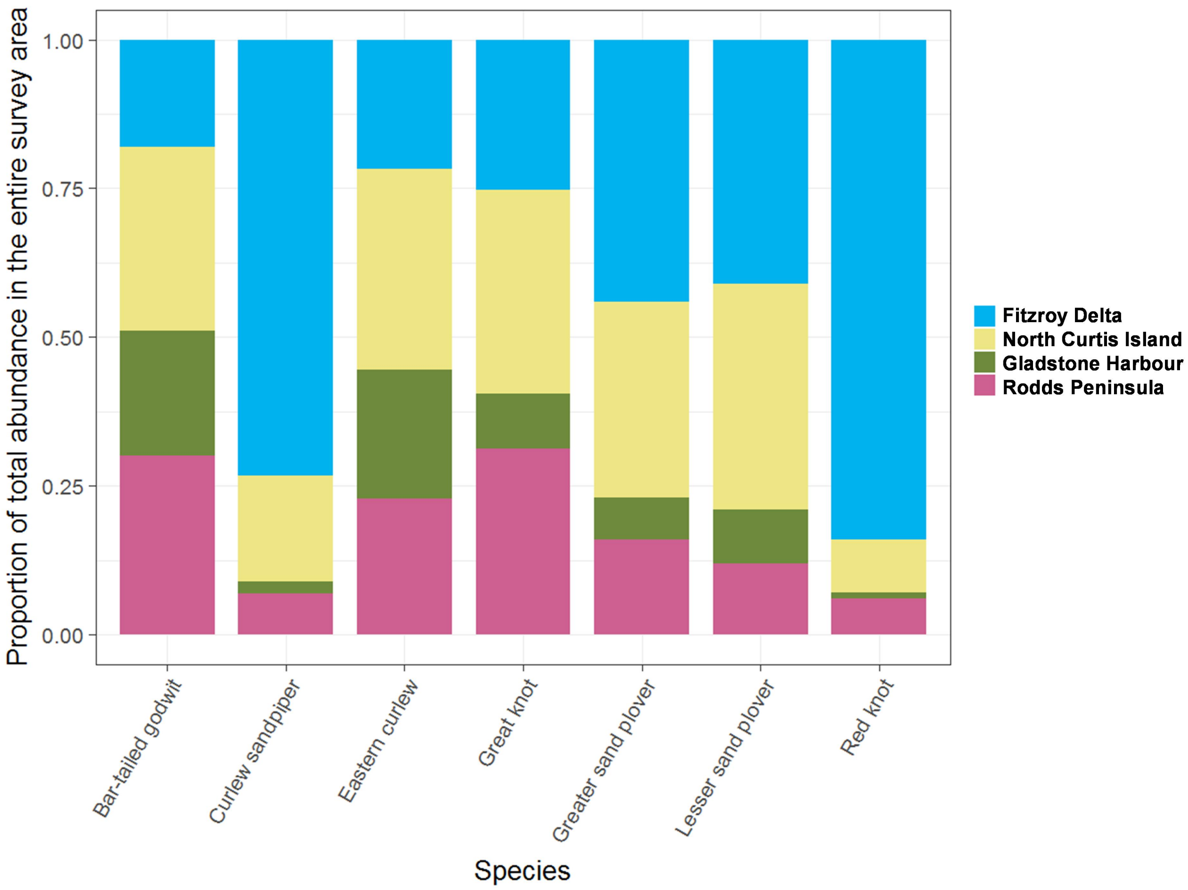


Figure 4.18 The relative abundance of threatened migratory shorebird species in the ERMP Survey Area based on the surveys conducted between 2011 and 2016.

The Fitzroy Delta and North Curtis Island support the highest overall abundance of northern hemisphere-breeding shorebirds, especially those threatened ones.

5. PART B: DETERMINE THE SIZE OF THE IMPACTED POPULATION

5.1 Describe the patterns of flow of birds into the study area, in relation to impact (Aim B1)

5.1.1. Summary

We conducted regular shorebird surveys at 13 high tide roosts and found that five species use the ERMP Survey Area primarily as a stopover site while on migration (northward for broad-billed sandpiper and ruddy turnstone; southward for red knot; both directions curlew sandpiper and sharp-tailed sandpiper). In contrast, eastern curlew, bar-tailed godwit, whimbrel, great knot, greater sand plover, grey plover and grey-tailed tattler primarily use the ERMP Survey Area as their non-breeding destination. Finally, three species appear to use the area as both a stopover site and non-breeding destination (lesser sand plover, red-necked stint and Terek sandpiper; Table 5.2). Analysis suggests that large-sized shorebird species tend to fly to their final nonbreeding grounds in Australia without stopping while smaller species are likely to make multiple stops prior to their final destination. We also found evidence that the same pattern occurs during the northward migration. Finally, we estimate that this high degree of movement of birds through the area prior to their final destination leads to the annual February survey missing up to 44% of migratory shorebirds using the ERMP Survey Area. The additional surveys during the northward and southward period conditioned during Years 1, 2, 9 and 10 of the ERMP are crucial in this regard.

5.1.2. Introduction

The ERMP Survey Area poses a logistically challenging environment for shorebird monitoring. Despite the fairly well-documented roost site distribution, many of these sites are remote (Figure 5.1), with the majority of them only accessible by boat. Despite the survey effort since 2011 as part of a conditioned requirement, the available shorebird count data from the ERMP Survey Area are inadequate for understanding the migratory movement (passage dates) or estimating the number of birds that are using the area on migration and during over-summering, because of (i) inadequate count coverage during the migration period, which varies by species (Figure A4), and (ii) underestimation of the number of birds using the area if some individuals in the population stop briefly and then leave the region before all the non-breeding birds arrive.

The first problem is illustrated by our observations in the first field season of at least 140 red knots in mid-October 2014 and 382 broad-billed sandpipers in late March 2015. Both records exceeded by a large margin the highest previous count in the ERMP Survey Area (previous counts were 86 and 32, respectively), even though we only surveyed 19 out of the possible

151 high tide roosts (Wildlife Unlimited 2015). A method for understanding the pattern of flow of birds was therefore needed to determine the total number of birds using the ERMP Survey Area.

We developed a novel approach to estimating the numbers of birds using the area by modelling the arrival and departure of migratory shorebirds along areas of eastern Australia for which there are sufficient data (Choi et al. 2016b), and have applied these models to count data collected from the ERMP Survey Area. The most relevant finding was an apparent tendency for small-sized shorebird species, such as curlew sandpiper, sharp-tailed sandpiper, red knot and red-necked stint to make several short hops from northern Australia to southeast Australia. We found that red knots had a short passage duration in the east coast of Australia (18 September to 10 October), which could be easily missed even if counts are conducted monthly (Choi et al. 2016b). With the results of this work in mind, we recorded 850 red knots in the ERMP Survey Area in the second field season (28 September 2016), nearly five times more than the previous highest count (30 August 2016), and sufficient for the ERMP Survey Area to qualify as a nationally important site for this nationally threatened species (Bamford et al. 2008). Moreover, we recorded at least three orange-flagged red knots, four white-flagged red knots and three orange-flagged curlew sandpipers (Table A10). These individuals were banded in Victoria and New Zealand, providing direct evidence that birds are using the ERMP Survey Area as migratory stopover.

In this section, we use count data from the ERMP Survey Area to describe the flow of birds into the survey area using the modelling approach that we developed (Choi et al. 2016b).

5.1.3. Methods

Survey methods

We used data from previous complete surveys in the ERMP Survey Area, in which most if not all of the high tide roosts were surveyed. Observers counted the number of shorebirds at 150+ high tide roosts, although some of which could be redundant and used by the same flock of birds at different stages of the tide. These roosts were identified from an extensive review of published materials and available records, and further refined in previous surveys (GHD 2011a; Wildlife Unlimited 2016). Coordinates of the sample sites and survey methods were detailed in the published reports (GHD 2011a, 2011b, 2011c, 2011d; Sandpiper Ecological Surveys 2012a, 2012b, 2012c; Wildlife Unlimited 2012, 2013, 2014, 2015, 2016, 2017).

We conducted a series of targeted surveys, selecting 13 of the 150+ high tide roosts for more regular survey. These roosts held a mean of 40% of the total number of shorebirds counted in the entire ERMP Survey Area, based on previous complete surveys (Driscoll 2013; Figure 5.1). Double-counting or failure to detect birds were minimised by surveying roosts at consistent times relative to high tide (± 2 hours) and by minimising the time between counts in adjacent roosts (synchronised when possible). We also recorded the age proportion data for some species and scanned for birds with leg flags on an opportunistic basis. Our targeted surveys typically took four to six days to complete (Table 5.1).

Ages of birds were recorded by careful observation through telescopes when we managed to approach birds closely enough. Relatively fresh primaries early in the non-breeding season and retention of juvenile coverts and tertials until the middle or late in the season allow first-year immatures to be distinguished from older birds in some species such as bar-tailed godwit (Hayman et al. 1986; Rogers et al. 2005). A number of different sites were visited to obtain age proportion data and both the number of adults and first-year immatures were recorded during the scan. The flocks of birds were usually so small that subsampling was unnecessary.

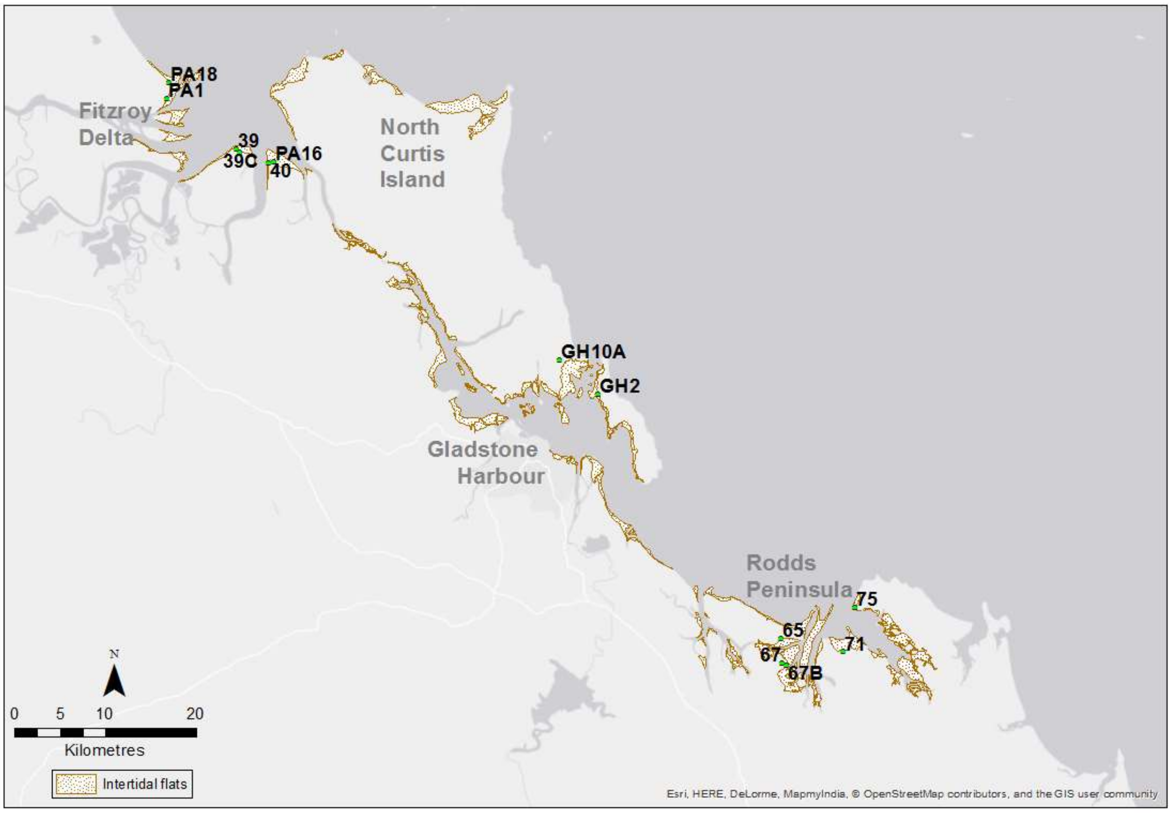


Figure 5.1 The 13 high tide roosts regularly surveyed in this project.

Table 5.1 Detailed information for the survey data used in this report.

Survey number	**Date range**	**Duration (days)**	**Number of sites surveyed with birds present**	**Observer**
1	2011 Jan 24–31	8	98	GHD
2	2011 Feb 16–21	6	110	GHD
3	2011 Mar 21–26	6	100	GHD
4	2011 Aug 14–18	5	125	GHD
5	2012 Jan 25–29	5	107	Sandpiper Ecological Surveys
6	2012 Feb 5–10	6	131	Sandpiper Ecological Surveys
7	2012 Mar 20–25	6	133	Sandpiper Ecological Surveys
8	2012 Aug 2–6	5	130	Wildlife Unlimited
9	2012 Sep 29 – Oct 3	5	130	Sandpiper Ecological Surveys
10	2013 Feb 10–14	5	131	Wildlife Unlimited
11	2013 Oct 5–9	5	108	Wildlife Unlimited
12	2014 Feb 14–18	5	141	Wildlife Unlimited
13	2014 Oct 7–12	5	19	UniQuest
14	2014 Dec 3–9	5	13	UniQuest
15	2015 Feb 4–8	5	134	Wildlife Unlimited
16	2015 Mar 3–4	2	9	UniQuest
17	2015 Mar 17–23	5	20	UniQuest
18	2015 Apr 15–18	4	13	UniQuest
19	2015 Aug 29 – Sep 1	4	13	UniQuest
20	2015 Sep 28 – Oct 1	4	13	UniQuest
21	2015 Dec 10–16	5	13	UniQuest
22	2016 Jan 9–16	5	10	UniQuest
23	2016 Feb 8–12	5	157	Wildlife Unlimited

Data selection and analysis

Data from the complete surveys were obtained from Gladstone Ports Corporation (GPC). This dataset included surveys conducted from January 2011 to February 2016. Data from the targeted surveys were collected as part of our current monitoring project from October 2014 to January 2016 (Table 5.1). To generate a modelled estimate of the passage dates and the number of birds using Thompson's modelling approach (Thompson 1993), we first aggregated count data from several separate migration seasons (Table 5.1) to calculate mean passage dates over several years. This was necessary as the data collected in a single year were usually too sparse for our models to fit. Only comparable count data were used (surveys that included all the 13 roosts we regularly counted). We then examined the count data with scatter plots to determine the most appropriate model to use, depending mostly on whether the species was making a stopover or spending the entire non-breeding season at the shorebird site.

All models were calibrated using the non-linear modelling procedure in SYSTAT 12 (Systat Software Inc 2007) with a least-squares loss function and more importance was given to higher counts. Before analysis, calendar days were transformed into the number of days since 1 June, assigning multi-day surveys their mean date for analyses. Starting values of the parameters to be estimated are needed for the calibrations and these values were estimated from the count data.

A range of starting values was then used to check how robust our estimates were and only robust results were presented. The quality of the estimate was evaluated based on R-square values, the asymptotic standard error and the test statistic of the parameter estimates. Occasionally, the models did not converge or the parameter estimates were not significantly different from zero, implying a poor fit of the model to the data. To overcome such problems in any species, we (i) excluded survey data conducted before the start of fieldwork for this project (October 2014), (ii) analysed the data by subregion (4 subregions) as well as all the surveyed sites as a whole (13 sites), (iii) fixed the count estimates as the peak counts before generating the passage date estimates (hard-wired approach), or (iv) excluded outliers if needed.

If the model still did not converge or the parameter estimates remained non-significantly different from zero, then the results were not presented. In cases where birds arrived and left the shorebird site within the study period, we calibrated the following model (Choi et al. 2015a):

$$Count_{j,day} = \sum_{j=1}^{\infty} (a_j n_j) * \left(ZCF(day, m1, s1) - ZCF(day, m2, s2)\right) \qquad \text{Equation 1}$$

where j is the year index: *1* for year 1, *2* for year 2, *3* for year 3 etc.,

$Count_{j,day}$ is the observed number of birds present on the indicated day in year j,

a_j is a dummy variable set to *1* for observations in year j, and *0* otherwise,

n_j is the estimated size of the transiting population in year j,

$m1$, $s1$ are the estimated mean and standard deviation of arrival dates,

$m2$, $s2$ are the estimated mean and standard deviation of departure dates, *ZCF(day,m,s)* is the cumulative normal distribution for a mean of *m* and a standard deviation of *s*.

On three occasions, namely for northward passage period of curlew sandpiper and both passage periods in sharp-tailed sandpiper, the passage dates were calculated as the mean between two counts due to the insufficient repeated count data available on these species.

5.1.4. Results and Discussion

The available dataset from targeted surveys conducted on the 13 sites in the ERMP Survey Area indicated that broad-billed sandpiper (northward), curlew sandpiper (both), red knot (southward), ruddy turnstone (northward) and sharp-tailed sandpiper (both) used the ERMP Survey Area mainly as a stopover. In contrast, eastern curlew, bar-tailed godwit, whimbrel, great knot, greater sand plover, grey plover and grey-tailed tattler mostly use the survey area as their final non-breeding ground. Lesser sand plover, red-necked stint and Terek sandpiper seem to have a mix of passage and wintering individuals in the survey area (Figure A4, Figure 5.2).

Thompsons' model allows passage dates to be estimated from repeated counts (Choi et al. 2015a; Choi et al. 2016b; Rogers et al. 2010; Thompson 1993). This approach yielded passage date estimates that generally agree with the results based on the same approach but using data collected from other sites along the east coast of Queensland (Table S1 in Choi et al. 2016b). The standard Thompson's modelling approach converged in 9 out of 18 cases and generated reasonable estimates. However, the model did not converge in six cases, and the number of birds in the non-breeding season needed to be fixed using the peak count, to enable the model to converge. In three cases where the number of counts was insufficient for modelling, we estimated the passage dates based on the mean between the first and last detection date (Table 5.2). The standard model typically converged in species that used the survey area as the final non-breeding ground, but often performed less robustly in species that were transiting or had a mix of transiting and non-breeding populations. The latter was particularly apparent in the early estimated departure dates for red-necked stint, Terek sandpiper and lesser sand plover. Care, then, is needed when using the passage date estimates in species with transiting populations in the ERMP Survey Area. The passage date estimates generated were then used to estimate the number of days that different shorebird species spend in the ERMP Survey Area — an important variable used in the carrying capacity estimates above.

These results are consistent with our earlier findings that southward migration strategies differ between species and that body size might play an important role in the migration strategy used by shorebirds. In larger species, adults are likely to fly from staging sites in the northern Yellow Sea to final nonbreeding destinations in Australia without stopping or with very brief stops. In contrast, smaller species are likely to make multiple stops in between (Choi et al. 2016b). Our results indicate that the same pattern also occurred during northward migration, with the presence of broad-billed sandpiper, ruddy turnstone, and the resurgence of curlew sandpiper and sharp-tailed sandpiper during northward migration (Figure 5.3). It seems that large shorebird species in this Flyway depend on a small number of staging sites whereas small species make a series of stops on their way south and therefore need a series of wetlands to complete their migrations. It should be noted that there was an observable drop in the number of grey-tailed tattler in November and December and an increase after February for both years. The latter was consistent with the finding that some tattlers tend to make multiple stops during both southward and northward migrations, before arriving at or after leaving the non-breeding grounds (QWSG 2014).

We combined our estimates of passage dates with the highest record of each species from October 2014 to February 2016, to model the number of birds that were present in the ERMP Survey Area each day during the non-breeding season. This allowed us to further investigate what species and how many birds could have been missed with the current annual February count. Using the count data from the 13 roosts, we found that up to 44% of migratory shorebirds could be missed in an annual February count (Figure 5.3). Species with small body size that tend to stop more regularly during migration (Choi et al. 2016b) are missed substantially, as only 10% of sharp-tailed sandpiper, 14% of curlew sandpiper, 20% of red-necked stint, 22% of broad-billed sandpiper and 32% of ruddy turnstone are present during February count. Overall, we estimate that the annual February count missed 1,073 and 6,391 migratory shorebirds in 2015 and 2016, respectively, by comparing the results from the complete annual February surveys with our regular targeted surveys without extrapolation or using any the modelled estimates.

An additional survey during southward migration at the beginning of October might be useful, especially in the Fitzroy Delta, where the majority of small-sized species are found (except ruddy turnstone; Choi et al. 2015b). It is worth noting that there is land access to the Cattle Point site which is an important roost in the Fitzroy Delta, and local birdwatchers have conducted surveys there in the past. Collaboration with local birdwatchers could improve temporal coverage of the shorebird monitoring programme at relatively low additional cost.

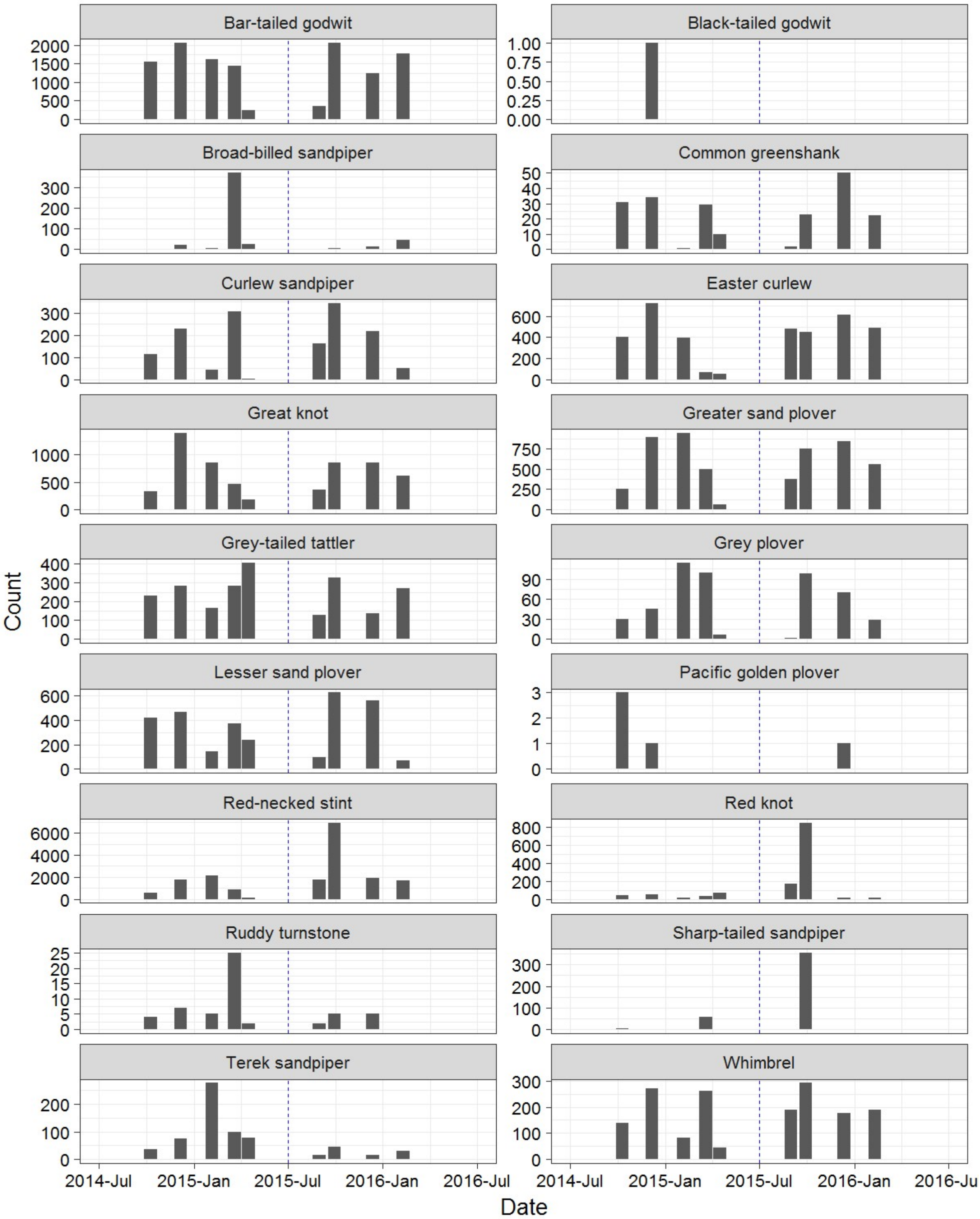


Figure 5.2 Total numbers of shorebirds recorded in the 13 targeted survey sites between October 2014 and February 2016.

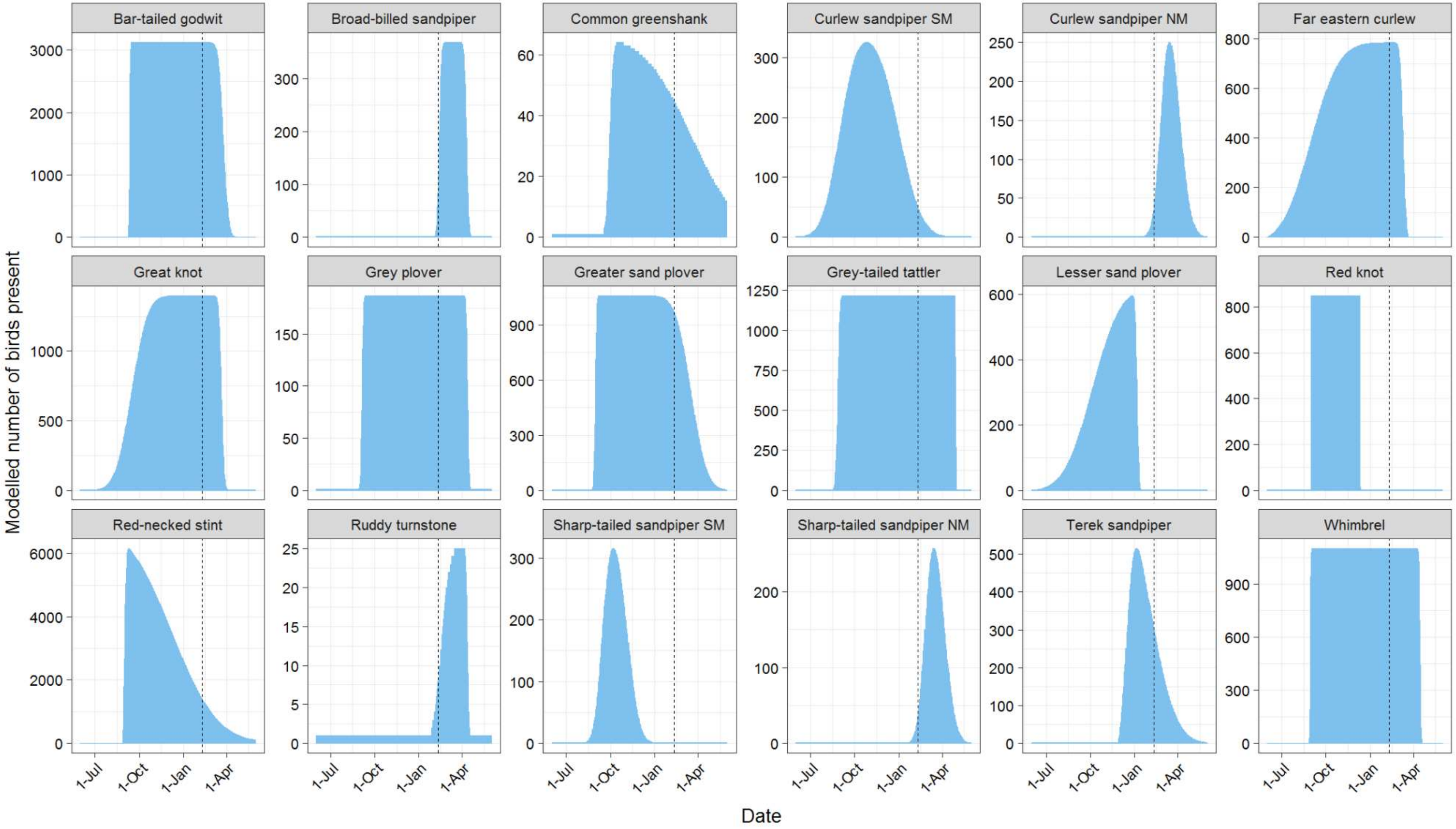


Figure 5.3 The modelled number of birds present during non-breeding season. Abbreviations: SM = southward migration, NM = northward migration. The vertical dotted lines correspond to 10 February, approximating the date when annual shorebird monitoring is conducted. When the peak of bird numbers does not overlap the dotted line, substantial numbers of birds could be missed by a single summer count.

Table 5.2 Passage day estimates based on shorebird survey data from the ERMP Survey Area from October 2014 to February 2016 (except for grey plover in which all six years count data were used). Standard approach refers to the Thompson's modelling approach; hard-wired approach refers to the Thompson's modelling approach with the population (n) fixed at the peak count number; subjective judgement refers to the use of the mean between first and final detection date as the passage date. Abbreviations: BAGO = bar-tailed godwit, BBSA = broad-billed sandpiper, COGR = common greenshank, CUSA = curlew sandpiper, FECU = eastern curlew, GRKN = great knot, GRPL = grey plover, GSPL = greater sand plover, GTTA = grey-tailed tattler, LSPL = lesser sand plover, REKN = red knot, RNST = red-necked stint, RUTU = ruddy turnstone, STSA = sharp-tailed sandpiper, TESA = Terek sandpiper, WHIM = whimbrel, NM = northward migration, SM = southward migration, Mix = mix of stopover and stay for entire summer.

Species	**Estimated mean arrival date ± S.D**	**Estimated mean departure date ± S.D**	**Length of stay (days)**	**Mean corrected R^2**	**R^2 (Observed vs Predicted)**	**Data source**	**Approach**	**Resident status**
BAGO	12-Sep ± 1.2	25-Mar ± 8.2	194	0.647	0.649	Pelican Banks	Standard	Stay for summer
BBSA	13-Feb ±3.6	10-Apr ± 3.9	56	0.994	0.996	All 13 sites; NM	Hard-wired	Stopover NM
COGR	29-Sep ± 6.4	18-Mar ± 79	170	0.771	0.783	All 13 sites	Hard-wired	
CUSA	31-Aug ± 28.4	2-Jan ± 36.8	160	0.773	0.774	All 13 sites; SM	Hard-wired	Stopover NM, SM
	27-Feb	3-Apr		na	na	All 13 sites; NM	Subjective judgement	
FECU	31-Aug ± 46.7	11-Mar ± 5.4	193	0.804	0.805	Pelican Banks	Standard	Stay for summer
GRKN	16-Sep ± 26.5	22-Mar ± 4.6	188	0.629	0.629	Pelican Banks	Standard	Stay for summer
GRPL	1-Oct ± 2.4	15-Mar ± 2.6	220	0.472	0.472	All 13 sites	Standard	Stay for summer
GSPL	31-Aug ± 2.3	18-Mar ± 25.8	199	0.94	0.941	All 13 sites	Standard	Stay for summer
GTTA	27-Aug ± 3.3	29-Apr ± 0. 8	246	0.226	0.226	Pelican Banks	Standard	Stay for summer
LSPL	6-Oct ± 46.1	7-Jan ± 3.4	92	0.254	0.423	Rodds Harbour	Hard-wired	Mix
REKN	31-Aug ± 0.02	11-Dec ± 0.3	102	0.937	0.959	All 13 sites; SM	Standard	Stopover SM
RNST	1-Sep ± 3	8-Dec ± 74.2	98	0.724	0.741	All 13 sites	Hard-wired	Mix
RUTU	17-Feb ± 13.6	12-Apr ± 2.8	55	0.723	0.873	All 13 sites; NM	Hard-wired	Stopover NM
STSA	15-Sep	5-Nov	87	na	na	All 13 sites; SM	Subjective judgement	Stopover NM, SM
	27-Feb	3-Apr		na	na	All 13 sites; NM	Subjective judgement	
TESA	16-Dec ± 12.4	29-Jan ± 43.5	44	0.848	0.856	Pelican Banks	Standard	Mix
WHIM	30-Aug ± 1	15-Apr ± 1.8	229	0.585	0.585	All 13 sites	Standard	Stay for summer

Some migratory shorebird species use the Survey Area as their non-breeding destination while others use it as a migratory stopover site.

Because of the high rate of bird movement through the area, the annual February survey underestimates the number of migratory shorebirds using the ERMP Survey Area by up to 44%.

5.2 Discover how birds move around the study area (Aim B2)

5.2.1. Summary

We radio tracked 35 birds of four species using hand-held, aircraft-borne and automated receiver systems, and supplemented this with 319 re-sightings of 86 birds marked locally by us, and 61 birds marked elsewhere. We observed marked birds from other states in Australia, as well as Alaska, Russia, Japan, China, and New Zealand. Combined results from these individually-marked birds indicated that:

(i) Birds typically stay within a small area both within and between non-breeding seasons;

(ii) Marked birds made regular (daily) local commuting flights of up to 10km between alternative feeding and roosting locations, strongly associated with tidal patterns. Shorebirds foraged by day and night, and some individuals roosted in different locations by day and by night;

(iii) Exploratory movements between regions of the ERMP Survey Area were rare; if they do occur, they were too infrequent to be detected; and.

(iv) There were migratory transitions through the ERMP Survey Area, consistent with the analysis of count data presented in Section 5.1.

5.2.2. Background to bird movement study

Shorebird movements occur on a variety of spatial scales, complicating management for their conservation. On the basis of our previous studies, supplemented by our recent field experiences in the study area, shorebird movements appeared prior to the radio-tracking exercise to be divisible into three categories, each with a different function. Categories have not been formally described previously, but we suspect they may be broadly applicable to coastal shorebirds, and indeed they were borne out by the results of the radio-tracking work. We refer to them as:

- ‘commuting’ (see Section 5.2.3 below). The minimal local movements made by shorebirds when they have established foraging areas;
- ‘exploratory’ (see Section 5.2.4 below). Non-migratory movements to locate locally rich foraging areas in dynamic coastal habitats; or
- ‘migratory’ (see Section 5.1). Stopovers to rest and refuel in the course of ongoing migration to breeding or non-breeding grounds.

The varied scale of these movements, ranging from <10km (commuting movements) to thousands of kilometres (migration) poses challenges for shorebird biologists. The ideal tool for their study would be GPS tags that log precise spatial position regularly and transmit the data to biologists via satellite. While it is likely that such tools will be developed in the relatively near future, prototypes at present remain too heavy to be carried by most shorebird species, and too risky for this study. As this approach is not yet feasible on shorebirds, we assessed the movement scales of the shorebirds of the ERMP Survey Area using a combination of automatic radio-telemetry to inform on local movements, supplemented by handheld radio-tracking on the ground and from a light aircraft, combined with re-sightings of individually marked birds made by searching for marked birds whenever shorebirds were under observation.

5.2.3. Methods for measuring commuting movements

Commuting flights comprise movements made by shorebirds between high tide roosts and low tide foraging areas on a daily basis, and also the suite of movements made over two-week periods, as movement routines often vary over a tide cycle. During neap periods, tidal flat exposure is restricted when the tide is low; during spring periods, tidal flat exposure is much greater when the tide is low, but this may be offset by more restricted availability of roost sites when the tide is high (Rogers et al. 2006a; Rogers et al. 2006c). Moreover, movements can differ between day and night; several previous studies have reported shorebirds selecting different roost sites at night (Rogers et al. 2006a), apparent reasons including nocturnal exploitation of dry roosts that have an inhospitably warm microclimate by day, and the reduction of risk of depredation at night when approaching predators are more difficult to detect. On the other hand, many shorebirds have been recorded to forage at night time (McNeil et al. 1992), including red-necked stints, sharp-tailed sandpipers and curlew sandpipers in Australia (Dann 1981). There have also been studies demonstrating differences in foraging site by night and by day (Sitters et al. 2001), including cases where foraging site choice of shorebirds was influenced by the presence of artificial lighting (Dwyer et al. 2013).

In tidal systems where there are two low and two high tides per day, shorebirds make four commuting flights every 24 hours. The energetic costs of commuting can therefore be considerable in regions where foraging sites are far from suitable roosts; regular commuting flights of up to 30km (i.e., 120km per day) have been observed in some studies (e.g., Rogers et al. 2006a; Sanzenbacher & Haig 2002). In the ERMP Survey Area, where roosts are relatively numerous and widespread, opportunistic behavioural observations made during the first season of fieldwork suggested commuting flights would range from about 1–10km.

The main tool we used to document commuting was radio-telemetry. We captured 57 shorebirds by cannon-netting and mist-netting on Facing Island and Pelican Banks (Near GH2 and GH10A in Figure 5.1) between 29 October and 13 November 2015 (The University of Queensland Animal Ethics approval #AE04108). We attached light VHF radio-transmitters to 16 grey-tailed tattlers, three Terek sandpipers (1.3g, model tailmount PIP41 tag, Biotrack Ltd, Dorset, UK) and heavier VHF radio-transmitters to eight eastern curlews and eight bar-tailed godwits (3.1g, model VIG115A tag, Sirtrack, Australia). Transmitters were superglued to the trimmed rump feathers of the birds, and all tagged birds were checked carefully to ensure the transmitters did not impair wing flap before release (Figure 5.4). The tattlers, Terek sandpipers and godwits were caught using a cannon net at the Facing Island roost, while the eastern curlews were caught using mist nets near the Curtis Island claypan roost (Figure 5.6). Capturing the birds required for radio-tracking proved to be extremely difficult, and as the planned capture period had to be extended, a planned week of intensive, systematic manual tracking had to be abandoned. Their local movements were then documented with an array (Figure 5.6) of automatic radio-receivers (Figure 5.5) when the birds occurred within the detection range of an automatic receiver (~0.5–3km in open habitats, depending largely on the elevation of the receiving antenna). Data from the automatic radio-receivers were supplemented by handheld radio-telemetry and behavioural observations to build a picture of local movement routines according to tide, weather and time of day. The information on movement range helped us to determine whether we should treat adjacent intertidal flats, the benthic organisms and shorebirds within them, as a single unit or multiple units, thus supporting the carrying capacity component of this study.

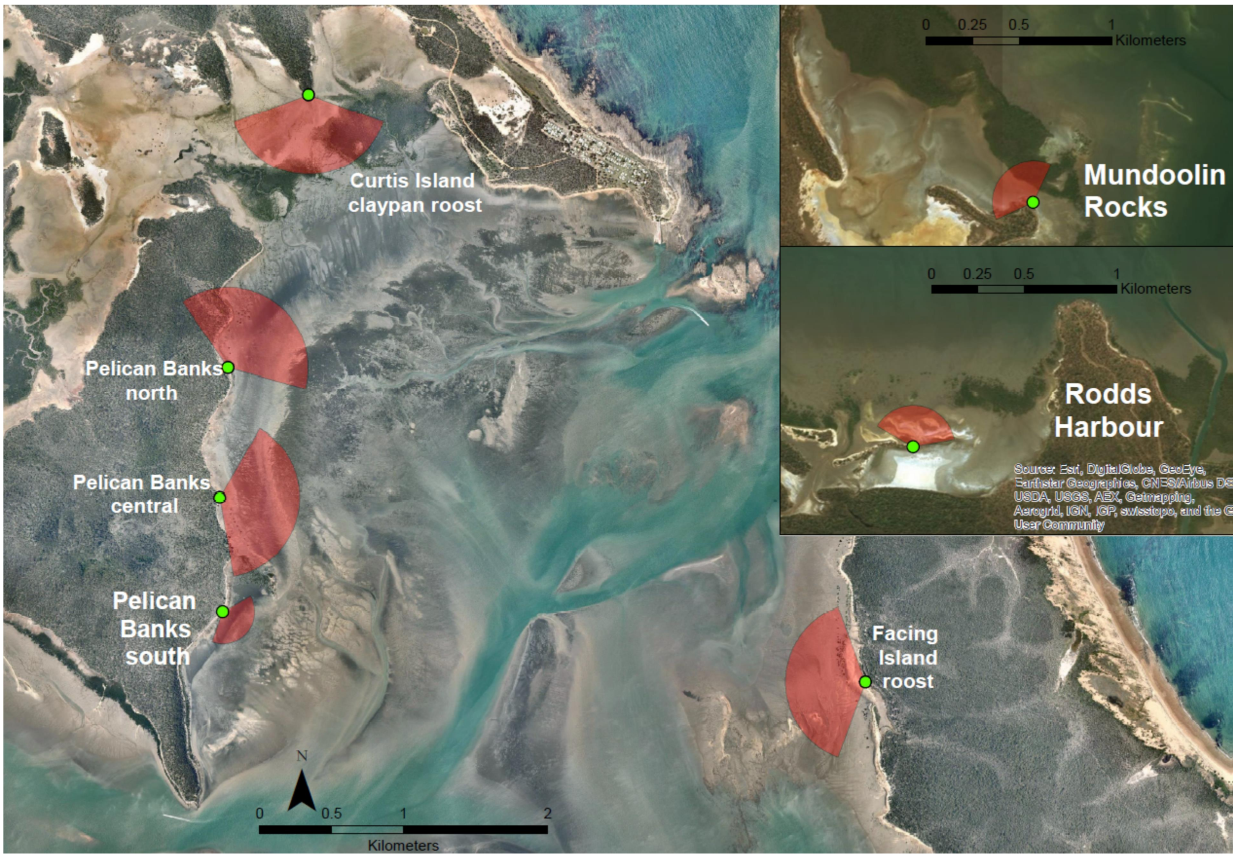
We deployed an array of five automatic receivers in the Port Curtis region between October and early November 2015, coinciding with our bird catching. These receivers were deployed at both roosts and key foraging areas in the area around Pelican Banks, southern Curtis Island and Facing Island, where we made our bird catches (Figure 5.6). We attached more than one antenna to all receivers: an omnidirectional antenna that detects birds at relatively short range, and a larger, 6-element Yagi antenna that detects birds at longer range, but only in a limited bearing.

In this study, we used ‘pip’ transmitters, also known as ‘bleepers’ (Figure 5.4). The head of the transmitter contains a battery and electronics, attached to a long thin antenna which emits a single ‘beep’ on a unique frequency at regular intervals. The strength of the pulse is limited by battery size, so on small birds the detection range is a few kilometres at most. The transmitters used in this study sent out signals in the 150MHz range, and each transmitter used in the study had an individual frequency that differed from the other transmitters by at least 0.015MHz.

Figure 5.4 Radio-tagged grey-tailed tattler just being released; the transmitter is concealed by the dorsal plumage, but the antenna can be seen projecting beyond the tail.

'Pip' transmitters have many advantages in radio-tracking studies, being light, affordable, and well-suited to manual tracking as well as studies with automatic receivers. However, they have the disadvantage that the 'beep' they emit is not a unique signal; despite the existence of dedicated frequency channels in Australia for wildlife radio-telemetry studies (the 150MHz range was used in this study), the signals can be confused with other sources of radio-waves. These include background noise, and there can be occasional bursts of electromagnetic radiation (caused by e.g., nearby motors, electrical storms, fluctuations in power supply) that can mimic the signals made by radio-transmitters and hence be recorded by the data-loggers. In practice these false records can be numerous. Distinguishing true from false signals is straightforward when using handheld radio-receivers, as the observer can listen to the signals in real time. However, automatic receivers log any radio-waves recorded in the specified frequency range and careful analysis to distinguish real from false records is always an important part of automatic radio-telemetry studies.

Figure 5.5 Example of an automatic radio-tracking station on Curtis Island, set on an elevated position (to increase detection range) overlooking Pelican Banks.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the G User Community

Figure 5.6 Location of automatic receiver stations and their minimum detection ranges (200–500m) in the Gladstone Harbour region and Rodds Peninsula (inserted). The Curtis Island claypan roost, Facing Island roost, Mundoolin Rocks, Rodds Harbour were located next to high tide roosts to monitor the roosting sites while the rest were located near the lower intertidal flat to monitor the foraging areas.

To distinguish true from false signals, we set up our automatic array with a scan cycle of six seconds per individual frequency, so that we could record several 'beeps' from a bird if it was present, and analyse the pulse interval to check that it had attributes consistent with the radio-tag. Signals were considered acceptable if pulse duration was within the range of 42–48 beeps per minute (BMP) for grey-tailed tattlers and Terek sandpipers, and 27–33 BPM for bar-tailed godwit and eastern curlew. A data file using only this filtering step was retained so that we could check for any evidence of brief flyovers of strategic points, but except where stated, we used a more refined data file in which records were only retained if (i) signals were received at least three times during each six-second scan (i.e., two measurements of pulse interval were available), and (ii) consecutive pulse intervals varied by less than 20 milliseconds (about 0.7 BPM).

We scanned for ten dummy frequencies during the study (transmitters that were not deployed on birds) and analysis of these frequencies revealed high levels of local radio-interference in the Gladstone area, presumably because of the abundance of local industry and shipping. In total our receiver array received 4,446 false signals from the dummy frequencies. Of these signals, 4,114 could be identified as false using the criteria outlined above: 332 of the false signals (i.e., 32 per transmitter) slipped through the filters. This was considered unacceptable, and we introduced an additional filtering step: signals were only treated as 'true' if they were recorded on two or more consecutive scan cycles. This final step was sufficient to filter out nearly all remaining false signals from the dummy transmitters, with a noteworthy exception discussed later in this section.

We used the final filtering step with some reluctance, because in addition to deleting many false records it probably also deleted some true records. Each scan cycle lasted five minutes, comprising consecutive six-second scans for 50 different frequencies. Birds would be expected to be present and recorded from one five-minute interval to the next if they were roosting or foraging in one spot. However, radio-tagged birds would have been excluded from the analysis if they were only briefly within range of the receiver (e.g., because they were flying past, or because they were near the limit of its range, or because other birds moved between them and the receiver). Our approach to filtering was therefore conservative, a necessity imposed by high levels of radio-interference in the study area.

5.2.4. Methods for measuring exploratory movements

Foraging patches in coastal regions are often impermanent, not least because shorebird predation can cause local depletion of prey abundance. In addition, some prey resources are naturally temporary: for example, immature bivalves favoured by red knots can occur in high local densities after a spat fall, but once the bivalves grow to full size they become too large for knots to swallow. Shorebirds appear to be remarkably skilled at locating new sites where prey are abundant, suggesting that they must explore to sample different areas and find patches with high prey abundance. Relatively little is known about these exploratory flights, in part because they are likely to be medium-length movements, too lengthy for ready detection in brief radio-tracking studies, but not long enough for confident identification in satellite-telemetry studies in which the geographical precision of fixes is often rather coarse. There is some evidence that the range covered in shorebird explorations varies among species (Rehfisch et al. 1996; Rehfisch et al. 2003) and even among individuals (Bijleveld et al. 2014).

In the ERMP Survey Area we increased our probability of detecting exploratory flights by conducting opportunistic handheld tracking, aircraft-borne tracking (Figure 5.7) and re-sightings of individually marked birds, through which we could detect these infrequent exploratory flights. A Cessna 182 aircraft was used with the 3-element Yagi antenna attached under a wing of the aircraft during the aerial survey (Figure 5.7). We flew between 1,500 and 2,000ft high at a speed of about 120 knots, covering most of the roosts in Figure 3.2 and additional loops were made at key roosts (Figure 5.1) to scan through all the possible frequencies. We also set up additional automatic receiver stations in the Rodds Peninsula subregion, 40km southeast from the birds' capture site, to detect exploratory flights (Figure 5.6). This combination of survey methods is arguably the best approach given our limited resources as automatic receiver stations allow continuous scans within a confined area while field observations, opportunistic handheld tracking and aircraft-borne tracking provide additional opportunities to detect exploratory flights in a larger spatial scale.

Figure 5.7 Aerial tracking over the exposed intertidal flat in the Rodds Peninsula subregion. The 3-element Yagi antenna was attached under the wing of the aircraft to improve the reception of radio signal.

5.2.5. Results

In the first field season (2014–2015), 45 shorebirds were captured in the Rodds Peninsula subregion at Mundoolin Rocks; 31 of these were marked with an engraved flag. In the second field season (2015–2016), 56 shorebirds were captured and flagged with engraved flags in the Gladstone Harbour subregion on the Facing Island and South Curtis Island. The five automatic receiver stations in the Gladstone Harbour subregion were deployed for a mean of 72 ± 14 days while the two, which were further south in the Rodds Peninsula subregion, were deployed for 26 ± 2 days (Table 5.3). However, actual scanning durations were shorter than this at several stations because of power failures; exact time of battery failure could not be defined, but plots showing all records (including false records) from each station indicate the periods when scanning was effective (Figure 5.8). Around 19,000 records of radio-tagged individuals were logged in total between November and February. Two aerial surveys of the entire ERMP Survey Area (22 November 2015, 27 December 2015) and 21 opportunistic manual handheld tracking sessions were also conducted.

Table 5.3 Summary of the seven automatic receiver stations set up in the ERMP Survey Area.

Station name	Location	Tidal stage targeted	Scanning effort (days)	Number of unfiltered records
RS01	South Curtis Island	High tide roost	76	130
RS02	Facing Island	High tide roost	82	14084
RS08	South Curtis Island	Low tide foraging area	73	2857
NEW1	South Curtis Island	Low tide foraging area	81	58
NEW4	South Curtis Island	Low tide foraging area	47	339
RS21	Mundoolin Rocks	High tide roost	27	27
RS22	Rodds Harbour (Middle Head)	High tide roost	24	1474

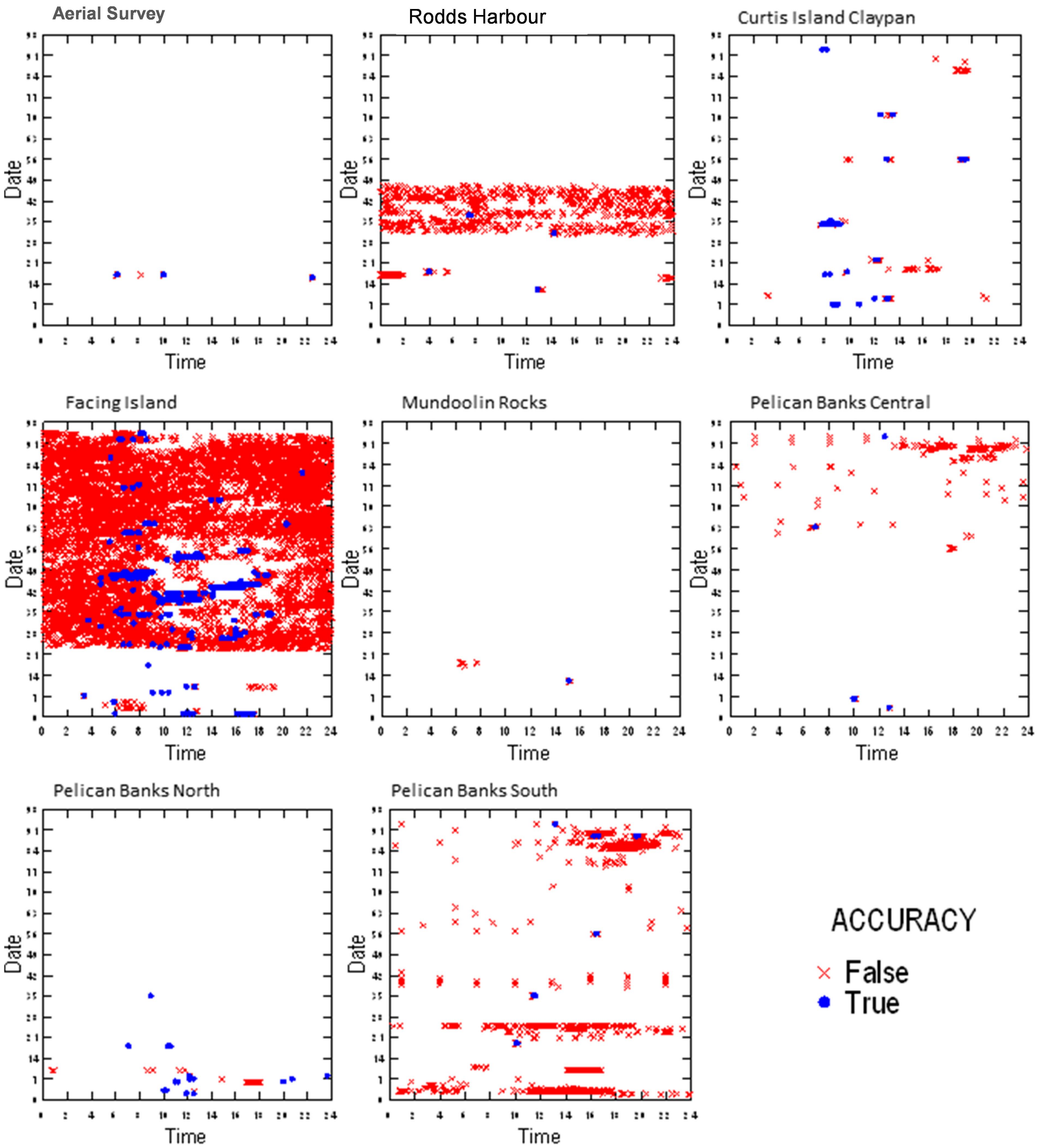


Figure 5.8 Plots of all logged signals from each automatic receiver, including false records. On the Y axis, Day Zero was 5th November. The receivers at Curtis Island and Pelican Banks North automatically deleted some of the false records before they were logged.

A summary of the valid data obtained from each tracking station is provided in Table 5.4. Facing Island proved to be the most successful tracking station, and 89.6% of records came from this site. There were also reasonable numbers of records from a claypan roost on the south of Curtis Island. At all other sites, there were few records, involving birds that only stayed in range of the automatic receivers for short periods. To a large extent the sparsity of signals reflects topography and limitations in signal detection. The automatic receivers had to be set on land, and were thus often distant from the periodically immersed areas where we expected shorebirds to occur. For example, the tidal flats of the Pelican Banks were >1 km wide on most low tides. With longer detection range this would not have been problematic, but because of the high levels of low radio-interference, we needed to apply tight filtering to exclude false records. Some valid records will have been excluded in the same process, and we suspect a disproportionate number of these would have been relatively distant birds. Even during high tide, a high spring tide is needed to force birds to get within the detection range of the receiver station at the Curtis Island claypan roost, thus the birds were out of detection range for almost all the time during neap tide cycle. After the filtering procedures were completed, there proved to be no valid records of radio-tagged birds at the Rodds Peninsula sites of Rodds Harbour or Mundoolin Rocks.

Table 5.4 Summary of radio-tracked bird occurrence at each automatic receiver site (including data from automatic receivers, manual tracking and resighting of leg-flags).

Station	Records by day	Records at night	Tide effects
Curtis Island claypan roost	83	0	All records logged by automatic receivers on tides between 2.5 and 3.0 m (i.e., at high tide, but only at the start and end of high tide periods). Handheld telemetry confirmed that on higher tides birds were present but out of receiving range of the automatic receiver.
Facing Island	1018	29	Logged birds mostly at high tide (n= 1,029), some at low tide (18).
Pelican Banks North	24	8	All automatic records were in neap tide series, on tide heights of 1.8 to 2.6 m, with a few records on higher tides only from handheld receivers.
Pelican Banks Central	2	0	Both records at high tide. Unexpected as the local habitat is not particularly suitable for roosting shorebirds, but the broad adjacent tidal flats can hold many birds.
Pelican Banks South	2	2	Both records at low tide.
Mundoolin Rocks	0	0	No validated records.
Rodds Harbour (Middle Head)	0	0	1,474 records were logged, but none passed the filters described above; no valid records

Nevertheless, plots of the validated records against date and time reveal new information about site usage in Gladstone Harbour. For example, claypans behind the mangrove fringe on southern Curtis Island are known to be an important roost site for migratory shorebirds by day, with counts of up to 1,351 recorded. On the basis of habitat appearance (large open areas far from potential cover for predators) we expected the site to be important for roosting shorebirds at night too. To our surprise this proved not to be the case (Figure 5.8); no radio-tracked shorebirds were found at this roost at night, either by automatic receivers or in the course of manual radio-tracking to check the unexpected result (The 'true' records visible at night were of a test transmitter being carried by nocturnal fieldworkers). Similarly, at Facing Island, records of radio-tracked birds by day far exceeded those at night (Table 5.4, Figure 5.8). The Facing Island station was opposite relatively narrow tidal flats and detected some foraging birds at low tide. Most of the low tide records occurred during the day (n = 16). There were only two records of birds foraging at Facing Island at night. Of eight radio-tracked birds detected on the Pelican Banks at low tide (< mean sea-level of 2.38m), two were detected at night.

Most individual birds that were radio-tagged were subsequently detected in the broader study area; only two grey-tailed tattlers and one Terek sandpiper were not detected after release. Twenty of the 35 radio-tagged individuals were recorded for 70–95 days after release, suggesting that battery life of the transmitters was sufficient for the three-month study. However, most individuals were detected infrequently, with only seven individuals being recorded more than 20 times (Table 5.5). In some of the individuals that were recorded multiple times, it was clear that fairly consistent daily routines were followed. For example, grey-tailed tattler #5 (Figure 5.9) used Facing Island as a daytime high tide roost in every tide series of the study, typically arriving and leaving the site when the tide height was close to local mean sea level. It was regularly recorded on neap high tides but did not use the site on spring high tides and it always foraged at low tide in sites beyond the reach of our receiver array.

Table 5.5 Summary of records of individual radio-tracked birds. Abbreviations: BAGO = bar-tailed godwit, FECU = eastern curlew, GTTA = grey-tailed tattler, TESA = Terek sandpiper.

				Number of high tide records (height >mean sea level, 2.38 m)					Number of low tide records (tide height > 2.38 m)		
Bird	Number of records	Minimum duration present (days)	Longest period undetected (days)	Curtis Island Claypan	Facing Island	Pelican Banks Central	Pelican Banks North	Pelican Banks South	Facing Island	Pelican Banks North	Pelican Banks South
BAGO1	4	71	38	1	3						
BAGO2	9	94	59	2	3		1		1		
BAGO3	10	93	43	1	4		1		2		
BAGO4	10	71	36	3	3		1			1	
BAGO5	21	93	21	10	2		7				
BAGO6	4	18	13		3						
BAGO7	13	93	38	4	5		1		1		
BAGO8	28	92	45	4	18	2	1		1		
FECU1	7	85	30	4			1		1	1	
FECU2	6	71	30	3	2		1				
FECU3	8	42	25	3			2		2	1	
FECU4	4	18	10	1			1		2		
FECU5	8	56	38	3			2			1	
FECU6	11	64	35	3	2		2		2		
FECU7	3	18	9				1				
FECU8	4	18	13	1			1				
GTTA1	5	46	26		3						
GTTA2	6	71	35		6				1		
GTTA3	2	94	94		1						
GTTA4	444	72	22	28	1		3			2	
GTTA5	357	92	12		1						
GTTA6	4	23	20		1						
GTTA7	6	92	21	3	1			2			
GTTA8	4	72	62		2						

Bird	Number of records	Minimum duration present (days)	Longest period undetected (days)	**Number of high tide records (height >mean sea level, 2.38 m)** Curtis Island Claypan	Facing Island	Pelican Banks Central	Pelican Banks North	Pelican Banks South	**Number of low tide records (tide height > 2.38 m)** Facing Island	Pelican Banks North	Pelican Banks South
GTTA9	2	56	56	3	3						
GTTA10	7	95	70		2						
GTTA11	1	0			444						
GTTA12	34	93	36		357						
GTTA13	1	0			3				1		
GTTA14	1	0		5	1						
GTTA15	6	92	56		4						
GTTA16	2	1	0	1	1						
TESA1	1	0			1						
TESA2	66	94	15		62				4		
TESA3	92	93	18		90						2

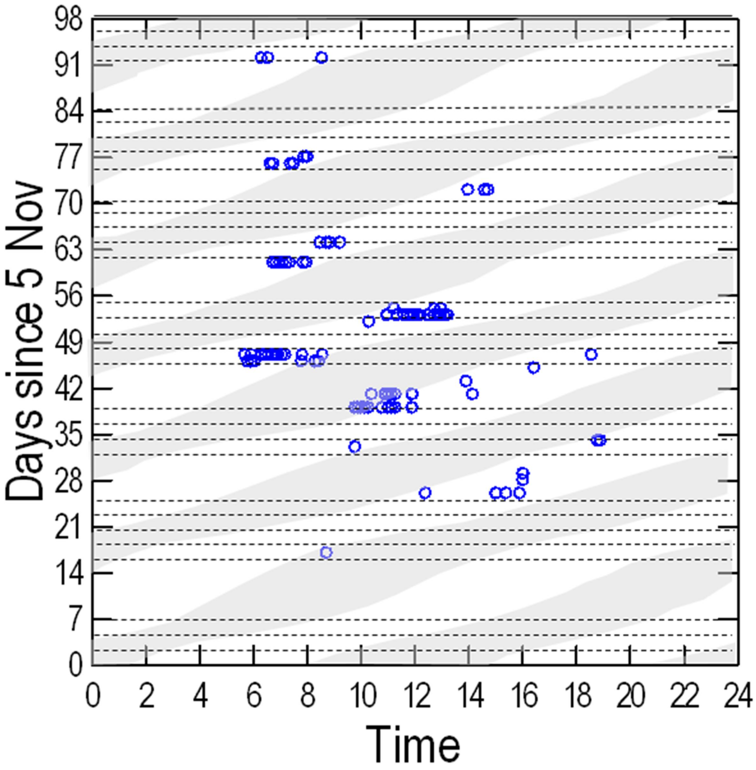


Figure 5.9 Records of radio-tagged grey-tailed tattler #5 in the study area. All records were from a single station, Facing Island. Periods of low tide (height <2.38m) are indicated by grey shading. Periods of tides approaching neap conditions (tidal amplitude <2m) are indicated by horizontal dashed lines.

Of the birds that were radio-tracked in this study, seven of eight bar-tailed godwits, seven of eight eastern curlews and two of three Terek sandpipers were recorded at multiple sites in the study area from Pelican Banks to Facing Island. Only 7 of 16 grey-tailed tattlers were recorded at sites beyond Facing Island, suggesting this species makes fewer local movements than the other species. The low detection probabilities for most individuals made it difficult to assess whether local movements followed a consistent diurnal or tidal routine, or whether local shifts in roost or foraging site were made. The latter scenario did occur in several individuals such as grey-tailed tattler #4, which regularly roosted at Facing Island in December, but was rarely recorded at the site in November or January (Figure 5.10). It must have roosted elsewhere in these periods. Similarly, eastern curlew #6 was recorded several times in November, roosting on Curtis Island at high tide or foraging on the nearby northern Pelican Banks at low tide. In December and January this individual was only recorded at Facing Island (Figure 5.11).

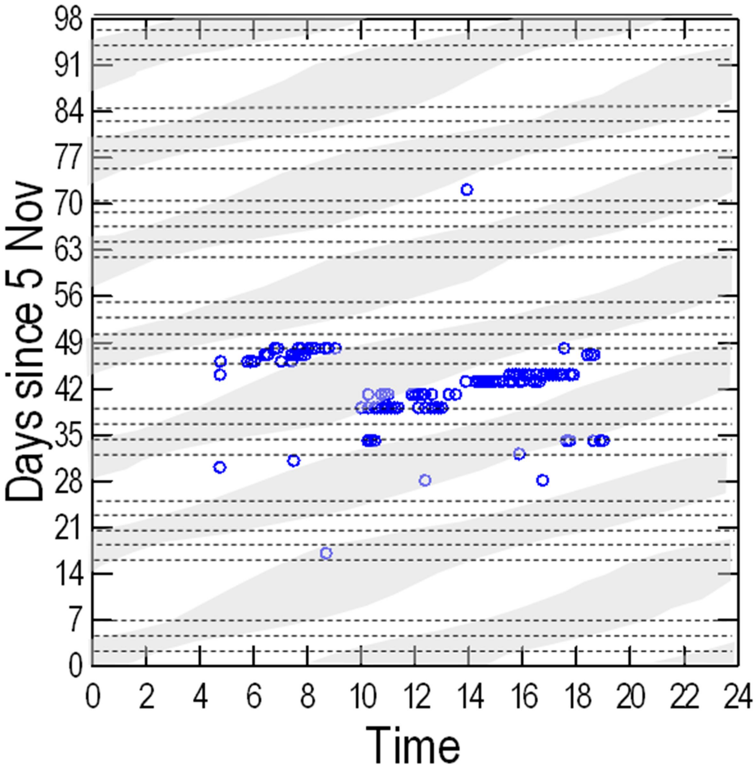


Figure 5.10 Records of radio-tagged grey-tailed tattler #4 in the study area. All records were from a single station, Facing Island. Periods of low tide (height <2.38m) are indicated by grey shading. Periods of tides approaching neap conditions (tidal amplitude <2m) are indicated by horizontal dashed lines.

Radio-tracking provided no direct evidence of exploratory movements of shorebirds beyond Gladstone Harbour. None of the study birds were detected by automatic receivers at the largest roosts of Rodds Harbour, in aerial surveys that covered the entire ERMP Survey Area and all the opportunistic manual tracking during this project (mostly at the 13 high-tide roosts). However, a number of individual birds 'went missing' for periods of over a month before being re-detected in the study area – indeed one grey-tailed tattler was only recorded on the first and the last day of the study, with its location being unknown in the intervening three months. While we do not know if these individuals left the study area, they had enough time to do so.

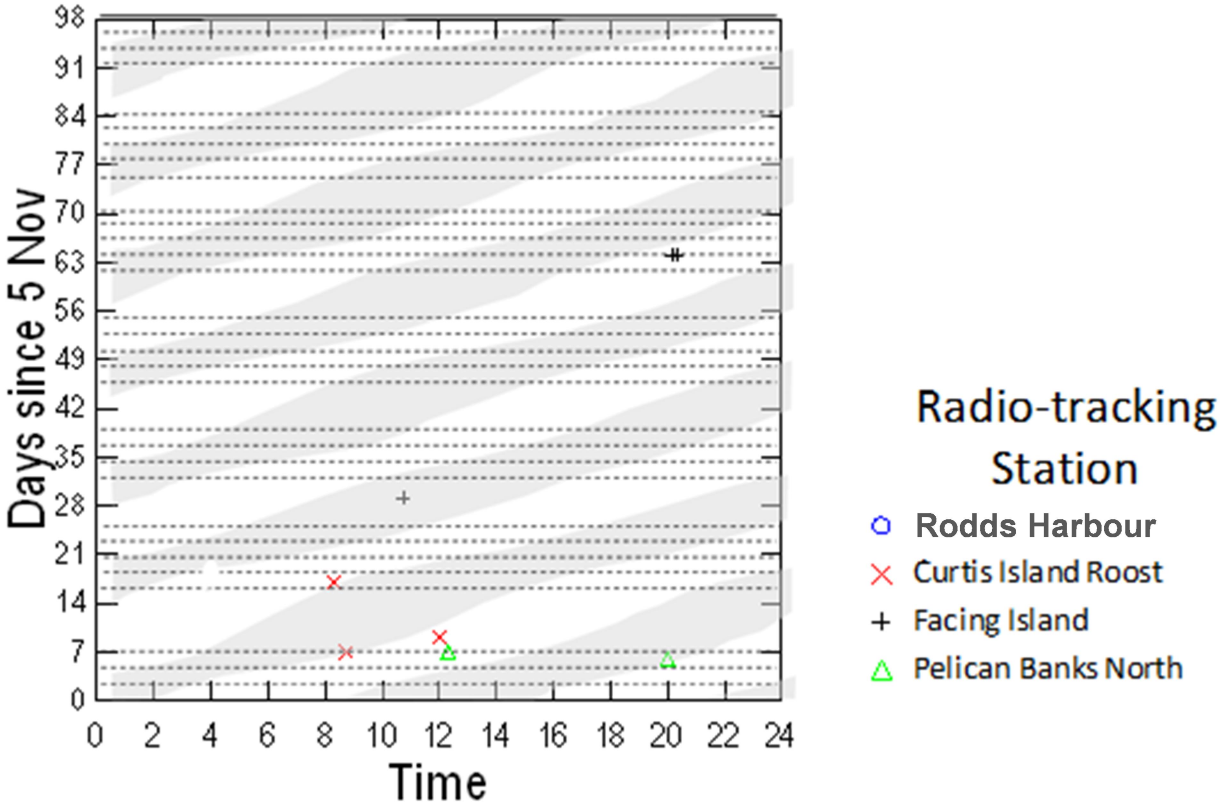


Figure 5.11 Records of radio-tagged eastern curlew #6 in the study area. Periods of low tide (height <2.38m) are indicated by grey shading. Periods of tides approaching neap conditions (tidal amplitude <2m) are indicated by horizontal dashed lines.

Results from the automated receiver array showed that birds commonly made commuting movements at a local scale in the Pelican Banks and Facing Island area (Figure 5.12). This highlights, for example, that management actions or threats at Pelican Banks will be impacting birds using northern Facing Island, and that these two areas need to be considered a single management unit for the purposes of migratory shorebirds.

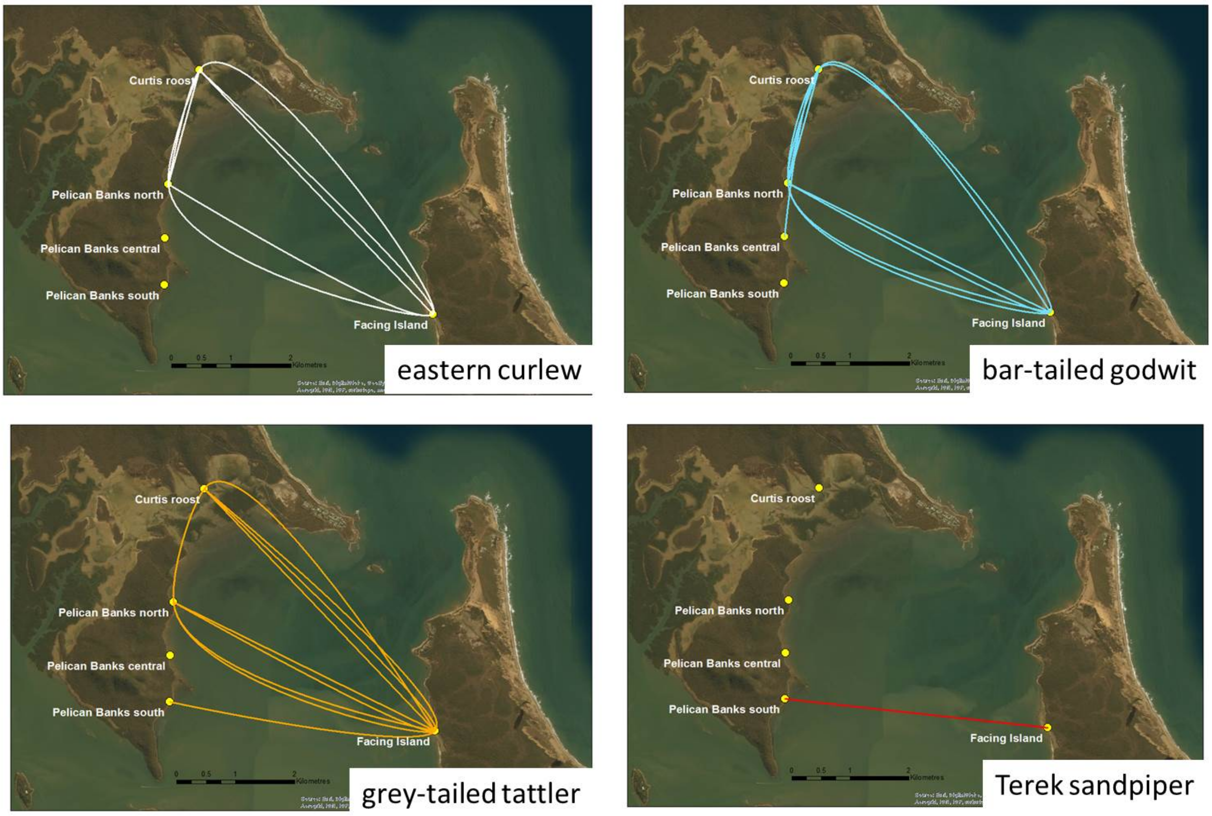


Figure 5.12 Commuting movements in the Pelican Banks/Facing Island area by eight eastern curlews, eight bar-tailed godwits, 16 grey-tailed tattlers and three Terek sandpipers. Receiver stations are joined by a line when a bird was detected by both stations.

In contrast to our tracking study, the banding and resighting work provided evidence for 'migratory' movement. Resighting of coloured leg flags and recapture of birds banded outside the ERMP Survey Area indicated that the shorebirds in the Study Area come from at least 13 different banding locations (Figure 5.13, Table A10). One third of these birds were banded in China, and another one-third in Victoria. Given the high non-breeding site fidelity that has been demonstrated in long-term shorebird banding studies in south-eastern Queensland (J Coleman unpubl data), in Victoria (Herrod 2010; C.D.T. Minton pers. comm.) and in New Zealand (Conklin et al. 2013), it is likely that the 24 individuals banded further south in Queensland, Victoria or New Zealand used the ERMP Survey Area as a stopover site on their way south. On the other hand, seven shorebirds captured in the ERMP Survey Area were eventually seen outside the region. Four grey-tailed tattlers were reported in Japan, one of which was also seen in Kamchatka in Russia, a bar-tailed godwit in South Korea, a great knot in Micronesia and an eastern curlew in Toorbul, near Brisbane.

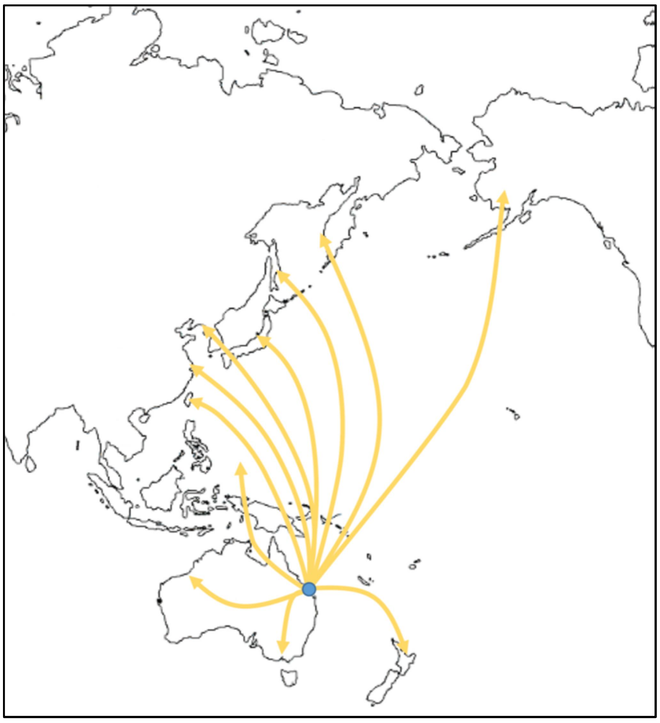


Figure 5.13 Migratory destinations of shorebirds from the ERMP Survey Area based on banding recoveries or resighting of marked birds in the field.

The resighting dataset also revealed ‘commuting’ movement of shorebirds within the ERMP Survey Area. Sixty-five individually-marked birds from eight different species were encountered more than once (Table 5.6). Forty-one of these individually-marked birds (63%) were recorded in different high-tide roosts between encounters, travel distances ranging from five to 10km. Despite these documented movements between high tide roosts, none of the birds was recorded outside the subregion where they were first encountered (Table 5.7). In other words, no evidence for ’exploratory’ movement was found using resighting data.

Among the 24 individually-marked birds flagged in the first field season, 15 were seen again in the second field season and all of these sightings were made from the same region where the birds were flagged, suggesting high site fidelity between years (eight out of 12 bar-tailed godwits, two out of five great knots, five out of five grey plovers).

Table 5.6 Distribution of individually-marked birds resighted in the three different subregions of the ERMP Survey Area. Only those individuals that were encountered more than once are included.

	Rodds Peninsula	**Gladstone Harbour**	**Fitzroy Delta**	**Total**
Bar-tailed godwit	10	9	0	19
Eastern curlew	0	4	0	4
Great knot	4	0	1	5
Grey plover	5	0	0	5
Grey-tailed tattler	0	26	0	26
Terek sandpiper	0	2	0	2
Total	**11**	**41**	**1**	**61**

Table 5.7 Summary of shorebird movements between high-tide roosts in the ERMP Survey Area based on resighting records. The codes in column headings refer to distinct roost locations.

Species\Movement within region	**Rodds Peninsula**			**Gladstone Harbour**		**All regions**	**Total**
	67–71	67–71–75	67–75	GH10A–GH2	GH2–GH10A	No change	
Bar-tailed godwit	8	0	0	1	8	2	19
Eastern curlew	0	0	0	0	0	4	4
Great knot	1	1	1	0	0	2	5
Grey plover	0	0	0	0	0	5	5
Grey-tailed tattler	0	0	0	0	21	5	26
Terek sandpiper	0	0	0	0	0	2	2
Total	**9**	**1**	**1**	**1**	**29**	**20**	**61**

5.2.6. Implications of movements study for assessing size of impact area

Several key discoveries in our movement study are relevant to assessing the size of potential impact areas in the ERMP Survey Area. First, it should be emphasised that some key sites in the ERMP Survey Area have yet to be discovered. The paucity of records of radio-tagged birds at roosts at night and on the highest spring tides indicates that there must be undiscovered roosts in the region. Their location remains unclear. Satellite imagery suggests that the most suitable habitats that we were unable to visit at night during the study may be on the large claypans of Facing Island, or the ocean beaches of Facing or South Curtis Islands.

It is unlikely that shorebirds of Gladstone Harbour undertake commuting movements outside the Gladstone Harbour region. Within this area, however, local movements are frequent and not entirely predictable (Figure 5.12). This suggests the shorebirds of Gladstone Harbour are mobile enough to find rich local prey patches, and that within the study area they can change their commuting routines. It was noteworthy that individual radio-tracked birds were only recorded foraging on the narrow tidal flats of northern Facing Island if they subsequently roosted there at high tide. This suggests that foraging site may be driven to some extent by roost site, or alternatively that choice of roost site may be driven to some extent by foraging site. Although it is not yet clear whether foraging sites drive roost selection or vice versa, it is clear that two are intertwined, and security of both roosts and foraging grounds is required by shorebirds in Gladstone Harbour. We found no evidence for exploratory flights beyond Gladstone Harbour. While we cannot rule out the possibility that such movements could occur, they are clearly highly infrequent at best. There was strong evidence from both colour-band re-sightings and count data that some shorebirds use the ERMP Survey Area largely as a stopover site.

We suggest that in the middle of the non-breeding season, a localised habitat change in the ERMP study would affect shorebirds in a relatively small impact area, as usual commuting routines of the local shorebirds do not involve long flights; on available evidence, most individuals occupy a modest home range, with roosts and foraging grounds no more than 5–10 km apart. While this suggests that local developments might have a geographically small 'footprint' on non-breeding shorebirds, it also suggests that local effects might be relatively severe, as individual shorebirds displaced by development or other habitat changes face the alternatives of losing roosting or feeding areas, or locating new sites that they rarely or never visit. There is evidence from studies overseas that when shorebirds are displaced to unfamiliar sites that are already occupied by other shorebirds, they experience declines in survival (Burton et al. 2006). On the other hand, the footprint of local habitat changes during the migration season could be very large, as some shorebirds use the ERMP Survey Area as a stopover site where they refuel before migrating further north or south. For example, changes to the ERMP Survey Area during the southward migration season (mainly September and April) could affect the survival, and hence populations, of shorebirds from non-breeding populations in south-eastern Australia or New Zealand (Figure 5.13).

Migratory shorebirds made daily local commuting flights of up to 10km between alternative feeding and roosting locations that were strongly associated with the tidal patterns.

Individually-marked birds showed high site fidelity both within and between non-breeding seasons.

5.3 Determine how many birds currently use the study area (Aim B1)

5.3.1. Summary

We conducted repeated shorebird surveys in 13 high tide roosts in the ERMP Survey Area from 2014 to 2016. During our study, we found higher numbers of broad-billed sandpiper, curlew sandpiper, great knot, grey plover, red knot (ten-fold higher than previous peak count), red-necked stint and sharp-tailed sandpiper, than any previous survey in the region. Combining these new peak records with those from the annual complete February surveys, we found that the ERMP Survey Area supported 14,511 and 17,948 migratory shorebirds during the non-breeding season in 2014–2015 and 2015–2016, respectively. The northern-hemisphere breeding shorebird community was dominated by adults, ranging from 90 to 100% in most of the shorebird species. Thompsons' modelling approach was used to estimate the number of transiting birds and passage dates based on repeated counts (Thompson 1993). However, this approach did not perform well in our study when we stretched the model period to the entire non-breeding season. Most of the modelled estimates of the number of birds were either lower than that of the peak counts, or failed to converge. These could arise due to the complex movement pattern of the shorebirds with species having both transiting and wintering populations in the ERMP Survey Area, and the sporadic movement of some species between surveyed sites and unsurveyed areas such as salt pans. The ERMP Survey Area is an internationally important non-breeding site (>1%) for ten northern hemisphere-breeding species.

5.3.2. Introduction

We used three different approaches to determine the number of birds currently using the ERMP Survey Area, namely the peak count from complete surveys, extrapolated peak count from targeted surveys, and modelled estimates based on repeated surveys.

The use of peak counts based on complete surveys to represent the total number of birds is a common and simple approach to determine the number of birds using an area. However, the timing of migration and peak occurrence of shorebirds can vary among species (Choi et al. 2016b). On the scale of the ERMP Survey Area, it is not feasible to conduct regular surveys through the entire non-breeding season to coincide with the peak occurrence of every shorebird species. Those species that make a brief stopover could be missed in the current complete survey conducted annually by consulting companies. We therefore conducted more frequent but targeted surveys to overcome this problem and extrapolated the results to the entire ERMP Survey Area based on an extrapolation function. This species-specific function was a weighted proportion of birds that the targeted survey sites support relative to the entire ERMP Survey Area, using the complete surveys conducted in the entire ERMP Survey Area from February 2012, when the number of sites surveyed became standardised.

It is likely that the actual number of birds using the ERMP Survey Area is larger than the peak counts, if some individuals use the area as a stopover site and leave the area before all individuals have arrived. Therefore, we also estimated the total number of birds using a modelling approach that allows us to estimate the number of transiting individuals. The approach generates abundance and passage date estimates by assuming normally distributed arrival and departure times (see Section 5.1 for details). Although this is a relatively coarse approach, it has so far generated passage date estimates that correspond well to results from direct tracking of individual birds (Choi et al. 2015a; Choi et al. 2016b; Rogers et al. 2010; Thompson 1993).

5.3.3. Methods

Details of the survey methods, data selection and analysis are given in Section 5.1.3.

Table 5.8 Numbers of migratory shorebirds recorded in the complete surveys of the ERMP Survey Area by previous workers, and the targeted surveys conducted in this project. Thirteen sites were visited regularly in this project while up to 157 sites were visited in the previous surveys. Extrapolated numbers of birds were calculated by dividing our highest count by the weighted mean proportion of birds recorded in our 13 sites relative to the total numbers obtained in previous complete counts. This number should be treated with caution due to the uncertainty in the extrapolation process. Numbers in bold represent the highest abundance of the species since October 2014.

Species	Peak count based on complete survey (all years)	Peak count based on complete survey (after 2014 Oct)	Peak count based on targeted surveys	Extrapolated bird number in the entire ERMP Survey Area based on targeted survey data	Survey period for the peak count	Modelled estimate based on all count data from last 2 years	WPE flyway population	Flyway % using highest count in all years
Bar-tailed godwit (*L. l. baueri*)	3890	**3125**	2056	3819	2015-02	1767	133,000	2.93
Black-tailed godwit	2	0	**1**	2	2014-12	NA	139,000	0.01
Broad-billed sandpiper	46	46	**369**	412	2015-03	369	25,000	1.48
Common greenshank	66	**66**	50	105	2016-02	48	100,000	0.07
Common sandpiper		1	0	0	2016-02			
Curlew sandpiper	151	101	345	375 (model=390)	2015-09	**359**	135,000	0.26
Eastern curlew *	1606	**812**	727	1734	2015-02	602	32,000	5.02
Great knot *	1359	1359	**1400**	2845	2014-12	920	290,000	0.48
Greater sand plover	1061	**1061**	949	1368	2015-02	959	79,000	1.34
Grey plover	187	**187**	114	169	2015-03	72	104,000	0.22
Grey-tailed tattler *	1218	**1218**	404	1773	2016-02	273	44,000	2.77
Latham's snipe		1	**0**	0	2015-02			
Lesser sand plover	1810	228	**623**	2445	2015-09	NA	188,500 – 218,500	0.83 – 0.96
Little curlew		**1**						
Marsh sandpiper	112	**112**	0	0	2016-02	NA	100,000 – 1,000,000	0.18 – 1.81

Species	**Peak count based on complete survey (all years)**	**Peak count based on complete survey (after 2014 Oct)**	**Peak count based on targeted surveys**	**Extrapolated bird number in the entire ERMP Survey Area based on targeted survey data**	**Survey period for the peak count**	**Modelled estimate based on all count data from last 2 years**	**WPE flyway population**	**Flyway % using highest count in all years**
Pacific golden plover	69	**56**	3	11	2016-02	NA	135,000 – 150,000	1.21 – 1.34
Red knot	86	28	**850**	1467	2015-09	850	99,000 – 122,000	0.7 – 0.86
Red-necked stint *	4201	3852	6931	10797 (model = 11375)	2015-09	**7302**	315,000	2.200
Ruddy turnstone	74	15	**25**	255	2015-03	25	28,500	0.260
Sanderling	72	**11**	0	0	2016-02	NA	22,000	0.327
Sharp-tailed sandpiper *	130	124	355	16419 (model = 21876)	2015-09	**473**	160,000	0.222
Terek sandpiper	1129	**782**	98	722 (model = 4820)	2015-02	654	50,000	2.258
Whimbrel	2636	**1099**	292	2112	2016-02	219	55,000	4.792

Source: Wetlands International (2016)

** Species endemic to the East Asian–Australasian Flyway*

5.3.4. Results

Bird numbers

Despite only 13 out of the 157 possible sites being surveyed regularly, our project documented higher numbers of broad-billed sandpiper, curlew sandpiper, great knot, grey plover, red knot, red-necked stint and sharp-tailed sandpiper, than any previous survey (Table 5.8). The most remarkable difference was the 10-fold increase in the red knot count, from a previous peak count of 86 individuals up to 850 individuals in our survey, followed by broad-billed sandpiper, which increased from 46 to 369 individuals. These new record totals stemmed largely from our completion of surveys at times of year when complete surveys have not been attempted in the past.

Extrapolating numbers of birds from the 13 sites surveyed to the entire survey area gave reasonable estimates for some species, such as eastern curlew, bar-tailed godwit and Terek sandpiper, the extrapolated numbers for sharp-tailed sandpiper, red-necked stint, and grey-tailed tattler greatly exceeded previous records (Table 5.8). On the other hand, most of the modelled estimates of the number of birds were either lower than that of the peak counts, or failed to converge, except for the curlew sandpiper, red-necked stint and sharp-tailed sandpiper.

The ERMP Survey Area is an internationally important non-breeding site (>1%) for ten northern hemisphere-breeding species, including the bar-tailed godwit, broad-billed sandpiper, eastern curlew, greater sandplover, grey-tailed tattler, Pacific golden plover *Pluvialis fulva*, red knot, red-necked stint, Terek sandpiper and whimbrel. This region is also an internationally important staging area (>0.25%) for the curlew sandpiper, great knot, grey plover *Pluvialis squatarola*, lesser sand plover, marsh sandpiper *Tringa stagnatilis*, ruddy turnstone, sanderling *Calidris alba* and sharp-tailed sandpiper.

Age structure

During the two years of study, many of the age-scans were conducted before October when juveniles might not have arrived. Bar-tailed godwit was the only species with a sufficient number of scans carried out after October. Bar-tailed godwits were dominated by adults (weighted average of 96.4% from ten scans of 732 individuals), a figure that is substantially higher than that recorded from banding in northwest (90.2%) and southeast Australia (82%; Minton et al. 2015, 2016).

5.3.5. Discussion

Using the complete and targeted surveys, as well as the modelled estimates, at least 19,894 northern-hemisphere breeding shorebirds were recorded in the ERMP Survey Area from 2014

Oct to 2016 February (Table 5.8). In the case of bar-tailed godwits at least, more than 90% of birds are adults. The higher abundances of seven species recorded in our targeted surveys occurred mostly during passage period (March, August and September), which could be missed in the annual February survey, thus our dataset is complementary to that already collected as part of the ERMP monitoring (Wildlife Unlimited 2015, 2016).

Extrapolation can potentially provide estimates of shorebird abundance from areas where counts were not conducted. We suspect that the relatively low detectability of the grey-tailed tattlers and the sporadic movement to inland wetland in the sharp-tailed sandpiper and red-necked stint may have confounding effects on the extrapolation function (Figure 5.2, Table 5.8). These could lead to low reliability in the extrapolated numbers even though data from as many as nine rounds of survey were used in estimating the extrapolation function.

Thompsons' model allows the number of transiting birds and passage dates to be estimated from repeated counts (Choi et al. 2015a; Choi et al. 2016b; Rogers et al. 2010). However, this approach did not perform well in our study when we stretched the model period to the entire non-breeding season, perhaps due to the complex movement pattern of the shorebirds with species having both transiting and non-breeding populations in the ERMP Survey Area, and the sporadic movement of some species between surveyed sites and unsurveyed areas such as salt pans (Section 5.2). In the case of curlew sandpipers and sharp-tailed sandpipers, the non-breeding season was split into southward and northward migrations and analysed separately to generate reasonable results. In short, we are not completely satisfied with any of the three approaches in determining the number of birds. The incomplete temporal coverage of annual February complete surveys missed 1,073 and 6,391 transiting shorebirds in 2015 and 2016, respectively (Section 5.1). The extrapolated peak count from repeated targeted surveys could overcome the problem of incomplete temporal coverage, but the extrapolations for some species were highly unlikely (red-necked stint and sharp-tailed sandpiper, Table 5.8). Modelled estimates based on repeated targeted surveys could provide a reliable estimate theoretically, but the final modelled estimates were always lower than the peak counts. Therefore, we adopted the most conservative approach and determined the number of birds by simply choosing the highest count of any species in all the surveys conducted in 2015 and 2016, including our repeated targeted surveys and the annual February complete surveys. We found that the survey area supported 14,511 and 17,948 migratory shorebirds during the non-breeding season in 2014–2015 and 2015–2016, respectively. These numbers were higher than those recorded from the annual February complete survey alone (13,752 in 2015 and 11,574 in 2016; Wildlife Unlimited 2015, 2016).

The age-structure of the northern-hemisphere breeding shorebirds in the ERMP Survey Area could only be described in bar-tailed godwit, where a sufficient number of scans were made after the arrival of juveniles (after October). Juvenile ratios in bar-tailed godwit in the survey area were lower than those found in the northwest and southeast Australia, potentially indicating a differential use of the sites among different age-classes of shorebirds (Minton et al. 2015, 2016). Long term monitoring effort in multiple sites would help to determine whether a differential use of the sites among age-classes occurs.

Resighting and banding records show that shorebirds using the ERMP Survey Area are linked to at least 20 other shorebird sites along the flyway, including Iyo in Japan, a city only 120km away from Gladstone's sister city (Saiki), providing further evidence for the important role that the ERMP Survey Area plays in the routes travelled by migratory shorebirds. Currently, part of the ERMP Survey Area in the Fitzroy floodplain and delta is recognised as an important bird and biodiversity area by Birdlife International (http://www.birdlife.org.au/projects/KBA/iba-maps), and five regions are listed as wetlands of national importance to Australia, including the Colosseum Inlet – Rodds Peninsula, Great Barrier Reef Marine Park, Northeast Curtis Island, Gladstone Harbour and The Narrows (Environment Australia 2001). However, there is no other formal protected area designation or international recognition such as Ramsar Wetlands of International Importance, to safeguard key parts of the ERMP Survey Area for waterbirds. Such recognition could benefit migratory shorebirds by (i) limiting future threats, (ii) providing an opportunity to engage with other site managers and access to tools for delivering flyway conservation outcomes, (iii) increasing awareness through international recognition, (iv) providing a model to encourage greater community engagement, which is essential if the region is to be managed in harmony with the values of both community and environment needs, and (v) increasing access to national and international funding for sustainable conservation management outcomes. Evidence is mounting that habitat loss overseas is the key driver for shorebird population declines (Studds et al. 2017), and this underlines the importance of Australian habitats in making sure the birds are good condition to undertake their long migrations. Despite the relatively low benthic biomass and relatively small shorebird numbers compared with other sites, the ERMP Survey Area remains critical for long distance migratory shorebirds because these birds simply have nowhere else to go at that latitude.

The Survey Area supports about 20,000 migratory shorebirds and qualifies as an internationally important site for ten shorebird species.

Effective monitoring and management of the area is crucial, including protected area designation.

5.4 Identify size of management units (Aim B4)

Weaving together the multiple strands of evidence arising from this project, we conclude that migratory shorebirds in this region need to be managed on a distinctly local scale. In practice, this means ensuring the birds have the resources they need (high quality foraging and roosting sites) in a relatively small area. Any determinations of impact, or plans for management, should consider foraging and roosting habitat at the scale of a local collection of sites (within a few kilometres), and not just assume these habitats need to exist somewhere in the study region, or that each roosting or feeding site can be managed independently of others in the vicinity.

The patterns of tidal exposure (Section 4.1) and benthic invertebrate abundance and community structure (Section 4.2) showed relatively fine scale variation, and birds keyed into this at a scale of kilometres, rather than tens of kilometres. Our marked individuals used a portfolio of roosting and feeding sites typically within 10km of each other (Section 5.2.5; Figure 5.12). Their use of multiple feeding and roosting sites, depending on the spring / neap tide cycle (Figure 5.8), and also nocturnally and diurnally (Table 5.4), indicates that birds will often need several “options” in an area. This suggests, for example, that where artificial roosts or restored tidal flats are being used compensate for loss of natural sites, several facilities may need to be put in, rather than a single one. Likewise, it implies that management of roosting sites (e.g., vegetation control to keep a roost site open) will need to happen at a site-by-site level, rather than managing just a few sites across the whole system.

While we cannot provide a map of the boundaries of management units, the considerations above, combined with the lack of detectable movements between subregions indicates at least that the main subregions in our study (Fitzroy Delta, North Curtis Island, Gladstone Harbour and Rodds Peninsula) need to be managed as essentially independent units. Each of these management units would benefit from its own migratory shorebird management plan, considering how to manage the main threats to shorebirds, e.g., future developments that result in loss of feeding or roosting habitat, recreation and disturbance, poor water quality, predation. A management plan should also include monitoring of feeding and roosting habitat availability, and a mechanism to detect major changes in the use of these by the birds. Facilitating community groups to undertake such monitoring has been useful in other areas, such as Moreton Bay, where the Queensland Wader Study Group carries out monthly monitoring of important shorebird sites throughout the Bay.

Within a subregion, shorebirds typically moved between roosts up to 10km apart, so long as they were surrounded by more or less continuous and large intertidal flats (e.g., between Pelican Banks and Facing Island; between Rodds Harbour and Mundoolin Rocks). However, birds seemed unlikely to travel for substantial distances across (e.g., between Mundoolin Rocks and Facing Island; between Pelican Banks and tidal flats in the Fitzroy Delta, Figure 5.1). We therefore recommend from a management perspective that the ERMP Survey Area is provisionally treated as four management units (Fitzroy Delta, North Curtis, Gladstone Harbour and Rodds Peninsula) until further information suggests otherwise. This local circulation of birds means that any impact within a subregion could potentially impact all the birds using that subregion, and an environmental impact assessment would need to start on that basis.

The main threats to migratory shorebirds and some of the approaches to management are listed in the Wildlife Conservation Plan for Migratory Shorebirds (Commonwealth of Australia 2015), and encompass habitat loss, habitat modification, anthropogenic disturbance, climate variability and change, harvesting of shorebird prey, fisheries by-catch and hunting. Only the last of these is unlikely to be a major contemporary issue in Australia. However, there is arguably a need for more specific guidance around managing migratory shorebirds in Australia especially given (i) the decision of whether to manage certain threats in Australia or elsewhere along the birds' migratory route, and (ii) the difficulty of managing system-level threats to an area, such as sea-level rise or water quality.

Many of Australia's migratory shorebirds are in rapid decline (Clemens et al. 2016). The principal driver of these declines is the loss of habitat in stopover sites along the migration routes to and from the Arctic (Amano et al. 2010; Piersma et al. 2016; Studds et al. 2017). This means that a combination of international actions and careful management of remaining habitats in Australia is crucial to ensure these amazing birds continue to thrive in Australia's coastal wetlands for decades to come.

6. ACKNOWLEDGEMENTS

Sincere thanks to Megan Ellis at Gladstone Ports Corporation for working efficiently alongside the team over the course of this project, and to Dave Wright of QVC Solutions for excellent project management. We thank Wildlife Unlimited (especially Adam Leavesley and Inka Veltheim), and Nick Murray for sharing their knowledge of the ERMP Survey Area, Sora Estrella, Amanda Lilleyman, Richard Lanctot and Jeff Hansen for comments and suggestions during the various stages of this project. This project could not have been completed without the help of Allan Briggs, Robert Bush, David Edwards, Xiaojing Gan, Stephen Macdonald, David Milton, Maddy Stigner in capturing shorebirds; Micheli Costa, Kwek Yan Chong, Charlotte Dudal, Yi Han, Micha Jackson, Girija Joshi, Emily Massingham, Dale Mullin, Rachel Paterson, Natalie Meiklejohn, Courtney Melton and Holly Urquhart for collecting, sorting and counting benthic organisms. We are indebted to Allan Andrew for assistance in the aerial survey, and Claire Fuller and Kathleen McLeod for logistics support. We also thank Anjana Singh, Daniel Spooner and Gavin Purtell for facilitating our work.

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8. APPENDIX

Table A1 Percentage contribution of each prey group to changes in benthic community composition along the serial gradient of decreasing height on the shore (0 = top of littoral zone; 5 = bottom of littoral zone). Only adjacent pairs of heights are shown. Data are shown for four of the sampling sites, with the lack of any clear distinction among the height bands for Rodds Harbour and Mundoolin Rocks meaning that invertebrate groups would provide little value as indicators of changing height on the shore.

	Bivalves	Copepods	Polychaetes	Isopods	Gastropods	Nemerteans
Cattle Point						
0,1	44.32	33.45	-	-	-	-
1,2	43.03	29.33	-	-	-	-
2,3	40.96	24.45	-	-	-	-
3,4	37.76	35.40	-	-	-	-
4,5	27.86	43.19	-	-	-	-
Warner Point						
0,1	32.11	-	17.32	12.65	-	-
1,2	32.02	-	18.34	9.69	-	-
2,3	23.44	-	26.33	10.50	-	-
3,4	23.83	-	24.07	-	-	-
4,5	26.89	-	17.48	-	-	-
Pelican Banks						
0,1	-	-	25.48	-	-	-
1,2	-	-	30.60	-	-	-
2,3	-	-	17.22	-	18.83	-
3,4	-	-	28.27	-	14.87	-
4,5	-	-	28.31	-	-	-
Facing Island						
0,1	18.93	-	19.09	-	-	10.17
1,2	9.19	-	27.39	-	-	9.43
2,3	10.15	-	19.84	-	-	9.62
3,4	8.53	-	25.24	-	-	12.01
4,5	10.17	-	25.54	-	-	13.88

Table A2 Results of analysis of similarity percentages (SIMPER) analysis to determine which of the invertebrate groups contributed most to the changes in benthic composition among the six sites at height band 0. The four taxa that appeared consistently across all pair-wise comparisons are shown, although for any specific comparison other taxa may have contributed as much or more than some of these.

	% contribution			
Site	**Bivalves**	**Copepods**	**Polychaetes**	**Crabs**
Cattle Point vs Warner Point	52.45	25.02	9.58	3.39
Cattle Point vs Facing Island	45.54	24.06	7.55	4.33
Cattle Point vs Pelican Banks	51.35	26.63	9.72	3.21
Cattle Point vs Rodds Harbour	43.16	20.48	14.32	2.76
Cattle Point vs Mundoolin Rocks	47.38	22.89	14.59	4.05
Facing Island vs Pelican Banks	25.49	7.20	19.98	9.08
Facing Island vs Rodds Harbour	18.49	2.20	23.11	7.47
Facing Island vs Mundoolin Rocks	21.10	2.53	26.36	9.67
Facing Island vs Warner Point	23.95	4.67	19.55	9.35
Pelican Banks vs Rodds Harbour	22.38	4.89	31.50	5.17
Pelican Banks vs Mundoolin Rocks	27.15	6.07	34.46	9.09

Table A3 Results of SIMPER analysis to determine which of the invertebrate groups contributed most to the changes in the benthic composition among the six sites for height band 1. The four taxa that appeared consistently across all pair-wise comparisons are shown, although for any specific comparison other taxa may have contributed as much or more than some of these.

	% contribution			
Site	Bivalves	Copepods	Polychaetes	Amphipods
Cattle Point vs Warner Point	53.80	28.02	4.66	5.17
Cattle Point vs Facing Island	45.62	23.70	12.00	4.35
Cattle Point vs Pelican Banks	57.02	27.57	5.87	5.22
Cattle Point vs Rodds Harbour	40.69	20.22	11.90	10.79
Cattle Point vs Mundoolin Rocks	41.61	20.90	16.03	3.80
Facing Island vs Pelican Banks	11.85	16.43	35.13	1.00
Facing Island vs Rodds Harbour	12.26	6.46	18.68	21.30
Facing Island vs Mundoolin Rocks	15.12	4.73	25.27	1.83
Facing Island vs Warner Point	24.97	8.02	28.19	5.05
Pelican Banks vs Rodds Harbour	10.69	11.49	23.59	23.93
Pelican Banks vs Mundoolin Rocks	13.06	10.61	35.56	1.23
Warner Point vs Pelican Banks	36.29	19.51	21.16	6.44
Warner Point vs Rodds Harbour	16.35	6.81	22.98	21.78
Warner Point vs Mundoolin Rocks	19.66	5.12	34.46	4.44
Rodds Harbour vs Mundoolin Rocks	8.14	4.91	18.34	20.46

Table A4 Results of unordered analysis of similarities and associated pair-wise tests, using Bray-Curtis similarity measure on square-root transformed data, testing for differences in benthic community composition among the six sites, for height band Two (Zero = top of shore; Five = bottom of littoral zone). Global test R=0.349, $P < 0.001$. Sites that are not significantly different from each other in terms of the composition of the benthic prey community are shaded in grey.

SITE	**Significance**
Cattle Point vs Warner Point	P < 0.001
Cattle Point vs Facing Island	P < 0.001
Cattle Point vs Pelican Banks	P < 0.009
Cattle Point vs Rodds Harbour	P < 0.001
Cattle Point vs Mundoolin Rocks	P < 0.006
Warner Point vs Facing Island	P < 0.004
Warner Point vs Pelican Banks	P > 0.981
Warner Point vs Rodds Harbour	P < 0.007
Warner Point vs Mundoolin Rocks	P > 0.142
Facing Island vs Pelican Banks	P < 0.002
Facing Island vs Rodds Harbour	P < 0.001
Facing Island vs Mundoolin Rocks	P < 0.004
Pelican Banks vs Rodds Harbour	P > 0.393
Pelican Banks vs Mundoolin Rocks	P > 0.355
Rodds Harbour vs Mundoolin Rocks	P < 0.009

Table A5 Results of unordered analysis of similarities and associated pair-wise tests, using Bray-Curtis similarity measure on square-root transformed data, testing for differences in benthic community composition among the six sites, for height band Three (Zero = top of shore; Five = bottom of shore). Global test R=0.202, P < 0.001. Sites that are not significantly different from each other in terms of the composition of the benthic prey community are shaded in grey.

SITE	**Significance**
Cattle Point vs Warner Point	P < 0.004
Cattle Point vs Facing Island	P < 0.001
Cattle Point vs Pelican Banks	P > 0.065
Cattle Point vs Rodds Harbour	P < 0.001
Cattle Point vs Mundoolin Rocks	P < 0.018
Warner Point vs Facing Island	P < 0.001
Warner Point vs Pelican Banks	P < 0.014
Warner Point vs Rodds Harbour	P < 0.007
Warner Point vs Mundoolin Rocks	P > 0.407
Facing Island vs Pelican Banks	P < 0.200
Facing Island vs Rodds Harbour	P > 0.303
Facing Island vs Mundoolin Rocks	P < 0.012
Pelican Banks vs Rodds Harbour	P < 0.003
Pelican Banks vs Mundoolin Rocks	P > 0.309
Rodds Harbour vs Mundoolin Rocks	P < 0.009

Table A6 Results of unordered analysis of similarities and associated pair-wise tests, using Bray-Curtis similarity measure on square-root transformed data, testing for differences in benthic community composition among the six sites, for height band Four (Zero = top of shore; Five = bottom of shore). Global test R=0.202, P < 0.001. Sites that are not significantly different from each other in terms of the composition of the benthic prey community are shaded in grey.

SITE	Significance
Cattle Point vs Warner Point	P < 0.001
Cattle Point vs Facing Island	P < 0.001
Cattle Point vs Pelican Banks	P < 0.001
Cattle Point vs Rodds Harbour	P < 0.031
Cattle Point vs Mundoolin Rocks	P < 0.018
Warner Point vs Facing Island	P < 0.001
Warner Point vs Pelican Banks	P < 0.014
Warner Point vs Rodds Harbour	P < 0.007
Warner Point vs Mundoolin Rocks	P < 0.001
Facing Island vs Pelican Banks	P > 0.262
Facing Island vs Rodds Harbour	P < 0.006
Facing Island vs Mundoolin Rocks	P < 0.001
Pelican Banks vs Rodds Harbour	P < 0.001
Pelican Banks vs Mundoolin Rocks	P < 0.050
Rodds Harbour vs Mundoolin Rocks	P < 0.001

Table A7 Results of unordered analysis of similarities and associated pair-wise tests, using Bray-Curtis similarity measure on square-root transformed data, testing for differences in benthic community composition among the six sites, for height band Five (Zero = top of littoral zone; Five = bottom of littoral zone). Global test R=0.202, P < 0.001. Sites that are not significantly different from each other in terms of the composition of the benthic prey community are shaded in grey. (Note well: This height was not present at Rodds Harbour).

SITE	Significance
Cattle Point vs Warner Point	P < 0.001
Cattle Point vs Facing Island	P < 0.001
Cattle Point vs Pelican Banks	P < 0.001
Cattle Point vs Mundoolin Rocks	P < 0.001
Warner Point vs Facing Island	P < 0.001
Warner Point vs Pelican Banks	P < 0.001
Warner Point vs Mundoolin Rocks	P < 0.008
Facing Island vs Pelican Banks	P > 0.391
Facing Island vs Mundoolin Rocks	P > 0.704
Pelican Banks vs Mundoolin Rocks	P > 0.865

Table A8 Key assumptions made in our carrying capacity estimates and the potential consequences if the assumption is violated.

Assumptions	Potential consequences to shorebird carrying capacity estimates if the assumption is violated
All benthic prey items would be available to all shorebird species	We assume that all benthic prey within the relevant depth segment was available to the shorebirds for which carrying capacity was estimated. If this is not the case, our carrying capacity is overestimated
No net loss of benthos over the shorebird non-breeding season	We assume there is no net loss and also no net production. If these occur this would lead to our carrying capacity being over or underestimated, respectively.
All benthos depletion was due to consumption by shorebirds	Other animals may also consume the benthos. Our carrying capacity may thus be overestimated
Shorebird fuel-deposition requires elevated intake rates and takes place during the final one-third of the birds' stay	If the actual total amount of energy required is larger than assumed (higher intake rates or longer fueling period), then our shorebird carrying capacity estimates will be overestimated (and vice versa).
Assimilation efficiency of 80%	If the actual efficiency is lower than assumed, birds need more food and our carrying capacity estimates is too high (and vice versa).
Energy requirements equal to twice the basal metabolic rate	A higher energy requirement would mean our carrying capacity estimates are overestimated (and vice versa).
Various diets for different shorebird species	If a shorebird species has a narrower diet than we assumed, then our carrying capacity estimate will be overestimated, but for other shorebird species that share the same prey, their capacity will be underestimated. (and vice versa)

Table A9 The average proportion of exposed tidal areas per day in each benthic sampling site, from August 2015 to April 2016.

Location	**Height band**	**Average proportion of exposed area per day (mean ± S.D.)**	**Area (km^2)**	**Average proportion of exposed area per site (weighted by the size of each height band)**
Cattle Point	1	0.83 ± 0.07	0.037	0.18
	2	0.73 ± 0.06	0.052	
	3	0.24 ± 0.04	0.719	
	4	0.15 ± 0.04	3.223	
Warner Point	1	0.33 ± 0.05	0.135	0.18
	2	0.27 ± 0.04	0.172	
	3	0.14 ± 0.05	0.84	
	4	0.18 ± 0.06	2.99	
Pelican Banks	1	0.33 ± 0.05	1.032	0.09
	2	0.14 ± 0.08	0.227	
	3	0.06 ± 0.05	3.1	
	4	0.02 ± 0.03	2.785	
Facing Island	1	0.21 ± 0.07	0.121	0.06
	2	0.11 ± 0.07	0.292	
	3	0.05 ± 0.04	0.493	
	4	0.02 ± 0.03	0.725	
Mundoolin Rocks	1	0.23 ± 0.07	0.121	0.10
	2	0.19 ± 0.07	0.228	
	3	0.16 ± 0.07	0.205	
	4	0.09 ± 0.06	6.483	
Rodds Harbour	1	0.29 ± 0.06	0.155	0.18
	2	0.24 ± 0.07	0.18	
	3	0.22 ± 0.07	0.256	
	4	0.17 ± 0.06	2.256	

Table A10 Sightings and recaptures of shorebirds that were originally banded outside the ERMP Survey Area. Individuals flagged in this project and seen beyond the ERMP Survey Area are shown in parentheses.

	Alaska	**Kamchatka or Sakhalin Island, Russia**	**Japan**	**South Korea**	**Yalu Jiang, Bohai Bay, or Jiangsu, China**	**Chongming Dongtan, China**	**Taiwan**	**Palau, Micronesia**	**Northwest Australia**	**Queensland (Brisbane and Toorbul)**	**Victoria**	**New Zealand**	**Total**
Bar-tailed godwit	3	0	0	0 (1)	1	5	0	0	0	0	3	0	**12**
Caspian tern	0	0	0	0	0	0	0	0	0	0	4	0	**4**
Curlew sandpiper	0	0	0	0	0	0	1	0	0	0	3	0	**4**
Eastern curlew	0	0	0	0	0	0	0	0	0	0 (1)	0	0	**0**
Great knot	0	1	0	0	0	7	0	0 (1)	0	3	1	0	**12**
Greater sand plover	0	0	0	0	0	1	2	0	0	0	0	0	**3**
Grey-tailed tattler	0	1 (1)	0 (4)	0	0	0	0	0	0	0	0	0	**1**
Lesser sand plover	0	0	1	0	0	1	0	0	1	0	0	0	**3**
Red knot	0	0	0	0	3	1	0	0	1	0	5	5	**15**
Red-necked stint	0	1	0	0	1	0	0	0	0	0	3	0	**5**
Sand plover sp.	0	0	0	0	0	1	0	0	0	0	0	0	**1**
Terek sandpiper	0	0	0	0	0	1	0	0	0	0	0	0	**1**
Total	**3**	**3**	**1**	**0**	**5**	**17**	**3**	**0**	**2**	**3**	**19**	**5**	**62**

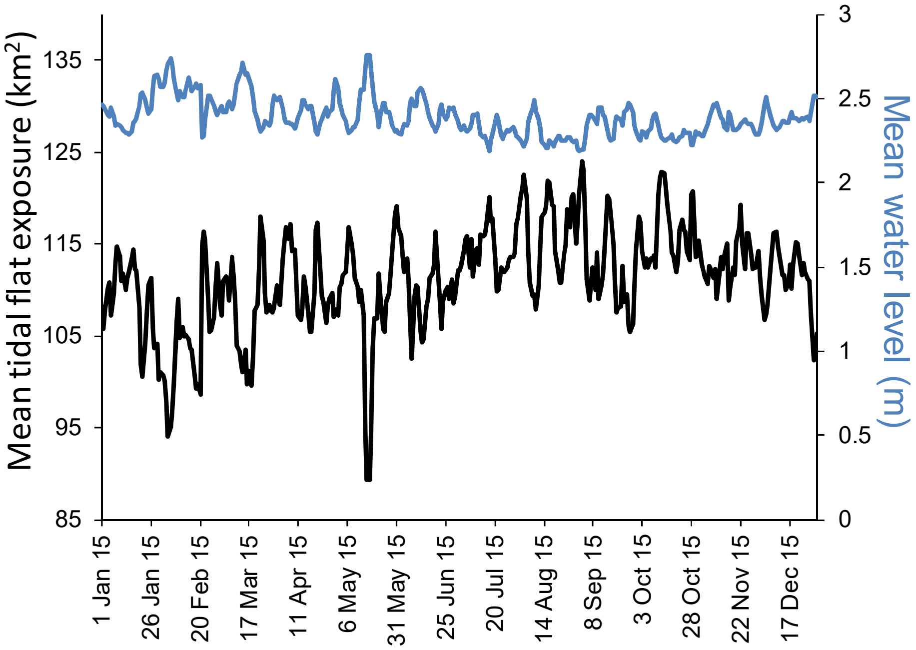


Figure A1 Daily variation in estimated mean tidal flat exposure across the ERMP Survey Area in 2015, alongside daily mean water level from the Auckland Point tidal gauge.

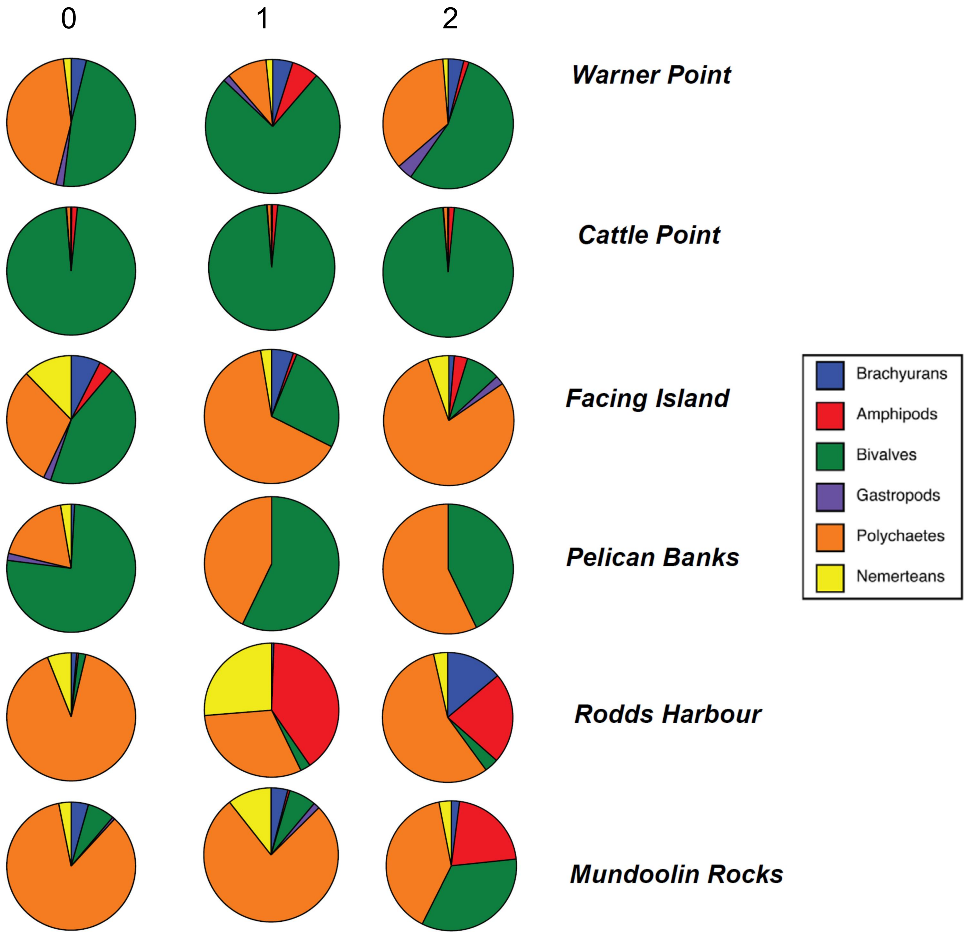
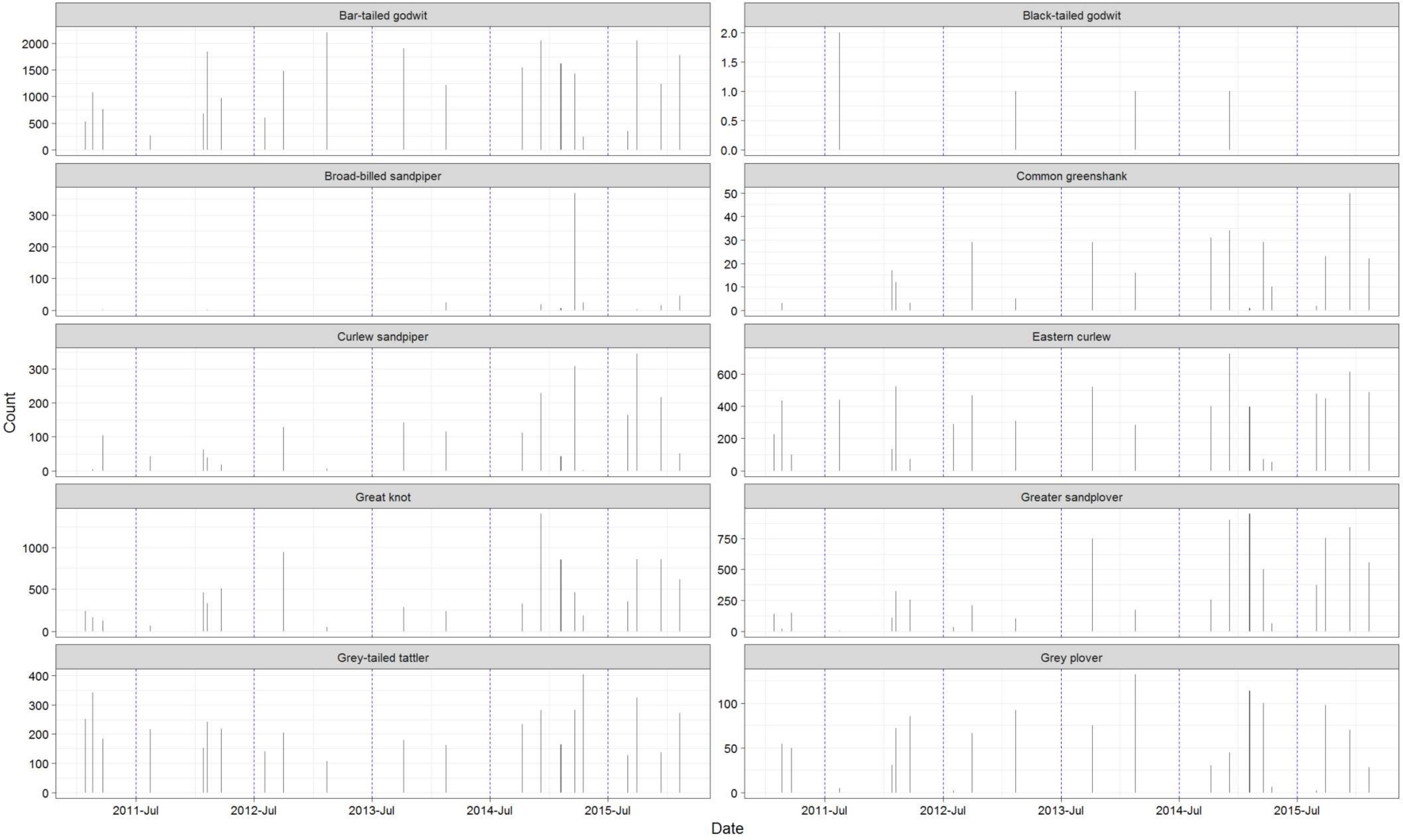


Figure A2 Relative proportion (expressed as % of individuals) of the six most abundant invertebrate taxa found in sediment samples across the six sites. Only the top three height bands are shown, because bands 2–5 showed similar patterns.

Figure A3 Large number of soldier crabs moving in big groups on the tidal flats in the Pelican Banks. These crabs were often seen in large numbers but their abundance might not be reflected accurately from our sampling method (estimated density in Pelican banks was 7 ± 33 m^2 or 9 individuals from 100 samples).



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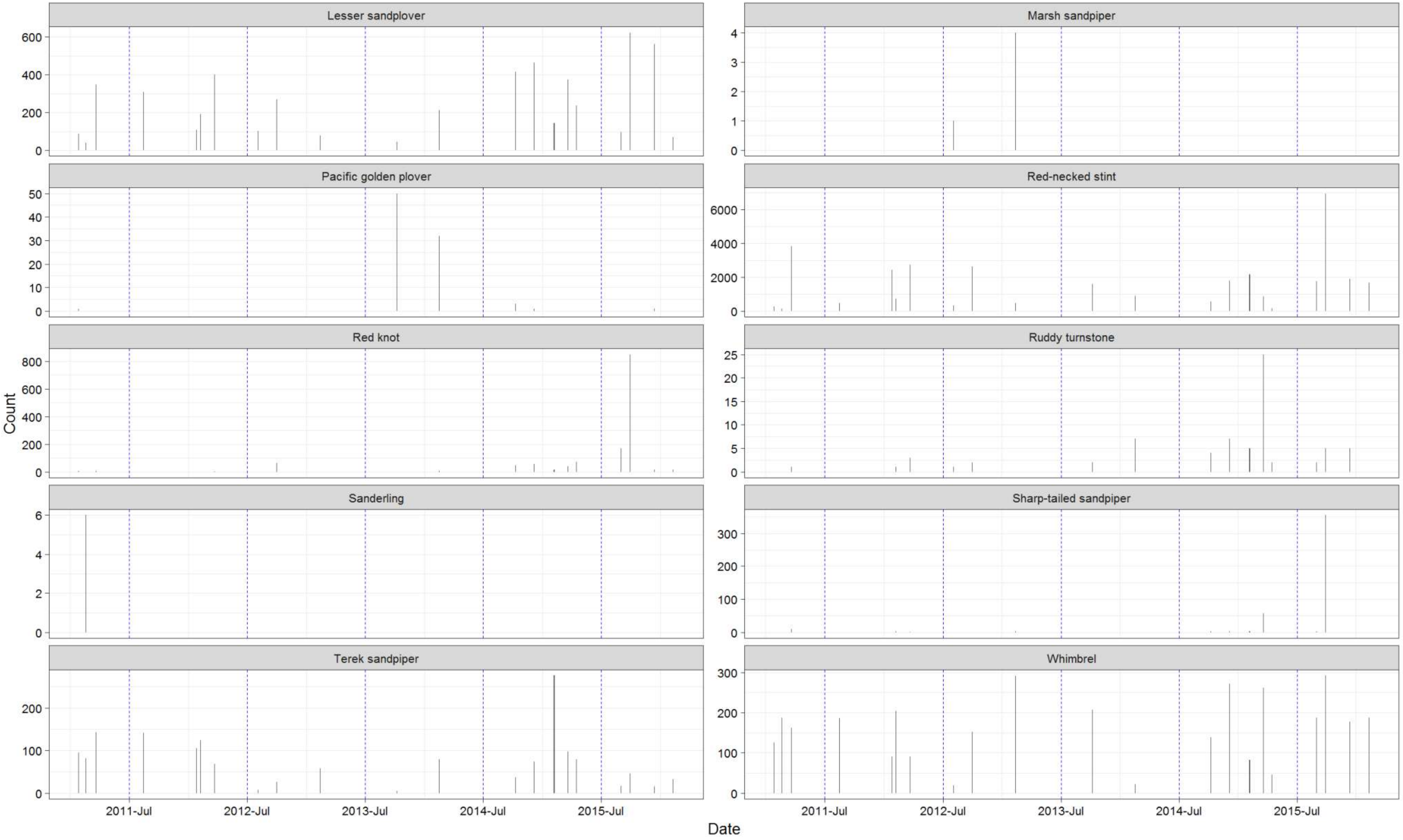

Figure A4 The number of shorebirds recorded in the 13 targeted survey sites since the shorebird monitoring programme started. The blue vertical dashed lines marked the middle of Austral winter when the adult migratory shorebirds left for the northern hemisphere for their breeding season.