Managing Threats to Migratory Shorebirds in Moreton Bay

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We acknowledge the Quandamooka People, Traditional Custodians of the lands, waters and seas on which this report is focused. We pay our respects to Elders, past, present and emerging. We believe the spiritual, cultural and physical consciousness gained through this custodianship is vital to maintaining the future of this region.

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Glossary of terms

Benthic	Referring to the lowest regions of a body of water, including the sediment surface and the layers immediately underneath it.
BirdLife Australia	BirdLife Australia is the national organisation that resulted from the merger of Birds Australia and Bird Observation & Conservation Australia (BOCA) in 2012.
Disturbance	The process whereby any human activity causes shorebirds to alter their normal behaviour. This might include ceasing foraging, increasing vigilance behaviours, flushing on foot or wing, or sounding alarm calls.
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999 (Cwlth) – nationally relevant legislation.
Flyway	The collection of routes followed by migratory birds on their journeys between their breeding and non-breeding grounds.
Internationally important site	There are nine criteria under the Ramsar Convention on Wetlands against which a site could be determined to be internationally important. Here we use criterion 6, since it relates specifically to individual species of waterbird. In this report, a site is considered internationally important if it regularly supports at least 1% of the individuals in a population of at least one species or subspecies of shorebird.
Intertidal	The part of the coastline that is periodically submerged by the tide.
LGA	Local Government Area – also known as city council, shire council or regional council.
Low tide foraging habitat	An area that is only accessible to shorebirds for foraging during low tide and is submerged at other times.
Marine Parks Act 2004	Queensland relevant legislation
Moreton Bay Marine Park	A marine protected area under the jurisdiction of the Queensland Government.
Nationally important site	A roosting or feeding site is considered nationally important if it regularly supports at least 0.1% of the individuals in a population of at least one species or subspecies of shorebird.
Nature Conservation Act 1992	Queensland relevant legislation. Abbreviated as NC Act.
Queensland Wader Study Group	The Queensland Wader Study Group (QWSG) was established in 1992 as a special interest group within Birds Queensland, to monitor wader populations in Queensland and to work towards their conservation.
Ramsar	The Convention on Wetlands, known as the Ramsar Convention, is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources (see http://www.ramsar.org for details).
Reclamation	The deposition of aquatically submerged spoil to form new land
Roost	A site used by shorebirds during the high water period for the performance of a range of behaviours including resting, sleeping, preening, or feeding.

Shorebird	A general term used to describe a collection of species from the taxonomic order Charadriiformes, often termed 'waders'. Migratory shorebirds are those that breed outside Australia, while non-migratory species are those that breed in Australia. Note that non-migratory species can undertake long distance movements within Australia and their abundance at the coast can vary substantially over time.
Supratidal foraging	Foraging carried out by coastal shorebirds during high tide, often on near-coastal wetlands that provide foraging habitat at times when tidal flats are submerged.
Tidal flats	A general term used to describe the intertidal zone where shorebirds forage. May be intermittently exposed on incoming and outgoing tides as well as at low tide.

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1 Executive summary

Much has been achieved in the years since the publication of the Shorebird Management Strategy for Moreton Bay by Queensland State Government (Environmental Protection Agency 2005). However, current analysis shows that most of the same threats to migratory shorebirds are still present, and many have increased since 2005. Enhanced management action is clearly warranted. Quandamooka country is one of Australia's premier sites for migratory shorebirds, and Moreton Bay is recognised through a listing as a site under the Convention on Wetlands of International Significance (the Ramsar Convention), i.e., as a Ramsar Site. The site has about 35,000 migratory shorebirds visiting during the non-breeding season, and thousands of young shorebirds use it as a year-round nursery before they are mature enough to migrate. Many migratory shorebird populations are declining in Moreton Bay. Habitat loss along the migration routes of the birds in the Yellow Sea is a major cause of the declines, but recent analyses have confirmed that threats in Moreton Bay play an additional role, indicating that local management is needed in addition to actions overseas.

1.1 Roosting sites

During the incoming and high tide, intertidal feeding areas are submerged and migratory shorebirds gather to roost above the waterline. Roosting migratory shorebirds generally need large, open, flat areas, with minimal vegetation, close to or bordering the open water at high tide, and free from disturbance. Because migratory shorebirds congregate in large numbers while roosting, most monitoring has occurred during this time. A well-organised community organisation of experts, the Queensland Wader Study Group, has monitored migratory shorebirds by counting them at high tide roosts in Moreton Bay since 1992. This has yielded high quality information about the status and trends of migratory shorebirds in Moreton Bay.

Internationally important numbers of nine migratory shorebird species regularly occur in Moreton Bay, and numerous individual roosting sites throughout the Bay support internationally or nationally important numbers. Important roost sites are spread throughout the Bay, indicating a need for widespread threat management. From a total of 218 roosting sites assessed in the Bay, 15 have become unsuitable for shorebirds in the past few decades, and approximately one third of Moreton Bay's migratory shorebirds are now dependent on habitat created by the construction of a permanent shorebird roost and temporary reclamation areas at the Port of Brisbane, with an additional 2,000 migratory shorebirds (and up to 4,000) regularly occurring at the nearby artificial shorebird roost at Manly Harbour.

Analysis of the impacts of three severe weather events revealed some minor changes in the abundance and distribution of migratory shorebirds in Moreton Bay immediately after the event, but these had disappeared a year later. This suggests that the current network of roosting sites exhibits low vulnerability to severe weather events, although whether this will change as sea-level rises over the coming decades remains unclear.

Roost sites are nonetheless heavily threatened by other factors in Moreton Bay, most of which are likely to be intensified by sea-level rise. A threat assessment for roosting sites found that 95% of sites for which information existed are, or have been, impacted by one or more threats. The most widespread threats were human disturbance (67 sites) development (43 sites) and mangrove growth reducing visibility and space for the birds to occupy the roost (25 sites). Several successful examples from around the Bay show that these threats to roosting sites can be addressed through appropriate planning and management actions. Of significant concern over the medium and longer term is the extent to which sea-level rise will exacerbate these threats, and ultimately lead to the inundation of some roost sites. Long term research could be designed to monitor this issue.

1.2 Feeding sites

All of the migratory shorebird species occurring in nationally or internationally important numbers in Moreton Bay feed on tidal flats exposed at low tide. Tidal flats occur widely throughout the Bay, covering about 100 km^2. Each major area of tidal flat has one or more nearby major roosting sites, although migratory shorebirds do not always roost at the nearest available location to their feeding grounds. There has been relatively little change in the overall extent or distribution of tidal flats in Moreton Bay over the last 30 years, but some significant localised losses to development have occurred.

Systematic counts of migratory shorebirds feeding in the intertidal zone between Sandgate and Lota reveal marked spatial variation in the density of birds present, and in some cases substantial overlap between the occurrence of birds and disturbance from recreational users of the foreshore, especially dogs being exercised off-leash. This work was undertaken in a small area; understanding whether this pattern occurs across the wider Bay, and addressing the issue of disturbance of shorebirds foraging at low tide are high priorities for migratory shorebird management in Moreton Bay.

Benthic sampling at Sandgate, Nudgee and Lota revealed spatially variable densities of invertebrate species suitable as migratory shorebird prey, and this variation was consistent with some of the differences in migratory shorebird abundance and diversity. Management to increase food availability in the intertidal areas (such as seeding the flats with bivalve spat) has been attempted elsewhere in the world, and it would be worth investigating its possible effectiveness and feasibility in Moreton Bay.

1.3 Conclusions

The following conclusions arose from the investigations presented in this report:

1. **Critical vulnerabilities exist**. Four critical vulnerabilities were apparent in the present network of migratory shorebird roosting sites in Moreton Bay. These are (i) threats to the roosts at Toorbul and Kakadu Beach, (ii) near-total reliance of about 8,000 of Moreton Bay's migratory shorebirds on roosting habitat at the Port of Brisbane that is only a temporary by-product of construction activity, (iii) the lack of protection and long term maintenance strategy for the critically important Manly Harbour roost, and (iv) the apparent lack of sufficient roosts adjacent to large areas of tidal flat along the western shore of Minjerribah (North Stradbroke Island).
2. **Critical vulnerabilities can be remedied by management**. These critical vulnerabilities in the current network of roosting sites could be addressed by (i) augmenting the threat abatement works underway at the Toorbul and Kakadu Beach roosts, and (ii) creating, augmenting, or protecting artificial roosting sites at Dynah Island, Minjerribah (North Stradbroke Island) and Manly Harbour. A management plan is needed to determine how the c. 8,000 shorebirds currently using temporary habitat at the Port of Brisbane will be accommodated after the Port reclamation is completed. The long-term future of the internationally significant artificial shorebird roost at Manly Harbour must be secured.
3. **Human disturbance management and vegetation control are needed at roosting sites**. Disturbance and / or vegetation overgrowth that reduces visibility and space (primarily mangroves) were identified as threats to more than two-thirds of assessed roosting sites in Moreton Bay. Substantially increased investment is needed to tackle these issues at a number of roost sites. A project prioritisation protocol would help determine the order of priority for roost site management. Judicious monitoring of these threats is also warranted at carefully selected sites as sentinels to warn of future change, and to test the effectiveness of management interventions.
4. **Trials of management of water levels to enhance roost suitability and supratidal foraging**. Provision of supratidal foraging habitat has proven to be highly effective at providing additional habitat for migratory

shorebirds. These artificial or actively managed wetlands also provide important roosting locations when they are close to tidal flats. Such methods could be trialled at artificial roosts at the Port of Brisbane, Manly Harbour, and potentially other locations around Moreton Bay. Additionally, shorebirds tend to use claypans when they are not completely dry or completely inundated. Relatively simple modifications using earthworks could be trialled at Tinchi Tamba to determine how to control claypan water level in a way that will increase the current effectiveness of such sites for shorebirds, and make them more resilient to sea-level rise and severe weather events.

5. **Effects of severe weather events are weak and short-lived**. Analysis shows that severe weather events in 2011, 2013 and 2017 had no consistent effect on the abundance and distribution of shorebirds in the Bay. As such there seems to be little need for emergency adjustments to shorebird management in the aftermath of future severe weather events, at least those equally or less severe than the 2011 event. However, oil spill from shipping caught in bad weather is a real risk, and it would be beneficial to include migratory shorebirds in oil spill response management plans for Moreton Bay.

6. **Off-leash dogs are disturbing foraging shorebirds at low tide**. We found high levels of disturbance to foraging birds at low tide by off leash dogs along the Brisbane foreshore at least between Deception Bay and Lota. The presence of dogs appears to reduce the number of shorebirds present at a site by about 20%, and also has an unknown long term effect on the number of birds choosing to use a region. With more than 80% of dogs on the foreshore currently being exercised off-leash, greatly enhanced management is needed to understand and reduce this threat to foraging shorebirds in Moreton Bay.

7. **Prey densities are variable**. Indicative sampling of benthic invertebrates living in the sediment at Sandgate, Nudgee and Manly foreshore indicate spatially variable densities of potential prey for shorebirds, and that most potential prey items are comparatively small bodied. This highlights the need for disturbance to foraging migratory shorebirds to be substantially reduced, and points to the need for more comprehensive surveys across Moreton Bay.

8. **Greater resourcing of the Queensland Wader Study Group is needed**. Partnerships are already occurring, but deeper in-kind contributions (e.g. further vessel support) would fill a number of identified gaps in shorebird monitoring, and direct investment will enhance the capacity of the Queensland Wader Study Group to undertake this increased monitoring. This is perhaps best achieved by employing or seconding a staff member for a fixed term to (i) expand the base of volunteer surveyors, and (ii) upgrade systems for data capture and flow. Of particular importance is a need to update the estimate of the total number of migratory shorebirds using Moreton Bay. The most recent Bay-wide census took place in 2008, which makes estimating recent or current populations challenging. Given the fundamental importance of population estimates for conservation and management (e.g., for meeting Ramsar criteria), annual or bi-annual Bay-wide censuses would be beneficial, but would likely require additional resourcing (e.g., boats and/or aircraft for Pumicestone Passage and southern Moreton Bay).

1.4 Top management priorities

The foregoing investigations suggest the following urgent and important management actions to mitigate threats to migratory shorebirds and their habitats in Moreton Bay, noting that the order in which they are presented is not intended to signal priority:

1. Conduct a major strategic planning process to establish how to ensure there will be sufficient roosting site capacity for the birds currently using the Port of Brisbane, as works to fill in the reclamation ponds take

place over the next three decades. The strategic plan must involve all relevant stakeholders, and carefully enumerate and evaluate possible options, including enhanced management of existing roosting sites, and the construction of additional artificial sites.

2. Implement threat management at roost sites. A project prioritisation process that evaluates the cost, benefit and feasibility of taking the necessary actions to mitigate threats at each roost, will enable the most cost-effective sites to be tackled first. Kakadu Beach and Toorbul are especially important sites in this regard, given the large number of birds these roosts support, the number of threats operating, and the already existing management plans and implementation efforts being conducted by Moreton Bay Regional Council.

3. Design and implement strategies to reduce disturbance to migratory shorebirds foraging at low tide. This could involve (i) measuring the density of foraging shorebirds throughout Moreton Bay, (ii) measuring disturbance to the birds, (iii) identifying the most appropriate form of management response (e.g. changes to legislation, guidelines, enhanced enforcement, awareness-raising, designating off-leash areas), to address the disturbance in different areas, and (iv) monitoring the success of the management, and using the information to modify the management strategy where necessary.

2 Ecological background and management context

Moreton Bay Marine Park is a major destination for migratory shorebirds breeding in the nortern hemisphere (**Figure 2.1**; **Table 2.1**). It forms part of the East Asian-Australasian Flyway, which is one of the nine major waterbird flyways globally, spanning 22 countries from the Alaskan and Siberian breeding grounds in the Palearctic, staging and stop-over areas in East Asia, and resting and refuelling habitats in Australia and New Zealand (Geering *et al.* 2007). Many migratory shorebird populations in the East Asian-Australasian Flyway are declining rapidly, with eight species or subspecies listed as nationally threatened in Australia (Studds *et al.* 2017; Fuller *et al.* 2019). All regularly occurring migratory shorebird species in Australia are listed as matters of national environmental significance under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Parts of Moreton Bay are also included as a Ramsar site, with shorebirds a key aspect of the ecological character of this Ramsar site.

As one might expect for a suite of species that occurs across such a large area, a multitude of threats face migratory shorebirds. Certain pressures are particularly intense in the East Asian-Australasian Flyway, with the key driver of shorebird population declines being the loss of two thirds of the intertidal habitat in the Yellow Sea over the past 50 years. These losses of intertidal habitat have substantially reduced the availability and quality of refuelling sites for the birds on their long journeys between their breeding grounds and Australia (Amano *et al.* 2010; Murray *et al.* 2014; Piersma *et al.* 2016; Studds *et al.* 2017). Species that largely avoid the Yellow Sea during migration are typically not declining, and some are even increasing (Studds *et al.* 2017), suggesting a critical role for Yellow Sea habitat loss in explaining the declines of Australia's migratory shorebirds (Clemens *et al.* 2016), and the declines observed within Moreton Bay specifically (Wilson *et al.* 2011; Dhanjal-Adams *et al.* 2019). Yet migratory species depend on a complete chain of intact habitats along their migration routes, and habitat degradation anywhere along the chain can impact the entire population (Iwamura *et al.* 2013; Runge *et al.* 2014). Population limitation can occur at any stage of the migration cycle, and can be exacerbated by the interaction of conditions experienced in one season that carry over to impact individual fitness in another season (Faaborg *et al.* 2010, Harrison *et al.* 2011). Thus, proper management of important sites such as Moreton Bay is crucial in the context of the birds' lengthy migration journeys.

There has been a general reduction in the number of birds returning to Moreton Bay each year from the breeding grounds (Wilson *et al.* 2011). Changes in shorebird numbers at various sites across Moreton Bay are not uniform (see **Section 4.1**), suggesting additional threats are operating within Moreton Bay. Indeed, a recent analysis showed that factors local to Moreton Bay as well as factors operating more broadly around the flyway interact to explain why migratory shorebirds are declining in Moreton Bay (Dhanjal-Adams *et al.* 2019). This is important because it demonstrates the need for robust management of the birds and their habitats within Moreton Bay. Enhanced management will enable migratory shorebirds to recover more quickly from their journeys, and gain sufficient body condition to successfully complete their northward migrations on leaving Moreton Bay.

There is a substantial legislative context to migratory shorebird management in Moreton Bay, with federal and state legislation such as the EPBC Act, *Nature Conservation Act 1992 and Marine Parks Act 2004* providing for the listing of shorebird species, declaration of marine and terrestrial protected areas, development of recovery plans, and assessment of actions that may impact shorebirds or their habitat. Moreton Bay was declared a Ramsar site in 1993, partly on the basis of shorebird populations, and is thus treated as matter of national environmental significance under the EPBC Act. The *Coastal Protection and Management Act 1995* manages development and land-use planning in the coastal zone, and determines matters of State interest such as marine park highly protected areas, ecologically significant wetlands and wildlife habitat. Some aspects of development and land-use planning in the coastal zone has been incorporated into the *Planning Act 2016*. Other pieces of legislation protect marine resources and habitats relevant to shorebird conservation in Moreton Bay including the *Environmental Protection Act 1994* and *Fisheries Act 1994*. Habitat for shorebirds in Moreton Bay is managed by local government and waterways authorities and incorporates a range of tenures such that there is great complexity and a degree of confusion regarding roles and responsibilities.

A critical feature of Moreton Bay Marine Park is the close proximity of the human population of Greater Brisbane, and the resulting demand for commercial and recreational use that must be accommodated within the context of wise use of the wetland. Human uses need to be balanced with conservation values, and this is currently achieved through the careful use of zoning that protects important habitat and regulates types of use through the *Marine Park (Moreton Bay) Zoning Plan 2008*. The zoning plan contains provisions that specifically protect shorebirds and their habitat from unreasonable disturbance, yet this has proven difficult to interpret and enforce, and disturbance to feeding and roosting habitats remains a major threat (see **Sections 4** and **5**). Zoning has at least been partially successful in managing threats to shorebirds in Moreton Bay, with marine national park zones showing the lowest frequency of disturbance to shorebirds at high tide roosts (Fuller *et al.* 2009), although disturbance, especially by off-leash dogs, continues to be a major problem in several important intertidal feeding areas (Dhanjal-Adams *et al.* 2016; Stigner *et al.* 2016).

As well as these general provisions that have implications for management of migratory shorebirds as one of many key values of Moreton Bay, there is also a document that sets out a number of management goals specifically for migratory shorebirds in the Bay. The *Shorebird Management Strategy: Moreton Bay* (Olds 2005), outlines the roles and responsibilities of the Queensland Government as well as other stakeholders in executing the various legislative and planning frameworks relevant to migratory shorebirds in the Bay. The *Strategy* provides a five-pronged approach to adequately protect migratory shorebirds. Specifically, it points to protecting shorebird habitat, protecting shorebirds from disturbance and protecting critical shorebird sites, which are differentiated from habitat as being high tide roost sites and specific areas of congregation (Olds 2005) (**Figure 2.1**; **Table 2.1**). Furthermore, raising community awareness and continued research and monitoring are highlighted as key management approaches. Our investigations reported here suggest that these five approaches remain appropriate for achieving effective conservation of migratory shorebirds in Moreton Bay.

Many of the pressures on shorebirds and their habitats in Moreton Bay have intensified since the *Strategy* was written in 2005. For example, the human population in coastal areas adjacent to the Bay has grown rapidly in the last 15 years, putting pressure on migratory shorebirds through the provision of new urban dwellings in coastal areas, but also increased incidence of disturbance through the sheer number of people using the coastal environment for recreational and commercial purposes. The increase in the urban footprint is coupled with an increase in impervious surfaces and subsequent deposition of contaminants (e.g. particulates from car exhausts on streets and roads) into the Bay, and it is possible that these factors are contributing to a reduction in benthic prey abundance at three locations (Clemens *et al.* 2012). The current status of the intertidal benthic environment in Moreton Bay is unclear, although we do know that the maintenance of shorebird populations will require adequate accessible benthic prey populations that provide sufficient energy, in combination with nearby roosting sites (Colwell 2010).

Active management of threats to shorebirds in accordance with the statutory and non-statutory tools described above depends on the responsibility and jurisdiction of relevant authorities. The *Strategy* outlines the need for the various governance entities across the Bay to work in a coordinated fashion. This was also emphasized by Steven *et al.* (2017) who reviewed the current status and threats to migratory shorebirds in southern Moreton Bay. While there is a solid legislative basis on which to base and guide shorebird management, funding for more effective enforcement of existing rules, and for more active management, is a matter of competing priorities within governments. Thus far, much of the management has been achieved in collaboration with natural resource management bodies and non-profit organisations that are eligible to apply for grant funding. There is currently no overarching coordinating group that brings together the range of entities involved in migratory shorebird management on a regular basis to enhance coordination and collaboration.

The Queensland Wader Study Group (QWSG; a special interest group of Birds Queensland) was established in 1992 to monitor and conserve shorebird populations. Run entirely by volunteers (like most shorebird monitoring in Australia; Hansen *et al.* 2018), close interaction between organisers and surveyors has been key to the impressive accuracy, precision, coverage and longevity of shorebird monitoring in Queensland. One notable feature of monitoring in parts of Queensland is monthly counts, which reduce within-year count variability and increase statistical power to detect trends compared with less frequent monitoring elsewhere in Australia (Wilson *et al.* 2011). Although QWSG works across the entire state, much of the activity of the group has focused on Moreton Bay, resulting in a robust monitoring dataset that enables sophisticated analyses of the magnitude and causes of trends in migratory shorebird population changes in Moreton Bay (Wilson *et al.* 2011; Dhanjal-Adams *et al.* 2019).

Figure 2.1

Roosting sites for migratory shorebirds in Quandamooka Moreton Bay, also showing LGA and Ramsar site boundaries, and the extent of tidal flats. Where a number of small roost sites occur in close proximity, they have been amalgamated in this map. See Table 2.1 for a list of roosting sites and their locations.

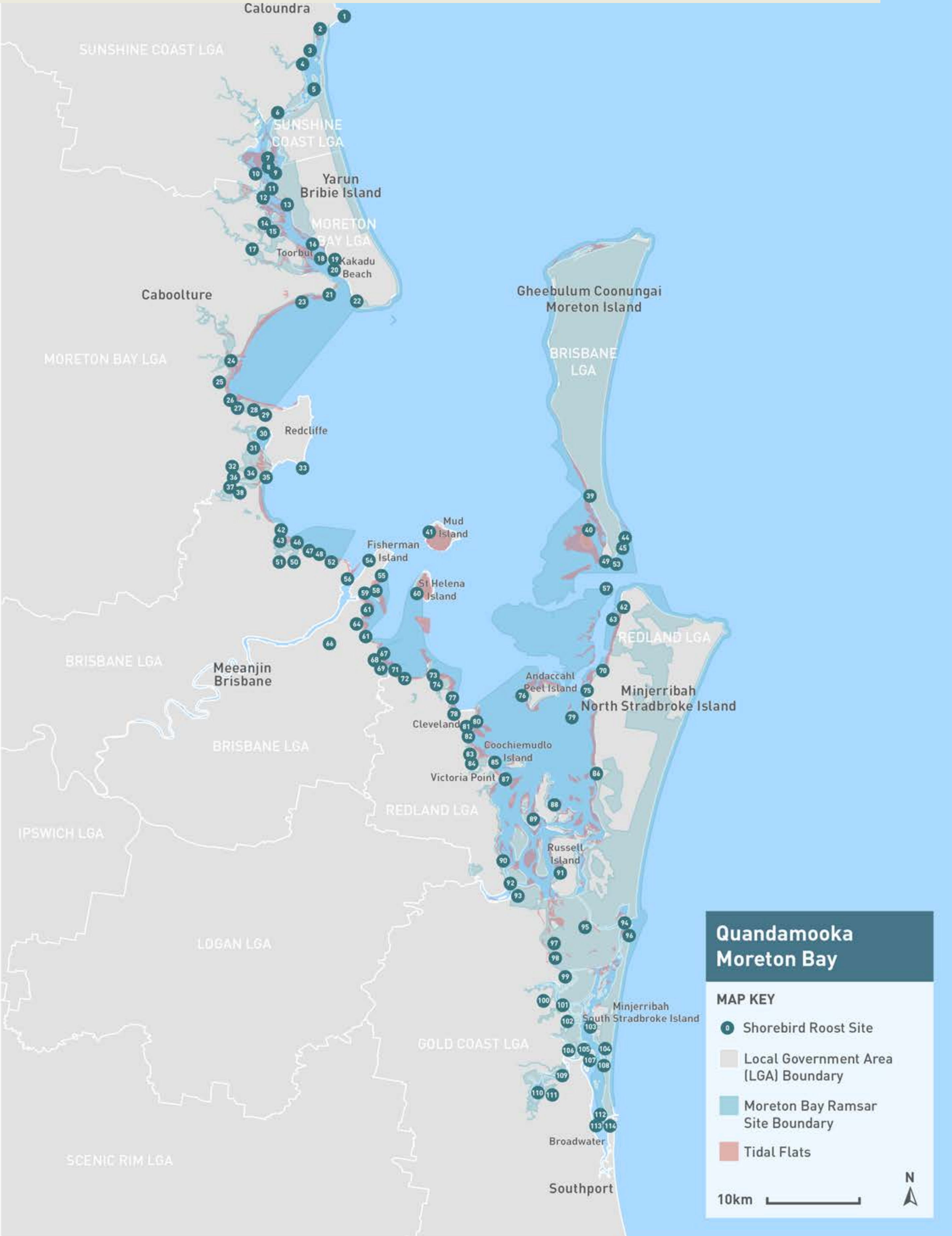


Table 2.1

Locations of migratory shorebird roosting sites in Quandamooka Moreton Bay. Where a number of small roost sites occur in close proximity, they have been amalgamated in this table. Refer to Figure 2.1 for a map of these roost sites.

LABEL	SITE NAME	LATITUDE	LONGITUDE
1	Wickham Pt	-26.801100	153.150300
2	Caloundra Bar	-26.811100	153.127800
3	Lamerough Ck	-26.833300	153.116700
4	Bell's Ck	-26.845800	153.109700
5	Egg Is	-26.873600	153.119400
6	Roy's Rd	-26.895800	153.084270
7	Long Island	-26.944400	153.075000
8	Thooloora Is	-26.950000	153.075000
9	Lime Pocket	-26.958300	153.083300
10	Tripcony	-26.958300	153.062500
11	Mission Pt	-26.975000	153.077800
12	Glass Mountain Ck	-26.980600	153.069400
13	Poverty Ck	-26.991710	153.093460
14	Donnybrook Claypan	-27.012800	153.070000
15	Bullock Ck mouth	-27.019330	153.078000
16	Toorbul	-27.033333	153.116669
17	Bishop's Marsh	-27.038900	153.058300
18	Avon Wreck	-27.050000	153.126400
19	Kakadu Beach	-27.050000	153.138900
20	Dux Creek	-27.052800	153.138900
21	Sandstone Pt	-27.083590	153.135800
22	Buckley's Hole	-27.091670	153.163100
23	Godwin Beach	-27.091700	153.108300
24	Caboolture R mouth	-27.151700	153.037500
25	Deception Bay Claypan	-27.172200	153.023100
26	Webster Rd	-27.195430	153.036740
27	Deception Bay South	-27.200600	153.040000
28	Redcliffe Airport	-27.202600	153.060600
29	Nathan Rd	-27.208300	153.066700
30	Clontarf West	-27.233334	153.066666
31	Gregory Rd	-27.245254	153.057198
32	Bray's Lagoon	-27.266700	153.036100
33	Woody Pt	-27.266700	153.105300
34	Korman Rd East Claypan	-27.272200	153.053300
35	Hornibrook Hwy sandbar	-27.275300	153.068100
36	Osprey House	-27.276900	153.037200
37	Deepwater Bend	-27.283300	153.033300
38	Pine Rivers Wetland Res	-27.291700	153.041700
39	North Sandhills	-27.291870	153.404400
40	Crab Is	-27.329600	153.400520
41	Mud Isd	-27.329700	153.239000
42	Shorncliffe Channel	-27.331900	153.086100
43	Dynah Is	-27.334700	153.084700
44	Mirapool	-27.337500	153.440300
45	Dead Tree Beach	-27.341424	153.435969
46	Nudgee Beach	-27.341700	153.100000
47	Jackson Ck Pt	-27.350800	153.113100
48	Brisbane Airport	-27.352840	153.120960
49	Day's Gutter	-27.359526	153.421324
50	Anne Beasley's Lagoon	-27.360000	153.099000
51	Kedron Brook Wetlands	-27.360800	153.083800
52	Serpentine Ck	-27.361100	153.133300
53	Reeders Pt	-27.361597	153.428244
54	Port of Brisbane Reclamation Area	-27.361700	153.175000
55	Port of Brisbane Shorebird Roost	-27.373890	153.186030
56	Luggage Pt	-27.377800	153.150000
57	South Passage Bar	-27.388900	153.419400
58	Fisherman Islands Claypan	-27.389480	153.176370
59	Fisherman Islands Visitor Centre	-27.391700	153.167020
60	St Helena Is	-27.394400	153.222200
61	Lytton Claypan	-27.406990	153.168930
62	Amity Pt	-27.409700	153.435300
63	Wanga Wallen Bank	-27.419780	153.428730
64	Lytton	-27.423600	153.164400
65	Wynnum Esplanade	-27.438890	153.175000
66	Kianawah Rd	-27.446870	153.141310
67	Manly Harbour	-27.459730	153.193190
68	Lota Esplanade	-27.466700	153.194400
69	Mooroondu Pt	-27.475000	153.200000
70	Myora Springs	-27.475000	153.416700
71	Thorneside	-27.476285	153.199969
72	Queens Esp.	-27.483300	153.208300
73	Wellington Pt	-27.483300	153.241700
74	Geoff Skinner Reserve	-27.486400	153.243100
75	Dunwich	-27.494370	153.401180
76	Peel Is	-27.500000	153.333300
77	Empire Point	-27.503300	153.261400
78	Raby Bay	-27.516666	153.266663
79	Goat Is	-27.517260	153.383910
80	Toondah Harbour	-27.524660	153.286420
81	Nandeebie	-27.533300	153.279200
82	Oyster Pt	-27.536100	153.280600
83	Thornlands Rd	-27.558300	153.282800
84	King Street Mudflat	-27.562500	153.283900
85	Point Halloran	-27.565600	153.308300
86	Blakesleys Camp	-27.576400	153.408300
87	Victoria Pt	-27.582460	153.318060
88	Perulpa Is	-27.608300	153.366700
89	Perrebinpa Pt	-27.622360	153.345800
90	St Clair Is	-27.666100	153.312200
91	West Russell Is	-27.678260	153.371830
92	Lagoon Is	-27.688900	153.320600
93	Logan R Mouth	-27.701610	153.325060
94	Swan Bay	-27.730000	153.439200
95	Cobby Cobby Is	-27.735000	153.398300
96	Horsehoe Bay	-27.743600	153.443060
97	Kangaroo Is	-27.752300	153.366000
98	Jacobs Well to Cabbage Tree Pt	-27.766666	153.366669
99	Dinner Is	-27.786100	153.377200
100	Cabbage Tree Pt	-27.813100	153.355820
101	Pimpama foreshore	-27.818870	153.372720
102	Coomera R	-27.835300	153.380600
103	Couran to Brown Is	-27.840800	153.403600
104	Currigee North	-27.866100	153.418890
105	Paradise Pt	-27.866100	153.397800
106	Sanctuary Cove	-27.866900	153.383100
107	Sovereign Is	-27.875000	153.404200
108	Currigee South	-27.882780	153.418600
109	Saltwater Ck	-27.893890	153.375000
110	Coombabah Lake	-27.911100	153.350000
111	Gold Coast WTP	-27.912500	153.362500
112	Carter Banks	-27.935700	153.412100
113	Wave Break Is	-27.945800	153.415300
114	Southport Spit Sandbar	-27.946100	153.420000

3

Project elements

This project is focused on Moreton Bay (**Figure 2.1**; **Table 2.1**; **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 Bay. For example, we consider information on broader population trends to enable us to understand the local patterns in context. We list the detailed activities carried out in the project in **Supplementary Table S1**, against each of the seven project aims:

1. Conduct a data-driven assessment of the adequacy of current high tide roosting sites in Moreton Bay;
2. Identify candidate sites for the creation of new high tide roosts in Moreton Bay;
3. Characterise benthic prey available to migratory shorebirds in northern Moreton Bay;
4. Create a map of shorebird feeding areas in Moreton Bay, and investigate options for their management;
5. Identify gaps in monitoring of migratory shorebirds in intertidal feeding areas of Moreton Bay;
6. Identify gaps in monitoring of migratory shorebirds in roosting areas of Moreton Bay; and
7. Write a draft strategy for managing threats to migratory shorebird habitats in Moreton Bay.

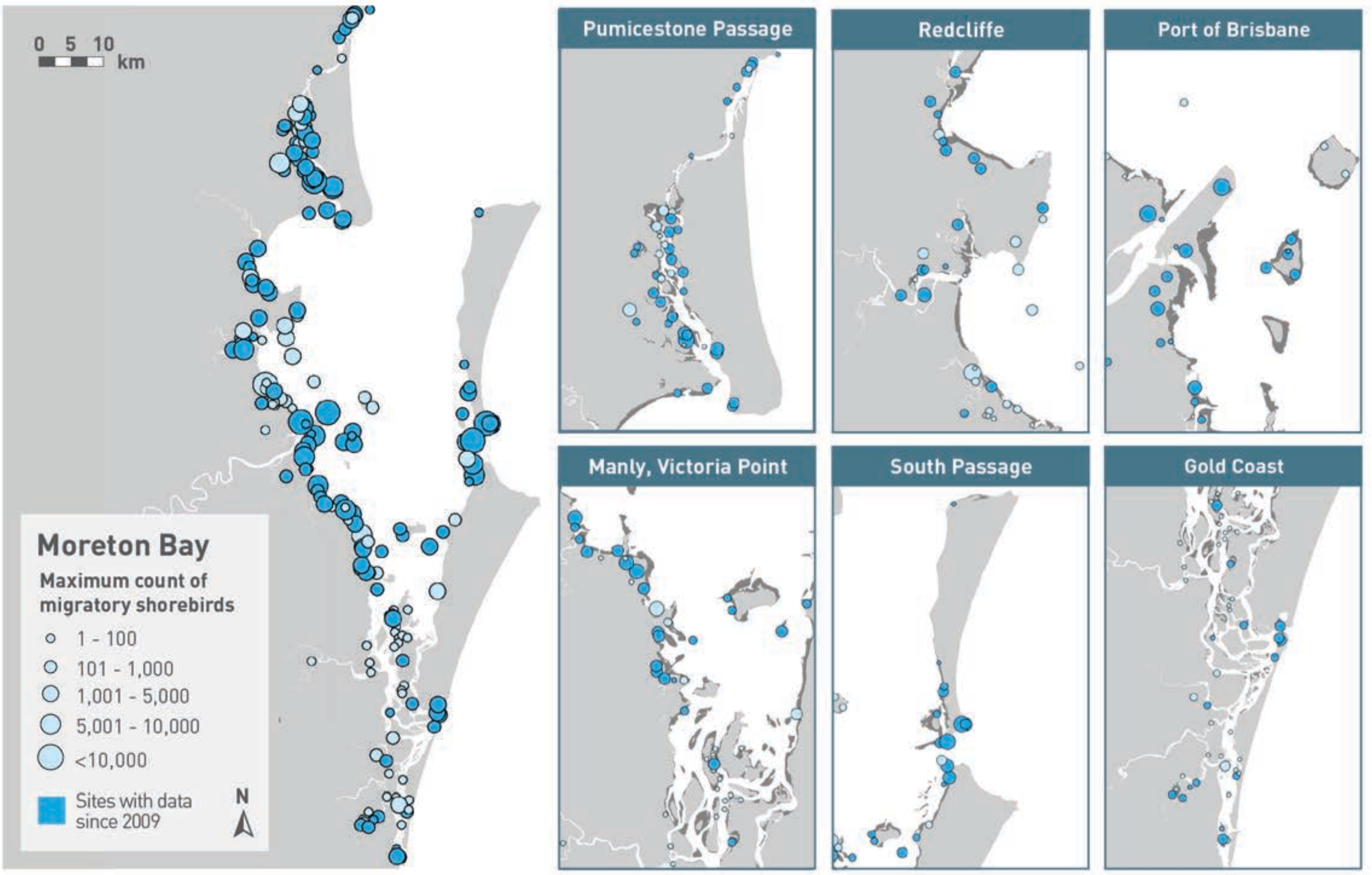


Figure 3.1 Maximum counts of migratory shorebirds at high tide roosts in Moreton Bay. Count data are from 1980 to 2018, and sites with data since 2009 are shown in darker blue. Point size is scaled by the maximum count of migratory shorebirds; this indicates relative abundance, but also means that the number of birds observed on any given visit to one of these sites is likely to be lower than is apparent here. Note that point sizes have been reduced in the insets to permit detail to be seen; refer to main map for maximum count of migratory shorebirds at each site.

4 Adequacy of high tide roosting sites in Moreton Bay

Moreton Bay is home to one of the largest concentrations of migratory shorebirds in eastern Australia, and hosts one of the largest populations of these birds near a major Australian city. Thirty-two species of migratory shorebird have been observed in the Bay during monitoring by the Queensland Wader Study Group, of which nine species occur regularly in internationally important numbers, with another one having exceeded the threshold for international importance at least once (**Table S2**). A further five species regularly occur in nationally important numbers, and five more have exceeded the threshold for national importance at least once (**Table S2**). A site is considered internationally or nationally important if it regularly supports at least 1% or 0.1% of the individuals in a population of a species or subspecies of shorebird respectively. Shorebirds generally forage in intertidal habitats when they are exposed by the tide, and then move to roosting sites above the high tide mark when the feeding grounds are covered by the sea.

Shorebirds choose roost sites according to a number of important criteria, and while the details vary markedly among species, there are several general principles that govern the choice of roost sites by shorebirds (see Rogers 2003; Rogers *et al*. 2006). A good roost site will minimise predation risk, which often means a clear line of sight for the birds using the roost, so that approaching predators can be detected during daylight, or shallow water to aid with thermoregulation and to reduce nocturnal predation. Vegetation growth around the site can compromise visibility. A roost site also needs to have low levels of disturbance, which can be from natural causes such as raptors, or anthropogenic causes such as dog-walkers or jet skis. Repeated disturbance will cause birds to take flight, expending energy and losing time to perform important body maintenance behaviours such as preening and sleeping. Conditions such as temperature, wind speed and wind direction will affect the thermoregulation costs incurred by the birds, and roosting sites that are located close to foraging sites will minimise energy spent on the commute. Finally, roost sites need a clear pathway for accessibility by the birds, that is not blocked by infrastructure.

Because the birds concentrate into a relatively small number of well-defined and often traditional roost sites over high water, most counts of shorebirds by the Queensland Wader Study Group have been conducted at high tide roost sites. There are relatively few high tide roost sites available to the birds, and habitat loss and disturbance threaten many of them (Fuller *et al.* 2009). Here we present an assessment of the adequacy and vulnerabilities of the present network of roost sites in Moreton Bay. We achieved this assessment by analysing monitoring data from the Queensland Wader Study Group, and by consulting experts (see **Section 8**) to identify threats to, and gaps in, the current network of high tide roosting sites in Moreton Bay.

4.1 Locations of high tide roosting sites throughout Moreton Bay

Migratory shorebirds in Moreton Bay have been systematically counted by volunteers at nearly 200 sites from as early as 1980, and more systematically at a subset of sites from 1992 onward (Milton & Driscoll 2006; **Figure 2.1**; **Figure 4.1**). Monthly counts are conducted around high tide (80% of visits were made within two hours of the time of high tide), when birds are concentrated at roosting sites located above the high tide mark (Zharikov & Milton 2009).

The number of sites visited per year increased rapidly between 1992 and 1995, but remained relatively stable thereafter, and the spatial extent of survey effort is greater in the summer months when non-breeding migrants are most abundant (Fuller *et al.* 2009).

Migratory shorebird roosting sites are widely distributed throughout Moreton Bay, and some roosts support many more birds than others (**Figure 3.1**). The largest concentrations of migratory shorebirds can be found near the South Passage between Moreton Island and Minjerribah (North Stradbroke Island), at or near the Port of Brisbane, at Manly Harbour, in the southern part of Pumicestone Passage and to a lesser degree along the mainland coast between Bribie Island and Victoria Point (**Figure 3.1**). It is worth noting that migratory shorebirds can occasionally be found roosting or foraging supratidally in small numbers in a range of other habitats, such as freshwater wetlands some distance from the coast, airports and golf courses.

4.2 Numbers of shorebirds using each high tide roosting site in Moreton Bay

While the overall number of migratory shorebirds present at a roost site varies markedly across the Bay, this variation is even greater at the species level. In this section we assess the abundance and distribution of all migratory shorebirds occurring in Moreton Bay that are listed as threatened under the EPBC Act, as well as all remaining species in which nationally or internationally important numbers occur (see **Table S2** for estimates of numbers of all species in Moreton Bay).

Sites were defined as being of international, national, minor, or unknown significance to migratory shorebirds based on maximum counts from the past 10 years (2009-2019). A site was considered internationally or nationally significant if the maximum count of at least one species exceeded 1% or 0.1%, respectively, of the estimated flyway population size (taken from Hansen *et al.* 2016). Minor significance refers to a site that did not meet the 1% or 0.1% threshold for any species and unknown significance refers to sites for which there are no count data since 2009. The flyway population sizes of several species are reported as a range in Hansen *et al.* (2016); in these cases site significance was calculated using the lower bound of the estimated population size.

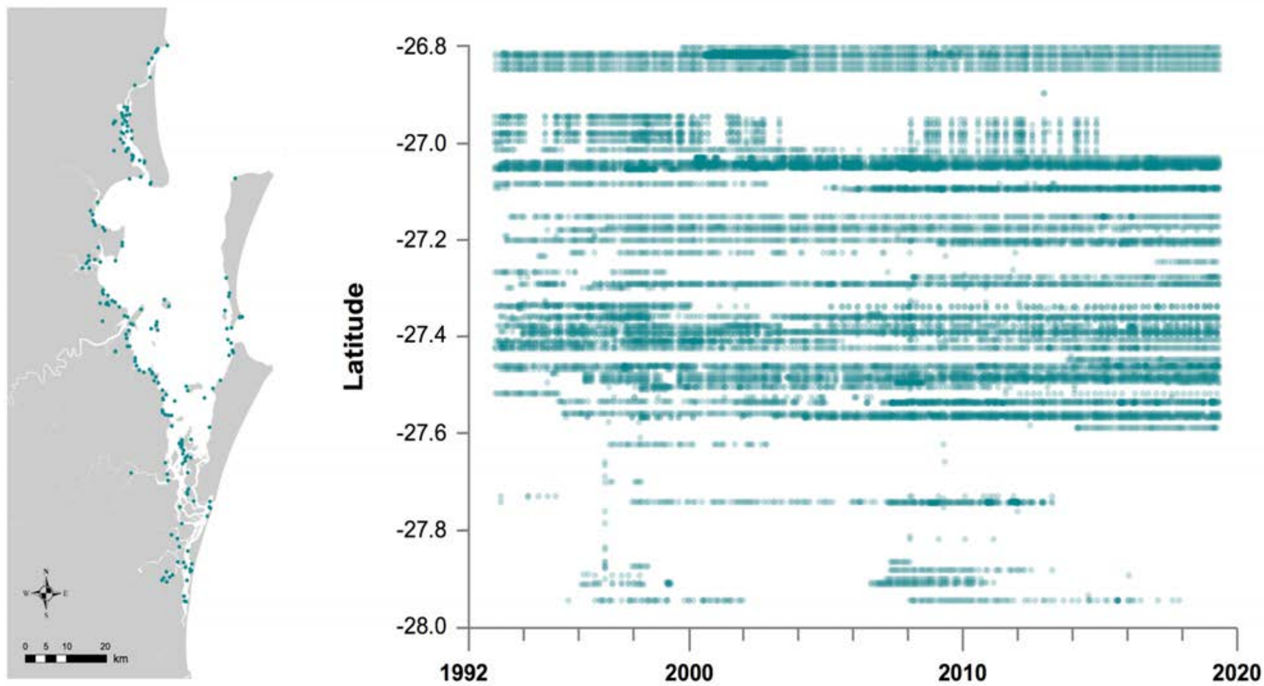


Figure 4.1 Monitoring of migratory shorebirds in Moreton Bay by the Queensland Wader Study Group, showing when each site was surveyed, arranged north to south. Each site on the map has a corresponding row on the figure on the right, with each green point representing a shorebird survey. There are monitoring gaps in Pumicestone Passage and the southern Bay (white areas indicate no surveys).

Bar-tailed Godwit *(Limosa lapponica)*

The Bar-tailed Godwit is the most abundant migratory shorebird in Moreton Bay with counts regularly exceeding 10,000 individuals in summer (Ramsar 2018). Bar-tailed Godwits are widely distributed throughout the Bay (**Figure 4.2**), with the largest roosts in southern Pumicestone Passage, South Passage, and at a series of roosts between the Port of Brisbane and Victoria Point. While there is a lack of recent data south of Victoria Point it is unlikely that many Bar-tailed Godwits would be found in these areas dominated by mangroves with few open roosting sites. It is possible that additional nationally important roosts could still occur between the Port of Brisbane and the south of Bribie Island, but no recent data are available in much of this area (see **Figure 4.1**). However, significant concentrations of this large-bodied and readily identifiable species are unlikely to have been missed entirely in this area over the last ten years, so it seems reasonable to conclude that there are genuinely lower concentrations of important roosts in the area between the Port of Brisbane and the south of Bribie Island despite there being apparently suitable intertidal habitats available (**Figure 5.1**).

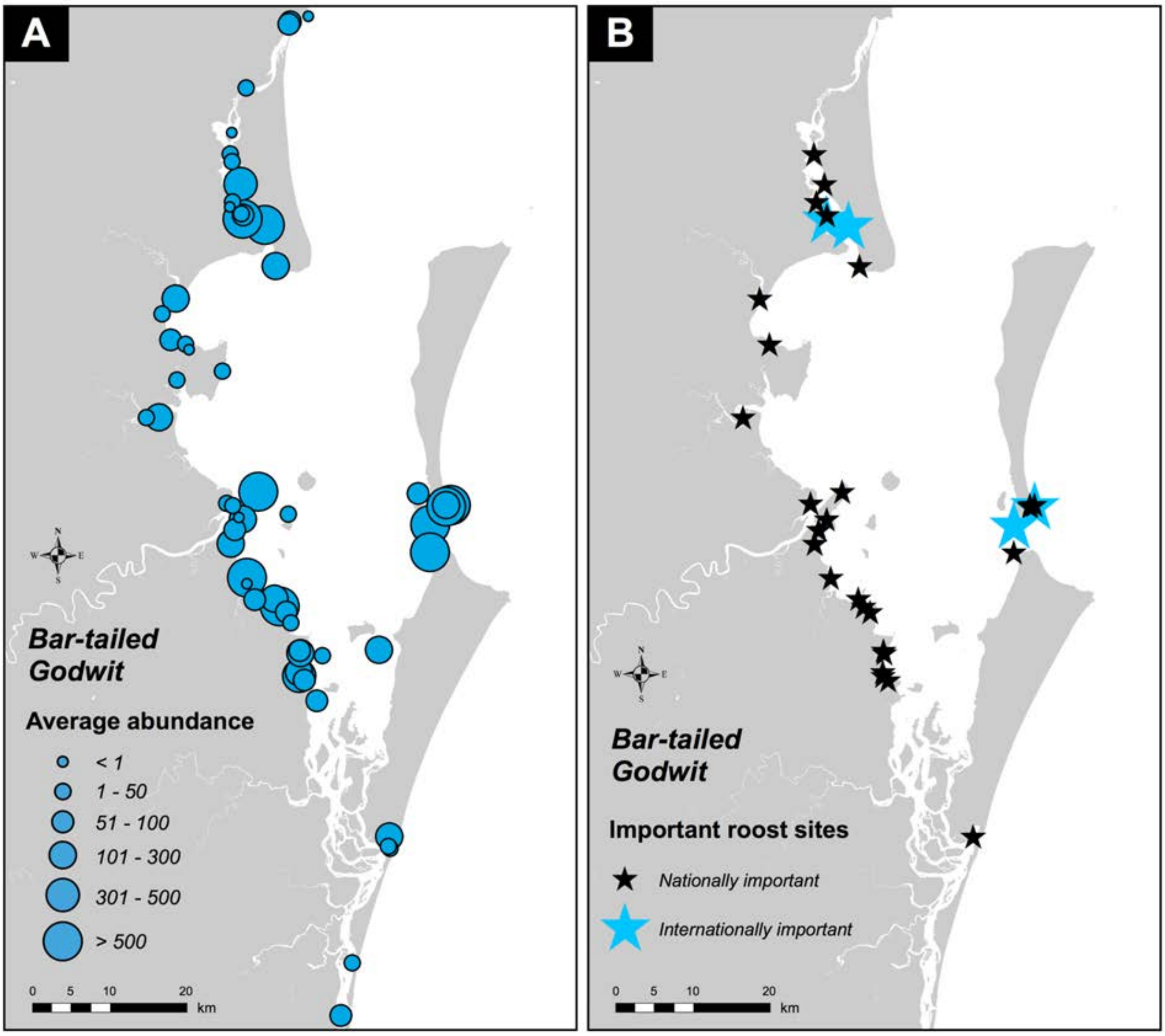


Figure 4.2 Abundance of Bar-tailed Godwit at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

Enhanced protection of the internationally important roosts for this species will require management that limits disturbance and ensures that large flat areas free of vegetation remain available as roosting habitat. In southern Pumicestone Passage, artificially enhanced areas have already proven effective at providing suitable roosting habitat, indicating that this species responds well to artificial construction or augmentation of roosting sites. Steps to manage dog walkers, boats and other human disturbance are also needed to ensure these roosts continue to be used by large numbers of birds. The broad distribution of roosting sites for this species across the Bay indicates that a large number of roosts will need management attention to maintain a robust network of roost sites. This includes a variety of roosts in the relatively densely populated mainland shoreline between the Port of Brisbane and Victoria Point. The roost at Manly Harbour provides an example of the kind of artificial roost which could be created to ensure that shorebirds have additional areas to roost free from human disturbance. Part of a dredge spoil site within a bounding rock wall, the Manly Harbour roost was specifically created for shorebirds under the guidance of QWSG shorebird experts. Ensuring intertidal habitats and the benthic food supply are also maintained in these areas will also be critical to maintaining populations. It would be worth exploring whether the tidal flats between the Port of Brisbane and Bribie Island as well as the western shore of Minjerribah (North Stradbroke Island) support large numbers of feeding Bar-tailed Godwits, or suitable prey for this species. If either are present, it seems likely that construction of suitable roosting sites in these locations would also be beneficial by providing roosts closer to available feeding areas.

Black-tailed Godwit *(Limosa limosa)*

The Black-tailed Godwit does not occur in internationally important numbers in Moreton Bay, although nationally important numbers have occurred at four roosts (**Figure 4.3**), with large numbers only occurring around the mouth of Pine River. It is possible that additional visits to the remote large claypans such as those north and south of Redcliffe would consistently return larger counts, since the numbers of Black-tailed Godwits vary enormously at such claypan roosts. Nevertheless, while such enhanced monitoring for this species might identify one or two more nationally important sites, the total number of Black-tailed Godwits in the region is relatively small compared to other regions of Australia. This is perhaps because it is strongly associated with soft mud foraging habitats, which are relatively scarce in Moreton Bay. The species is listed as Near Threatened by the IUCN, although not listed as threatened under the EPBC Act.

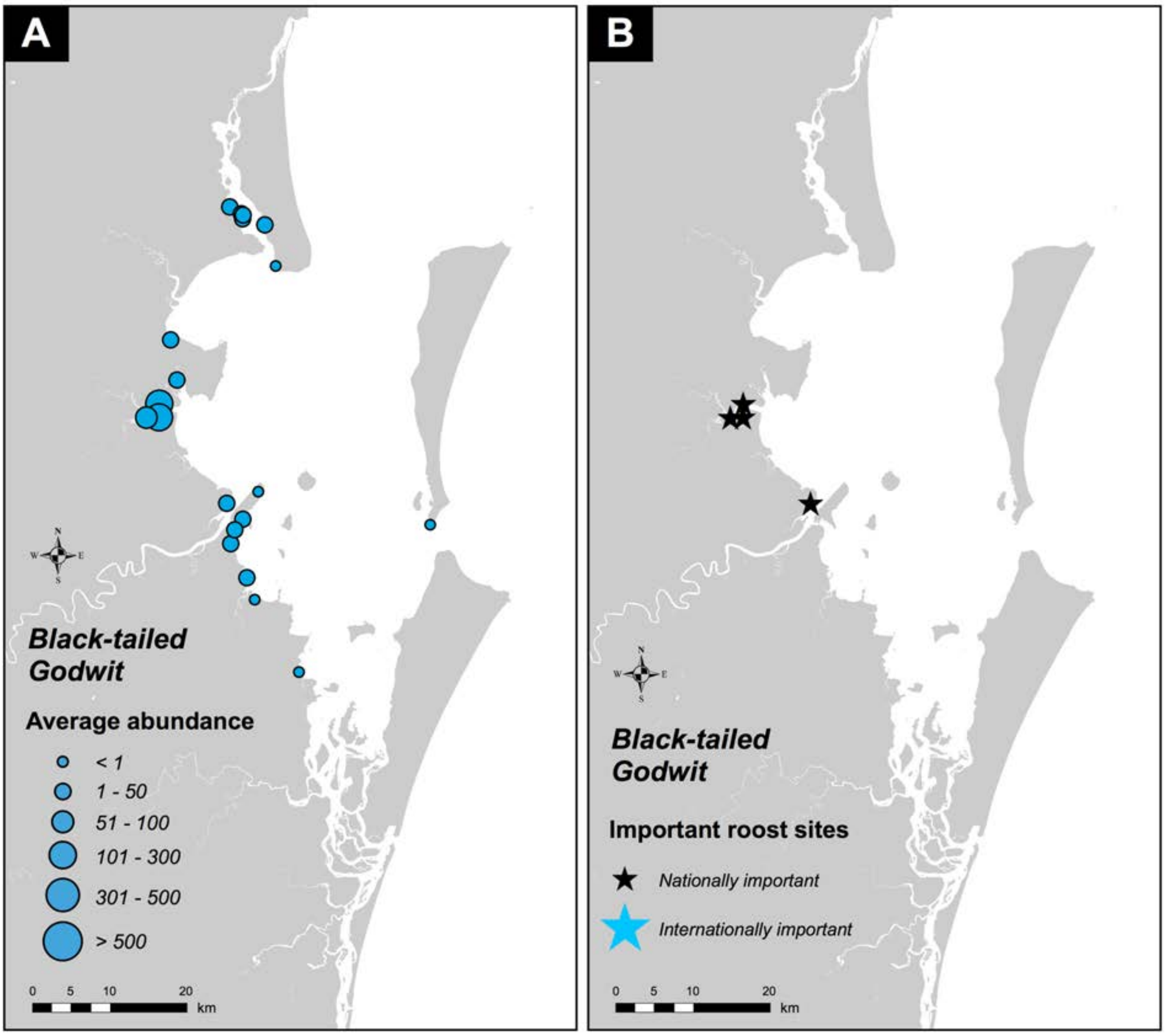


Figure 4.3 Abundance of Black-tailed Godwit at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Common Greenshank *(Tringa nebularia)*

The Common Greenshank is not listed as threatened under the EPBC Act and has not been reported in numbers exceeding national importance at any single roost. However, it has occurred in nationally important numbers across Moreton Bay as a whole (Milton 2008), and it is likely that if all roosts in the Bay were visited regularly, nationally important numbers would be exceeded regularly. Common Greenshanks are widely distributed in small numbers throughout the bay, but tend not to be found in less sheltered coastal habitats. They are often more abundant at sheltered claypans, or inland wetlands and have been observed at wetlands far from coastal habitats. On tidal flats, Common Greenshanks eat a range of large active invertebrates and small vertebrates (Nethersole-Thompson & Nethersole-Thompson 1979). Only about 17% of the flyway population of the Common Greenshank visits Australia, but given the widespread population declines in Australia (Clemens *et al.* 2016), steps to protect this species are needed. Common Greenshanks can be found in artificial or heavily managed habitats and actions taken to protect feeding and roosting habitats for other shorebirds in Moreton Bay would also help Common Greenshanks. They rarely occur in any habitat in large numbers. Protection of the full variety of habitats and locations they use will therefore be required to keep them in nationally important numbers in Moreton Bay.

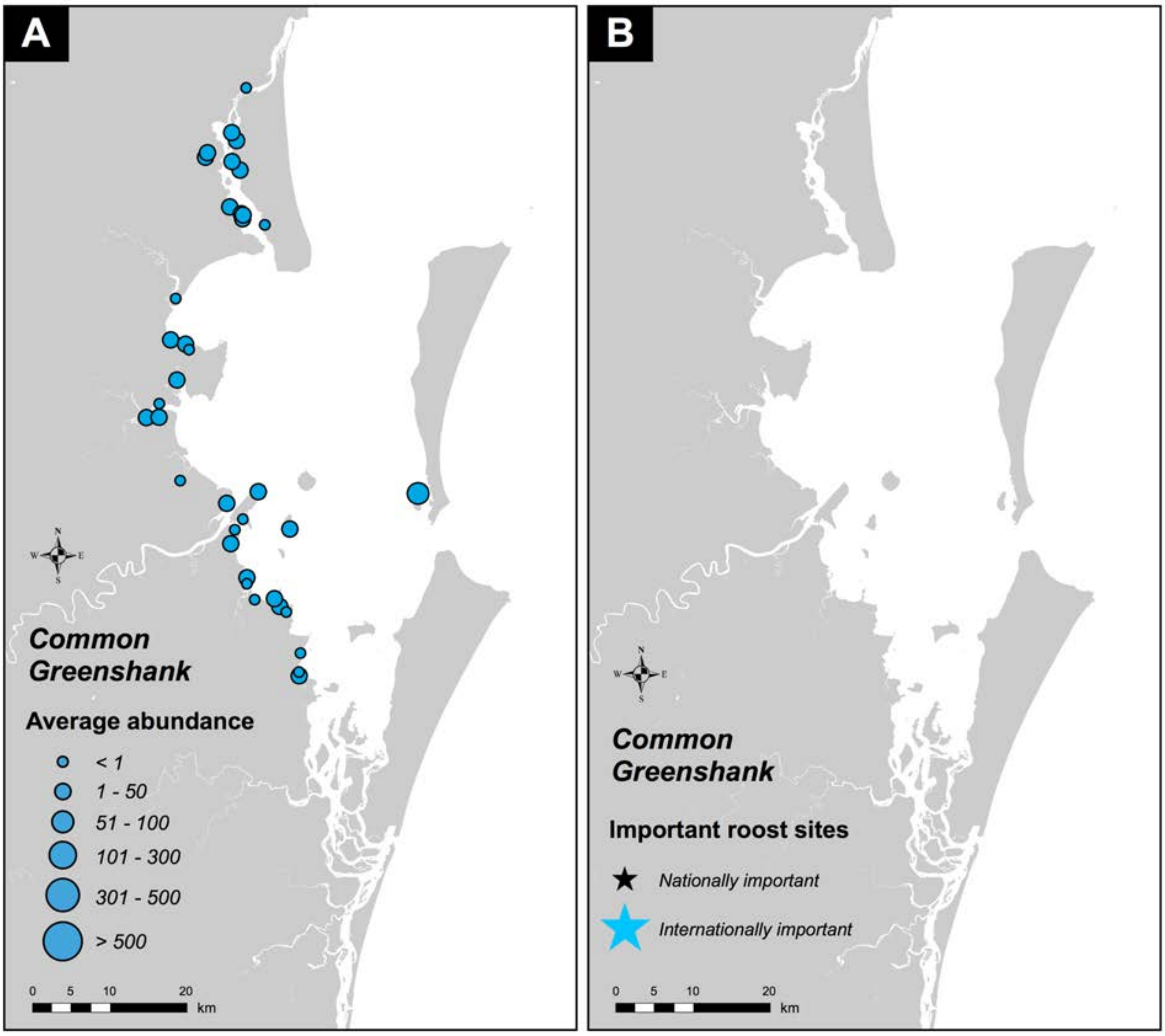


Figure 4.4 Abundance of Common Greenshank at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows that there are no sites that have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

Curlew Sandpiper *(Calidris ferruginea)*

The Curlew Sandpiper is listed as Critically Endangered under the EPBC Act, and thus it is of enormous significance that over 2,000 individuals of this species are regularly observed within Moreton Bay. Notably, while this species is declining nationally at an extremely rapid rate (Studds *et al.* 2017), numbers in Moreton Bay are somewhat more stable, showing a much more modest decline (Wilson *et al.* 2011). This suggests that the Bay could be acting as a “safe haven” for this species, and it seems likely that the temporary creation of highly suitable roosting areas for this species at the Port of Brisbane has helped slow its decline in Moreton Bay. Carefully directed management that is aimed at protecting and enhancing habitat for this species could therefore deliver outcomes that are nationally and internationally significant.

Curlew Sandpipers frequently occur in internationally important numbers at the Port of Brisbane, and have occasionally been observed in nationally important numbers at ten other roosts between Manly and Bribie Island in the last ten years (**Figure 4.5**). Anecdotal reports from Moreton Bay suggest that Curlew Sandpipers are often most abundant at roosts that are large, flat, and have some shallow water allowing for feeding during high tide (see **Section 5.2** for a discussion of supratidal

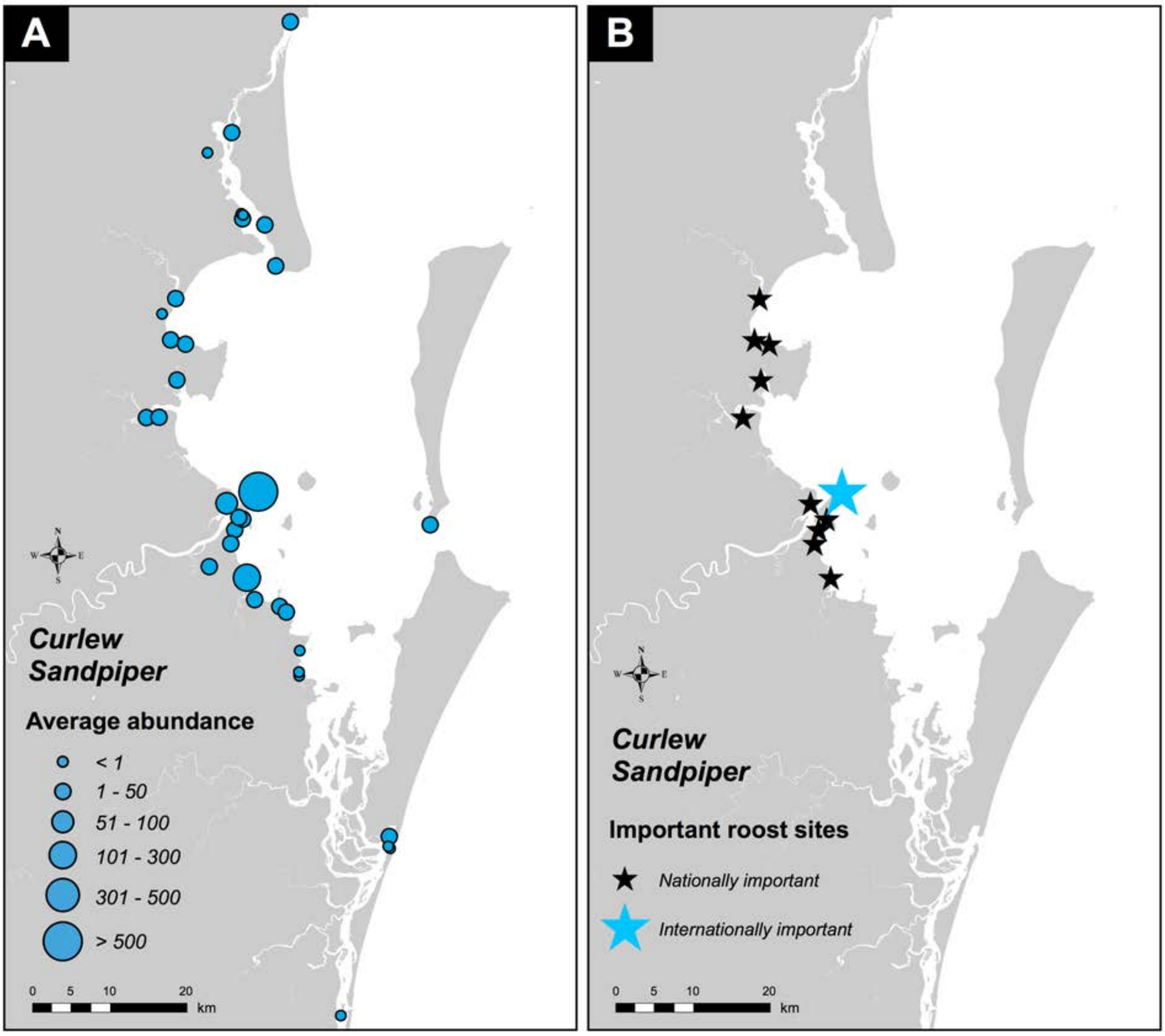


Figure 4.5 Abundance of Curlew Sandpiper at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

foraging). Ensuring that a large roosting area (as large as the reclamation areas within the Port of Brisbane) continues to be available within Moreton Bay after the reclamation areas at the Port are filled in would maximise the chances of maintaining stable Curlew Sandpiper numbers in the region over the long term. If suitable alternative roosting site options cannot be found for the birds currently using the Port of Brisbane, it seems highly likely that internationally important numbers of this species would no longer occur in Moreton Bay. Up to 1,000 Curlew Sandpipers have been observed feeding during the low tide period on the extensive tidal flats at Nudgee Beach, and it seems likely there is strong connectivity between the foraging grounds at Nudgee and roosting sites at the Port of Brisbane. The presence of large numbers of feeding birds at Nudgee also suggests that creating some roosting options there (for example at Dynah Island; see **Section 6.1**) will address a critical vulnerability for this species.

Double-banded Plover *(Charadrius bicinctus)*

The Double-banded Plover is not listed as threatened under the EPBC Act. It is a winter visitor to Moreton Bay from breeding grounds in New Zealand. It has been recorded in nationally important numbers at 12 roosts, and internationally important numbers at one roost.

Double-banded Plovers use a wide variety of habitats, and are not surprisingly widespread throughout the bay, with most occurring in the South Passage, Geoff Skinner Reserve, Port of Brisbane, and Manly Harbour. This wide distribution suggests that actions taken to protect other migratory shorebirds would also protect the Double-banded Plover, except that managing disturbance in winter, rather than summer, would be important. The Double-banded Plover is the only migratory shorebird species with a non-breeding abundance in Moreton Bay that peaks in winter, and is the only species which would not be impacted by threats occurring in the northern Hemisphere.

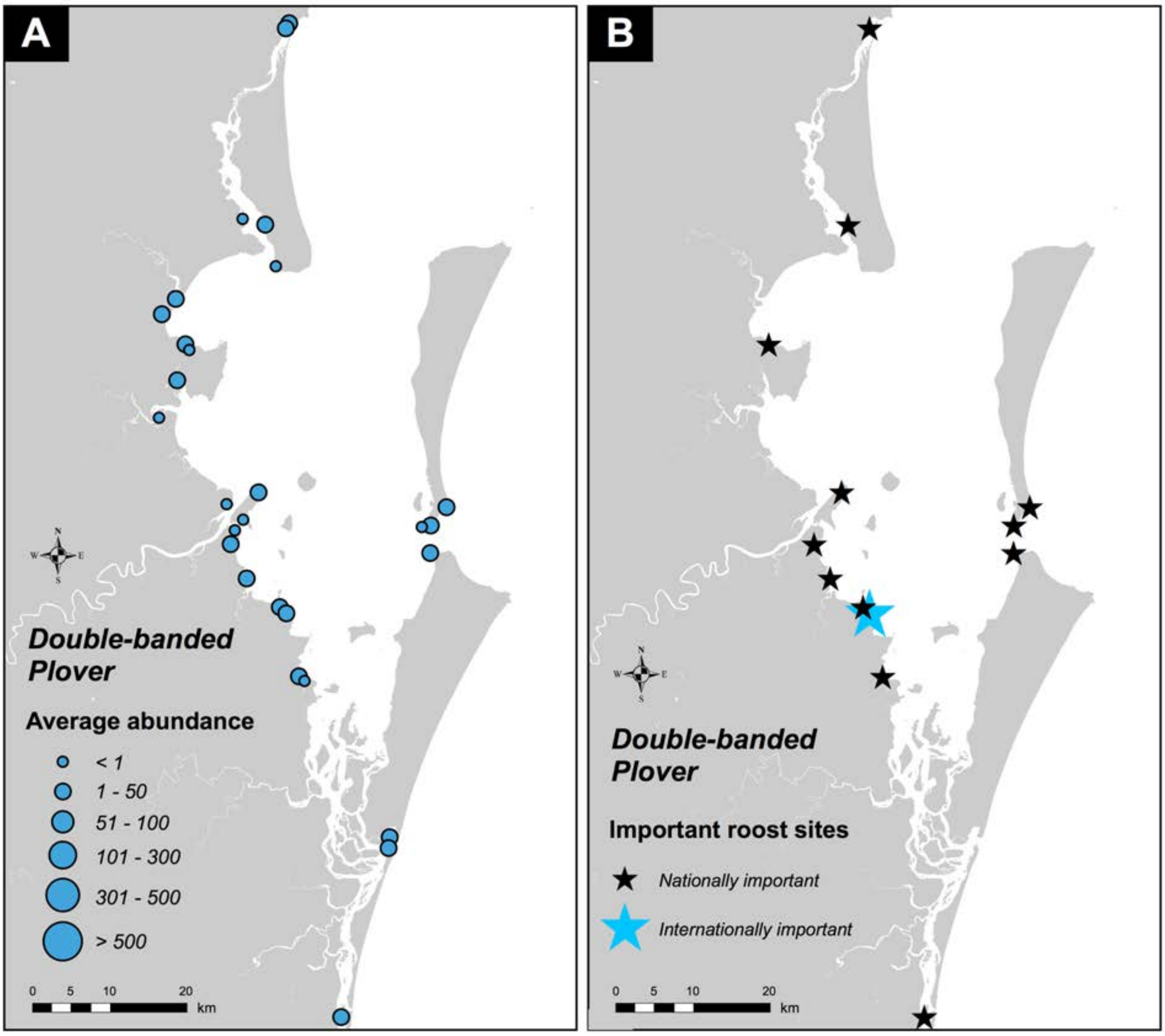


Figure 4.6 Abundance of Double-banded Plover at roosting sites in the winter months (March-August, inclusive) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

Far Eastern Curlew *(Numenius madagascariensis)*

The Far Eastern Curlew is listed as Critically Endangered under the EPBC Act, and Moreton Bay is one of the most important non-breeding areas for this species in the world. There are regularly more than 3,000 Far Eastern Curlews present in Moreton Bay during the non-breeding season, representing just under 10% of the remaining world population of this species. Far Eastern Curlew is also one of the most widely distributed migratory shorebird species in the Bay (**Figure 4.7**). Internationally important numbers of Far Eastern Curlews occur at roosts near Cleveland, Thornlands, South Passage, southern Pumicestone Passage and near the southern end of Minjerribah (South Stradbroke Island). Nationally important numbers have occurred at roosts throughout the Bay, indicating that widespread management of roosting and feeding sites will be necessary to safeguard the long term future of this species in Moreton Bay. Given that almost 10% of the world population of Far Eastern Curlew occurs in Moreton Bay, local management for this species is of the utmost global significance.

As a territorial feeder, the Far Eastern Curlew is

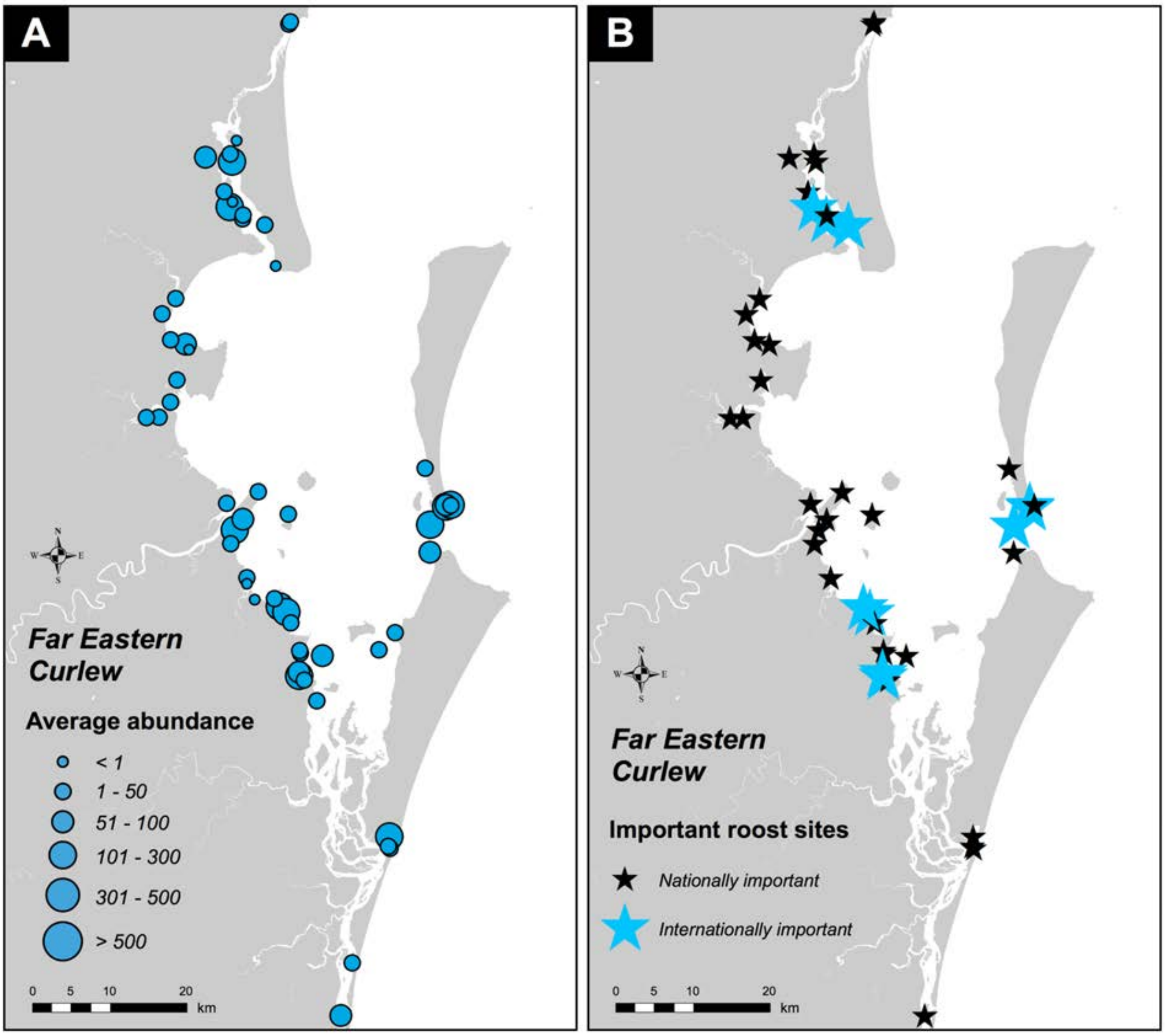


Figure 4.7 Abundance of Far Eastern Curlew at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

widely distributed over available tidal flats and roosts in the closest suitable habitat, perhaps explaining its broad representation at roost sites throughout the Bay. Aside from protecting the intertidal flats that these birds rely on for food, roosts are preferred if they are sheltered from human disturbance. Claypans fringed by mangroves, such as Geoff Skinner Wetlands, the fenced in roost at Manly Harbour, and remote shorelines are most preferred. Saltmarshes are rarely used in Moreton Bay, but this might reflect the rarity of this habitat type in the region. These disturbance free roosts will need to be maintained throughout the bay to ensure Moreton Bay remains one of the most important places for Far Eastern Curlew in the world. This will likely require active management in areas of increasing human population density.

Great Knot *(Calidris tenuirostris)*

The Great Knot is listed as Critically Endangered under the EPBC Act (Table S2). The species does not occur in internationally important numbers in Moreton Bay, and only occurs in nationally important numbers in southern Pumicestone Passage and at the Port of Brisbane (Figure 4.8). While Great Knots are occasionally observed in smaller numbers at many roosts throughout Moreton Bay, it is not clear why most birds are concentrated into these two locations, and this issue deserves further study. It is possible these areas are closer to some preferred food source, which is unevenly distributed across the mudflats. The Great Knot is typically most abundant in roosting sites adjacent to open water, and protection of these key roosts will be essential to safeguarding its future in Moreton Bay, noting in particular its heavy reliance on temporary habitat created by the reclamation ponds at the Port of Brisbane. Additionally, the identification and protection of the foraging sites being used by the species is critical, and this is likely to include invertebrate species that are less frequently eaten by other migratory shorebirds.

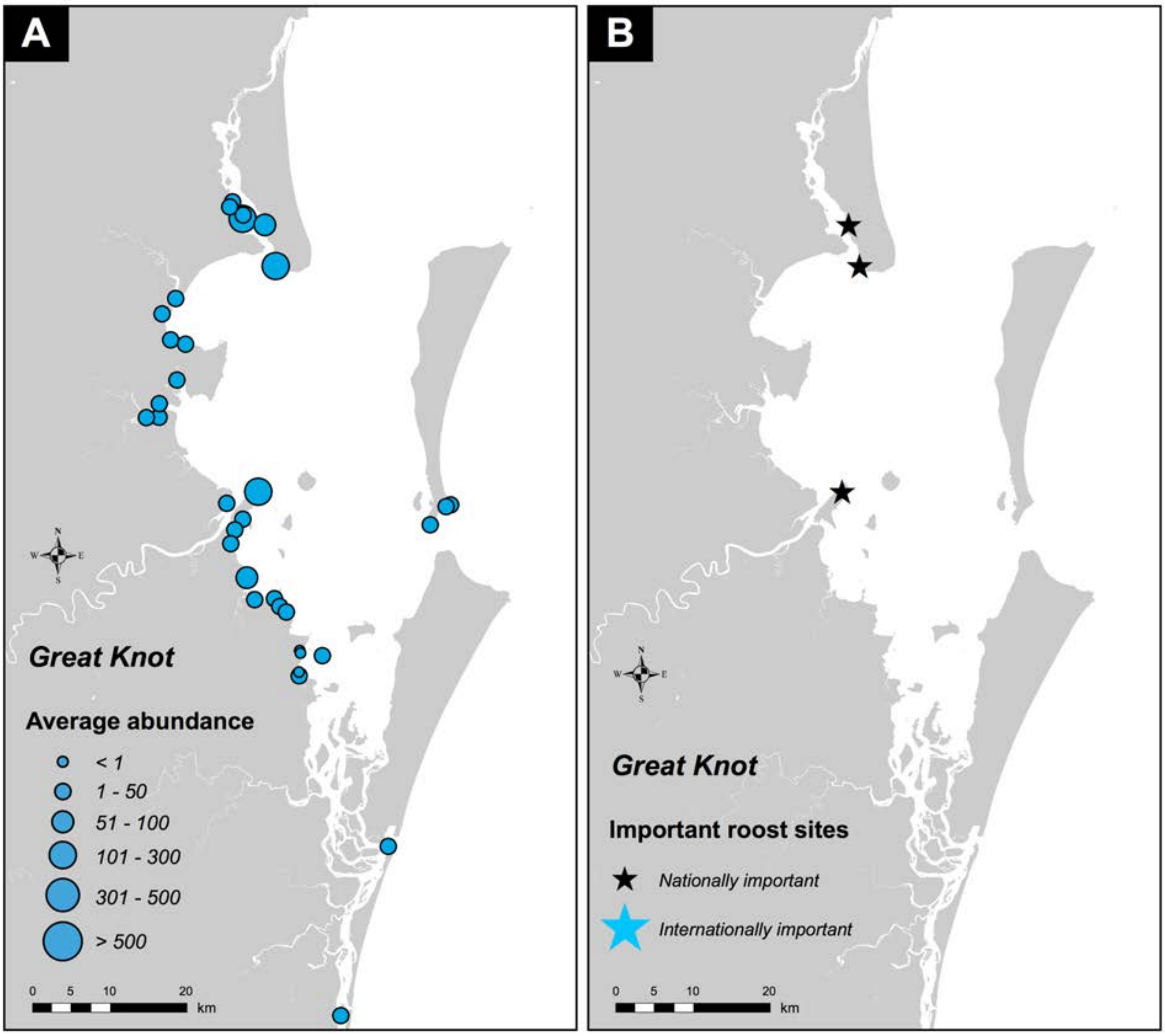


Figure 4.8 Abundance of Great Knot at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Greater Sand Plover *(Charadrius leschenaultii)*

The Greater Sand Plover is listed as Vulnerable under the EPBC Act, and although it does not occur in internationally important numbers in Moreton Bay, it is found in nationally important numbers at roosting sites in southern Pumicestone Passage and at the Port of Brisbane (**Figure 4.9**). Greater Sand Plovers are visual hunters that pick prey off the surface of the mud or sand (Geering *et al.* 2007). This allows them to find prey along sandy beaches as well as mudflats and explains why there are relatively large roosts around Bribie Island, Moreton Island and Minjerribah (North and South Stradbroke Islands). It is also a little surprising that the largest roost is at the Port of Brisbane given it is energetically beneficial for shorebirds to roost close to where they feed, and there are no known major feeding areas close to the Port of Brisbane. It seems likely that the energetic and safety gains from roosting on the large open and undisturbed reclamation area at the port outweigh the additional energetic costs of commuting to the Port. The large size of the area that is flat and free of vegetation allows individuals to see predators, such as raptors

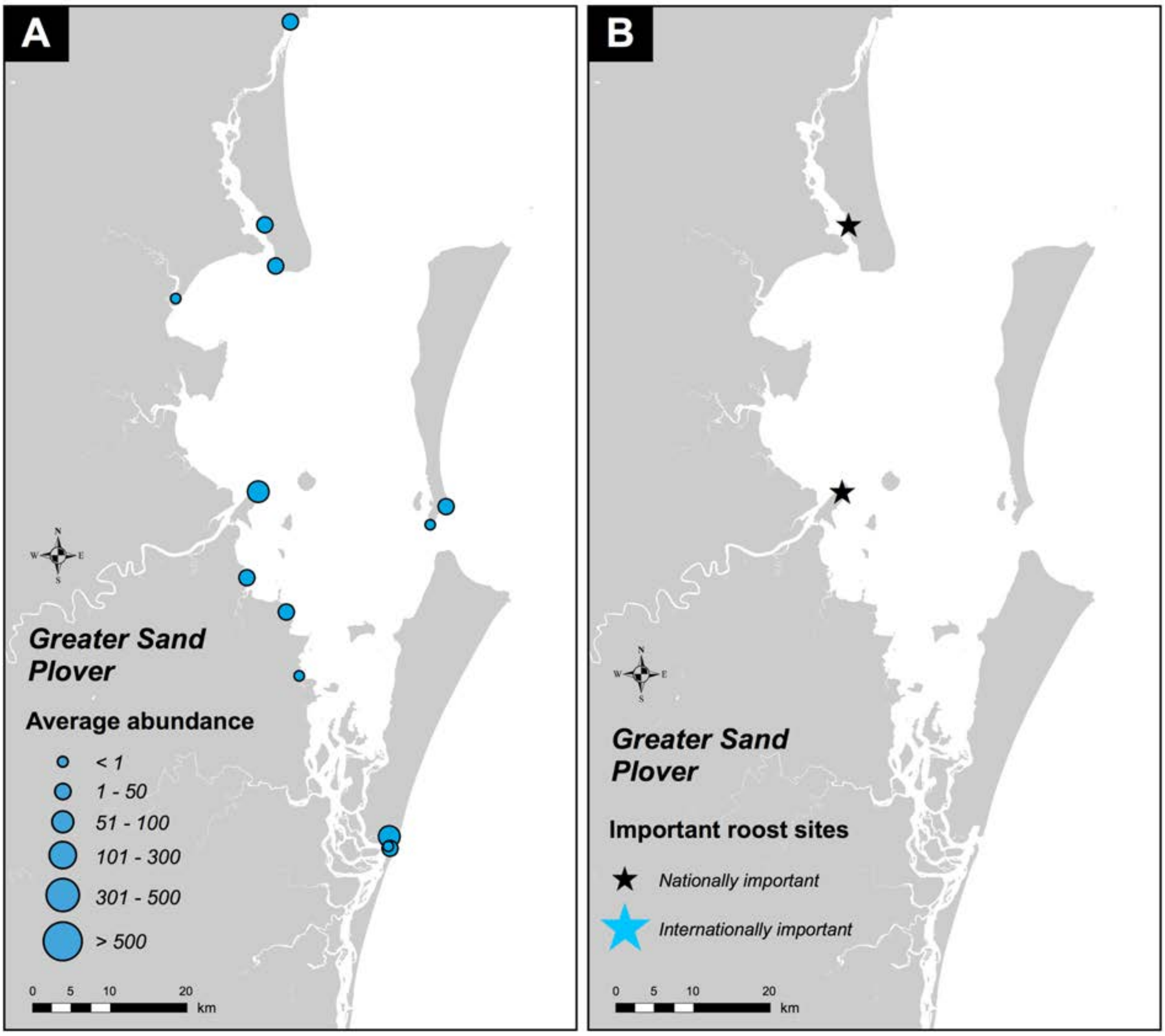


Figure 4.9 Abundance of Greater Sand Plover at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

earlier, and provides a reduced chance of individual predation given the large number of shorebirds using the roost. It is also likely the roosting area least impacted by human disturbance, so birds are probably able to expend less energy at this location at high tide. It is also possible that the combination of large open areas and open water in ponds provides some opportunity to continue foraging at high tide, although this has not been widely observed during QWSG counts of Greater Sand Plovers roosting at the Port of Brisbane.

Greater Sand Plover is another species with a heavy reliance on the Port of Brisbane as a roosting site, and the future of this species in Moreton Bay must be regarded as threatened given the long-term plans to fill in the main reclamation ponds currently being used by the species at the Port. Protection of roosting habitats will be important to maintain populations and protection of foraging areas with relatively high densities of surface mud or sandflat invertebrates will also be important. Like many species that use the Port in large numbers it is possible that creation of large roosting areas closer to where the birds are foraging at low tide could provide additional energetic benefits to individuals. Such actions would be especially important if the roosting area at the Port of Brisbane was lost or substantially reduced, and it seems unlikely that the existing artificial roost at the Port will be large enough for all the birds that are currently using the reclamation areas.

Grey Plover *(Pluvialis squatarola)*

The Grey Plover is not listed as threatened under the EPBC Act, and it has not been observed in nationally important numbers at any roost in the Moreton Bay area. However, nationally important numbers of Grey Plover were observed on the one complete count of all known roosts at Moreton Bay (Milton 1998), and we think it likely that nationally important numbers still occur in the Bay as a whole. Grey Plovers use a variety of habitats, but can be quite commonly found on ocean beaches, which is an under-surveyed habitat type, and it is possible that more Grey Plovers could be found along the eastern coasts of Bribie Island, Moreton Island, and Minjerribah (North and South Stradbroke Islands). The highest counts of this species tend to occur relatively close to the open ocean on the southern tip of Moreton Island and Minjerribah (North Stradbroke Island) as well as at the Port of Brisbane. This suggests that some Grey Plovers are using sandy coastlines, and some are using mudflats near to the relatively undisturbed roosts at the Port of Brisbane. Conserving these roosts and the surrounding tidal flats will help to ensure that nationally important numbers of Grey Plovers continue to occur in Moreton Bay.

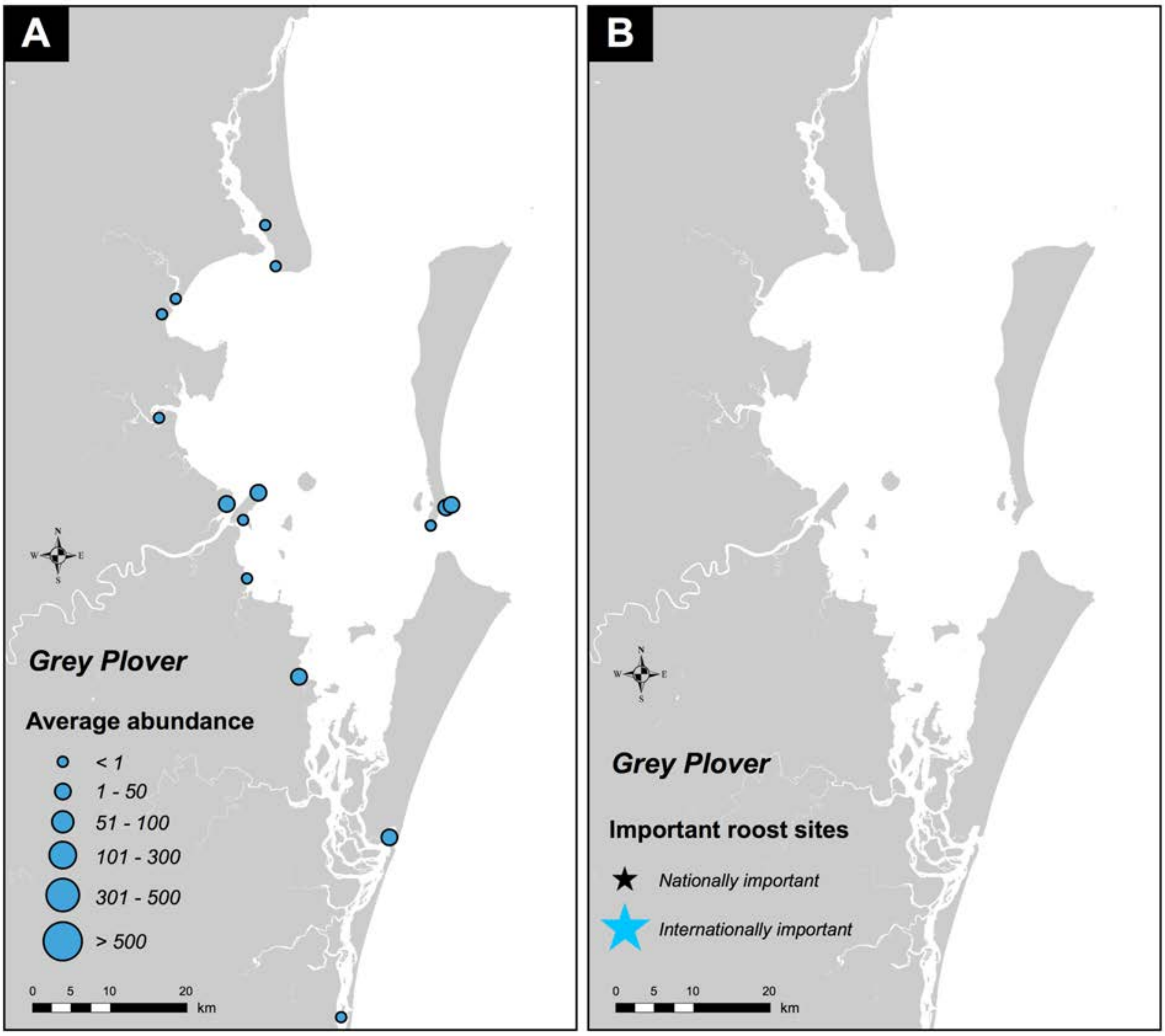


Figure 4.10 Abundance of Grey Plover at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows that there are no nationally or internationally important sites for this species in Moreton Bay, based on the maximum count observed between 2009 and 2019 inclusive.

Grey-tailed Tattler *(Tringa brevipes)*

The Grey-tailed Tattler is not listed as nationally threatened under the EPBC Act, but it does occur in internationally important numbers that regularly exceed 2000 individuals in Moreton Bay. Internationally important numbers have occurred in Pumicestone Passage, Manly Harbour, and the Port of Brisbane. Nationally important roosts occur between the Port of Brisbane and Thorneside, at Goat Island, and at several locations in Pumicestone Passage (**Figure 4.11**). Grey-tailed Tattlers often roost facing open water on rocky shores, or on open branches of mangroves. Mangrove habitats are difficult to access at high tide, and have been rather poorly represented in Queensland Wader Study Group surveys (Fuller *et al.* 2009). It is therefore likely that present estimates of the number of Grey-tailed Tattlers using Moreton are too low, and that more birds would be found if bespoke surveys focused on mangrove habitats were conducted in Pumicestone Passage and among the islands between Minjerribah (South Stradbroke Island) and the mainland. It is also possible that nationally important numbers could be found in other large patches of mangroves throughout the bay.

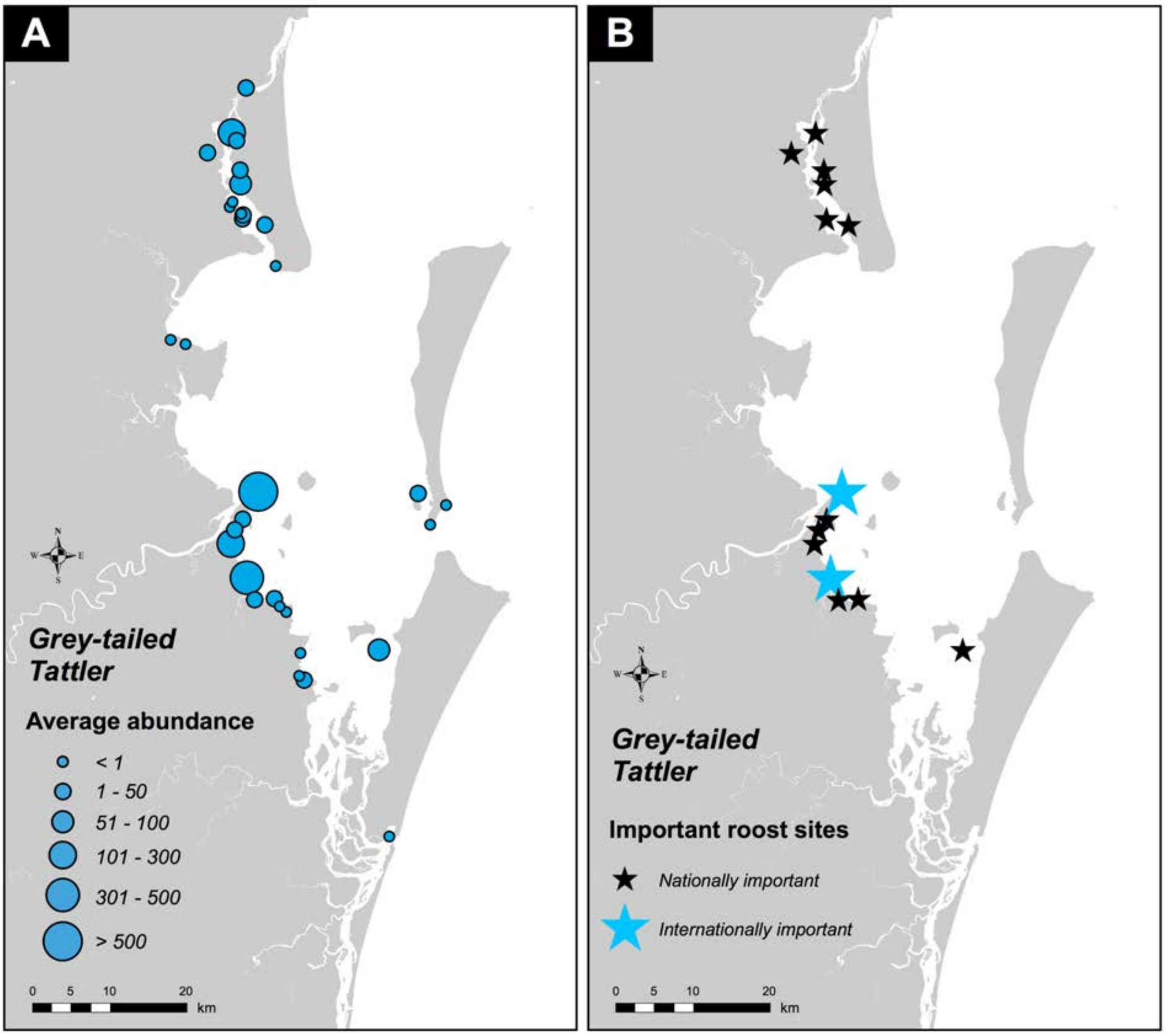


Figure 4.11 Abundance of Grey-tailed Tattler at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

The Port of Brisbane is very important as a roosting site for the Grey-tailed Tattler, yet unlike many other migratory shorebird species, it is not the wide open reclamation ponds that are favoured by the tattler, but rather the rocky sea walls that enclose the ponds. The situation at Manly Harbour is similar, with Grey-tailed Tattlers preferring to roost on the artificial rock wall that encloses the site. This suggests that suitable roosting areas for this species could be maintained after the Port of Brisbane reclamation is filled in, if rock walls facing the open water of Moreton Bay could be maintained. However, it is critical to ensure disturbance is minimised by limiting public access to the rocky areas and mangroves preferred as roosting sites by this species.

Lesser Sand Plover *(Charadrius mongolus)*

The Lesser Sand Plover is listed as Endangered under the EPBC Act, and occurs in internationally important numbers in Moreton Bay that regularly exceed 1,900 birds. At individual roosts, Lesser Sand Plovers have only been observed in nationally important numbers (**Figure 4.12**), but they occur in internationally important numbers at the Port of Brisbane when considering all the individual roosts at the Port inaggregate. Lesser Sand Plovers are visual hunters that pick prey off the surface of the mud or sand, and this allows them to find prey along sandy beaches as well as mud flats, especially where there are rocky substrates present, but like Greater Sand Plover they concentrate at roosts along the mainland especially at the Port of Brisbane. It is possible the Port offers foraging opportunities over the high tide period, but feeding during this period has not often been observed at the Port. Therefore, it seems likely that the large open undisturbed roost allows individuals to save energy and reduce predation probability.

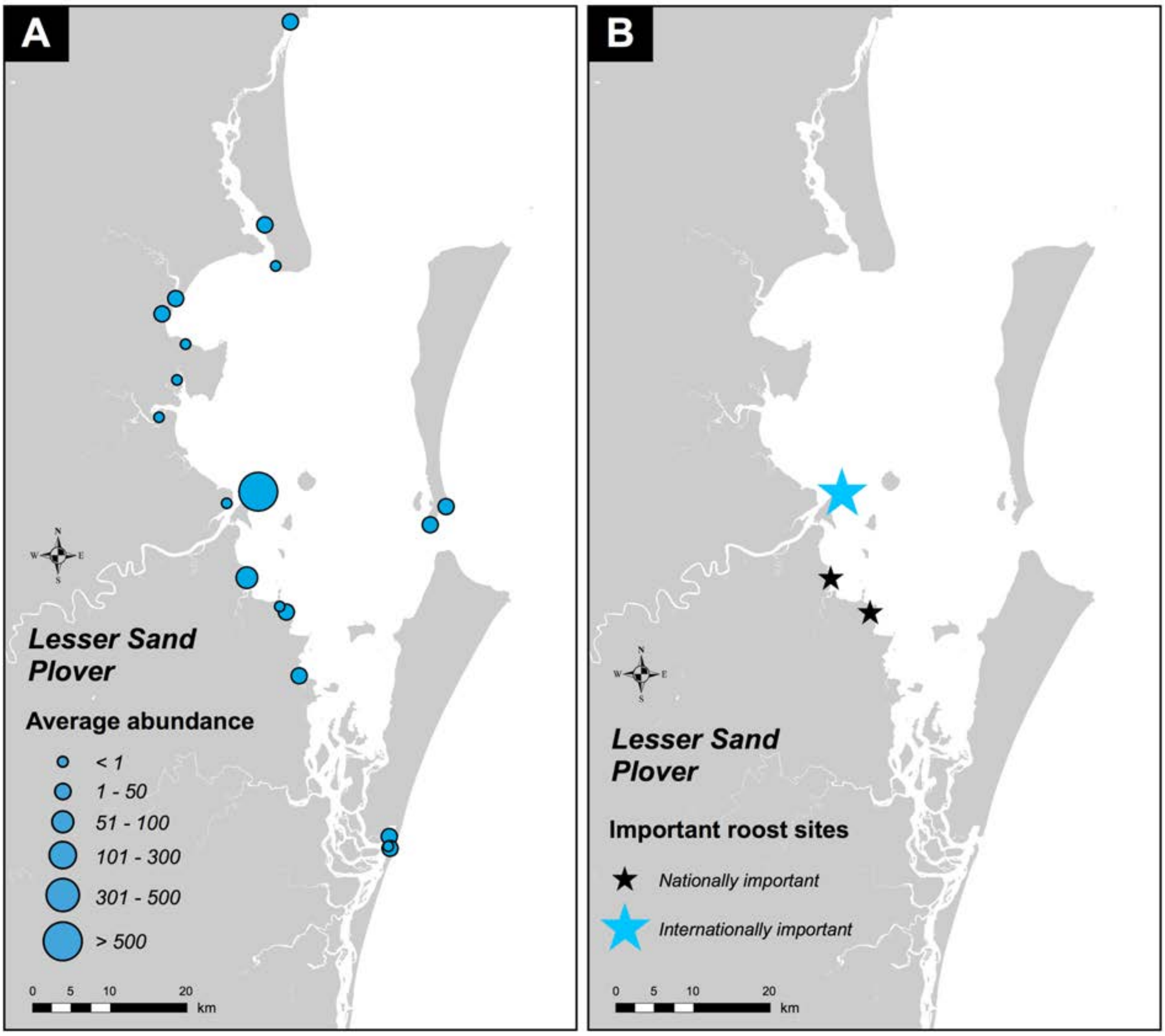


Figure 4.12 Abundance of Lesser Sand Plover at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

The Lesser Sand Plover relies heavily on the Port of Brisbane as a roosting site, and the future of this species in Moreton Bay must be regarded as threatened given the long-term plans to fill in the main reclamation ponds currently being used by the species at the Port. Protection of roosting habitats will be important to maintain populations and protection of foraging areas with relatively high densities of surface mud or sandflat invertebrates will also be important. Like many species that use the Port of Brisbane in large numbers it is possible that creation of large roosting areas closer to where the birds are foraging at low tide could provide additional energetic benefits to individuals. Such actions would be especially important if the roosting area at the Port was lost, and it seems unlikely that the existing artificial roost at the Port will be large enough for all the birds that are currently using the reclamation area.

Pacific Golden Plover *(Pluvialis fulva)*

The Pacific Golden Plover is not listed as threatened under the EPBC Act, and it does not occur in internationally important numbers in Moreton Bay, although nationally important numbers occur at roosts in and around the Port of Brisbane and near Point Halloran (**Figure 4.13**). Smaller numbers occur at many roosts throughout Moreton Bay, and it is possible that several additional roosts have yet to be discovered. Pacific Golden Plovers often roost in open areas near the coast, often among short saltmarsh vegetation such as samphire, or occasionally in grassy areas. These habitatsoften occur around the fringes of claypans in areas that are difficult for surveyors to access, and because this habitat is not widely used by other shorebirds, it is possible numbers are substantially underestimated. This specific habitat use also means that special consideration will often be needed to ensure continued roost site availability for Pacific Golden Plover, especially aligning it with strategies for saltmarsh conservation in Moreton Bay. However, like many shorebird species, the large undisturbed roosting areas offered at the Port of Brisbane appear to provide a habitat that is at times preferred over their more traditional roosting habitats, and this is another species that can show very high abundance on the reclamation ponds at the Port.

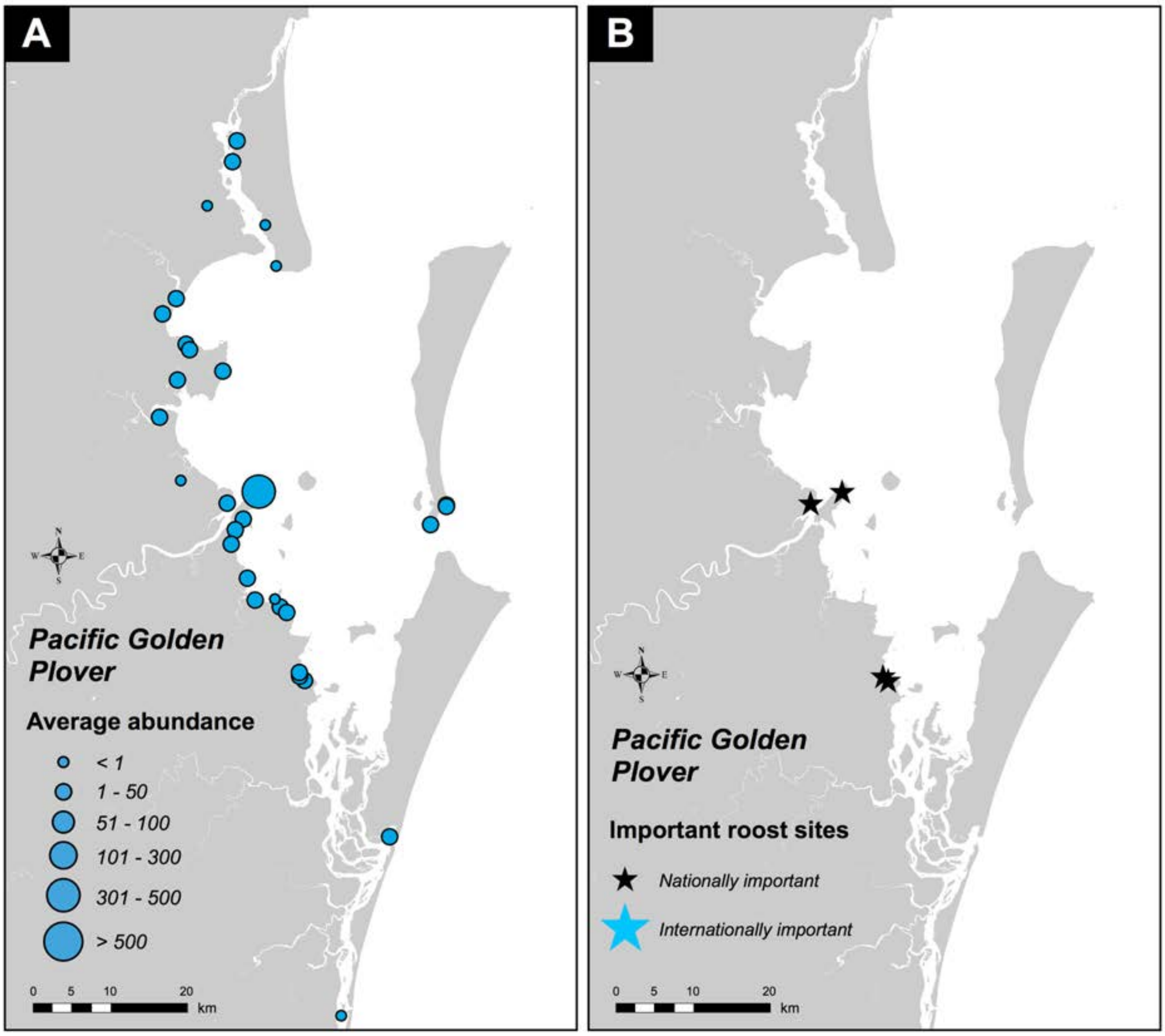


Figure 4.13 Abundance of Pacific Golden Plover at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Red Knot *(Calidris canutus)*

Listed as Endangered under the EPBC Act, the Red Knot is not found in internationally important numbers in Moreton Bay. Nationally important numbers have been observed once in the last decade near Lytton, and smaller numbers have occasionally been observed at a variety of roosts in Moreton Bay (**Figure 4.14**). Larger numbers of Red Knot use Moreton Bay as a stopover site while on migration to non-breeding grounds in south-eastern Australia and New Zealand, and the species is in fact most common in September and October. This means that any surveys to assess the impact of developments, or importance of an area for roosting or feeding shorebirds, need to take into account that the peak time for this species is not in summer, but rather in spring. Red Knots specialise in eating small bivalves, and can be highly restricted in their low tide foraging distribution (Choi *et al.* 2017), so a better understanding of their low tide distribution in Moreton Bay would be worth obtaining, to ensure that their intertidal feeding areas can be safeguarded. This is especially important for the birds using Moreton Bay as a stopover site, since they need to fuel up quickly before moving on.

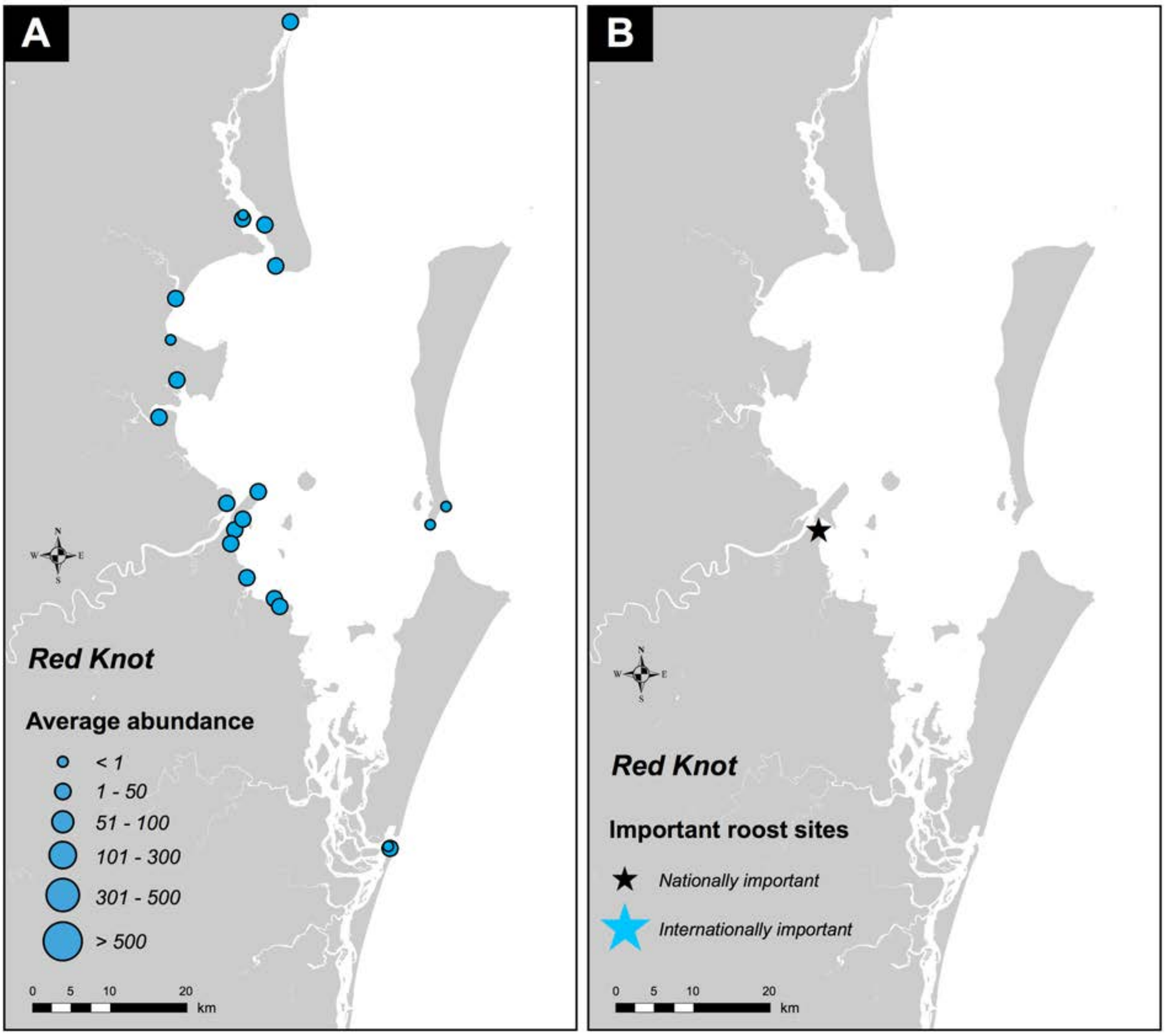


Figure 4.14 Abundance of Red Knot at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Red-necked Stint *(Calidris ruficollis)*

The Red-necked Stint is listed as Near Threatened by the IUCN, although it is not listed as threatened under the EPBC Act. It regularly occurs in internationally important numbers in Moreton Bay with around 5,000 typically present each year. Internationally important numbers frequently occur at the Port of Brisbane (**Figure 4.15**), and the creation of the shallow lagoons as part of the reclamation process has probably increased the amount of suitable habitat for this species in Moreton Bay, and been responsible for the long term modest increase in its numbers (Fuller *et al.* 2009; Wilson *et al.* 2011). Nationally important numbers have been observed occasionally at individual roosts between Caboolture and Geoff Skinner Reserve as well as at South Passage, and Red-necked Stints have been observed in smaller numbers at many roosts throughout the bay (**Figure 4.15**).

In Moreton Bay, Red-necked Stints typically roost where large areas of shallow water are available to allow them to continue foraging during high tide, and to provide long distance visibility. The ponds in the reclamation area appear to provide some foraging opportunities as well as wide open areas free of disturbance.

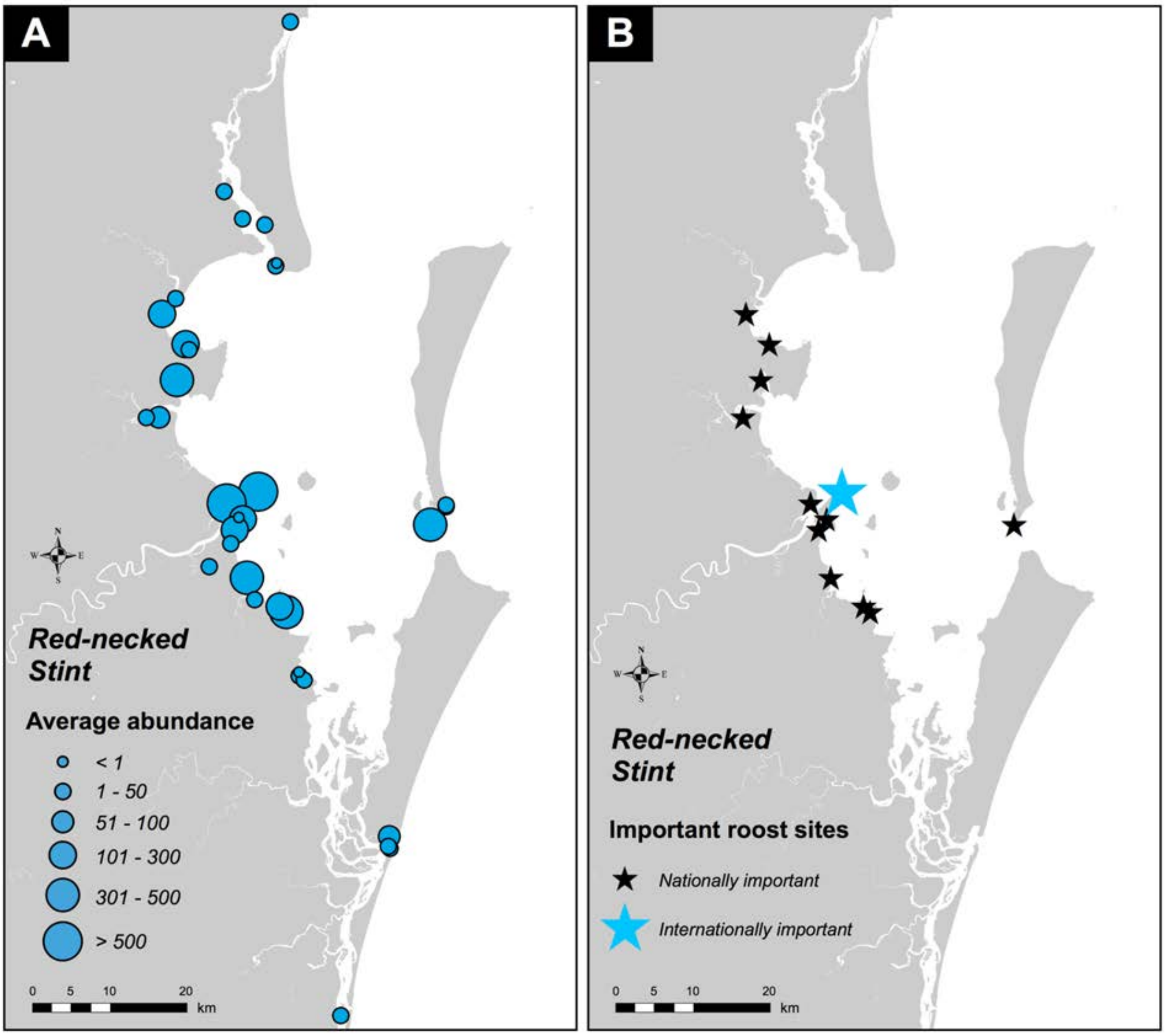


Figure 4.15 Abundance of Red-necked Stint at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

Roosts such as those currently found at the Port will need to be provided in the future when the reclamation areas are filled in, to maintain internationally important numbers in Moreton Bay. Provision of supratidal foraging habitat and strategic adjustment of water levels would likely further benefit this species (see **Section 6.2**).

Ruddy Turnstone *(Arenaria interpres)*

The Ruddy Turnstone is not listed as threatened under the EBPC Act, but it has been recorded in nationally important numbers within Moreton Bay at both the Port of Brisbane and at Manly Harbour. Ruddy Turnstones can be found in a very wide variety of habitats, but are most common along rocky shorelines, or near large piles of beach-cast seagrass or macroalgae. Both these habitats are relatively scarce in Moreton Bay, but it is possible that the open coastlines along the eastern shores of Bribie Island, Moreton Island and Minjerribah (North and South Stradbroke Island) could have regular concentrations of beach-cast seagrass or macroalgae that could support significant numbers of Ruddy Turnstones. Unless specific areas with reliable concentrations of Ruddy Turnstones are found, it appears that protection of foraging and roosting habitats used by other shorebird species would also serve to protect Ruddy Turnstones. As with some other species, Ruddy Turnstones favour the large undisturbed artificial roosts at the Port of Brisbane and Manly Harbour. Maintaining these kinds of roosts in Moreton Bay will be needed to ensure nationally important numbers of Ruddy Turnstone continue to occur. While not listed as nationally threatened, long term declines have been identified for this species in southern Australia (Clemens *et al.* 2016).

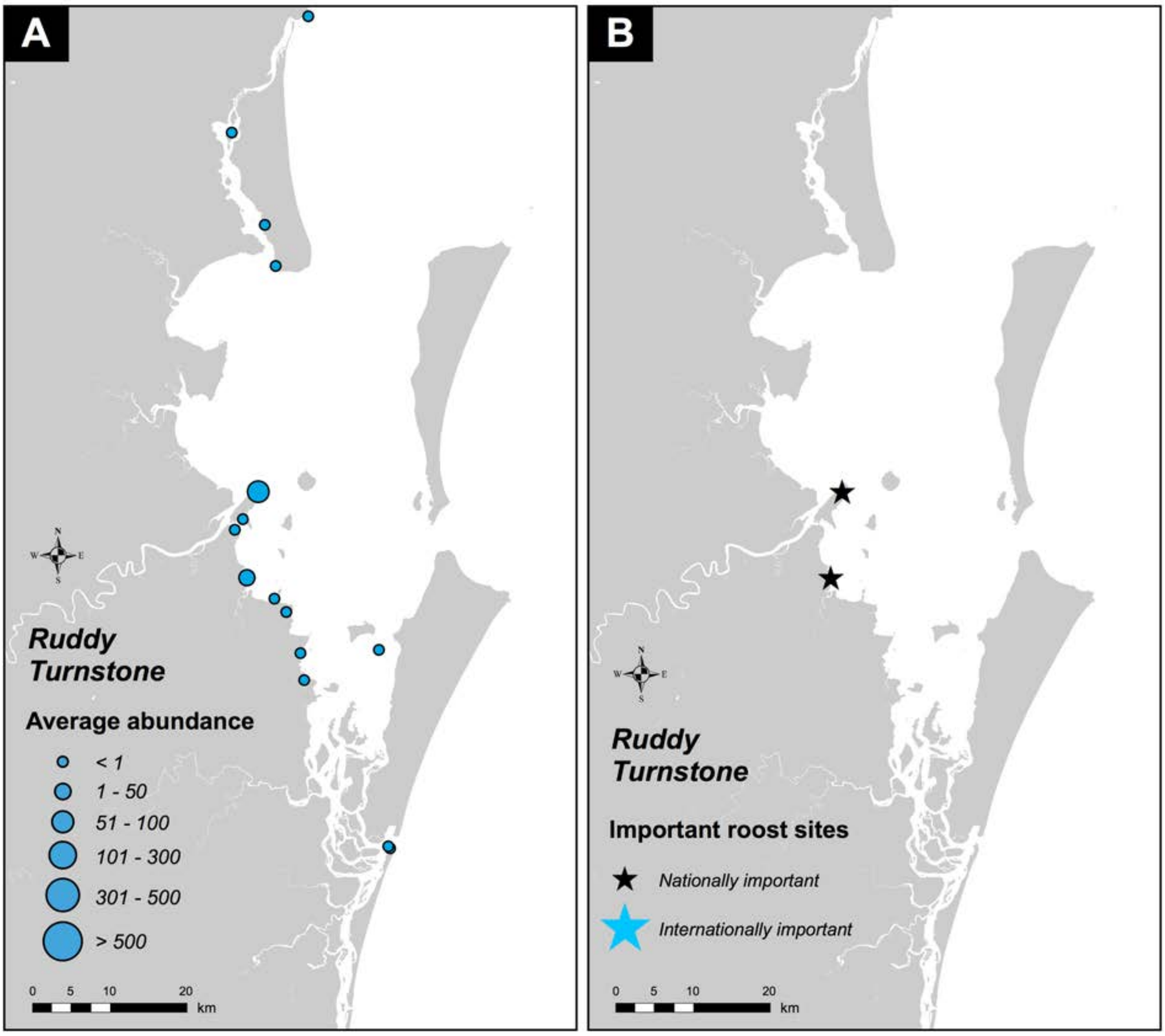


Figure 4.16 Abundance of Ruddy Turnstone at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Sanderling *(Calidris alba)*

The Sanderling is not listed as threatened under the EPBC Act. It has been recorded in nationally important numbers on the south end of Moreton Island near the South Passage. Sanderlings are found almost exclusively on open sandy beaches, a habitat that has not been widely surveyed by the Queensland Wader Study Group. It is possible that more regular surveys along the sandy beaches on Moreton Island, and Minjerribah (North and South Stradbroke Islands), would uncover additional regular concentrations of these shorebirds. Overall, the Sanderling does not appear to be declining in Australia, but disturbance might be leading to local declines in southern Australia (Clemens *et al.* 2016). The foraging habitats of the Sanderling include the surf zone of sandy ocean beaches regularly covered and uncovered by each wave. These habitats are occasionally also used by Grey Plovers and Red-necked Stints, but generally there are few other shorebird species occurring in these areas, making the Sanderling a unique management proposition. Further, there are often sections of sandy beaches that are more regularly used by Sanderling, and identifying these favoured areas and ensuring levels of disturbance are kept low in those areas will be needed to maintain Sanderling numbers in Moreton Bay.

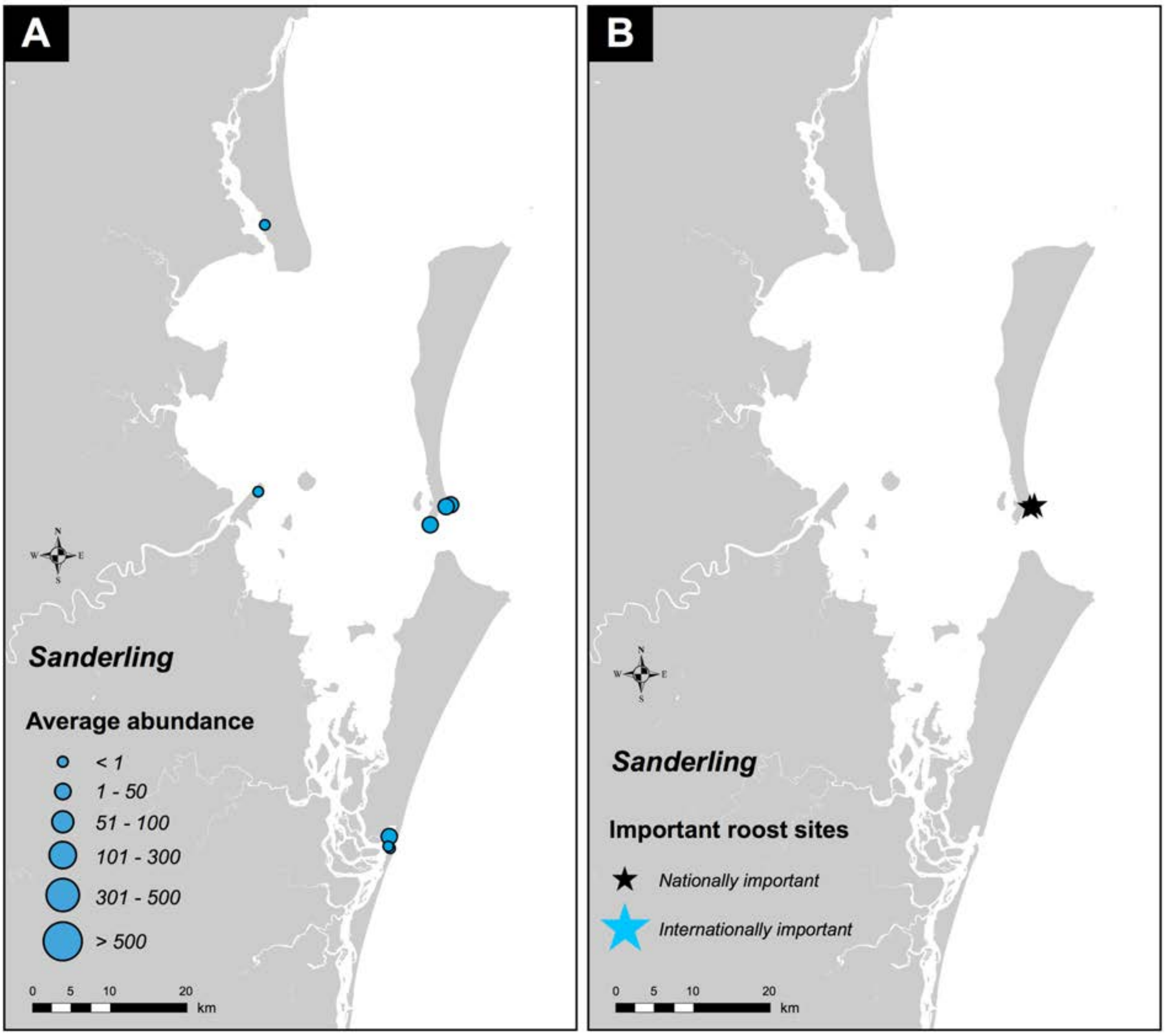


Figure 4.17 Abundance of Sanderling at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Sharp-tailed Sandpiper *(Calidris acuminata)*

The Sharp-tailed Sandpiper is not listed as threatened under the EPBC Act, but it is observed regularly in internationally important numbers above 1,500 (**Figure 4.18**). Internationally important numbers have occurred at the Port of Brisbane and the claypan at nearby Luggage Point. Nationally important numbers have occurred occasionally at roosts from Pumicestone Passage and at Geoff Skinner Reserve (**Figure 4.18**), and Sharp-tailed Sandpipers occur in smaller numbers at sites scattered throughout the bay. Like Curlew Sandpiper and Red-necked Stint, Sharp-tailed Sandpiper may find foraging opportunities as well as wide open areas free of disturbance at the Port of Brisbane.

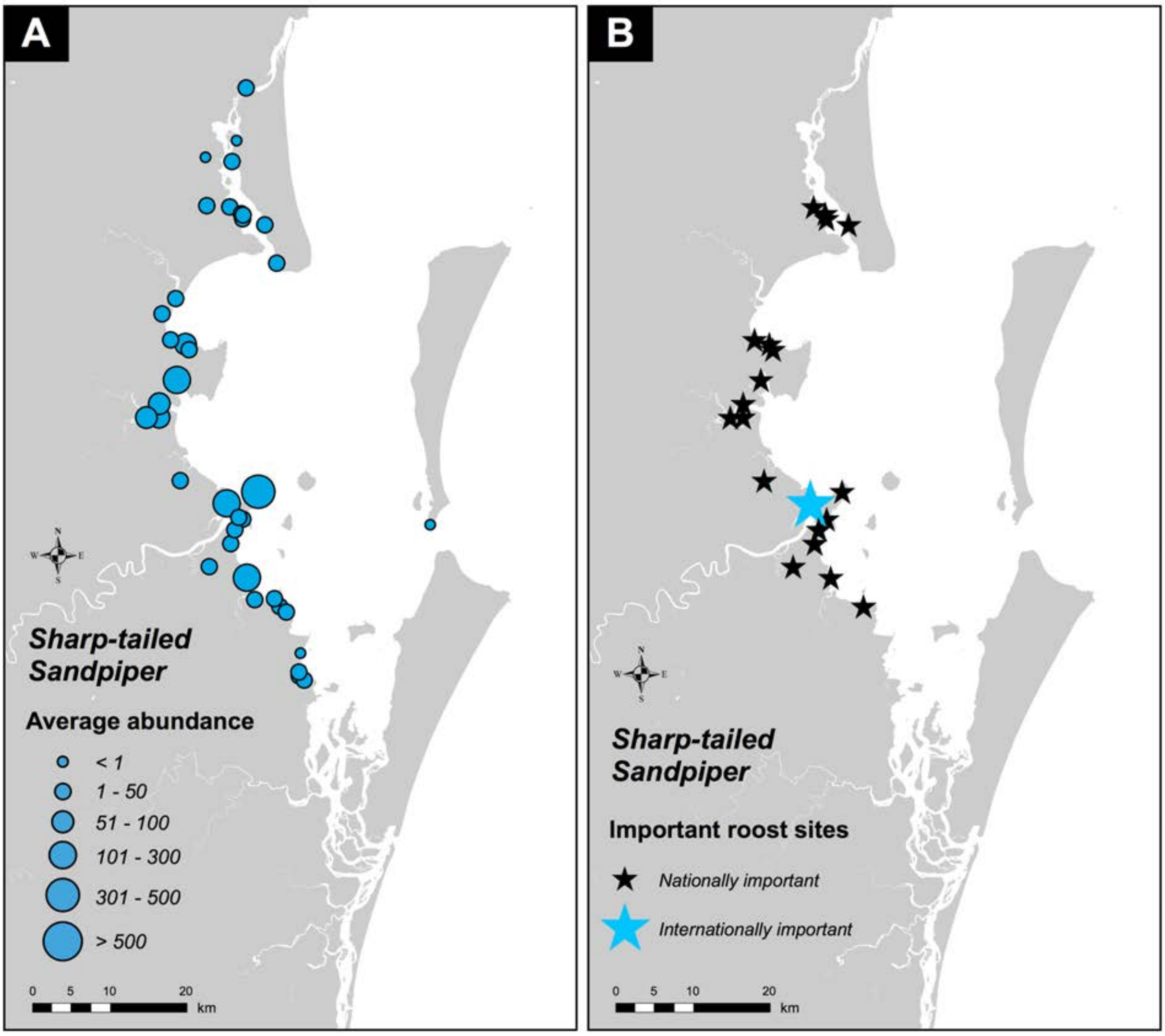


Figure 4.18 Abundance of Sharp-tailed Sandpiper at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally or internationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive.

Terek Sandpiper *(Xenus cinereus)*

The Terek Sandpiper is not listed as threatened under the EPBC Act and available data do not indicate that it regularly occurs in internationally important numbers in Moreton Bay. However, there is an important caveat to this, since Terek Sandpipers roost in mangroves, which are difficult to access, and not frequently counted by Queensland Wader Study Group surveyors. If the extensive mangrove areas such as those between Minjerribah (South Stradbroke Island) and the mainland were comprehensively surveyed, it seems highly likely that Moreton Bay would be discovered to hold internationally important numbers of this species, since the current number of birds is only just short of the threshold (**Table S2**). Internationally important numbers have been counted once in Pumicestone Passage, prior to 2009, and nationally important numbers have been recorded at Manly Harbour and Wellington Point (**Figure 4.19**).

Identification and protection of mangrove roosts will help conserve Terek Sandpipers in the bay.

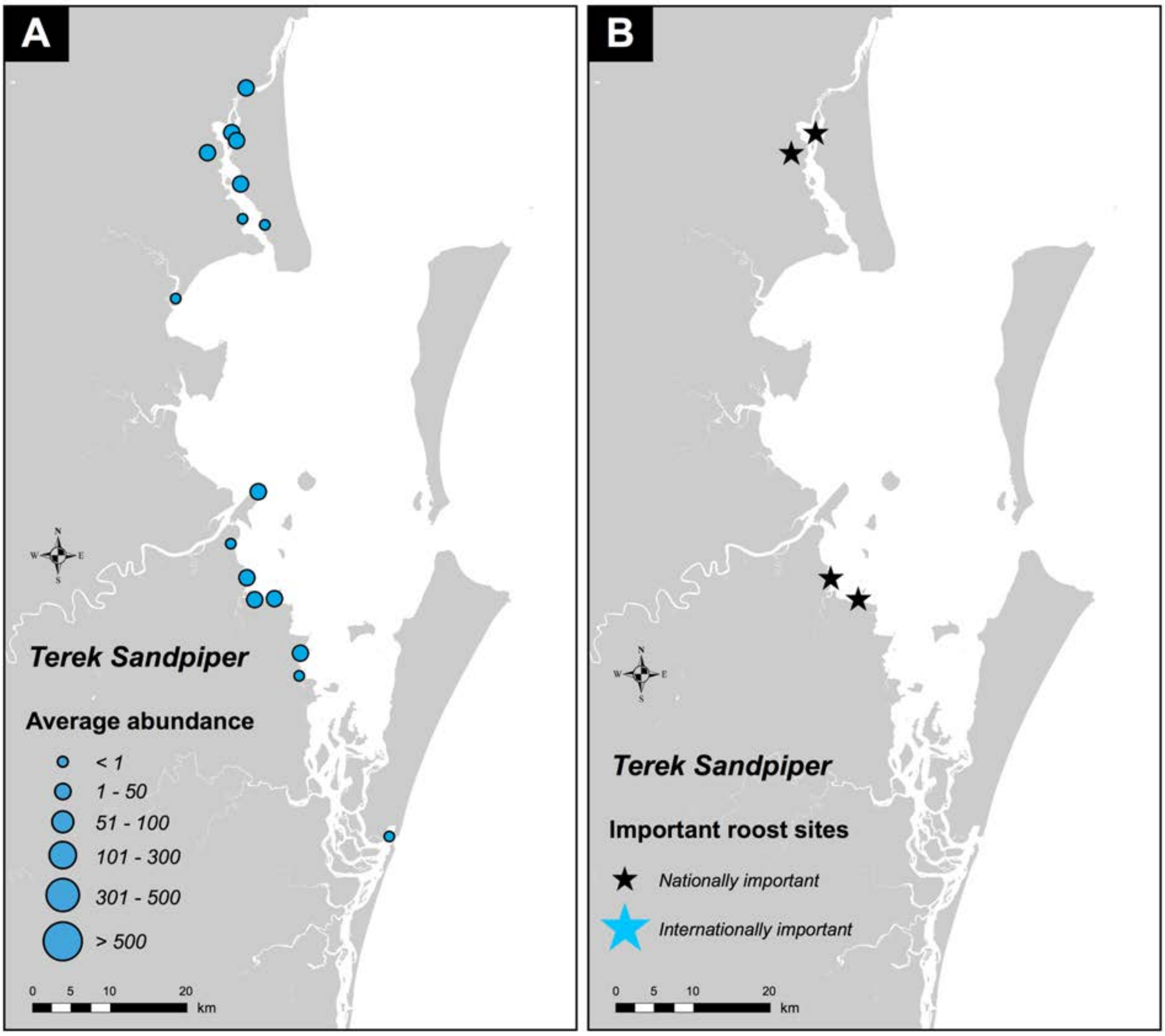


Figure 4.19

Abundance of Terek Sandpiper at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are currently no internationally important sites for this species in Moreton Bay.

Since the birds roosting in mangroves are likely to be spread rather thinly across a large area, management options aimed at generally limiting disturbance to mangroves at high tide might be more effective in conserving this species than specific site-based interventions. This said, it is also possible that specific characteristics of mangroves are preferred by roosting shorebirds, such as horizontal branches in stands of mature trees. Such sites might ultimately prove to be rather rare, and it could be the case that suitable opportunities for mangrove roosting are rather more limited that they might appear.

Whimbrel *(Numenius phaeopus)*

The Whimbrel is not listed as threatened under the EPBC Act, but it does occur regularly in internationally important numbers exceeding 1,100 in Moreton Bay. In Moreton Bay Whimbrels are most abundant in mangrove roosts in Pumicestone Passage, South Passage and near Goat Island, but they are widely distributed in nationally important numbers at roosts throughout Moreton Bay (**Figure 4.20**). It is likely that dedicated surveys of the larger mangrove forests would identify further nationally important concentrations in areas such as the islands between Minjerribah (South Stradbroke Island) and the mainland, as well as mangrove areas north or south of Redcliffe.

Whimbrels are territorial feeders that spread themselves rather thinly across intertidal habitats at low tide. Saltmarsh is occasionally used for foraging, but it is a very narrowly distributed habitat in Moreton Bay. Whimbrels roost over high tide in thick mangroves as well as open areas along the water's edge, claypans and artificial roosts. This makes them difficult to survey comprehensively, and also means that large aggregations in single sites tend not to occur. Management of this species thus needs to be thought about on a bigger scale (e.g. zoning to minimise high tide disturbance to mangrove forests) in addition to site-level interventions.

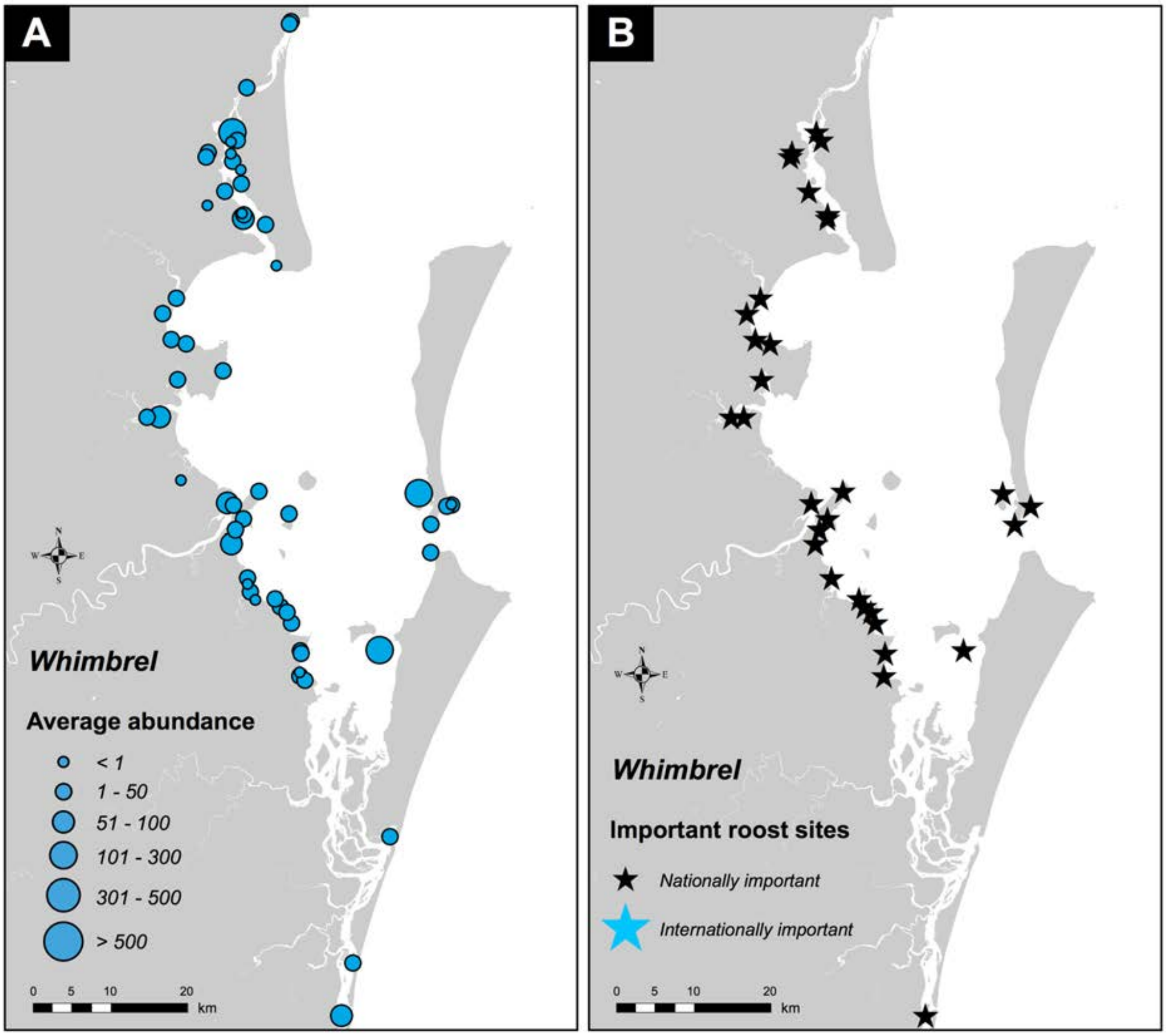


Figure 4.20

Abundance of Whimbrel at roosting sites in summer (November – February) between 2009 and 2019. (A) shows the average number of birds counted across all summer surveys. (B) shows roost sites that on one or more occasions between 2009 and 2019 have supported nationally important numbers of birds, based on the maximum count observed between 2009 and 2019 inclusive. There are no internationally important sites for this species in Moreton Bay.

Non-migratory and less common species

In addition to the relatively widespread or numerous migratory shorebird species described above, Moreton Bay also supports a number of non-migratory and less common migratory shorebird species. Below we list each of these species along with the number of records obtained by the Queensland Wader Study Group, and the number of years in which they were recorded (since November 1992). Species lists are ordered by the number of records (most to least; an approximate indication of relative abundance).

Migratory species: Marsh Sandpiper (1144 records, 27 years), Broad-billed Sandpiper (282 records, 27 years), Wandering Tattler (160 records, 24 years), Latham's Snipe (133 records, 23 years), Common Sandpiper (65 records, 21 years), Asian Dowitcher (56 records, 10 years), ruff (14 records, 6 years), Little Curlew (13 records, 8 years), Pectoral Sandpiper (10 records, 7 years), Wood Sandpiper (5 records, 3 years), Long-toed Stint (4 records, 4 years), Buff-breasted Sandpiper (4 records, 1 year), and Oriental Plover (3 records, 2 years).

Non-migratory species: Black-winged Stilt (7514 records, 27 years), Masked Lapwing (7083 records, 27 years), Australian Pied Oystercatcher (6336 records, 27 years), Red-capped Plover (6121 records, 27 years), Red-necked Avocet (1060 records, 27 years), Black-fronted Dotterel (851 records, 27 years), Sooty Oystercatcher (611 records, 27 years), Red-kneed Dotterel (584 records, 27 years), Beach Stone-curlew (401 records, 26 years), Banded Lapwing (10 records, 7 years), Banded Stilt (6 records, 4 years), Australian Painted Snipe (5 records, 4 years), and hooded plover (2 records, 1 year).

4.3 Changes in distribution and abundance of migratory shorebirds in Moreton Bay as a result of severe weather events

While many of the threats to migratory shorebirds in Moreton Bay arise from anthropogenic pressures such as habitat loss and disturbance, natural events such as floods and severe storms could also have important impacts. Moreover, the impacts of severe weather events could be exacerbated in a system that is already under pressure from human activity, and where many historically available roosting sites have disappeared. In this section we analyse Queensland Wader Study Group survey data to establish whether there are clear, repeatable effects of severe weather events on the number of birds present at roost sites in Moreton Bay, and in the distribution of birds across the Bay. We take the general approach of comparing bird numbers at individual roosts before and after the severe weather event, both in the short term (months) and in the longer term (years).

Severe weather events could impact roosting sites by washing them away, or temporarily inundating them with water too deep to allow for roosting. The severe winds can damage surrounding vegetation, or render a roost site physically unsuitable for birds during the storm event itself. Flooding resulting from severe weather events can profoundly impact foraging habitat, by washing large volumes of sediment into the Bay, with the resulting turbidity and newly-deposited sediment later killing benthic prey species or at least making them temporarily unavailable. Such flood events also give us a useful indicator of the possible vulnerabilities of certain species or areas to sea-level rise. In the longer term, severe weather events and associated sedimentation plumes could also result in a redistribution of benthic prey, and nutrients could change the balance of abundance of different benthic invertebrate species. Pollutants flushing into the Bay could also heavily impact certain benthic species.

Major severe weather events involving storms and flooding have occurred three times in the last decade in Moreton Bay. The largest severe weather event occurred in January 2011, with smaller events in January 2013, and March 2017. The January flood of 2011 followed two months of flooding throughout much of Queensland and saw the Brisbane River peak at 4.46 m, which inundated 20,000 homes and saw substantial sediment influxes into Moreton Bay. Maximum tide height at Brisbane Bar during the event was 3.1 m (Bureau of Meteorology Whyte Island gauge). The flood in 2013 was associated with Cyclone Oswald which caused flooding throughout much of Queensland and New South Wales. While much smaller in magnitude than the 2011 event, dam releases and heavy rainfall in January 2013 (260 mm in Brisbane) led to widespread flooding with associated silt and sediment discharges into Moreton Bay. Maximum tide height at Brisbane Bar during the event was 2.8 m (Bureau of Meteorology Whyte Island gauge). The 2017 severe weather event, the smallest of the three systems, came after extensive rainfall which was associated with ex-Cyclone Debbie. Cyclone Debbie made landfall in the Whitsunday region of Queensland before the system moved south resulting in over 200 mm of rain in the Brisbane area and which led to local flooding and discharge of sediment into Moreton Bay at the end of March, early April 2017. Maximum tide height at Brisbane Bar during the event was 2.6 m (Bureau of Meteorology Whyte Island gauge). Monthly counts in Moreton Bay (Milton & Driscoll 2006) allow for comparisons to be made over both the short and the long term at a large number of roosts. Comparisons are also made somewhat easier due to the high site fidelity that non-breeding migratory shorebirds typically exhibit, with individuals returning to the same area year after year unless something drastic changes in their environment (Herrod 2010; Rogers *et al.* 2010; Purnell *et al.* 2012).

Note that the major impact of these events on Moreton Bay is not necessarily the heights of the tides themselves, but rather the sediment deposition accompanying the floods. However, the 2011 event was an extremely high tidal surge, and represents a useful case study of inundation of the roost sites usually used supratidally by shorebirds.

Measuring migratory shorebird responses to severe weather events

We compared average abundance before and after each severe weather event for each species at each roost. Only data from November to March inclusive were included in these comparisons. We required that the maximum count of a given species was greater than five birds, and there had to be at least two counts in the pre- and post-severe weather event comparison data. To avoid the counts either side of the events having different sample sizes, the number of visits was filtered to be equal on either side of the event. For example, if there were only two pre-flood visits, the mean for post-flood abundance used two randomly-selected visits, even if there were ten post-flood visits within the eligible time period. There were sufficient data to make comparisons for the 11 most common species present in Moreton Bay: Bar-tailed Godwit, Curlew Sandpiper, Far Eastern Curlew, Great Knot, Greater Sand Plover, Grey-tailed Tattler, Lesser Sand Plover, Pacific Golden Plover, Red-necked Stint, Sharp-tailed Sandpiper and Whimbrel.

To compare changes in abundance in the short term, average counts in the two months prior and two months after the severe weather events were compared. We used paired Whitney U tests to indicatively compare all pre-severe weather event median counts to all post-severe weather event median counts for the entire Moreton Bay region. The same comparisons were repeated in longer-term comparisons that included data from the summer previous to, and following the severe weather event.

Changes in migratory shorebird numbers after severe weather events

Neither overall numbers of migratory shorebirds, nor the numbers of individual species showed consistent changes in abundance at any roost, or throughout the whole of Moreton Bay that were unambiguously related to the three severe weather events investigated, either for the short term or long term comparisons (**Figure 4.21**; **Supplementary Figures S1** to **S11**). While there was substantial variation in abundance at individual roosts before or after individual severe weather events, patterns were not obviously consistent across multiple events or among species that might be expected to be affected in similar ways. Of the possible acute effects of severe weather events observed at several roosts throughout the Bay, most noticeable was the higher variation in the counts immediately after the severe weather events than there was in the longer term (**Figure 4.21**), with an especially large variability in migratory shorebird abundance between roosts around Thornlands. Roosting sites that seemed particularly vulnerable to severe weather events were Luggage Point, Manly Harbour, East and West Geoff Skinner Reserve, King Street Mudflat and Thornlands Road. Not all of these roosts were negatively affected after each severe weather event, but each of them showed at least one major acute reduction in the number of birds present after an event. However, it is possible that these reductions are just part of the natural variability in shorebird numbers present at a roost (Wilson *et al.* 2011), and not a result of the severe weather event itself. Some of the details of these changes in abundance at individual roosts were different to those reported previously from the 2011 severe weather event (Clemens *et al.* 2012). These differences result from different methods of subsetting data, further suggesting that most of the patterns observed in shifts in abundance at individual roosts relate to the inherent variability in monthly count data rather than consistent, repeatable changes at roosts. Indeed, post severe weather event comparisons which indicated large drops in the short-term abundance of small shorebirds in the immediate term after the 2011 severe weather event, especially near the mouth of the Brisbane River were less obvious after the 2017 severe weather event. These results imply that (i) impacts on bird abundance from severe weather events are weak and/or of very short duration, and (ii) detailed monitoring with weekly or even daily counts would be needed to robustly discover their underlying structure. Further work may uncover less obvious long term impacts of severe weather events on shorebird abundance in Moreton Bay or at individual roosts, but much of the apparent variation at individual roosts probably relates to other factors such as tide height, wind speed and direction, and disturbance.

Further detail on changes in the numbers of individual species at roost sites throughout the Bay after all three severe weather events are shown in **Supplementary Figures S1** to **S11** and **Supplementary Table S3**.

Oil spill

Severe weather events can also lead to oil spills from shipping. For example, caught up in Cyclone Hamish in March 2009, the cargo ship Pacific Adventurer lost an estimated 270 tonnes of fuel oil seven nautical miles east of Cape Moreton (Miller 2009). The oil impacted the outer beaches of Moreton Island and Bribie Island quite severely, and also entered the Bay and into the Brisbane River. Only about 16 oiled birds were treated, but the true number of birds affected remains uncertain (Miller 2009). Although this spill was not large by global standards, and did not appear to have a severe or lasting impact on the ecology of Moreton Bay, or shorebirds in particular, it does serve to illustrate the vulnerability of the Bay to oil spills. While such events cannot be prevented, close attention needs to be paid to effective planning for managing the impact to wildlife of future such events in Moreton Bay, especially given the importance of the Port of Brisbane (a destination for much heavy shipping) for migratory shorebirds. In particular, the availability of spatial mapping tools in state government databases that indicate the locations and sizes of shorebird roosting and feeding sites will be crucial in mounting rapid responses to future spills in terms of checking known roosting and feeding sites, and attending to affected birds.

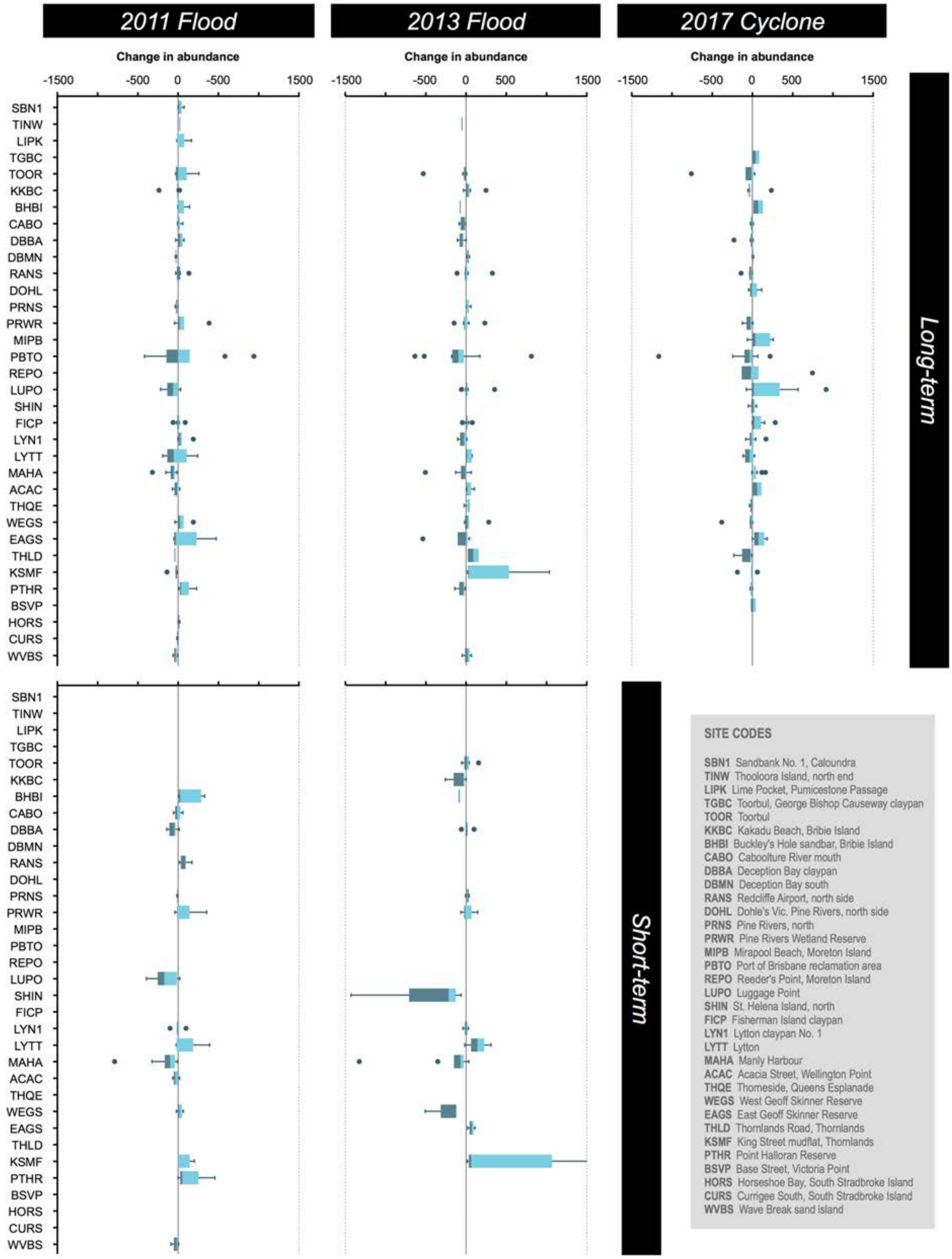


Figure 4.21 Changes in overall numbers of migratory shorebirds at roosting sites across Moreton Bay before and after three major severe weather events, in January 2011, January 2013 and March 2017. The short term response compares the numbers of roosting birds in the two summer months immediately prior to, and after, each severe weather event. The long term response compares counts in the previous summer to counts in the following summer. See Supplementary Figures S1 to S11 for data on individual species' responses to these severe weather events.

4.4 Threats, gaps, and vulnerabilities in the network of high tide roost sites in Moreton Bay

Migratory shorebirds are widely dispersed across a number of regular roosting locations in Moreton Bay (**Figure 3.1**). While this might give the impression that migratory shorebirds have an abundance of options for roosting, and that the availability of roosting sites is not limiting, urbanisation, infrastructure development and vegetation succession have led to many roost sites being deleted or heavily degraded over the past few decades. This has caused partial or total abandonment by migratory shorebirds in some cases, and the emergence of spatial gaps and vulnerabilities in the network of roosts. Moreover, disturbance to roosting sites is widespread, and extremely acute at some sites. Yet there has not yet been a comprehensive assessment of the threats to migratory shorebird roosting sites in Moreton Bay, and so we lack a robust database on which to build an assessment of the gaps, vulnerabilities, and ultimately the management priorities for roosting sites in the Bay. Here we present results of an expert consultation process to identify threats to migratory shorebird roosting areas across Moreton Bay.

Identifying threats to roosting sites in Moreton Bay

We asked 20 expert witnesses to describe cases of roost site loss in Moreton Bay. In the first part of the process, we convened a group of long-time core members of QWSG to discuss at length the threats to shorebird roosts in Moreton Bay over two day-long sessions. We then distributed an online survey to all QWSG counters, capturing similar information to that obtained during the face-to-face meetings with QWSG core members. The survey asked participants to (i) list which threats are operating at each roost for which they had direct knowlegde, (ii) estimate whether this threat has already reduced the number of shorebirds at this roost, (iii) estimate whether the threat is currently active, and (iv) list any additional roosts they know have been destroyed or abandoned. Experts were given an open-ended question format so they could describe the threats in their own words. We used the responses to subsequently group the threats into seven groups: development, disturbance, erosion, mangrove encroachment, land management, unknown, or none identified. Mangrove encroachment refers to the growth of mangroves into the open areas used as roosting sites by migratory shorebirds, reducing visibility and lines of sight for birds using the roost, and limiting the available space. Notably, three species actually prefer to roost in mangroves (Whimbrel, Terek Sandpiper and Grey-tailed Tattler), and are thus not affected by this threat. Disturbance was primarily recreational disturbance (e.g., from boats, kite surfers, dogs, or anglers). Threats from land management primarily encompassed issues such as weeds (e.g., at Manly Harbour) or overgrowth of other non-mangrove vegetation. None identified refers to the case where a site was assessed but no threats were reported, whereas unknown refers to a site that was not assessed (e.g., no response to the survey or a lack of information). Many sites for which threats are unknown are not part of the regular count program and have only been visited irregularly by QWSG surveyors. We did not consider the temporality of the threat (e.g., whether the threat occurred in the past, is ongoing, or may occur in the future), but simply whether the threat was identified as affecting the roosting site or not. The threats are suggested to be operating despite the existence of any management strategies at particular sites, so the threat assessment can be considered as a summary of threats that are not sufficiently managed.

All count sites in the Port of Brisbane reclamation area were aggregated into a single site for mapping threats, excluding the Port of Brisbane Artificial Roost, Fisherman Island Claypan, and Fisherman Island Visitor’s Centre. Threat information for the Broadwater region (defined here as sites from Swan Bay, Minjerribah (North Stradbroke Island) south to Curlew Island) was not linked to specific sites within the QWSG database, but rather to general areas in the Broadwater region (e.g., Jumpinpin). To represent this information spatially, we assigned threats to one or more sites in the QWSG dataset if they were within or in close proximity to the following areas: Swan Bay, Jacobs Well, Jumpinpin, Upper Pimpama River, North Branch Coomera River, Coombabah Lake, Brown Island, and Curlew Island.

Types and prevalence of threats affecting roost sites in Moreton Bay

Fifteen of 218 assessed migratory shorebird roosting sites have been identified as now unsuitable for shorebirds (**Table 4.1**), 11 as a result of development impacts, three to mangrove overgrowth and one to erosion. This included eight individual roosting sites at the Port of Brisbane, although it is probably more correct to think of these as replaced rather than destroyed, since the earlier stages of the development of the Port were later replaced with the large reclamation ponds that now support around 8,000 migratory shorebirds. Though currently set aside for shorebirds, the potential for development to adversely impact the internationally significant artificial roost at Manly Harbour remains very strong unless it is granted long-term protection (e.g., under the Nature Conservation Act or the Marine Parks Act).

Development at Raby Bay resulted in the loss of one of the larger roosts in that area (up to ~4,500 roosting shorebirds), and there have been no shorebird counts conducted there since 1995. A nearby small roosting area was constructed in an attempt to make room for the displaced birds (Lawler 1995), but it never supported large numbers of birds, and eventually it was overgrown with vegetation again. The birds displaced from this roost are now likely to be flying further to alternative roosting sites, but it is unclear if these alternate roosts include the network of roosts within a few kilometres, or if some are now opting to go to the less disturbed roosts at Manly Harbour or the Port of Brisbane that are nearly 15 km away. Conversely it is also possible that fewer birds are now using the tidal flats in the Raby Bay area given the long distance from suitable roosting sites. It remains unclear how these kinds of impacts coupled with increasing rates of human disturbance may be affecting pre-migration condition of the shorebirds foraging in areas close to where roost sites have become unsuitable for shorebirds or become degraded. Thornlands, Geoff Skinner and King Street mud flats appear to be the last 'traditional' mud flats for roosting flocks in this part of the Bay, and strong protections and management actions are needed to maintain them.

A major roosting site at Dynah Island near Nudgee Beach became unsuitable as a result of mangrove growth. Originally a dredge spoil disposal site, the roost has now been completely overgrown by mangroves, and it appears that the 1,000 - 2,000 migratory shorebirds that regularly forage in the Nudgee Beach area now go to roost at the Port of Brisbane or Luggage Point area, several kilometres away. This appears to represent a vulnerability in the current roost site network in the sense that there is now an extreme reliance on the temporary roosting habitat in the reclamation ponds at the Port of Brisbane for birds foraging in a reasonably wide surrounding area. The expert witnesses suggested that (re)construction of a roost site at Dynah Island could be an option worth considering to replace the lost site and reduce the vulnerability of the roost site network in this area.

A third major historical roost site at Dux Creek on Bribie Island was initially created by and subsequently lost to development, but was replaced with a managed roosting area at Kakadu Beach. This roost is now heavily used by migratory shorebirds, indicating that replacement with artificial sites can be successful, although there is disturbance at Kakadu Beach that requires ongoing enforcement activity, and periodic machine work is being conducted by Moreton Bay Regional Council to keep the roost site profile flat and open. Moreton Bay Regional

Council also has specific maintenance plans for the Kakadu Beach roost (updated 2017) and the Toorbul roost (updated 2016). This example of good practice by Moreton Bay Regional Council illustrates the importance of a long term commitment to management works in artificial roost sites.

Almost every roosting site across Moreton Bay is being affected by one or more threats. Of the 129 roosting sites with information on threats from the expert witnesses, 123 (95%) had one or more threats operating, and many nationally and internationally important sites were subject to threats (**Figure 4.22**). Disturbance was identified

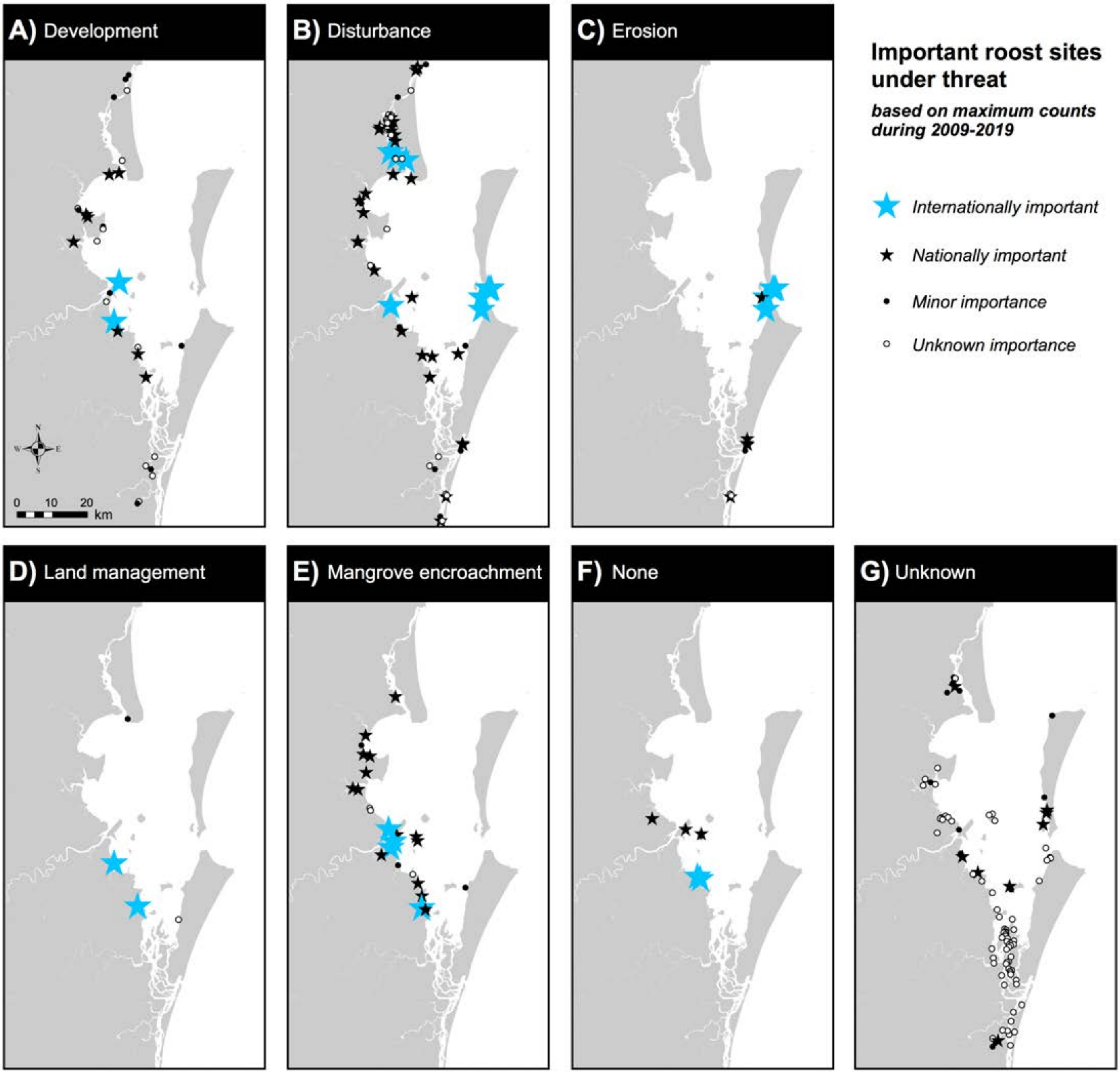


Figure 4.22 Threats to migratory shorebird roost sites in Moreton Bay. The map shows the location of every roost impacted by each of the five threats, and also those with no threats apparent, and those where threat status is currently unknown. If multiple threats were identified for a site, then the site will occur in multiple panels. Sites of unknown importance (open circles) are those for which there are no count data since 2009.

as a threat at 67 sites, development at 43 sites, mangrove encroachment at 25 sites, erosion at 14 sites, and land management issues at 4 sites (**Table 4.1**). Disturbance is threatening roost sites pervasively throughout Moreton Bay, even on the islands (**Figure 4.22**), while development and mangrove encroachment pressure are particularly problematic along the mainland coast. Erosion is affecting some sites on the barrier islands, an effect that is directly visible in the tidal flat change maps (**Figure 5.5**).

Finally, it should be noted that this threat analysis should serve as a basis for further discussions on management options and that there are additional resources of data on shorebirds in Moreton Bay available (e.g. state managed databases; https://wetlandinfo.des.qld.gov.au/wetlands). In addition, when interpreting the threat analysis it should be taken into consideration that threats are as identified from Queensland Wader Study group members only. It is possible that the overall perception and weighting of threats would differ depending on the role of the individual assessing the threat. It is therefore suggested that, whilst this document would serve as an excellent source for initial discussions, other stakeholder groups be consulted with different perspectives on specific roost sites. This could be combined with a detailed research programme that quantitatively assesses and monitors threats at roost sites, perhaps through a standardised annual survey. Such a survey could also be the basis for researching the effectiveness of management actions taken to reduce or mitigate these threats to identify best practice options to help conserve shorebirds.

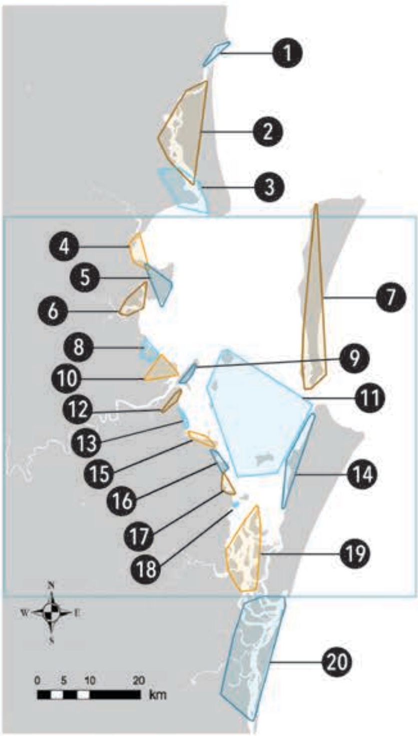
Sea-level rise as a threat to migratory shorebirds in Moreton Bay

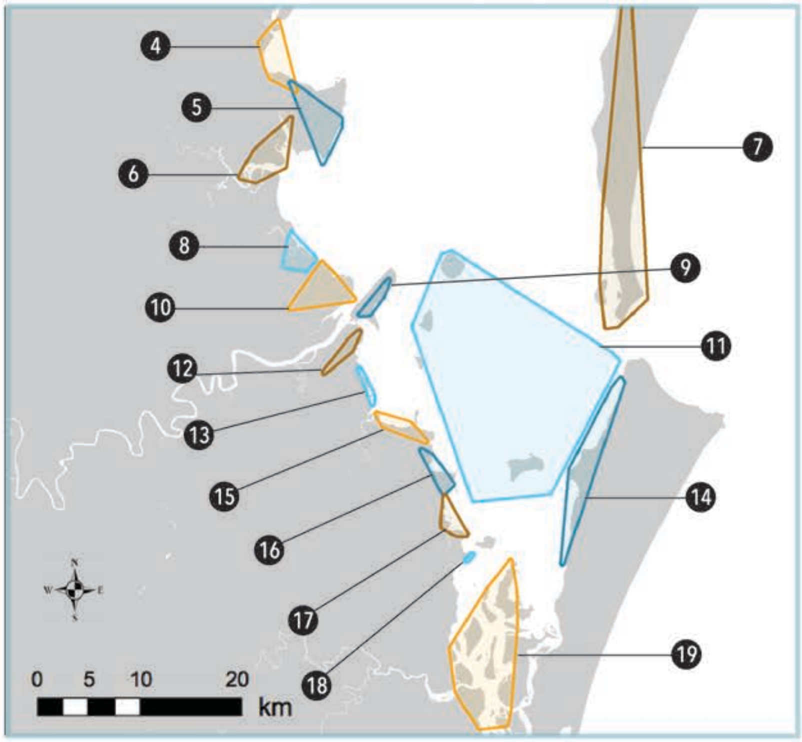
The climate in South-east Queensland is projected to change rapidly in the near future, with an increase in median annual temperature of between 1.2°C and 1.7°C by 2050 and a reduction in annual rainfall of 5% - 7%, with the reductions concentrated in the autumn, winter and spring (Saunders *et al.* 2019). Climate change also means that the region's sea-level will rise by an estimated 21 cm – 27 cm by 2050, and 43 cm – 86 cm by 2090, depending on which models of climate change and sea-level rise forcing are adopted (Saunders *et al.* 2019). Predicting the precise extent of inundation and storm damage impacts of this sea-level rise is exceptionally difficult because small errors in estimates of elevation can yield large differences in inundation projections, and this is multiplied when considering the uncertainty in the amount of sea-level rise itself (Leon *et al.* 2014). However, there have been several published attempts to model the impacts of sea-level rise on ecosystems within Moreton Bay (Traill *et al.* 2011; Runting *et al.* 2013, 2017; Mills *et al.* 2016; Saunders *et al.* 2019). Most models suggest declines in most ecosystems, and that these are exacerbated by coastal squeeze, in which built infrastructure prevents the necessary landward shift of coastal ecosystems as the sea-level rises. For example, seagrasses are predicted to decline in extent by about 6% by 2050 and 15% by 2100 as a result of sea-level rise, with the impacts being more severe in the more turbid waters of the western part of the Bay (Saunders *et al.* 2013). A decrease of up to 24% in saltmarsh and 52% in sedgelands is predicted by 2100 (Traill *et al.* 2011). There is one major exception to the general ecosystem declines. Detailed modelling suggests that mangroves are expected to increase in the southern Bay by 60% - 90% by 2050 depending on model uncertainty and the magnitude of sea-level rise (Saunders *et al.* 2013). A more generalised model for the entire Bay was created by adapting the Sea Level Affects Marshes Model by Traill *et al.* (2011), who predicted that mangroves were likely to expand by 35% in a rising sea-level by 2100, and that the expansion was likely despite coastal squeeze in some places caused by infrastructure and development along the shoreline. However, the mangrove results were sensitive to the choice of climate change scenario, with the upper estimate of 1.8 m of sea-level rise by 2100 leading to a decline in mangroves of 18% (Traill *et al.* 2011). Ocean-facing beaches were also likely to increase according to Traill *et al.* (2011), but there are no estimates available for intertidal flats. Filling this knowledge gap would be a useful research project for Moreton Bay.

Sea-level rise is an ultimate threat that operates through a number of proximate pathways to cause threats specifically to shorebirds. Given the results of the sea-level rise modelling efforts in Moreton Bay so far, the most likely proximate causes for shorebird impact appear to be inundation of claypans (especially where these are bounded on the landward side by built infrastructure), overgrowth of roost sites with mangroves, and loss of saltmarsh and associated supratidal vegetated habitats.

Two responses for migratory shorebird conservation in Moreton Bay seem warranted. First, addressing the threat of mangrove expansion and saltmarsh decline through appropriate vegetation management at roost sites is made even more critical in the light of the looming threat of sea-level rise. Given the large number of roosts currently affected by mangrove overgrowth, it seems likely that these effects of sea-level rise are already being felt, and that management action to address these threats is needed. So, rather than suggest a suite of management actions that are specific to sea-level rise, it seems reasonable for practical management actions to focus on the proximate threats as they start to impact shorebird habitats, as detailed above in **Section 4.4**. It would also be worth conducting a detailed assessment of patterns of inundation and water level assessments at all shorebird roost sites across Moreton Bay. By observing the frequency of inundation and the depth of tidal water coverage at shorebird roost sites, it would be possible to create a baseline against which change in sea-level might be impacting the space available for shorebirds to roost. Combined with an assessment of the extent to which landward built infrastructure is limiting the potential for the shifting of each roost site, this could provide a useful mechanism for monitoring the more insidious forms of change in roost site quality as sea-level rise continues.

A second set of responses to the threat of sea-level rise entails longer term planning, ensuring protected areas are in place to allow for coastal retreat and minimise the impact of coastal squeeze over the coming decades (Mills *et al.* 2016). This is especially important because most of the habitat expansion in Moreton Bay as a result of sea-level rise is going to occur outside the current protected area system (Saunders *et al.* 2019). Given the substantial investments that would be needed, and the complex interplay among multiple competing social and ecological demands, such planning needs to involve an enormous range of stakeholders, and indeed multi-agency efforts are already underway to plan for climate change impacts across Moreton Bay. Mechanisms involving payments for ecosystem services might be needed to ensure such long term adjustments to protected area networks are viable (Runting *et al.* 2017). From the perspective of the present document, ensuring that migratory shorebirds and their habitats are adequately represented in such planning is an important long term priority.





Region	No. of sites	Sites lost	Development	Disturbance	Erosion	Land management	Mangrove encroachment	None identified	Unknown
1. Caloundra / Pelican Waters	2	0	0	2	0	0	0	0	0
2. Pumicestone passage	25	0	2	22	0	0	0	0	3
3. Toorbul /Bribie Is	15	1	3	10	0	1	1	0	2
4. Deception Bay	7	0	3	4	0	0	3	0	0
5. Redcliffe	4	0	4	1	0	0	1	0	0
6. Pine Rivers North / Hays Inlet	9	0	0	1	0	0	3	0	5
7. Moreton Is	11	1	0	4	6	0	0	0	5
8. Nudgee	9	2	0	1	0	0	2	1	5
9. Port of Brisbane*	21	8	19	0	0	0	1	1	0
10. Brisbane Airport / Luggage Pt	5	0	0	0	0	0	1	0	4
11. Moreton Bay North	14	0	0	4	1	0	2	2	6
12. Lytton	4	1	1	1	0	0	3	0	0
13. Manly / Wynnum	4	0	1	0	0	1	1	0	2
14. North Stradbroke Is	6	0	1	1	0	1	1	0	4
15. Thornside / Wellington Pt	7	0	1	2	0	0	1	2	2
16. Cleveland	4	2	2	0	0	0	2	0	1
17. Thornlands	6	0	0	1	0	1	3	0	1
18. Victoria Pt	2	0	1	1	0	0	0	0	1
19. Moreton Bay South	33	0	0	0	0	0	0	0	33
20. Broadwater	30	0	5	12	7	0	0	0	15
TOTAL	218	15	43	67	14	4	25	6	89

Table 4.1

Summary of threats to roosting sites in Moreton Bay, giving the total number of sites at which each threat was identified. Multiple threats were identified for some sites, thus the row sums will sometimes exceed the number of sites in a region. Sites lost indicates the number of sites lost to development, mangrove encroachment or erosion. *Development works at the Port of Brisbane can simultaneously result in the creation and removal of sites, and several of the sites lost have been replaced with other roosting sites.

4.5 Gaps in monitoring of migratory shorebird roosting areas in Moreton Bay

The roost count data collected by QWSG has proven highly effective at monitoring changes in migratory shorebird populations within Moreton Bay (Wilson *et al.* 2011), and has formed a critical part of reporting on national shorebird trends (Clemens *et al.* 2016, Studds *et al.* 2017). The QWSG approach of monthly monitoring in Moreton Bay clearly demonstrates the value of frequent counting in overcoming the inherent high variation in numbers of birds present at a roost (Wilson *et al.* 2011). These data also allow estimations to be made of the total number of shorebirds using Moreton Bay, and determinations of which species meet thresholds of international importance. Further, these data have been routinely used in local, state and national planning documents (Hansen *et al.* 2018). With ongoing monthly counts at approximately 67 roosting sites by QWSG, Moreton Bay is relatively well-monitored (**Figure 3.1**). However, Moreton Bay is at the doorstep of a major city with ongoing human population growth, which is likely going to increase pressure on remaining habitats and the birds that occupy those habitats. This increasing pressure will lead to a growing need to identify where and how to take conservation action. While monitoring of the shorebirds themselves could always be improved (e.g., by implementing some of the changes outlined below), the first step for improving shorebird management is to improve monitoring of threats to roosting and feeding areas (e.g., disturbance, erosion, development, mangrove encroachment). Consistent, structured monitoring of various threats to migratory shorebirds lags far behind monitoring of numbers which is still important for continuing to meet the objective of detecting changes in shorebird populations.

While the current monitoring covers 67 of the most threatened roosts that hold the most birds, there remains a large number of roosts that are not regularly monitored. In fact, monitoring has been discontinued at 82 roosts, and yet another 69 roosts have only been visited once since monitoring began (**Figure 4.1**). Crucially though, it is likely that only small numbers of birds occur at most of the roosts with a single or few recent visits, although conducting reconnaissance visits at least annually would help identify any roosts which are especially threatened or that hold large numbers of birds that should be added to the monthly count program. The last complete census of Moreton Bay was conducted in 2008, so there would be immediate value in initiating an annual survey of all the roosts in Moreton Bay to allow more precise estimates of the total number of individuals using Moreton Bay regularly.

Gaps in monitoring shorebird numbers

Pumicestone Passage. The northern section of the Pumicestone Passage, stretching approximately 30 km north from Toorbul to Caloundra is an under-monitored section of the Bay, yet historically was known to contain a number of important roosting sites. Since monitoring in this region requires a boat to navigate the shallow, sandy, mangrove-lined passage, it has been difficult to maintain the monitoring effort continuously over the years, and revisiting this area will fill an important gap in current monitoring efforts.

Hays Inlet. Hays Inlet extends approximately 5 km northwards from Korman Rd on the western edge of the inlet and Clontarf on the eastern side of the inlet. With the exception of the large claypan at the end of Gregory Road, there is no ongoing monitoring occurring in Hays Inlet but the region could be used by substantial numbers of mangrove-roosting species, such as Whimbrel and Grey-tailed Tattler. There are also several claypans in the area that might be used depending on water and weather conditions. Like Pumicestone Passage, Hays Inlet requires a boat to survey the mangroves lining the channel, whereas the claypans are likely best accessed by foot from overland access points, much of which would involve gaining access to private land.

Southern Moreton Bay and Broadwater Region. With a few notable exceptions, the southern portion of Moreton Bay extending from Victoria Pt and Jencoomercha (Macleay Island) southwards is the least well-monitored part of the Bay. This region contains numerous islands, developed and undeveloped, and thus is logistically challenging and costly to monitor but could be heavily used by migratory shorebirds.

There are currently no sites south of Victoria Point of which we are aware where counting by the QWSG is ongoing. However, more recent data from several key sites in the Gold Coast Broadwater region have been collected by other organizations (https://shorebirdsgc.blogspot.com/p/counts.html) and are available through eBird (such as https://ebird.org/hotspot/L2553306). At least part of this monitoring gap could perhaps be filled by identifying any standardised counting efforts outside the ambit of QWSG, and aligning and integrating these with the QWSG dataset. This would ensure a single, authoritative source of monitoring data for migratory shorebirds in Moreton Bay.

Barrier islands. Monitoring of important roost sites on southern Moreton Island, Amity Sandbank, and other small sandbanks and islands in the central part of the bay currently occurs on an approximately quarterly basis (October, January, April, July). Increasing the frequency of monitoring to monthly, especially during the summer months (November, December, January, February) would improve data robustness. The southern portion of Moreton Island has historically been one of the most numerically important roost sites in all of Moreton Bay for migratory shorebirds, including Far Eastern Curlew, so increased monitoring of shorebird numbers and threats (especially disturbance from beach driving and boaters) in that area is definitely warranted.

There could be some additional small groups of migratory shorebirds, such as Sanderlings, Ruddy Turnstones or Wandering Tattlers, scattered across the eastern (ocean side) shoreline of Bribie Island, Moreton Island, and Minjerribah (North and South Stradbroke Islands). A one-off, complete census of these long beaches could determine if small numbers of migratory shorebirds are using these open beach habitats, or the few interspersed rocky headlands.

Bay-wide censuses

Another type of monitoring gap is that Bay-wide censuses are not part of QWSG's regular count programme. Bay-wide censuses are important for (i) identifying which species occur in nationally or internationally significant numbers in Moreton Bay as a whole, and (ii) identifying roost sites that were previously unoccupied or previously undiscovered. The most recent Bay-wide census took place in 2008, which makes calculating recent or current population estimates challenging. Given the importance of population estimates for conservation and management (e.g., for determining whether Ramsar criteria are met), periodic Bay-wide censuses would be beneficial, but entail additional resourcing (e.g., boats or aircraft for Pumicestone Passage and southern Moreton Bay, organisational and administrative assistance).

Monitoring threats

Given the pervasiveness of the threats to migratory shorebird roosting and feeding sites identified in this report, we conclude that increased monitoring of threats and their impact would be worthwhile, to facilitate an understanding of the actions that can be taken to continue to protect Moreton Bay's shorebird populations. Discussions with expert counters has revealed that development, vegetation encroachment or erosion have been responsible for 15 roost sites becoming unsuitable for shorebirds, noting that a number of these were at the Port of Brisbane, where lost sites were subsequently replaced with new habitat that was suitable for roosting (**Table 4.1**). Further, a reduction in shorebird abundance of between 25% and 75% at some roost locations was believed to have resulted from either disturbance or mangrove encroachment. The QWSG tracks the number of potential disturbances (dogs, people, boats, or jet skis) on each count at each roost. These data provide an excellent baseline measure of disturbance at high tide roosts. Adding annual surveys with questions on the threats at the roost, and the impact counters think those threats are having would provide additional updated tracking of emerging threats. However, more targeted research into what the thresholds of disturbance are before roosts are abandoned would help managers set buffers around roosts, and identify where recreational disturbance needs to be reduced. There is a growing scientific understanding of these issues (West *et al.* 2002, Durell *et al.* 2005, Goss-Custard *et al.* 2006, Rogers *et al.* 2006, Peters and Otis 2007) but spatially explicit rates of disturbance could be better quantified at roosts around Moreton Bay and there is ample room for further study into the levels of disturbance that can be tolerated by roosting shorebirds. There is also a lack of research looking at the total energetic costs of disturbance, which is something that has been shown to be quantifiable in studies of other kinds of energetic costs (Wiersma and Piersma 1994). Research on the changes in numbers of shorebirds at roosts related to mangrove encroachment might be possible by using aerial photography or other imagery available of the roosting sites over time (e.g., using newly available mangrove canopy cover data available on www.nationalmap.gov.au). Annual snapshots from a drone, could be coupled with shorebird count data to pick up correlations if historic aerial imagery is not available. Ongoing monitoring of development plans would also improve current monitoring by allowing potential impacts to be identified sooner potentially allowing development plans to be adjusted more easily.

Finding capacity for additional monitoring

It is critical that any efforts to fill these gaps in monitoring do not impact the 25 year on-going monitoring effort conducted by the QWSG. If QWSG volunteers were paid for the work they did at $25 per hour, assuming each of 35 volunteers worked eight hours a month on average, $84,000 would be required each year just to continue monitoring efforts in Moreton Bay. For another 25 years of monitoring that would require $2.1 million. Considering it takes considerable time to build the specialist skills needed to identify and count these birds, and that many of the volunteers are professionals who would ordinarily be paid far more than $25 per hour, the work undertaken by the QWSG would be very hard to replace. The QWSG needs to be central to discussions on how best to fill these gaps, while ensuring their resourcing needs are met. This would ensure that future efforts to fill gaps did not impact the remarkable ongoing efforts by the members of this organisation.

Closing remarks on monitoring

In light of the ongoing declines in migratory shorebird populations (Wilson *et al.* 2011, Clemens *et al.* 2016, Studds *et al.* 2017) and growing threats to shorebirds emerging in Moreton Bay, there is an urgent need to both fill the gaps in current spatial monitoring of shorebird numbers as well as a need to monitor threats in conjunction with monitoring the outcomes of any management actions. We have identified three spatial gaps in regular migratory shorebird monitoring in Moreton Bay (Pumicestone Passage, Hays Inlet, and the southern Bay), as well as a gap in regular Bay-wide censuses. The resources needed to fill these gaps are (i) vessel support and identification of suitable counters to cover Pumicestone Passage and Hays Inlet, (ii) data sharing agreements or other form of integration with those monitoring outside the ambit of the Queensland Wader Study Group to cover the southern Bay, and (iii) substantial injections of funds, vessel support and administrative support to achieve regular Bay-wide censuses. To ensure migratory shorebird monitoring data can be used to inform planning and assessment, these data need to be regularly collated and made available to relevant agencies. While some of this activity is already underway through discussions and agreements between QWSG and state government, data on migratory shorebirds for Moreton Bay remain somewhat scattered among a number of different organisations.

We have identified four areas of focus when monitoring threats. These include: (i) improved monitoring of spatially explicit disturbance and research into its impact; (ii) improved monitoring and quantification of how rapidly open areas used for roosting are shrinking due to mangrove encroachment; (iii) an ongoing review of all development applications that could impact shorebirds in the bay; and (iv) targeted monitoring to provide evidence of any benefits of management or mitigation actions taken to reduce the impact of these threats.

5 Shorebird feeding areas in Moreton Bay

Migratory shorebirds forage almost exclusively on intertidal habitats, which in Moreton Bay are primarily mudflats and sandflats (McPhee 2017). Shorebirds have a range of different bill morphologies, ranging from short-billed species such as plovers that are mainly visual foragers of prey items on the surface of the flat, to very long-billed species such as the Bar-tailed Godwit or Far Eastern Curlew, which probe deep into the sediment to extract buried prey (Geering *et al.* 2007). A small number of shorebird species in Moreton Bay also use supratidal habitats for feeding, such as the reclamation ponds at the Port of Brisbane, or inland wetlands such as those as Kedron Brook Reserve. There are no robust quantifications of the amount of time Moreton Bay shorebirds spend feeding on supratidal versus intertidal habitats, but many species are exclusively intertidal feeders in Australia (Finn 2007, Jackson *et al.* 2020), and good management of intertidal habitats is fundamental to ensuring a continuing supply of food for migratory shorebirds.

During low tide, migratory shorebirds can be observed feeding almost everywhere across the tidal flats of Moreton Bay, yet their density varies enormously. Detailed benthic sampling work in the Gladstone region showed that many shorebird species had very specific low tide distributions that matched the distribution and density of their preferred invertebrate prey (Choi *et al.* 2017), and indicative benthic sampling for this project in Moreton Bay has also highlighted much variation in benthic prey occurrence (see **Section 5.3**). Yet, there are no comprehensive studies of the distribution of each species of foraging shorebird in Moreton Bay, and so a reasonable first proxy for assessing the status and distribution of feeding areas is to map the distribution and change in tidal flats across the Bay, recognising that not all species will be found across the entire area of tidal flat. Fortunately, excellent tidal flat mapping has recently become available, and a time series of change enables us to track how feeding areas for shorebirds in Moreton Bay have changed.

In this section we use two recently available tidal flat mapping products to measure the distribution, extent and change of tidal flats in Moreton Bay, and consider the drivers of observed changes in tidal flats over the last three decades.

It must be remembered that the term intertidal flats is very general and there are many different habitat types with this based on factors such as sediment type, water quality, and degree of freshwater input. Queensland state government has developed a detailed mapping protocol for depicting this variation spatially (Department of Environment and Science 2020), and it would be very interesting to determine how the distribution of migratory shorebirds at low tide varies among the different categories of intertidal habitat.

5.1 Intertidal flats in Moreton Bay

Tidal flats have recently been mapped globally using Landsat data (Murray *et al.* 2019), and a useful feature of that approach was that it created a time series of maps that allows change in tidal flat extent and distribution to be detected over time. Murray *et al.* (2019) used 707,528 Landsat archive images to develop global maps of tidal flat ecosystems, employing a machine-learning classification model to determine whether every 30 m pixel across the global coastal zone was tidal flat, permanent water or terrestrial. Satellite images were grouped into periods of three years, from 1984-1986 through to 2014-2016. Because the amount of satellite data available in the first time period was very small, we commence the present analysis in the 1987-1989 time period.

Extent and change of tidal flats in Moreton Bay

Tidal flats cover about 100 km^2 within Moreton Bay (**Figure 5.1**; **Figure 5.2**). Tidal flats occur widely throughout the Bay, although there are concentrations in Pumicestone Passage, Deception Bay, southern Moreton Island, the Manly foreshore, the inner coast of Minjerribah (North Stradbroke Island), and the southern Bay islands (**Figure 5.1**). Notably, one or more major roosting sites is associated with all of these major areas of tidal flat (**Figure 3.1**), underlining the critical importance of roost site availability everywhere across Moreton Bay. Yet it should not be assumed that all the birds foraging on a particular tidal flat will automatically go to the nearest available roost. For example, a Far Eastern Curlew fitted with a satellite tracking device would typically roost over high tide in the Geoff Skinner wetlands, yet traverse the Bay to feed along the inner shore of Minjerribah (North Stradbroke Island) on each low tide (**Figure 5.3**). This travel involves a direct fight of about 20 km, which sums to about 80 km of commuting every 24 hours, given that there are two high and two low tides per day. This is another indication of how limited roost site availability is in Moreton Bay, since this bird preferred the energetic costs of 80km flight per day to the risks of roosting at sites closer to the feeding area.

Overall, there has been relatively little change in tidal flats in the last 30 years (**Figure 5.2**; **Figure 5.4**), which is perhaps surprising given the regularity of severe weather events and ongoing

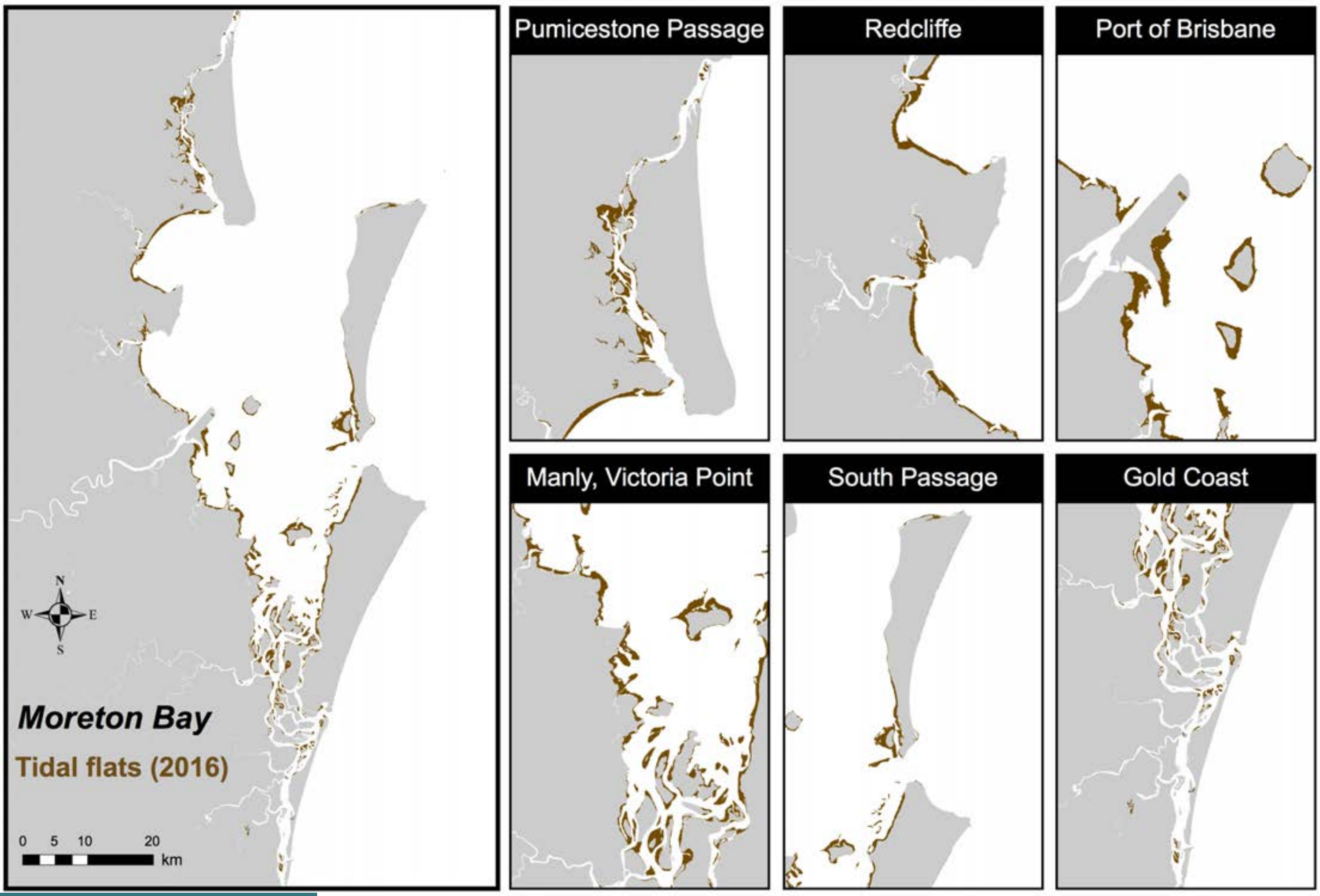


Figure 5.1 Current extent of tidal flats in Moreton Bay. Tidal flats occur throughout the Bay, particularly along the mainland coastline, and the only major regions without large flats are Bribie Island, much of Moreton Island, and the rocky headland at Redcliffe. This image is created by combining available satellite imagery from 2014-2016, using the method described in Murray *et al.* (2019).

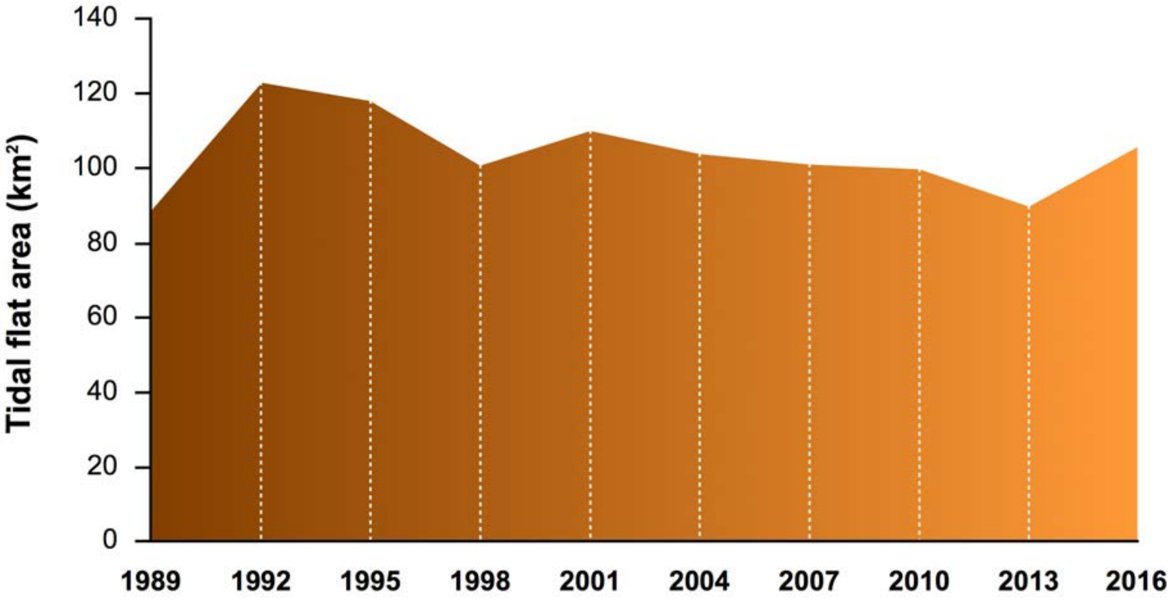


Figure 5.2

The extent of tidal flats in Moreton Bay shows no strong overall trend in recent times, with approximately 100 km^2 occurring within the Bay in the last 25 years.

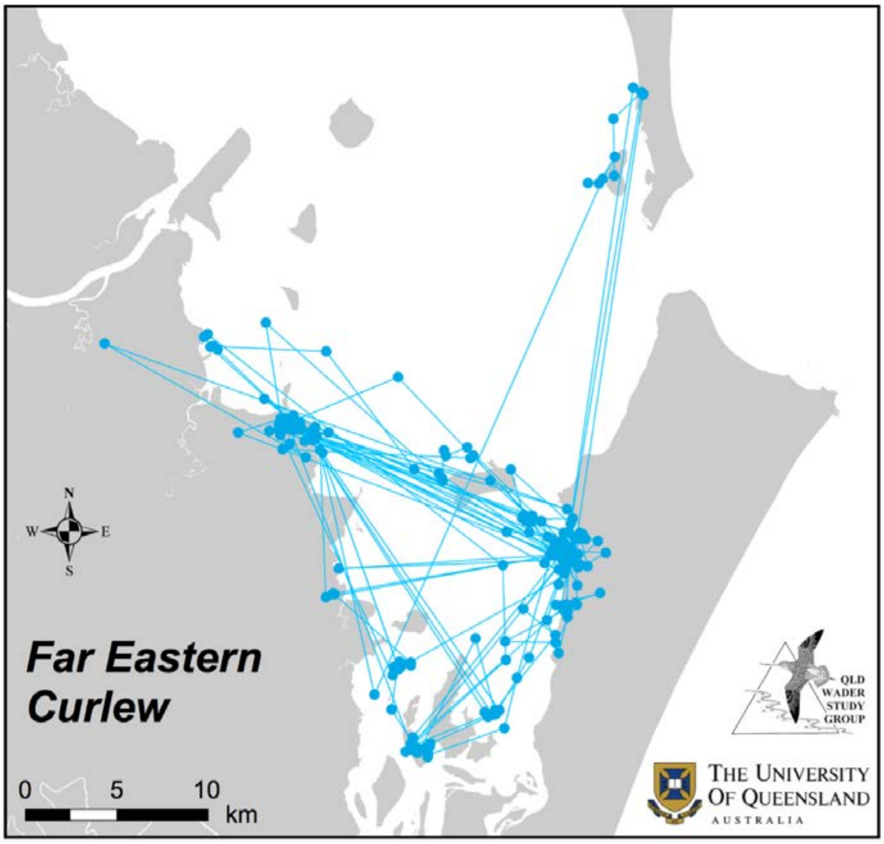


Figure 5.3

The movements of a satellite-tagged Far Eastern Curlew show that this bird is using a number of different sites for feeding and roosting. It was tagged at Geoff Skinner Wetlands (Wellington Point), and typically roosts there, but has a portfolio of several different areas in which it feeds, including the tidal flats off Dunwich, and various parts of southern Moreton Bay and the occasional excursion to Moreton Island. This underlines the fact that many migratory shorebirds will be affected by threats, and thus their management, at multiple sites. Data are from 17th March to 12th May 2019.

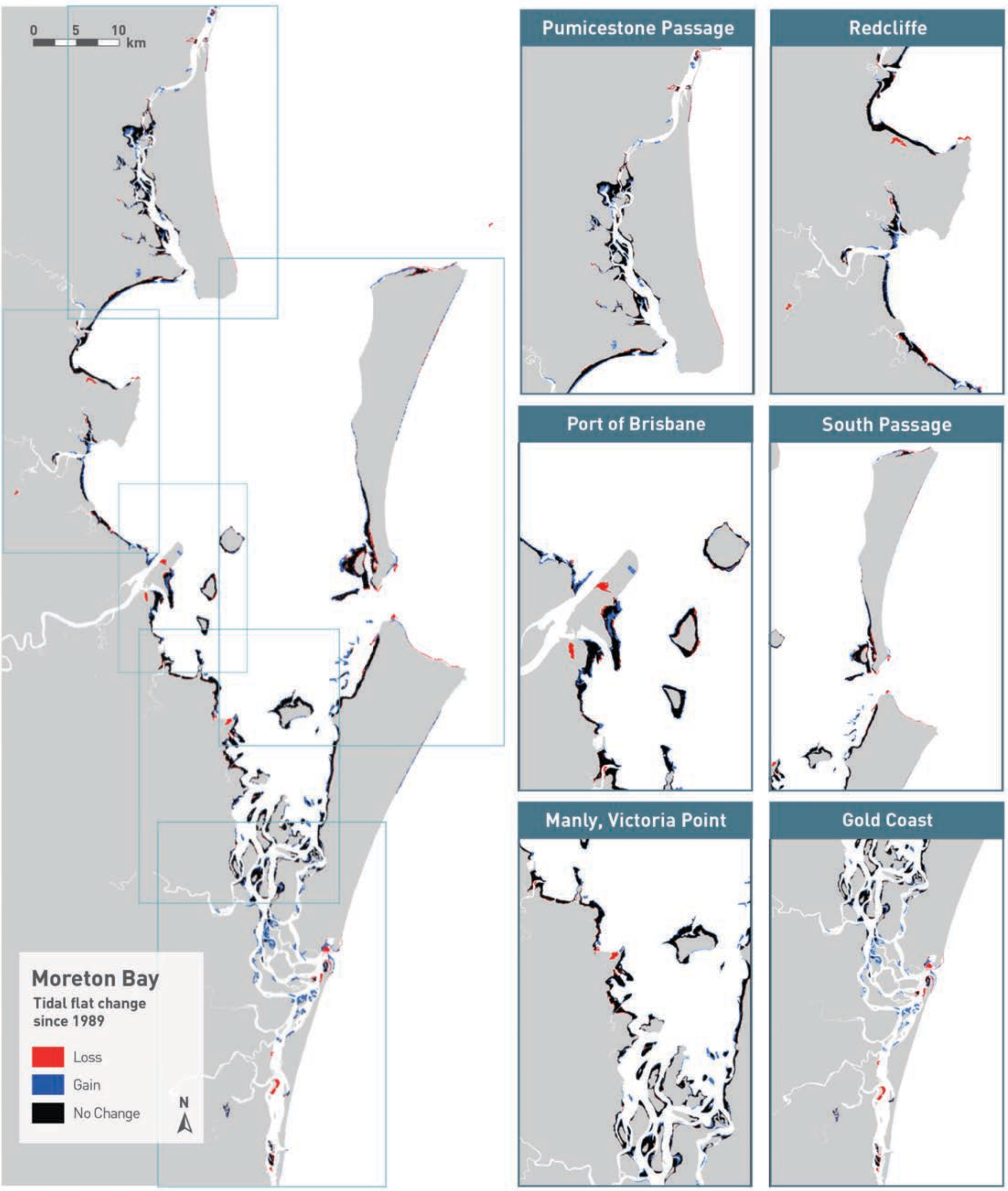


Figure 5.4 Losses and gains of tidal flats between 1989 and 2016. Using the dataset created by Murray *et al.* (2019), area in which tidal flats were present in 1989-1991, but absent in 2014-2016 are shown in red, and vice versa in blue. There are some significant areas of losses (southern Bay, Port of Brisbane area), and also gains (far south, South Passage, Hays Inlet). Approximately 10-15% of this change is likely to be a result of classification errors in the underlying dataset, since no tidal flat mapping method is perfectly accurate, and underlying accuracy of the Murray *et al.* (2019) dataset is about 85%.

urbanisation around Moreton Bay. Yet the overall stability in tidal flat extent masks some increases and decreases in certain small areas. Comparing the distribution of tidal flats in 1989-1991 with 2014-2016, there have been marked losses in the Port of Brisbane area and southern Bay, but gains in the far south, South Passage and Hays Inlet (**Figure 5.4**). Some of the losses have obvious anthropogenic causes, such as the loss of intertidal habitat as a result of the major expansion of the Port of Brisbane that began in the 1970s, and which culminated in the joining of Andaccahl (Fisherman Islands) to the mainland via a causeway and the reclamation of various coastal habitats for inclusion in the Port footprint (**Figure 5.5**). The pattern of tidal flat loss can be observed through the tidal flat time series, but what is also apparent is the creation of artificial wetlands, a temporary feature of the reclamation process. This has resulted in the formation of a major roosting site for shorebirds at the Port of Brisbane, used by up to and sometimes exceeding 10,000 migratory shorebirds, about one-third of all migratory shorebirds present in Moreton Bay. As well as the direct change in tidal flats with the Port footprint, there also appears to have been a loss of the lower fringe of the remaining tidal flat to the south of the Port (see the red lower edge of the tidal flat in **Figure 5.5a**), although it is hard to say whether this is a result of hydrological changes from the Port development, or has some other cause.

In other cases, unambiguous loss of intertidal flats has resulted from coastal development projects. For example, a significant area of tidal flat was reclaimed to create the Raby Bay canal housing estate (See Manly Harbour, Victoria Point inset in **Figure 5.4**; **Figure 5.5**). Many other such losses presumably occurred prior to 1989, when the available tidal flat time series begins.

In some cases, dramatic change in tidal flats has occurred apparently naturally, or at least with no obvious proximate human cause. For example, the sand bar at the south-eastern edge of Moreton Island has been very mobile over the years, reflected in its changing position in the different stages of the tidal flat mapping (**Figure 5.5b**), and it seems possible that the reduction in the size of the Moreton Banks tidal flat (off Kooringal) is also the result of natural dynamics, although it is also possible that dredging or other forms of disturbance have altered the sediment dynamics in the area. Erosion was identified by experts as a factor threatening roost sites around South Passage (see **Figure 4.22**), tying these observed changes in tidal flats together with changed numbers of migratory shorebirds. Additionally, severe weather events are likely to be dramatically affecting the size and position of the sand bars in southern Moreton Island and perhaps elsewhere in the Bay, and these changes could be exacerbated in areas where there is substantial concrete infrastructure along the coastline, increasing the wave energy during severe weather events. Other areas, such as Jacobian (Peel Island; **Figure 5.5d**) have shown almost perfect stability in tidal flats over the last 30 years, and stability is the pattern for most areas across the Bay, perhaps reflecting the sheltered conditions prevalent within Moreton Bay. The impacts of past sea-level rise, and projected impacts of future sea-level rise, on the extent and distribution of tidal flats in Moreton Bay remain unknown, and this would be an excellent topic for further investigation.

These maps depict the fullest extent of the tidal flat, but a key feature of tidal flats is that the exposed area is continually changing as the tide moves in and out. In fact, the amount of tidal flat exposed changes non-linearly with tide height, for example only half of the maximum extent of tidal flat is exposed when the tide is about 80% of the way out (**Figure 5.6**). This means that the extensive tidal flats that are far down the shore will only be exposed for a brief period each tide, and will be inaccessible to the birds for most of the time. On neap tides, many of those extensive lower flats will remain covered by the tide for the entire tidal cycle. This can mean that shorebirds are forced to use exposed tidal flats on a neap tide that are closer to cover (hence increased predation risk; Whitfield 2003) and potentially more prone to disturbance. It is possible that there are particular locations that are favoured by shorebirds during neap low tides; research to identify such sites, and manage them appropriately would be worthwhile.

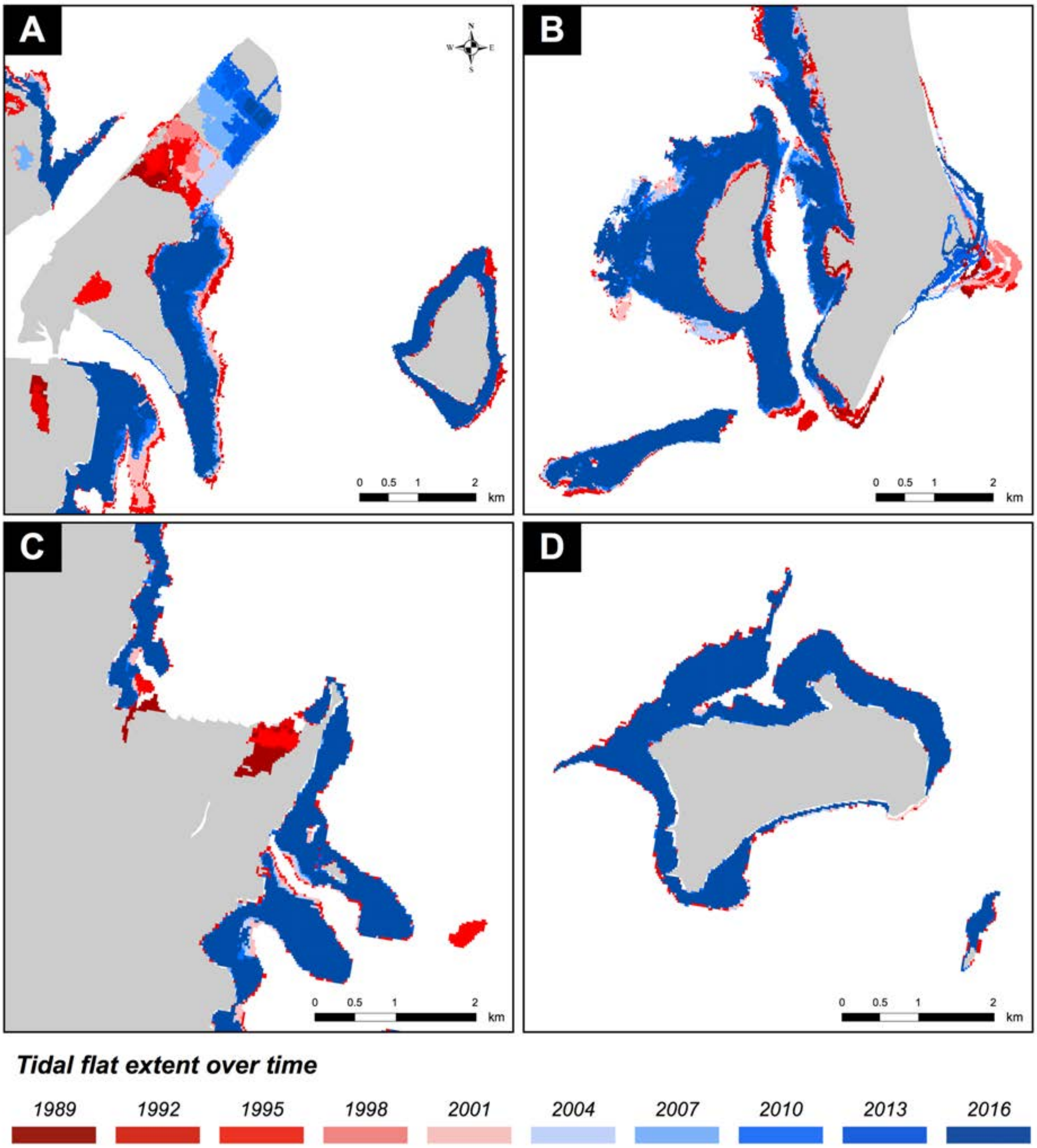


Figure 5.5

Examples of change in tidal flat over time in selected areas of Moreton Bay, showing (A) reclamation progressing at the Port of Brisbane, along with loss of the lower edge of the tidal flats to the south of the Port, (B) natural sandflat dynamics off the southern tip of Moreton Island, (C) a marina development at Raby Bay, and (D) relative stability at Jercroobai (Peel Island). Because of intermittent wetting and drying, some parts of the reclamation area are misclassified as tidal flat by this dataset (see Murray *et al.* 2019 for further explanation on these misclassifications).

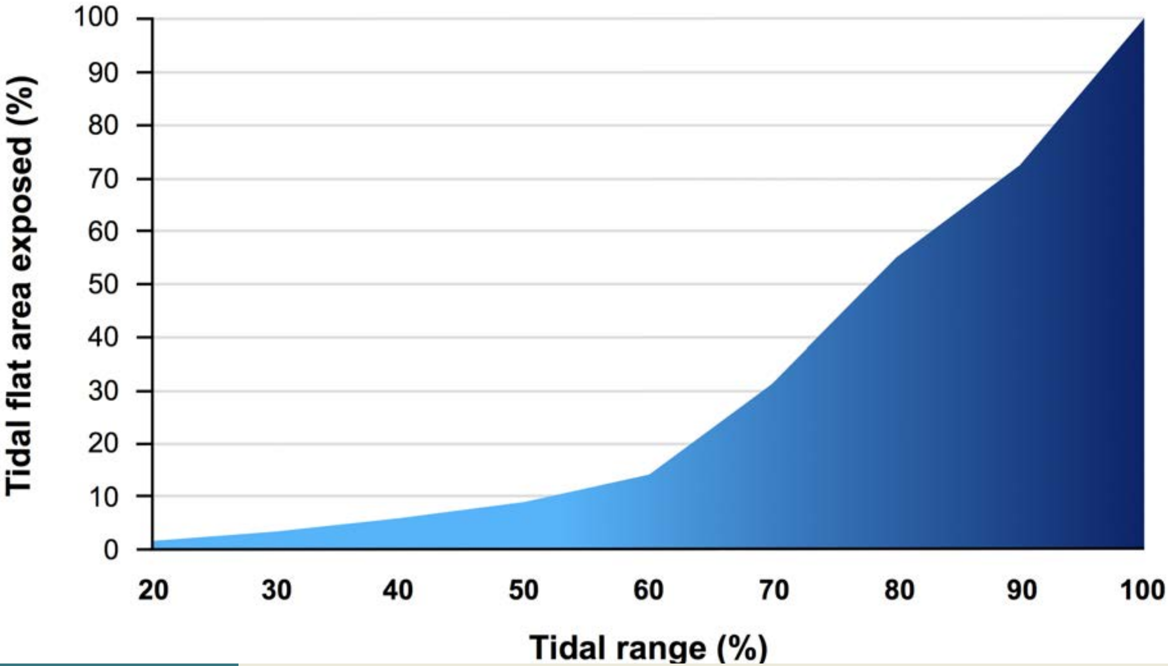


Figure 5.6 Area of intertidal habitat exposed at the midpoint of each decile of the observed tidal range, from the highest observed tide on the left to the lowest observed tide on the right, for the whole of Moreton Bay. For example, at half-tide (50% tidal range), just under 10% of the maximum extent of tidal flat area is exposed, indicating that birds will often only have relatively brief access to the most extensive areas of their foraging grounds when the tide is low. Data from Geoscience Australia (2016).

5.2 The low tide foraging distribution of migratory shorebirds in northern Moreton Bay

For efficiency of counting, the Queensland Wader Study Group predominantly surveys shorebirds while they are concentrated into roosting sites (Fuller *et al.* 2009). The distribution of shorebirds at low tide in the Bay is relatively poorly understood, and this is problematic for shorebird conservation and management in at least three distinct ways. First, gaining a clear understanding of how the distribution of foraging shorebirds is related to the distribution of their invertebrate prey is crucial in understanding why they are more abundant in some places than others. For example a major survey of Far Eastern Curlews feeding at low tide in Moreton Bay revealed that they select tidal flats with generally softer substrate, even where these flats are relatively long distances from a roost site, or subject to human disturbance (Finn *et al.* 2007). Second, changes in food availability are difficult and expensive to detect, since they require benthic sampling programmes that are very time-consuming (Choi *et al.* 2017). This means that changes in food availability could go unnoticed, unless targeted monitoring of the benthic community can be achieved in key low tide foraging areas (see **Section 5.3** for an example of how such a programme could be set up). Third, some threats operate primarily at low tide, and need distinct management actions to address them. For example, disturbance to foraging shorebirds by recreational users of the foreshore can have a significant impact on the daily energy budget of the birds, and a good understanding of the areas of overlap between the threat and the distribution of feeding birds at low tide is critical to start targeting management.

To make a start in mapping the distribution of foraging migratory shorebirds at low tide, we conducted counts of foraging birds in the intertidal during summer 2018. This survey used the same method as an earlier survey in 2014, the results of which were published in Stigner *et al.* (2016) with a focus on using the data for optimal management of dog disturbance on the foreshore. This study was focused on northern Moreton Bay to provide information to Brisbane City Council on interactions between off leash dogs and foraging shorebirds. At the time of this work, off-leash dogs were not permitted anywhere along the intertidal zone within the Brisbane City Council boundary. Here, we present mapping from the summer 2018 surveys, to indicate the extent of variation in the low tide distributions of foraging shorebirds in this part of the Bay, recognising that similar data for other parts of Moreton Bay do not yet exist. The key messages are that foraging shorebirds are highly unevenly distributed along the foreshore at low tide, and there are hotspots of critical overlap between recreational activity and shorebird feeding distributions that require urgent management responses. Management options include stronger enforcement of existing regulations, and trialling of designated foreshore dog off-leash areas to concentrate disturbance into defined areas that are well separated from the main areas preferred by foraging shorebirds.

Systematic surveys of the low tide distribution of Moreton Bay shorebirds

We divided a section of the mainland coastline of Moreton Bay comprising the mainland coast of the Brisbane Local Government Authority area between Sandgate and Lota into count areas each approximately 600 m in length. These count areas were grouped into three management regions: Sandgate, Nudgee and Manly (**Figure 5.7**; **Figure 5.8**; **Figure 5.9**). Observers (RF, BW) visited each planning unit on 10 occasions in November and December 2018, identifying and counting migratory shorebirds. Observers generally stood on the landward side of the high tide mark to count birds from a distance using a telescope where necessary, minimizing the chance of observers themselves causing disturbance to the birds. In some cases, observers needed to go down onto the tidal flats to facilitate counting birds in the larger sites. Disturbance caused by the presence of the surveyors was kept to a minimum, and double counting of birds was avoided by taking care to note any bird movements. Counts were conducted within 2 hours each side of low tide, when the tidal flats are used by migratory shorebirds for foraging. Surveyors stayed in an area only as long as was needed to count all of the birds present, and so the data represent a snapshot of the birds present at that time, and not a continuous observation of use of the tidal flat over the course of a tide.

As well as counting the birds, sources of potential disturbance were also counted, as one indicator of threat to shorebirds foraging at low tide. These comprised anglers, boats, kite-surfers, walkers, on-leash and off-leash dogs, and horses. The number of each potential source of disturbance present in the survey area at the time of the count was recorded, and again these represent a snapshot rather than an assessment of use by recreationalists over a tidal cycle.

Sandgate

The most noticeable pattern in the low tide distribution of migratory shorebirds at Sandgate was appreciable numbers of birds present along the extensive flats in the north of the area, and very few birds along the narrow, rock-strewn intertidal around the Shorncliffe headland. The surveys in this area revealed an average of 210 migratory shorebirds present at any one time on the intertidal flats at low tide, which is much lower than the numbers found at Nudgee (average = 1166 migratory shorebirds) or Manly (average = 2408 migratory shorebirds). Given the large expanses of tidal flat present in this region, it seems somewhat surprising that the numbers of migratory shorebirds foraging in this region are relatively low (**Figure 5.7a**). Yet this apparent anomaly is perhaps rather neatly explained by the relatively low abundance of benthic invertebrates discovered in this area during our indicative benthic sampling (see

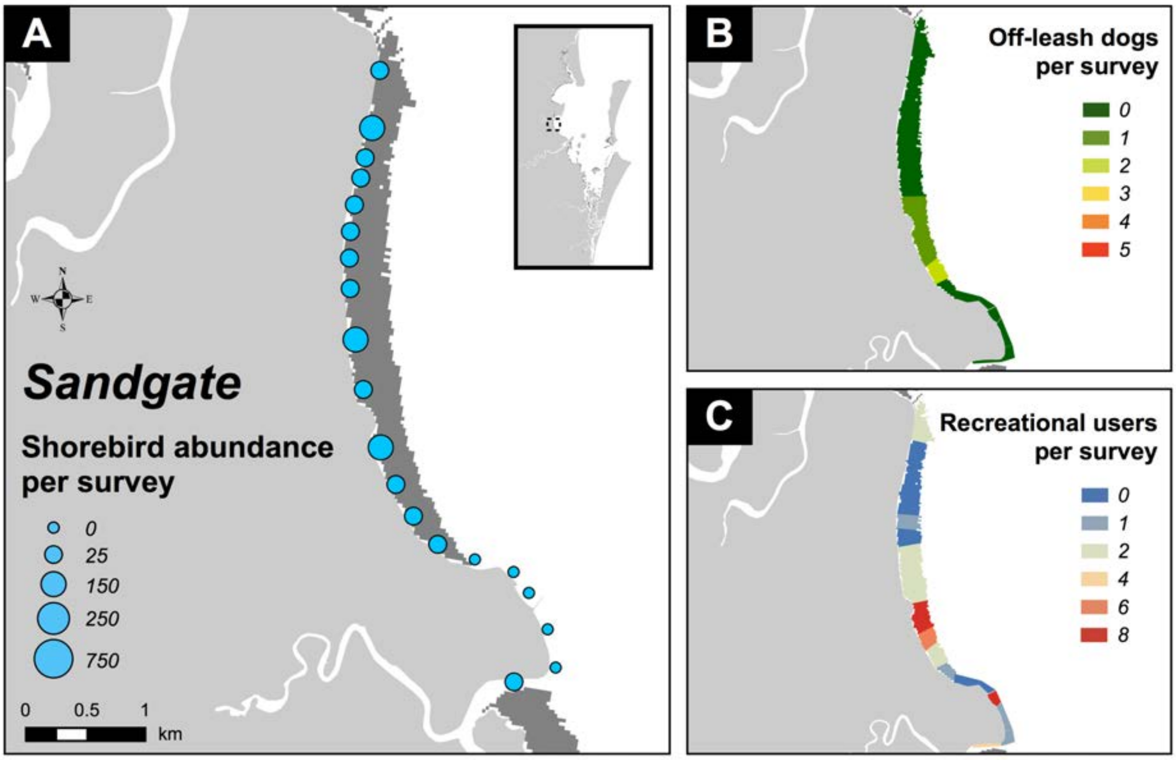


Figure 5.7 The distribution of shorebirds and recreationalists on the foreshore at Sandgate during 10 low tide surveys in November and December 2018. Shorebird numbers (blue circles) were relatively low throughout the area, with slightly higher numbers in the north and middle than the south. In contrast, off-leash dogs specifically (B) and recreational users more generally (C) were highly concentrated into the area south of Arthur Davis Park. Areas with highest demand for recreation are in this case adjacent to the most important areas for foraging shorebirds on the Sandgate foreshore.

Section 5.3). The general pattern at Sandgate is that the northern sector is favoured by foraging shorebirds, with relatively few (although still appreciable numbers of) off-leash dogs and other recreationalists (**Figure 5.7b,c**). The far southern section around the Shorncliffe headland attracts almost no shorebirds or recreationalists, mostly comprising rock-strewn narrow tidal flats, but the middle section running south of Arthur Davis Park supports medium numbers of shorebirds and many dog recreationalists. Clearly there is high demand for recreation in this area. Overall in the Sandgate study area, off-leash dogs were present on 15% of surveys, walkers on 23%, horses on <1%, anglers on 3%, bait diggers on 1%, and kite surfers on 4%.

Nudgee

This is a very important region for shorebirds at low tide, with hundreds of birds present on every survey. It is also heavily used by recreationalists with dogs, creating a very concerning threat, and a difficult prospect for management. The surveys during summer 2018 revealed up to 2273 migratory shorebirds present between the mouths of Cabbage Tree Creek and Kedron Brook. This included a peak count of 1014 Curlew Sandpipers on 16th December. This species is listed as Critically Endangered under the EPBC Act (**Supplementary Table S2**), and since 900 birds is the threshold to define an aggregation as internationally important, this individual tidal flat represents an internationally important feeding site for this species. A number of other threatened migratory shorebird species also occur in large numbers in the Nudgee area

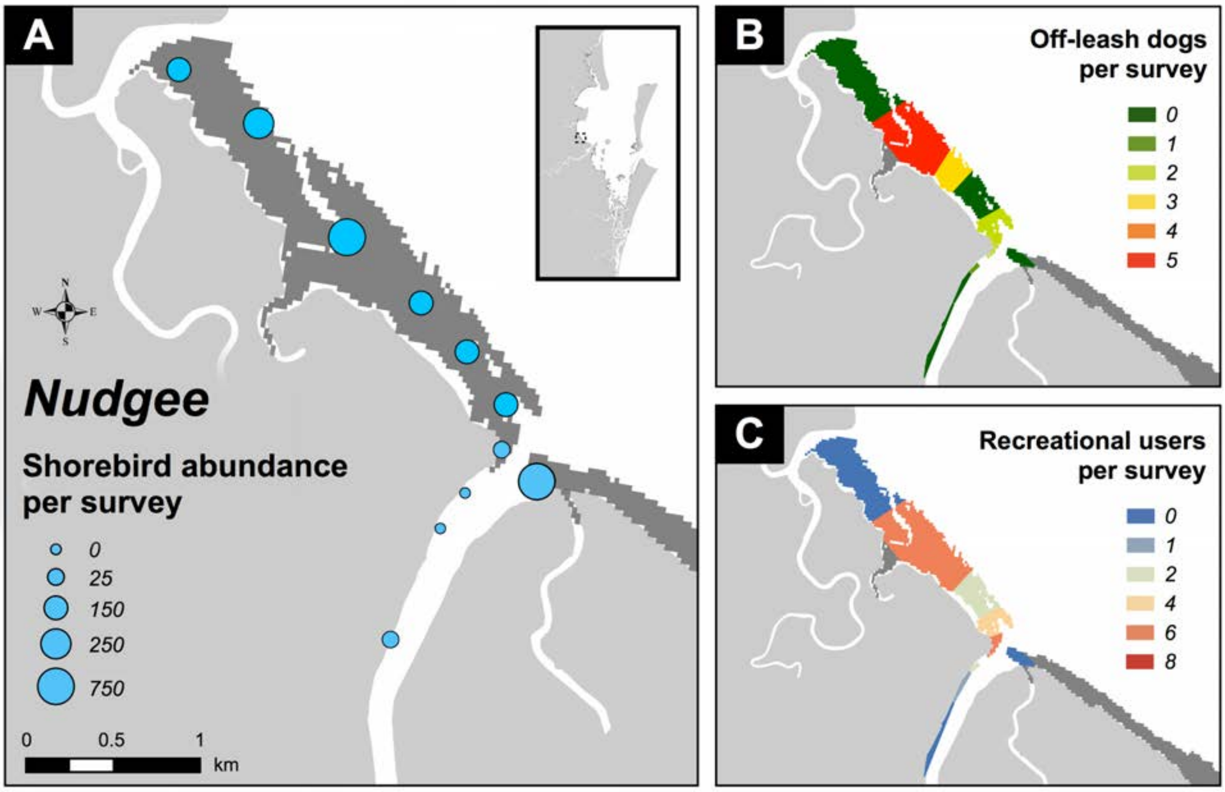


Figure 5.8 The distribution of shorebirds and recreationalists on the foreshore at Nudgee during 10 low tide surveys in November and December 2018. Shorebird numbers (blue circles) were highest on the large tidal flats in the north of the area (A), and recreational users, including off-leash dogs were also present in large numbers in this region (B,C). This pattern suggests substantial overlap in this region between recreational users and foraging migratory shorebirds, creating a difficult prospect for management.

(see **Section 4.2**). Large numbers of migratory shorebirds occurred throughout the foreshore areas, with far fewer birds present in the intertidal flats fringing Kedron Brook (**Figure 5.8**). The tidal flats are very extensive in this region, and benthic sampling indicated relatively high densities of invertebrates in the upper 5cm of the sediment (see **Section 5.3**), consistent with the high numbers of birds present at this site. Moreover, the landward side of the flats at Nudgee mostly comprises natural vegetation, with an extensive mangrove forest.

Recreational use of the foreshore was very intense in comparison with other surveyed regions, with high numbers of off-leash dogs in particular (**Figure 5.8b**) and recreationalists in general **Figure 5.8c**). Off-leash dogs were present on 51% of surveys, walkers on 54%, horses on <1%, anglers on 10%, bait diggers on <1%, and kite surfers on 2%. Recreationalists mostly used the area adjacent and to the north of the car park at the end of Fortitude Street (red survey area on **Figure 5.8b**). This overlaps significantly with the main concentrations of foraging migratory shorebirds in the region, and highlights the enormous challenges of managing disturbance to foraging shorebirds in parts of Moreton Bay.

Manly

The Manly foreshore is an important region for foraging migratory shorebirds at low tide, with very large numbers present almost continuously along the foreshore, which is mostly soft muddy substrate. Moreover, there is a comparatively high species richness in this region, with 16 species of migratory shorebird recorded foraging at low tide during the surveys on the Manly foreshore (in comparison with 18 species at Sandgate and 12 species at Nudgee). Perhaps because the substrate is typically rather soft and muddy, and there is a track along the esplanade just above the high tide mark, very few recreationalists were observed on the intertidal foreshore itself (**Figure 5.9b,c**). However, kite-surfing that occurs in nearshore waters, particularly in the southern region near the internationally significant Manly Harbour shorebird roost site and extensive intertidal feeding areas at Lota, is an increasingly popular activity and a potentially significant source of disturbance to both roosting and feeding shorebirds that warrants future investigation. Overall, off-leash dogs were present on 9% of surveys, walkers on 22%, horses on 0%, anglers on 3%, bait diggers on 7%, and kite surfers on 5%.

Supratidal foraging

Foraging in migratory shorebirds isn't confined solely to intertidal habitats, but in some cases birds continue to feed over the high tide period. While supratidal foraging by a small number of birds occurs at most roost sites, the reclamation area at the Port of Brisbane is one location where supratidal foraging is undertaken by a relatively large number of birds, including Curlew Sandpipers, Red-necked Stints, and several plover species (authors; personal observations). Such supratidal foraging can result from the availability of superabundant food resources, but also from insufficient energy intake during the low tide feeding period (Fuller *et al.* 2013). Supratidal foraging has been quantified elsewhere in Australia (e.g. Dann 1999), but there are no formal data from Moreton Bay. This is an important research gap to fill since it would

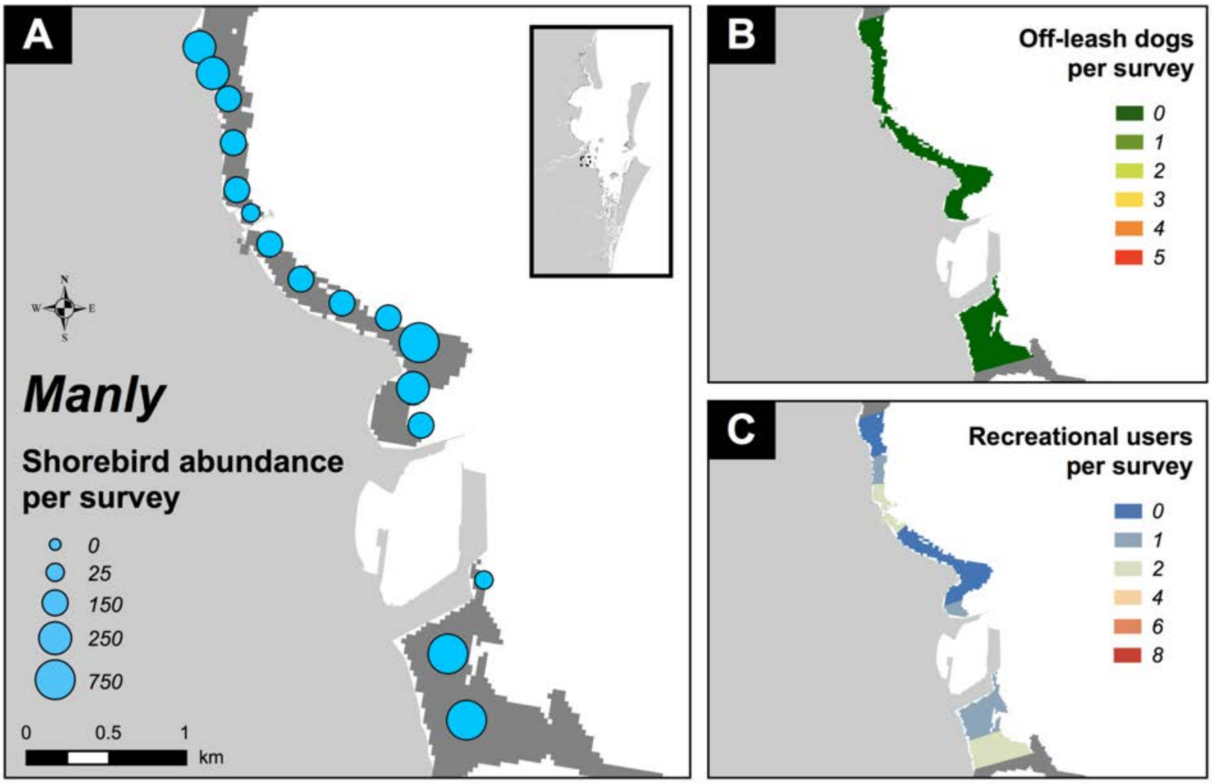


Figure 5.9 The distribution of shorebirds and recreationalists on the foreshore at Manly during 10 low tide surveys in November / December 2018. Shorebird numbers (blue circles) were very high throughout the area (A), and recreational use of the intertidal flats was generally very low, with the exception of some off-leash dog activity on the small beach at the end of Davenport Drive (0.7 dogs per survey), walkers on the foreshore adjacent to Wynnum, and anglers at Lota in the far south of the region (B,C). This pattern suggests rather little threat from foreshore recreation to foraging shorebirds in this area.

provide (i) an understanding of which species use supratidal foraging resources, and would therefore benefit from their effective management, and (ii) insight into whether certain species are facing energetic shortfalls during their intertidal foraging period.

Conclusions on intertidal distribution of migratory shorebirds

These results indicate that the density of foraging migratory shorebirds can vary enormously from tidal flat to tidal flat, and that the biggest numbers of birds do not necessarily occur in the areas with the most extensive flats. This suggests that bespoke surveys of foraging birds will be needed to get a clear picture of the distribution of birds in the intertidal zone, and to correctly determine which areas might require management. There would be much value in such surveys being ongoing, because (i) shorebird prey density can be highly dynamic, with the location of hotspots where prey is most abundant changing over time, and (ii) monitoring shorebird numbers at selected sites over low tide may help to detect declines in usage associated with disturbance or other threats.

Given the threat of disturbance to feeding migratory shorebirds by off-leash dogs and little to no enforcement of existing laws prohibiting off-leash dogs in the Moreton Bay Marine Park, Stigner *et al.* (2016) proposed designating a small number of foreshore dog off-leash areas in places where shorebird foraging abundance is relatively low and recreational demand is relatively high to reduce overall disturbance relative to current levels. In October 2018, Brisbane City Council announced a one-year trial of foreshore dog off-leash areas to commence in October 2019. The surveys we have conducted formed a baseline against which to assess whether the off-leash areas serve to concentrate recreational activity into areas that are less favoured by shorebirds, and reduce the overall amount of contact between off-leash dogs and migratory shorebirds along the Moreton Bay foreshore. Three candidate sites for foreshore dog off-leash areas were trialled by Brisbane city Council, one each in Sangdate, Nudgee and Manly. The area at Nudgee was closed at the end of the trial period, but the sites at Sandgate and Manly remain open, and form Brisbane's first designated dog off-leash areas on the foreshore (Brisbane City Council 2021). The Queensland Department of Environment are in the process of producing guidelines to assist councils and other agencies in setting up and managing foreshore dog off-leash areas within and adjacent to marine parks (Department of Environment and Science 2019).

Another important finding from these low tide surveys is the fact that up to 2,000 migratory shorebirds are feeding at Nudgee Beach, yet there are no nearby roost sites. Historically, there was a major roost site near the mouth of Cabbage Tree Creek at Dynah Island (1.5 km distance), where many of the shorebirds of this area would roost. Informal observations on the rising and falling tide at Nudgee suggested that the birds foraging in this area are now flying south to roost, perhaps at the Port of Brisbane (c. 9 km distance), or at the Luggage Point claypan (c. 6 km distance).

5.3 Benthic prey available to migratory shorebirds in northern Moreton Bay

Migratory shorebirds specialise in feeding on invertebrates found in the sediments of the intertidal flats in Moreton Bay. Foraging success for migratory shorebirds is influenced by a number of factors, including the availability of benthic prey on and in intertidal flats, the proximity of foraging sites to nearby roost sites and the perceived level of threat from human disturbance and predators (Yasué *et al.* 2008; Fuller *et al.* 2013). Within Moreton Bay, it has been shown there is a direct relationship between shorebird foraging success and the abundance and accessibility of benthic prey (e.g. Zharikov and Skilleter 2003, 2004). Understanding the distribution and abundance of prey on intertidal flats is therefore crucial to the management and long term survival of migratory shorebird populations in the Bay.

Macrobenthic invertebrates on intertidal flats can be broadly classified into one of two groups: mobile species that live predominantly above ground – the so-called “epifauna” and; sessile species that live predominantly below ground – the so-called “infauna” (Barnes and Hughes 2004). These above ground and below ground components of the shorebird prey community are exploited to varying degrees by different species of shorebird and this has important implications for the distribution of the birds (Choi *et al.* 2016). Firstly, different species of shorebird display different physiological and behavioural adaptations to maximise foraging success on their preferred prey items (Zwarts and Ens 1999). Some species such as the Greater Sand Plover rely solely on visual methods for detecting prey and feed predominantly on epifauna. Others, such as the Far Eastern Curlew employ both visual and tactile methods to capture prey and take a more varied range of prey items comprising both epifauna and infauna (Zharikov and Skilleter 2004). Among these probing shorebird species, bill length substantially influences the type and depth of prey consumed. Smaller species such as the Red-necked Stint are only able to access prey in the top 2 cm of the substrate whereas Far Eastern Curlew are able to capture prey buried up to 20 cm (Marchant *et al.* 2006). This means that the consequences of changes in either infauna or epifauna density will vary among shorebird species.

Benthic sampling between December 2011 and May 2012 in the intertidal zone between Toorbul and Wavebreak Island suggested a great deal of spatial variability in the abundance of benthic invertebrates present (Clemens *et al.* 2012). Moreover, there is some evidence of a long term decline in invertebrate densities along the mainland coast of Moreton Bay between 1997 and 2012, with a particularly rapid decline occurring at Nudgee, where invertebrate density in 2012 was less than one quarter of that in 1997 (Clemens *et al.* 2012). As far as we are aware, no more recent data of direct relevance to shorebird prey exist, and against this backdrop of historical declines in benthic invertebrates in at least some parts of Moreton Bay, there is an urgent need to establish regular benthic monitoring in the context of imperilled migratory shorebird populations.

Here we report on a pilot study designed to provide a rapid assessment of the current status of shorebird macroinvertebrate prey on three intertidal flats on the western side of Moreton Bay. We catalogue the species composition and density of macrobenthic prey potentially available to migratory shorebirds, and characterise patterns in the distribution of benthic prey by comparing prey densities between different intertidal flats. We consider whether differences in shorebird foraging densities at three sites on the western side of Moreton Bay are consistent with differences in density and composition of available prey. The spatial scope of this preliminary study was focused on three intertidal areas at Sandgate, Nudgee and Manly because (i) we had data on the abundance of foraging shorebirds and could use this to guide the locations of the sampling, (ii) available funding and project timetabling meant that the survey needed to be carefully limited in scope and scale.

Benthic sampling protocol

To characterise shorebird prey on the western side of Moreton Bay, we sampled prey communities across three intertidal flats – Sandgate, Nudgee and Manly (**Figure 5.10**). On the basis of the count data reported in **Section 5.2** and by Stigner *et al.* (2016), these tidal flats support consistently low, medium and high densities of foraging shorebirds respectively. By comparing prey densities between these regions, we can determine whether these differences in foraging shorebird densities between intertidal flats are consistent with corresponding differences in available prey.

Shore height and exposure time are known to affect macrobenthic species distributions on the intertidal shore leading to clear zonation patterns, such as has been documented for Gladstone (Choi *et al.* 2017). For this pilot study we limited sampling to the mid-intertidal zone. Similarly, although the intertidal areas of Moreton Bay present a range of different habitats for foraging shorebirds (seagrass, shallow tidal creeks, unvegetated sand flats etc.), and each of these habitats presents a potentially unique composition of intertidal macrobenthic prey species, sampling in this pilot study was focused on unvegetated intertidal areas.

Owing to the fixed timeframe of this project, benthic sampling had to be carried out in late May and early June 2019. At this time of year, most migratory shorebirds have departed for the return migration to arctic and subarctic breeding grounds. Benthic invertebrate communities are highly temporally variable, and so carrying out this work at a time of year when the birds are largely absent was less than ideal. Further work that monitors benthic prey in important shorebird foraging sites will be needed in future to make more robust conclusions. Sampling was carried out during daylight hours within a four hour window around the low tide.

Epifauna

Invertebrates living primarily on the surface of the tidal flats are impossible to sample effectively using sediment coring devices, since they tend either to burrow deeply or move away as a person approaches. We therefore conducted eight instantaneous visual surveys at each tidal flat during the low tide on 16th of May (Nudgee) and the 17th of May (Sandgate). The presence of seagrass meadows across most of the low intertidal area at Manly precluded the use of visual surveys in this region, since trials at Manly revealed that many epifauna would remain concealed in the seagrass, limiting the utility of epifaunal counts there. Future studies could explore using method that completely removes a sample of sediment and seagrass to enable a complete characterisation of the epifauna (e.g. Whippo *et al.* 2018).

Within each intertidal flat, four plots (2.5 by 2.5 m) were randomly located in the lower and upper intertidal shore, with the constraint that each plot was located at least 100 m from all other plots. Plots were surveyed during daylight hours within two hours of the plot becoming exposed by the receding tide. Plot boundaries were marked with unobtrusive garden stakes and twine.

Once the boundary of a plot had been marked, observers retreated to a distance of 10 m allowing any animals that burrowed during the approach and plot set-up to return to the surface. After an acclimation period of 10 minutes, all animals visible within the plot were identified and enumerated from 10 m distance using a pair of Nikon Monarch 8 x 42 binoculars.

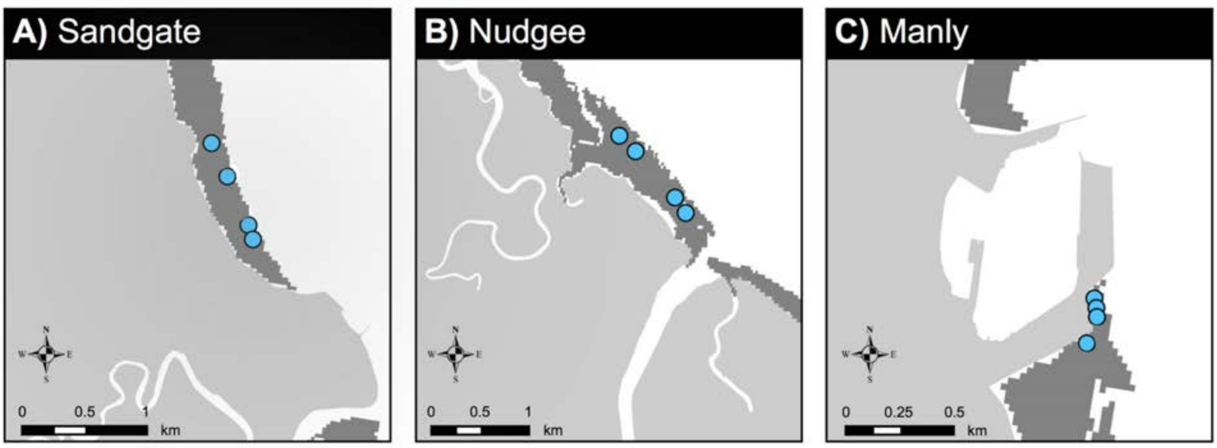


Figure 5.10 Benthic sampling locations. At each site, four groups of three benthic samples were taken, yielding 12 samples per site, and a total of 36 samples.

Infauna

To characterise infaunal communities, a total of 36 core samples was collected between 29 May 2019 and 6 June 2019. At each intertidal flat, 4 plots of 2.5 x 2.5 m were randomly located in the mid-intertidal zone, subject to the constraint that each plot was at least 100 metres away from any other plot. Within each plot, 3 replicate randomly located sediment cores were collected. Sediment cores were collected with a vacuum-sealable PVC coring device with a diameter of 10 cm. The coring device was plunged into the sediment to a depth of 15 cm. A vacuum seal was then created by closing a valve atop the corer via a long cast iron pipe. The coring device was excavated, the opening capped and the entire sample transferred into a small flat-bottomed tray. The top 5 cm of each sample was separated from the remainder of the core sample immediately after collection. In this way, it was possible to examine between-flat differences in prey separately for smaller probing shorebird species (e.g. red necked stints) and larger probing shorebirds (e.g. Far Eastern Curlews). Each component of the sample was individually agitated through a sieve (aperture size = 500 µm) to remove the bulk of the sediment and debris from the sample. The remaining contents were placed in 250 mL plastic jars and fixed in a 5% buffered formalin solution. A Rose Bengal stain was also added to each sample to aid sorting and identification. After a period of at least 72 hours, all samples were transferred into 70% ethanol solution. All animals in each sample were counted and identified to an appropriate taxonomic level, depending on the type of organism.

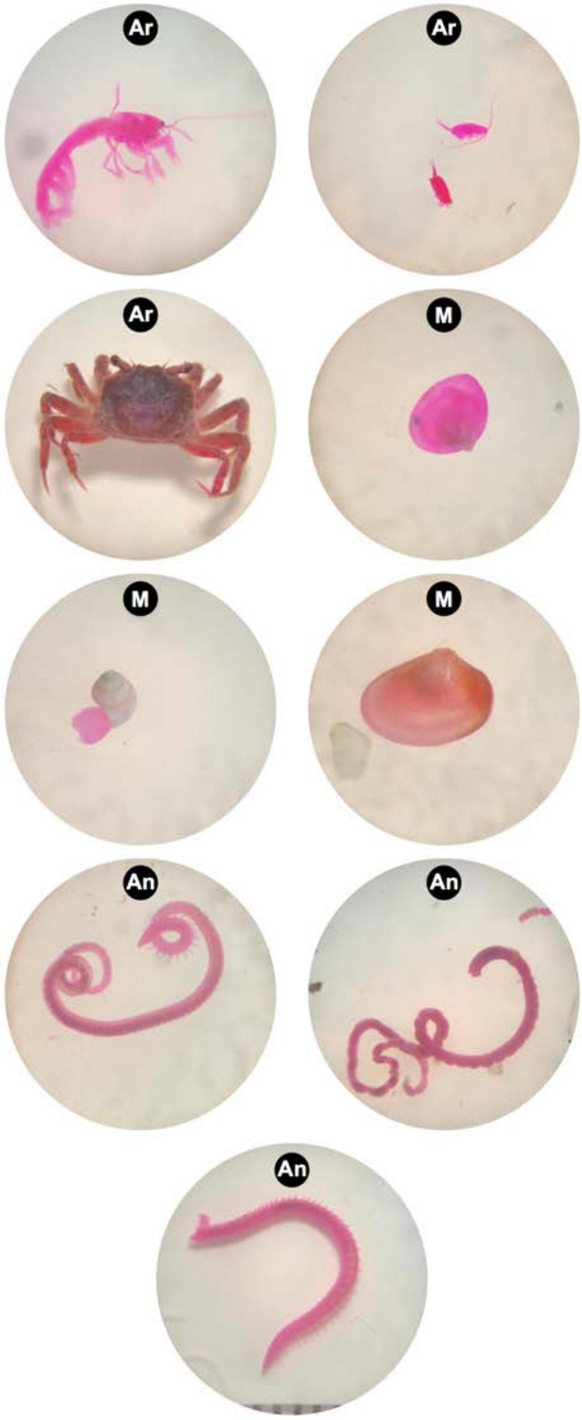


Figure 5.11 Examples of species found in infaunal samples. Most species were from one of three phyla: Arthropoda, crustaceans (Ar); Mollusca, bivalves and gastropods (M); and Annelida, polychaetes and allies (An).

Density and community composition of benthic organisms

Epifaunal communities

In the two intertidal flats surveyed, the large mobile epifauna were dominated by soldier crabs *Mictyris longicarpus*. Other species of epifauna observed during the visual surveys included green paddle worms *Phyllodoce novaehollandiae*, hermit crabs (Diogenidae) and several gastropod species: *Nassarius pullus*, *Nassarius coronatus* and *Conuber sordida*, though most of these species were not visible through binoculars and were only observed when laying out the plot boundaries. Soldier crabs were the dominant organism, although they did not occur in any of the lower intertidal zone plots. However, across the other plots, there was a much higher average density of soldier crabs in Sandgate (average = 6.12 ± 3.19 crabs / m^2) than Nudgee (2.16 ± 1.45).

Infaunal communities

In total, 1192 invertebrates comprising 68 species were identified across all regions (**Figure 5.11**). In all three regions sampled, polychaetes were the dominant taxonomic group accounting for 73% percent of animals per sample on average. Crustaceans and bivalves were the next most abundant groups accounting for 13% and 6% percent respectively of animals per sample on average.

Infaunal animal density differed considerably among regions (**Figure 5.12a**). The highest infaunal densities occurred in Nudgee (average = 48,599 ± 10,930 animals / m^3) of which 29% occurred above 5 cm depth. Manly had the next highest infaunal density (average = 22,284 ± 4,036) of which approximately 42% occurred above 5 cm depth. Infaunal density was lowest at Sandgate (average = 13,441 ± 4,647 animals / m^3), although in contrast with other regions, most infauna (c. 70 %) occurred above 5 cm depth.

There were clear differences in the types of benthic organisms occurring at the three regions (**Figure 5.12b,c**), with bivalve densities being highest in Manly (1,769 ± 244 bivalves / m^3), followed by Sandgate (1,556 ± 561) and Nudgee (990 ± 561). Most of the bivalves in Manly, Sandgate, and Nudgee occurred above 5 cm depth (65%, 66% and 91% respectively; **Figure 5.12b**). In contrast, polychaetes were far more abundant at Nudgee (32,607 ± 1), than Manly (17,614 ± 3,512) and Sandgate (9762 ± 1548). Most of the polychaetes in Nudgee and Manly occurred below 5 cm depth (75% and 57% respectively; **Figure 5.12c**).

Infauna mean species richness was highest in Manly (12.9 ± 0.8 species), followed by Nudgee (10.5 ± 0.7) and Sandgate (7.5 ± 0.3). The composition of the assemblage was also markedly different among the three regions, with Sandgate standing out in particular as being dissimilar to the other two regions (**Figure 5.13a**), which might in part explain the lower density of foraging shorebirds at Sandgate.

In all three regions, polychaetes largely comprised species from three families: Capitellidae, Spionidae and Paraonidae, all are deposit feeding burrowing species. The occurrence and relative density of these three polychaete families varied among regions and largely accounted for the between-region differences in species composition (**Figure 5.13b**). Paraonids were completely absent from Manly but were the most abundant polychaete at Nudgee. Paraonids at Nudgee occurred at densities more than ten times higher than that at Sandgate (average density = 15,209 ± 2,881 and 1,132 ± 367 paraonids / m^3 respectively). Spionids were also most abundant in Nudgee (average density = 16,483 ± 6,760 spionids / m^3) followed by Sandgate (2,617 ± 1,131), but were all but absent from Manly (141 ± 95) . Finally, capitellids occurred in Manly at high density (5,872 ± 1,315) in comparison with Nudgee (3,254 ± 1,006) and Sandgate (1,061 ± 406). It should be noted that abundance is only one measure of prey, and that estimation of biomass, which also takes into account the size of each prey item, would be a useful next step (see, e.g. Choi *et al.* 2017).

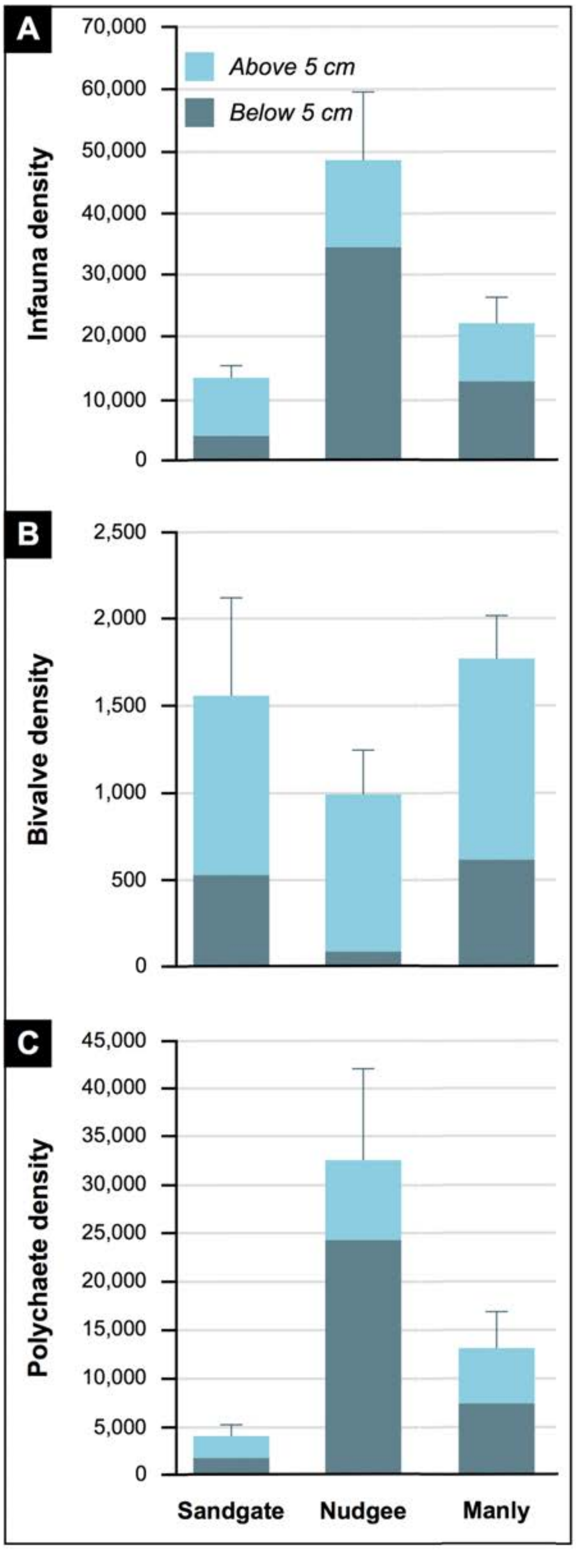


Figure 5.12 Average density of (A) infauna, (B) bivalves, and (C) polychaetes across three intertidal flats in northern Moreton Bay. Results are the number of animals per m^3, and the animals occurring above and below 5 cm depth are distinguished. Error bars show standard error.

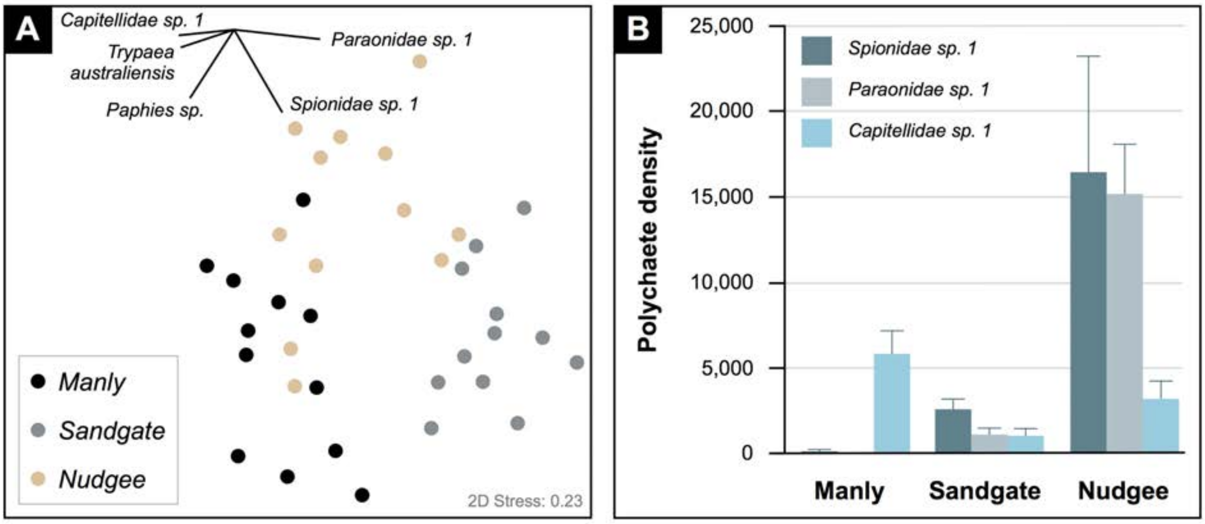


Figure 5.13 (A) Non-metric dimensional scaling ordination of infaunal community composition from three intertidal flats (Manly, Sandgate and Nudgee) in northern Moreton Bay. The further apart two samples are, the more distinct their community composition. Community composition at Sandgate is quite distinct from the other two regions, which substantially overlap with each other. The ordination is based on a Bray Curtis dissimilarity matrix of fourth root transformed abundance data. Vector overlay shows the main species contributing to differences among samples. These included 3 species of polychaete (Paraonidae sp.1, Spionidae sp. 1 and Capitellidae sp. 1), one species of bivalve (*Paphies* sp. 1) and yabbies (*Trypaea australiensis*) which were only present in samples from Manly. (B) Density of animals from the three dominant families of polychaetes collected at Manly, Sandgate and Nudgee. Results are the number of animals per m^3, and error bars show standard error.

Conclusion

This pilot study has revealed enormous differences in infaunal prey communities among three intertidal flats in northern Moreton Bay. Not only did intertidal flats differ in the numbers of infaunal organisms and species potentially available to shorebirds as prey but each intertidal flat sampled exhibited a distinct community of infauna. Sandgate had relatively low overall density of infaunal organisms, mainly comprising bivalves. Nudgee had a very high density of infaunal organisms, mainly comprising polychaetes, and consistent with the large number of migratory shorebirds feeding there. Manly showed a moderately high density of bivalves, together with a moderate density of capitellid polychaetes. This marked spatial variation in the benthic prey base has been noted before in Moreton Bay (e.g. Skilleter 1998, Zharikov and Skilleter 2003) and elsewhere in Queensland (e.g. Choi *et al.* 2017). This variation indicates that detailed benthic sampling work would be needed to fully understand why some intertidal areas are more attractive than others for certain species of migratory shorebird, and to propose management actions aimed at improving the prey base.

5.4 Conclusions on low tide feeding habitats in Moreton Bay

These results show that migratory shorebirds and their prey are highly unevenly distributed along the Moreton Bay foreshore between Sandgate and Lota. Substrate appears to be a big driver of this, with birds avoiding rock-strewn and hard-packed sandy foreshores, and occurring in much larger numbers in muddier substrates. Further structuring seems to be associated with dramatic differences in the density and type of prey available. It is not altogether clear why there are so few birds at Sandgate, and so many on broadly similar substrate at Nudgee. Perhaps the intact mangrove forest and trio of creeks emptying onto the foreshore at Nudgee helps to maintain a healthy and continuous supply of food for benthic invertebrates at Nudgee, and infauna density was three times higher at Nudgee than Sandgate (see **Figure 5.12a**). Crucially, trying to estimate the importance of an area as low tide foraging habitat for migratory shorebirds will not be possible just from considering substrate extent or type alone. Direct surveys of foraging shorebirds will be needed in any region where management of the intertidal zone is being considered, to ensure that the right actions can be focused on the right areas. The bird surveys reported above were relatively cheap to obtain, requiring only about 120 hours of surveyor time spread across 10 different days (6 hours per day for each member of the two-person team), and about 1,000 km of road travel expenses. The benthic surveys would entail significantly more time resource if scaled up to a full study. For just this small pilot study alone, we used approximately 5 hours in the field for the epifaunal survey per region, 4 hours in the field per region for the infaunal surveys, and approximately 14 hours for sorting and processing the samples per region. These estimates do not include travel to and from sampling sites, analysis or presentation of results. A fully specified study across Moreton Bay of the type similar to that conducted recently for Gladstone (Choi *et al.* 2017) would entail the equivalent of sampling hundreds of regions, and would require a large financial investment. A formal power analysis could be conducted to ensure the design of such a study has sufficient robustness to cope with the high spatial and temporal variation in benthic invertebrate abundance and community structure.

The data presented in this section suggest that the most urgent management action within foraging habitat for migratory shorebirds in Moreton Bay is to minimise disturbance. However, given the marked variation in benthic communities, research into the options for, and the benefits of, attempting to enhance the prey base in the intertidal zone would be interesting.

6 Management and monitoring options for migratory shorebird roosting and feeding areas in Moreton Bay

Against the backdrop of declining migratory shorebird populations in Moreton Bay (**Section 4**), potential declines in the benthic prey base (**Section 5.3**), and the fact that migratory shorebirds are threatened in feeding sites (**Section 5.2**) as well as roosting sites (**Section 4.4**), it is critical to consider what management options exist for trying to turn this situation around. Here we step through a number of potential management options, considering their likely effectiveness, relative cost, and feasibility. We then distil these into a set of conclusions about the core components of a future management strategy for migratory shorebird conservation in Moreton Bay.

6.1 Creating new high tide roosts

In this report we have identified a number of important gaps in the network of roost sites available to migratory shorebirds in Moreton Bay. We conclude that options for creating new high tide roosts to replace lost sites should be considered in at least two regions in Moreton Bay.

Port of Brisbane / Nudgee. About 8,000 birds, but sometimes in excess of 10,000 birds (in the latter case representing approximately one-third of all the migratory shorebirds in Moreton Bay), use the Port of Brisbane area as a high tide roosting site. This represents a critical vulnerability in the roosting site network because much of the reclamation area at the Port is only a temporary by-product of construction activity, and almost all of it will eventually be filled in to create footing for expanded Port infrastructure (Port of Brisbane 2015). If further reclamations were to occur in the future at the Port, it could be planned and executed in a way that will more deliberately give rise to, and protect, habitat for migratory shorebirds. A second aspect of the acute roost site vulnerability in this area is that a major former roosting site at Dynah Island near Nudgee Beach (10 km west of the Port of Brisbane reclamation area, but close to the main shorebird feeding areas at Nudgee) was overgrown with mangroves in the late 1990s and then became completely unsuitable for roosting birds (Hopkins & White 1998). Currently, the Port of Brisbane (including the adjacent claypan roosts at Lytton) is the only major roosting site left between Sandgate and Manly. Reducing this vulnerability will involve carefully managing threats to the other remaining roosts (see next section), but there is also the option of re-creating the Dynah Island roost near the mouth of Cabbage Tree Creek. It was initially formed by the disposal of dredge spoil into a bunded area. Dredging events occurred in 1960, 1983, 1987 and 1992, but then ceased because marine plant assemblages had begun to colonise, and there was concern about depositing further spoil in an area that was heavily used by migratory shorebirds (Hopkins & White 1998). Ironically the consequent vegetation overgrowth led to the roost site being abandoned, and it now appears (though is not confirmed) that most of the migratory shorebirds foraging in the Nudgee Beach area go to roost at the Port of Brisbane or Luggage Point area, several kilometres away. Expert witnesses that we spoke to as part of this project suggested that purposeful reconstruction of a roost site at Dynah Island could be one way to reduce reliance by migratory shorebirds on temporary habitat at the Port of Brisbane, and serve to reduce the vulnerability of the roost site network in this area. Other options for roost site creation that will also achieve these goals might exist, such as re-working the landscape at the Lytton claypan roosts to increase their suitability and capacity as roosting sites, or creating a second major artificial roost on Andaccahl (Fisherman Islands) or at another nearby site likely to be adopted by the birds currently using the Port of Brisbane.

The Port of Brisbane has already constructed an artificial roost on the south side of the port peninsula, but additional capacity might be needed in case the full set of birds currently using the Port do not adopt this purpose built habitat. If additional shorebirds do start to shift to this purpose built roost, its expansion will almost certainly be required to accommodate the full number of birds in the Port area. Additional management at the artificial roost is also likely to be needed, including continuation of the programme of ongoing active management of water-levels, clearing of vegetation, and more complete visual screening of the roosting area from surrounding human activity. Given the critical importance of maintaining a suitable roost site, and the considerable expense involved in creating a new roosting area, we conclude that it might be beneficial to conduct some controlled synchronised flushes of birds from the entire outer Port complex at high tide to learn what alternative roosting site they would use, at least in the context of this short-term trial. If trials were conducted in early December, and not done daily, impacts would probably be acceptable, given the utility of the knowledge gained. Aside from the artificial roost, there are also other roosting areas in open areas and claypans nearby which may in concert provide roosting habitat sufficient to hold the 8,000 - 10,000 birds currently using the Port. Some of these alternate roosts may require work to enlarge the available open area bounded by open water at high tide, to keep them free of vegetation (or revert them to this state), and to screen them from human activity. It is possible that optimal management at all these alternative locations and at the artificial roost would still be insufficient to provide disturbance free roosting areas for this local population of roosting shorebirds. We therefore conclude that serious consideration is given to construction of a new roosting site at Dynah Island or similar location.

The current expectation is that infill of the remaining reclamation area at the Port of Brisbane will occur by about 2044, although the rate of infill of the reclamation area will depend on economic growth (which drives demand for new Port land), approvals for offshore dredge spoil disposal (which affect the rate of infill) and the rate of automation of port handling procedures (which can reduce the size of the Port land footprint needed and reduce the demand for new Port land). Even once infill has been completed, an area has been earmarked for dredge rehandling, and this is envisaged to be managed in a way that is cognisant of environmental values, although the planning for this has not yet commenced given the uncertainty around timelines and the land use mix that will be needed (Port of Brisbane 2015). The dredge rehandling area could well constitute effective shorebird roosting habitat if managed correctly, and be a useful part of the suite of options for “re-homing” the one-third of Moreton Bay’s migratory shorebirds that are currently dependent on the Port as a roosting area.

We conclude that forward planning to deal with the eventual major reduction in roosting capacity at the Port of Brisbane is needed now, so that alternative sites can be scoped and constructed, and the birds have sufficient time to begin to find and use the sites before further substantial infill of the reclamation ponds at the Port of Brisbane occurs. This is a major project with a 25-year time horizon, and thinking around this critical vulnerability for Moreton Bay’s environmental future needs to commence as soon as possible. In such a planning exercise, there would need to be careful consideration of a broad range of competing ecological values, such as mangroves and fisheries.

Minjerribah (North Stradbroke Island). Despite the presence of intertidal habitat in areas south of Victoria Point and along much of the west coast of Minjerribah (North Stradbroke Island), the numbers of shorebirds observed at roosts have been relatively lower than in other areas of Moreton Bay which are also adjacent to intertidal habitats. Local experts have suggested that shorebirds feeding on these mudflats are often then flying across Moreton Bay to the mainland, to roost at the only available, but increasingly threatened roosts in those areas. Indeed, a satellite-tagged Far Eastern Curlew did just this (**Figure 5.3**). It is possible that depositing enough sand to build a sandbar at a couple of locations along that west coast, or at the shores of one of the islands in the area would provide temporary roosting habitat that would be closer than any other available roost to their feeding grounds. In fact, when sand was deposited off the west shore of Minjerribah (North Stradbroke Island) some years ago, an active roost was created which was used for several years before the sandbar dispersed and the birds abandoned the site.

Methods for roost site creation: In both of these cases, it must be borne in mind that while the technology and machinery to replace unsuitable or severely degraded roosting sites exist, there is no guarantee that birds will adopt the newly created roost, or adjustments might be needed before use by the birds occurs. Therefore, several approaches may need to be trialled before finding one that works. Fortunately, within Moreton Bay there are several examples of constructed areas that are large, open, near the shoreline and free of vegetation and these do provide roosting habitat that are used by internationally important numbers of shorebirds. Further, when they are carefully designed and managed to minimise disturbance, and vegetation succession is well controlled, constructed roosting sites can be regularly used by very large numbers of shorebirds. The roosts at Toorbul and Kakadu Beach are areas that have been cleared of vegetation near the shoreline, but frequent disturbance leads the birds to shift between alternative roosts. The Port of Brisbane and the roost at Manly Harbour comprised bare ground that extends into Moreton Bay like a peninsula. Both these areas have fencing and restricted access which excludes nearly all recreational visitation. These two roosts have the least amount of disturbance in large, open areas free of vegetation, and perhaps not surprisingly have some of the largest regular concentrations of migratory shorebirds in Moreton Bay.

Effectiveness, cost and feasibility. Creation of roosting sites is costly, although it needn't entail very large *de novo* expenditure if made to form a component of contemporaneous dredging or construction works. While construction of roosts may be needed, the use of floating roosts might soon be an option to increase areas of undisturbed roosting habitat. Floating roosts are currently being trialled in Victoria, New South Wales and South Korea by BirdLife Australia. A larger floating barge covered in dirt could also be considered if options for constructed roosts are limited. It is also possible that clearing, or management of existing roosts could help. Whatever the engineering solution used, roost site creation needs to be thoroughly scoped both in terms of optimal location, and also optimal design, and a clear long term management plan needs to be put in place to ensure the site fulfils its potential. There are examples of failed roost site creation in Moreton Bay (see **Section 4.4**), and even where this approach has been successful locally (e.g. Kakadu Beach and Port of Brisbane constructed roost), continuous ongoing management has been needed to maintain the sites. Careful consultation with migratory shorebird experts, architects, engineers and managers of successful (and failed) projects will be a necessary feature of any future attempts to create further roosting sites in Moreton Bay. Given appropriate resourcing, the construction of roost sites is highly feasible. The main risk factor at play is uncertainty around whether birds will adopt any new constructed roost site, and institutional arrangements around maintenance. In this regard, we urge patience, since it can be many years before birds begin to use a new roosting option, and to determine precisely what maintenance regime is needed.

6.2 Managing threats at roosting sites

Roosting migratory shorebirds generally need large, open, flat areas, with minimal vegetation, close to or bordering the open water at high tide, and free from disturbance. And all of these attributes need to be consistently managed over the long term, together with appropriate protected area designations when needed. Ninety-five percent of roost sites for which we obtained information were identified by experts as having one or more threats serious enough to be impacting the number of birds able to use the site, yet most of these threats are highly amenable to management. In this section we first highlight some of the roosting sites where threat management is most urgently needed, and then consider in turn some of the key threat management options that could be deployed across the roosting site estate more broadly.

Critical management priority I: Southern Pumicestone Passage. Threats to the roosts at Toorbul and Kakadu Beach were identified by experts, and these sites would benefit urgently from increased management, given their numerical importance for shorebirds, and the existence of a management plan and ongoing implementation of physical reprofiling, mangrove regrowth removal and slip rail gate installation at Kakadu Beach by Moreton Bay Regional Council. At Toorbul in particular, urgent attention to the physical layout of the roost site was recommended by migratory shorebird experts, since there were concerns that this site is under pressure that is so intense, birds will soon abandon it altogether. The Toorbul roost is situated at the southern end of the Toorbul Esplanade, and being so close to the road, the birds are frequently subject to disturbance that causes all the roosting birds to depart the site, when they often fly across to Kakadu Beach. Potential management responses to disturbance at this site are complicated by the different powers available to different jurisdictions. At Kakadu Beach, recent earthworks by Moreton Bay Regional Council have maintained the physical suitability of this roost site for migratory shorebirds, but the site is still subject to disturbance from land-based and water-based recreationalists. Importantly, many birds move between Kakadu Beach and Toorbul on a given high tide, especially where disturbance pushes birds off one of the roosts. Thus, the management of these two sites needs to be considered in tandem.

Critical management priority II: Manly Harbour Roost. The constructed roosting site at Manly Harbour plays a critical role in providing a safe haven for roosting birds in the heavily developed Manly region of the Brisbane foreshore. Earthworks are periodically conducted there in consultation with experts from the Queensland Wader Study Group to ensure the physical integrity of the site, but ongoing management to keep the area free of vegetation, to manage water levels, and to continue to restrict public access will require essentially permanent commitments to maintain the area for shorebirds. To our knowledge no arrangement exists to ensure that the artificial shorebird roost at Manly Harbour remains as such in perpetuity, and we conclude that a management strategy should be developed for this site that places responsibilities on a set of defined stakeholders, with top priority given to ensuring the long-term protection of the site (e.g., under the Nature Conservation Act or Marine Parks Act). Substantial degradation or loss of this site would have major consequences for migratory shorebirds in Moreton Bay, with thousands of birds having to find alternative places to roost along an already crowded coastline. Many shorebirds feeding on the adjacent tidal flats at Lota use the Manly Harbour roost, and the energetic costs of shifting to a more distant roosting site have not been determined.

Development pressure. Expert witnesses indicated that development pressure is impacting or has impacted 43 roosting sites in Moreton Bay. The mainland coast of Moreton Bay is densely populated, and development has led to the loss of important roosting sites (e.g. Raby Bay, Cleveland and Dux Creek, Bribie Island), will continue to lead to the creation, replacement, and eventual loss of roosting sites at the Port of Brisbane, and could possibly occur close to (e.g., Toondah Harbour development adjacent to the Oyster Point, Nandeebie Park, and Sandy Bank staging and roost sites) or at (e.g., Manly Harbour) roost sites in the future. Given the widespread occurrence of threatened migratory shorebirds throughout Moreton Bay, it is crucial that future developments are planned in such a way as to ensure minimal or no impact on migratory shorebird roosting sites.

Disturbance management. Migratory shorebirds are particularly sensitive at roost sites because they are concentrated into small areas often with some distance to the nearest suitable alternative sites. Expert witnesses indicated that disturbance is threatening a large number of sites in Moreton Bay, and that sites across all regions of the Bay are affected, including on the islands (**Figure 4.22**). Previous analysis has suggested that dogs and walkers are the most frequent causes of disturbance to roosting shorebirds in Moreton Bay (Fuller *et al.* 2009), but any human activities close to or within roosting sites has the potential to impact roosting shorebirds, and prevent them from gaining the rest they need while their foraging sites are covered by the tide. Disturbance to shorebird roosts in Moreton Bay is substantially lower inside Marine Park green zones (Fuller *et al.* 2009), suggesting that the management regime can influence disturbance levels.

Vegetation control. Mangrove growth was identified as an issue affecting 25 roosting sites in Moreton Bay, and land management was an issue at four sites (**Table 4.1**). Threats from land management primarily encompassed issues such as weeds or overgrowth of other non-mangrove vegetation. Because shorebirds need open, flat areas where they can detect approaching predators, they are usually reluctant to roost in vegetated areas. While there are some exceptions to this, with a few species frequently roosting within vegetation (e.g. Whimbrel, Terek Sandpiper, Grey-tailed Tattler), vegetation encroachment into a roosting site will generally reduce the number of birds using the site. Weed growth needs to be carefully monitored and controlled in those circumstances, and a continuous ongoing commitment to vegetation control will almost always be needed, not just a one-off effort. Vegetation control can present a difficult management dilemma where the "weeds" happen to be mangroves, a vegetation type that has been heavily cleared in Australia and is protected under a number of pieces of legislation. Typically, the decision to remove mangroves from a shorebird roost should be taken by weighing up the impact on the surrounding mangrove forest and other wildlife it supports, and the benefit to migratory shorebirds of keeping the roosting site suitable for them. An important research priority in this space would be to create a structural decision-making framework for resolving this difficult coastal management dilemma to ensure effective conservation of both mangroves and shorebirds. Given the sensitivities around mangrove clearance, and the likely public perception that mangroves are an important natural ecosystem that should not be cleared, any management involving mangrove removal should perhaps be accompanied by outreach work to ensure that stakeholders (including the general public and multiple levels of government) can understand why the work is needed.

Erosion control. Erosion was listed as a threat to 14 roost sites, and depending on the particular conditions prevailing at each of these sites, various engineering solutions could be employed to tackle these issues. Discussions with shorebird experts suggested that the severity of the threat of erosion was generally rather low, and respondents attributed higher priority to management interventions that tackled other threats.

Provision of supratidal foraging. At some roosts, water level management might also prove beneficial, and we encourage trials to establish its cost, benefit and feasibility in Moreton Bay. Water levels can be strategically managed, such that they are drawn down in preparation for times when birds arrive, to enable shorebirds to access infaunal prey. Many shorebirds, especially the smaller sandpipers could then continue to forage in these wetlands currently predominantly used as roosts while the tide is in. These kinds of management interventions could be taken more regularly at artificial roosts at the Port of Brisbane and Manly Harbour, as well as in any large open areas near the coast, and sewerage works. Finally, claypan roosts are usually large flat open areas surrounded by mangroves, which can support very large numbers of shorebirds at times. While the number of shorebirds observed at claypan roosts tends to vary widely, there is a tendency for higher usage when the claypan is neither dry nor completely flooded in deeper water. It is possible that artificial management of water levels, through drainage and pump systems could maintain more consistently good conditions that shorebirds could exploit in a similar way to artificial wetlands which are managed for shorebirds. There would be a need for experiments or adaptive management to discover how to prevent the establishment of vegetation (likely to be a problem if water levels are shallow for long periods), and ensure that there is shorebird prey in the wetlands.

Effectiveness, cost and feasibility. Roost site management activities are generally highly effective, and the likely costs and benefits of different actions are well understood. Each site needs to be considered on a case-by-case basis, and could involve working through a checklist, ensuring that the basic needs of the birds are met through the provision of large, open, flat areas, with minimal vegetation, close to or bordering the open water at high tide, and free from disturbance. We urge the use of the project prioritisation protocol (Joseph *et al.* 2009), which would provide a simple and transparent way to determine which roosts should be managed given the available resources. Briefly, the method estimates the cost efficiency of each project option in a set by dividing measures of species importance, biodiversity benefit and probability of success by project cost.

6.3 Managing disturbance at feeding sites

When feeding at low tide, birds need access to tidal flats that are free from disturbance to ensure they can maximise energy intake during this small window of opportunity to forage. Yet, our low tide surveys along the Brisbane foreshore showed that disturbance is a widespread threat for foraging birds at low tide (see **Section 5.2**), and that there are some critical areas where foraging birds are being continuously and heavily disturbed. However, these surveys are very limited in their spatial scope, and data from more regions across Moreton Bay would be very helpful. Numerous studies have demonstrated the deleterious impacts disturbance can have on local populations of shorebirds and waterbirds alike (Glover *et al.* 2011; Steven *et al.* 2011). Management to increase food availability in the intertidal areas (such as seeding the flats with bivalve spat) has been attempted elsewhere in the world, but our judgement is that the risks of causing ecological disruption outweigh the potential benefits in this case, and that management of disturbance at low tide would be more cost-effective. Additionally, preparatory studies for such an intervention would be costly and would take years.

Previous research has shown that off-leash dogs reduce the number of foraging shorebirds present in a location by about 20%, and importantly that includes only the acute effect of the presence of the dogs, not the long term avoidance of an area that is subject to sustained high levels of disturbance (Stigner *et al.* 2016). Dogs on a leash, and people alone without dogs do not appear to have a strong effect on bird numbers. There are two major management approaches to addressing this issue, and importantly they are not mutually exclusive.

First, stronger enforcement of existing regulations around foreshore activities will help reduce disturbance. This could involve hard and soft measures to reduce disturbance levels, and mathematical modelling in Moreton Bay has shown that such enforcement will have the greatest return on investment when focused on areas with the highest numbers of shorebirds, not simply the places with the highest level of disturbance (Dhanjal-Adams *et al.* 2016). Hard measures include increased patrols, more decisive use of penalty infringement notices rather than warnings, and closer collaboration between council and state government enforcement efforts. Softer measures include enhanced signage, awareness-raising events, media campaigns, including the issue in environmental education programmes. Such approaches need to be friendly, innovative and imaginative, otherwise there is a potential for them to turn into heated arguments and entrenched positions. Carefully trained staff dressing up as a curlew, and wandering about on the foreshore speaking to owners of off-leash dogs, for example.

Second, enforcement and awareness-raising can only go so far in creating widespread change. Since off-leash dog exercising along the foreshore is so commonplace, with more than 80% of dogs on the foreshore currently off-leash, ultimately a pervasive behavioural change is needed among recreationalists, and existing enforcement and awareness-raising activity seems to be having little effect on the problem. While increased enforcement of the existing rules should be the first option, and will always be critically important in areas with high shorebird values, Stigner *et al.* (2016) argued that trying to ensure all dogs are kept on-leash while on the foreshore is unlikely to succeed with anything other than astronomical levels of investment. They investigated whether designating foreshore dog off-leash areas in places where shorebird foraging abundance is relatively low and recreational demand is relatively high could result in reduced overall disturbance to migratory shorebirds, and concluded that 97% of migratory shorebirds along the Brisbane foreshore would be rendered free from off-leash dog disturbance if several off-leash zones were designated. The idea is that the off-leash dog areas serve to concentrate the disturbance into carefully chosen zones that are known to be less favoured by migratory shorebirds, thus reducing pressure on the shorebirds' favoured sites. In October 2018, Brisbane City Council announced a one-year trial of foreshore dog off-leash areas to commence in winter 2019. The surveys we have conducted form a baseline against which to assess whether the off-leash areas will indeed serve to concentrate recreational activity into areas that are less favoured by shorebirds, and reduce overall the amount of contact between off-leash dogs and migratory shorebirds along the Moreton Bay foreshore. This will indicate whether off-leash zoning is a possible management action to reduce disturbance to migratory shorebirds foraging at low tide in Moreton Bay. If so, a similar approach could perhaps be adopted for other forms of foreshore disturbance.

It must be borne in mind that any management actions taken in the intertidal zone must be cognisant of not interfering with important places for the shorebirds at other stages of the tidal cycle. For example, at high tide, shorebirds gather into roosting sites, and these need very special protection from disturbance, since any disturbance event at a roost affects a large number of shorebirds simultaneously. Any management actions in the intertidal must, for example, verify that they are not proximal to important roosting sites. The Department of Environment and Science is currently preparing guidelines for the establishment of Local Government declared dog off leash areas in state marine parks, and the principles enshrined in these guidelines apply to ensuring any management action that is taken in the intertidal zone for migratory shorebirds does not compromise important values for shorebirds at other stages of the tide.

6.4 Enhanced monitoring

Roosting areas

The primary of objective of shorebird monitoring conducted by the QWSG has always been to monitor populations of these birds at the roosting habitats, where they form large flocks that are more readily counted. Most of these shorebirds feed at very low densities, so numeric estimates across the feeding areas are far more difficult and expensive to achieve. The QWSG has been able to achieve that objective exceedingly well for the more common migratory shorebirds in Moreton bay, which is a well-monitored region by national standards (Fuller *et al.* 2019). While we regard implementing management as the top priority for achieving migratory shorebird conservation in Moreton Bay, enhanced monitoring will enable four connected outcomes. First, increased surveillance could lead to the earlier detection of threats operating at a location. With so many roosting sites being threatened all across the Bay, organised monitoring can help "call in" management efforts before a threat has caused abandonment of the site by a large number of birds. Second, monitoring can help determine whether or not management interventions are having the desired effect, or to choose among alternative courses of action based on the empirical data from the results of monitoring. Third, enhanced monitoring will enable a clear determination to be made as to whether certain species occur in nationally or internationally significant numbers, and to keep track of population declines. Finally, monitoring activities help cultivate motivated people, who are inspired to make contributions to scientific knowledge through their efforts, to monitor threats, and to argue for better conservation outcomes for migratory shorebirds and their habitats.

Many roost sites in Moreton Bay do not have any available count data from recent years (**Figure 4.1**), and we have outlined in **Section 4.5** some of the key gaps in the current monitoring effort. In the northern part of Pumicestone Passage and around the small islands in the south of Moreton Bay, many roosts have not been visited recently because these small roosts, often distributed through the mangrove forests, are difficult to access and individually probably contain comparatively small numbers of birds. Nonetheless it seems likely that collectively these roosts might contain substantial numbers of particular species, whose population size in Moreton Bay is currently being underestimated. The only known attempted complete census of Moreton Bay shorebirds occurred in 2008, and we conclude that further complete censuses will be invaluable to detect Bay-wide changes in migratory shorebird abundance and distribution since that time.

There are many reasons why a site might be no longer monitored, ranging from known or suspected abandonment by the birds, to the lack of availability of a local counter, access being denied, or insufficient resourcing to access sites by boat. There are a number of roost sites that have been surveyed only a handful of times and others where monitoring used to occur on a consistent basis but no longer does. A strategy to systematically determine why some sites are no longer monitored would be an important first step for identifying where gaps might exist, prioritizing which should be filled first, and determining how they could be filled.

Monitoring of important roost sites on southern Moreton Island, Amity Sandbank, and other small sandbanks and islands in the central part of the bay currently occurs on an approximately quarterly basis (October, January, April, July). Increasing the frequency of monitoring to monthly, especially during the summer months (November, December, January, February) would improve data robustness for this internationally significant and threatened portion of the Bay. The southern portion of Moreton Island has historically been one of the most numerically important roost sites in all of Moreton Bay for migratory shorebirds, including Far Eastern Curlew, so increased monitoring of shorebird numbers and threats (especially disturbance from beach driving and boaters) is perhaps warranted. Rather few roosting locations have been identified along much of Moreton Island's extensive shorelines, although this is perhaps not surprising since there are only small expanses of adjacent intertidal habitat (**Figure 5.1**) and few flat open areas suitable for roosting.

There could be some additional modestly sized groups of migratory shorebirds scattered across the eastern (ocean side) shoreline of Bribie Island, Moreton Island, and Minjerribah (North and South Stradbroke Islands). Sanderling is the species that might be expected in these open beach habitats, and these places could be surveyed at least occasionally. Given the potential of supratidal foraging as an indicator of energy balance, and the role it plays in supplementary feeding, noting the number of foraging birds during roost site monitoring counts would be useful.

Intertidal feeding areas

While tracking overall change in numbers is probably best done via high tide roost counts, monitoring at low tide can provide crucial information about where and when birds are choosing to forage in certain areas, and can inform management decisions such as foreshore dog off-leash areas, or marine park zoning. Five low tide count sites are currently being monitored on a regular basis by QWSG: four in Caloundra / Pelican Waters and one site in Pine Rivers North. One of the largest scale monitoring efforts so far is perhaps that reported in Stigner *et al.* (2016), and the repeat of that work for the mainland coast between Sandgate and Lota reported here (see **Section 5.2**). While counting shorebirds at low tide is challenging, it is by no means impossible, and it can be reasonably cost effective (see **Section 5.4**).

One promising option for counting migratory shorebirds at low tide is to use aerial photography, with a camera carried by a small unmanned aerial vehicle. Pilot testing of this approach for counting birds on the tidal flats is getting underway in Moreton Bay, with early results suggesting that images of sufficient quality can be obtained, and detection of birds on the flats can be automated relatively easily (**Figure 6.1**). It remains to be seen whether the birds can be identified to species level. One enormous advantage of this approach is that the precise distribution of birds on the tidal flats can be ascertained, which can help pinpoint management units in the intertidal zone e.g. where disturbance should be excluded. "Heat maps" can be created that enable patterns of use to be summarised over a defined time period (**Figure 6.2**).

Figure 6.1 Image of resting Gull-billed Terns at Geoff Skinner Reserve taken from a drone. An automated classifier scans the image and provides an assessment of the birds present, identified as individual objects. Each detected object has a probability associated with it, so the error rates can be calibrated and the classifier refined. *Image and classification by Joshua Wilson*.

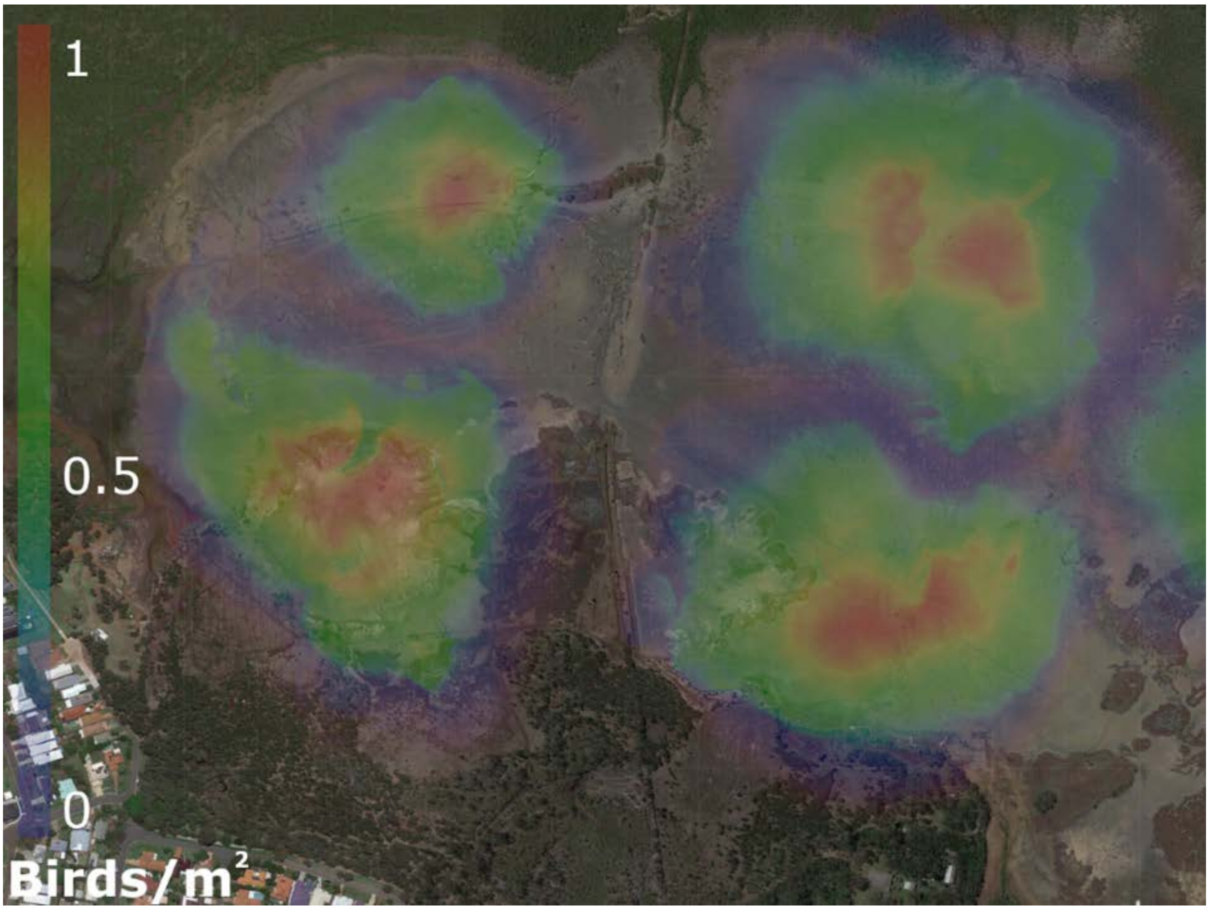


Figure 6.2 Detections of birds can be summarised to provide a "heat map" of the precise areas of a wetland being used by birds. This image is of Geoff Skinner Reserve. *Image and classification by Joshua Wilson*.

7 Conclusions

Based on the foregoing, we outline a number of conclusions, which we consider to be a useful basis for updating the existing migratory shorebird management strategies for Moreton Bay. We do not presume here to consider our thoughts a draft strategy, but rather as one input among many into a collaborative decision-making and management process to be carried out by all the necessary stakeholders, ideally under the purview of a steering committee, technical reference group or task force. We recognise that implementing these actions is enormously challenging in the massive multi-stakeholder environment of Moreton Bay, and have discussed a number of these challenges in previous sections of this report.

7.1 Critical vulnerabilities exist

We identify four critical vulnerabilities in the present network of migratory shorebird roosting sites in Moreton Bay. These are (i) threats to the large roosts at Toorbul and Kakadu Beach, (ii) near-total reliance of about 8,000 of Moreton Bay's migratory shorebirds on roosting habitat at the Port of Brisbane that is only a temporary by-product of construction activity, (iii) the lack of protection and long term maintenance for the critically important Manly Harbour roost, and (iv) the apparent lack of sufficient roosts adjacent to large areas of tidal flat along the western shore of Minjerribah (North Stradbroke Island).

7.2 Critical vulnerabilities can be remedied by management

These critical vulnerabilities in the current network of roosting sites could be addressed by (i) enhancing threat abatement works at the Toorbul and Kakadu Beach roosts, and (ii) creating, augmenting, or protecting artificial roosting sites in the vicinity of Dynah Island, Minjerribah (North Stradbroke Island) and Manly Harbour. A management plan is needed to determine how the c. 8,000 shorebirds currently using temporary habitat at the Port of Brisbane will be accommodated after the Port reclamation is completed and the long-term future of the internationally significant artificial shorebird roost at Manly Harbour must be secured. These are major projects, that would require substantial planning and investment over multiple years.

7.3 Human disturbance management and vegetation control are needed at roosting sites

Disturbance and/or vegetation overgrowth (primarily mangroves) were identified as threats to more than two-thirds of all roosting sites in Moreton Bay. Substantially increased investment is urgently needed to tackle these issues at a number of roost sites. A project prioritisation protocol would help determine the order of priority for roost site management. Judicious monitoring of these threats is also warranted at carefully selected sites as sentinels to warn of future change, and to test the effectiveness of management interventions. Managing the competing values of multiple stakeholder groups will be a particular challenge in implementing these activities.

7.4 Trials of water level management at roosting sites are needed

Active management of water levels has proven to be highly effective at providing foraging habitat for many shorebirds especially the critically endangered Curlew Sandpiper and other small migratory shorebirds. These artificial or actively managed wetlands also provide important roosting locations when they are close to tidal flats. These methods could be trialled at artificial roosts at the Port of Brisbane, Manly Harbour, and potentially other locations around Moreton Bay. Additionally, water levels are highly variable at a number of claypan roosts, limiting the consistency with which they are usable by shorebirds for roosting and foraging. Relatively simple modifications using earthworks could be trialled at Tinchi Tamba to determine how better to control water level in a way that will increase the current effectiveness of the sites for shorebirds, and make them more resilient to sea-level rise and severe weather events. Implementing such an option would need to consider the potential need for EPBC Act referral and assessment given the location in a Ramsar Site.

7.5 Effects of severe weather events are weak and short-lived

Analysis shows that severe weather events in 2011, 2013 and 2017 had no consistent effect on the abundance and distribution of shorebirds in the Bay. As such we see no need for emergency adjustments to shorebird management in the aftermath of future severe weather events, at least those equally or less severe than the 2011 event. However, oil spill from shipping caught in bad weather is a real risk, and it would be beneficial to include migratory shorebirds in oil spill response management plans for Moreton Bay.

7.6 Off-leash dogs are disturbing foraging shorebirds at low tide

At low tide, approximately 100 km^2 of intertidal habitat is exposed, constituting substantial potential foraging habitat for migratory shorebirds. The overall extent of intertidal flats has not substantially changed since the late 1980s, although there are some localised losses to development. Yet an increasing human population has undoubtedly increased the disturbance to foraging birds at low tide by off leash dogs along the Brisbane foreshore at least between Deception Bay and Lota, reducing the number of birds present at a site by about 20%, and also having an unknown long term effect on the number of birds choosing to use a region. With more than 80% of dogs on the foreshore currently being exercised off-leash, greatly enhanced management is needed to reduce this threat and safeguard the foraging habitats of migratory shorebirds in Moreton Bay. The fact that one of the three trial sites in the Brisbane City Council foreshore dog off-leash area trial was discontinued attests to the real challenges of implementing these sorts of actions in practice.

7.7 Prey densities are variable

Indicative sampling of benthic invertebrates living in the sediment at the Sandgate, Nudgee and Manly foreshores indicate spatially variable density of prey for shorebirds, and that most potential prey items are comparatively small bodied. This further highlights the need for disturbance to foraging migratory shorebirds to be substantially reduced, and points to the need for more comprehensive surveys across Moreton Bay.

7.8 Greater resourcing of the Queensland Wader Study Group is needed

Partnerships are already occurring, but deeper in-kind contributions (e.g. further vessel support) would fill a number of identified gaps in shorebird monitoring, and direct investment will enhance the capacity of the Queensland Wader Study Group to undertake this increased monitoring. This is perhaps best achieved by employing or seconding a staff member for a fixed term to (i) expand the base of volunteer surveyors, and (ii) upgrade systems for data capture and flow. Of particular importance is a need to update the estimate of the total number of migratory shorebirds using Moreton Bay. The most recent Bay-wide census took place in 2008, which makes estimating recent or current populations challenging. Given the fundamental importance of population estimates for conservation and management (e.g., for meeting Ramsar criteria), annual or bi-annual Bay-wide censuses would be beneficial, but would likely require additional resourcing (e.g., boats and/or aircraft for Pumicestone Passage and southern Moreton Bay).

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10 Supplementary tables and figures

Table S1

Activities carried out for each project aim.

Aim 1: Conduct A Data-Driven Assessment Of The Adequacy Of Current High Tide Roosting Sites In Moreton Bay	Activities completed
Aim 1.1: Map all high tide roosting sites throughout Moreton Bay.	Using existing data held by QWSG, we mapped the locations of all known high-tide roost sites used by migratory shorebirds in Moreton Bay.
Aim 1.2: Characterise the numbers of shorebirds using each high tide roosting site in Moreton Bay.	Using existing data held by QWSG, we calculated, presented, and discussed numerical statistics for every high-tide roost site identified in Aim 1.1, comprising the average and maximum numbers of birds of each species.
Aim 1.3: Identify any changes in distribution or abundance of migratory shorebirds in Moreton Bay as a result of severe weather events.	We conducted a GIS analysis of changes in the numbers and distribution of migratory shorebirds at high-tide roosts before and after three major weather events (floods in 2011 & 2013, and cyclone Debbie in 2017).
Aim 1.4: Characterise gaps and vulnerabilities in the network of high tide roost sites in Moreton Bay.	We conducted a gap analysis to determine whether there are any gaps in the current network of high-tide roost sites, namely (i) major areas of intertidal flats and / or known feeding habitats that are not close to any known roosting site, (ii) high-tide roost sites that are surrounded and / or encroached by anthropogenic threats, (iii) sites that are vulnerable to sea-level rise and severe weather events, based on expert assessment combined with data from Aim 1.3 and previous published models of sea-level rise in Moreton Bay.
Aim 2: Identify Candidate Sites For The Creation Of New High Tide Roosts In Moreton Bay	**Activities completed**
Aim 2.1: Determine where new high tide roosts could be created, or existing sites better managed.	By combining data on the risks identified in Aim 1.4 with input from expert stakeholders, we have proposed candidate sites for the potential creation of new high tide roosts, or enhanced management of existing sites, to fill the gaps in the current network across northern Moreton Bay.

Table S1 *continued*

Aim 3: Characterise Benthic Prey Available To Migratory Shorebirds In Northern Moreton Bay	**Activities completed**
Aim 3.1: Design and implement a pilot benthic sampling program to sample potential shorebird prey in northern Moreton Bay.	Conduct pilot benthic sampling comprising 30 sediment cores in known migratory shorebird intertidal feeding habitat, to indicate which prey types are present in areas of high (10 cores), medium (10 cores) and low (10 cores) shorebird abundance.
Aim 3.2: Characterise the types of shorebird prey present, and their approximate densities.	Use the results of the benthic sampling to list the types of food and their approximate density available in intertidal areas of high, medium and low shorebird abundance. This will include a comparison with invertebrate densities found in other estuarine ecosystems in Australia.
Aim 4: Create A Map Of Shorebird Feeding Areas In Moreton Bay, And Investigate Options For Their Management	**Activities completed**
Aim 4.1: Map the distribution of intertidal flats in Moreton Bay.	Use recently available satellite data on tidal flats (Murray *et al.* 2019) to map the extent of potential intertidal feeding habitat for migratory shorebirds in northern Moreton Bay.
Aim 4.2: Map the low tide foraging distribution of migratory shorebirds in northern Moreton Bay.	We mapped the relative abundance of migratory shorebirds in intertidal feeding sites on the mainland northern Moreton Bay foreshore between Deception Bay and Lota..
Aim 4.3: Assess management options for intertidal shorebird feeding habitat.	We provide an assessment via expert consultation and from review of the scientific literature of potential feeding habitat management activities to cope with future sea-level rise and extreme weather events.
Aim 5: Identify Gaps In Monitoring Of Migratory Shorebirds In Intertidal Feeding Areas Of Moreton Bay	**Activities completed**
Aim 5.1: Assemble available existing data on numbers of migratory shorebirds foraging intertidally in northern Moreton Bay.	Collate all available intertidal shorebird count data for northern Moreton Bay.

Table S1 *continued*

Aim 5.2: Characterise the numbers of shorebirds using each low tide feeding site in northern Moreton Bay.	Calculate, present, and discuss numerical statistics for each intertidal feeding site identified in Aim 5.1, comprising the average and maximum numbers of birds of each species.
Aim 5.3: Propose options for enhanced monitoring of shorebird numbers in low tide feeding areas.	Propose ways to enhance the monitoring of shorebird feeding areas in northern Moreton Bay, on the basis of identifying potentially important gaps in survey coverage of intertidal feeding areas.
Aim 6: Identify Gaps In Monitoring Of Migratory Shorebirds In Roosting Areas Of Moreton Bay	**Activities completed**
Aim 6.1: Propose options for enhanced monitoring of shorebird numbers in high tide roosting areas.	On the basis of data from Aims 1.1 and 1.2, propose ways to enhance the monitoring of shorebird high-tide roosting areas in northern Moreton Bay, on the basis of identifying potentially important gaps in survey coverage of intertidal feeding areas.
Aim 7: Write A Draft Strategy For Managing Threats To Migratory Shorebird Habitats In Moreton Bay	**Activities completed**
Aim 7.1: Consult stakeholders to enumerate strategies for managing threats to migratory shorebird habitats in Moreton Bay.	Engage with relevant stakeholders including shorebird experts, local government, state government and community for input, advice and comment on draft materials produced for Aims 1-6.
Aim 7.2: Collate and display stakeholder input.	Collate data, information and expert advice, and utilise this information to prepare the key elements of the strategy and management actions.
Aim 7.3: Prepare a draft shorebird management strategy for Moreton Bay.	On the basis of the outputs from Deliverables 1-6, together with advice from relevant stakeholders, write a draft Strategy for Managing Threats to Migratory Shorebird Habitats in Moreton Bay.

Table S2

List of migratory shorebird species observed in Moreton Bay, with maximum counts reported by the Queensland Wader Study Group in summer (Nov-Feb inclusive) and at any time during the year since 2008. For each species also listed are flyway population estimates (Hansen *et al.* 2016), EPBC Act 1999 status, IUCN status, and Queensland's Nature Conservation Act status.

Species name	Summer maximum	Annual maximum	Importance	EPBC status	Population estimate	IUCN status	Qld (NC Act)
Asian Dowitcher (*Limnodromus semipalmatus*)	3	3 [d]	Below thresholds	Marine, Migratory	14,000*	NT	LC
Bar-tailed Godwit (*Limosa lapponica*)	11,650	11,650 [a]	**International (3.6%)**	VU (*baueri*), Marine, Migratory	325,000*	NT	V
Black-tailed Godwit (*Limosa limosa*)	655	655 [b]	**National**	Marine, Migratory	160,000*	NT	LC
Broad-billed Sandpiper (*Limicola falcinellus*)	80	131 [d]	National	Marine, Migratory	30,000*	LC	LC
Buff-breasted Sandpiper (*Calidris subruficollis*)	0	1 [d]	Vagrant	Marine	15,000–56,000†	NT	LC
Common Greenshank (*Tringa nebularia*)	170	170 [a]	National	Marine, Migratory	110,000*	LC	LC
Common Sandpiper (*Actitis hypoleucos*)	3	3 [d]	Below thresholds	Marine, Migratory	190,000*	LC	LC
Curlew Sandpiper (*Calidris ferruginea*)	2,443	2,443 [b]	**International (2.7%)**	CR, Marine, Migratory	90,000*	NT	E
Double-banded Plover (*Charadrius bicinctus*)	1	248 [c]	**International (1.3%)**	Marine, Migratory	19,000*	LC	LC
Eastern curlew (*Numenius madagascariensis*)	3,651	3,651 [a]	**International (10.4%)**	CR, Marine, Migratory	35,000*	EN	E
Great Knot (*Calidris tenuirostris*)	1,433	1,433 [a]	**National**	CR, Marine, Migratory	425,000*	EN	E
Greater Sand Plover (*Charadrius leschenaultii*)	336	336 [c]	**National**	VU, Marine, Migratory	200,000–300,000*	LC	V
Grey Plover (*Pluvialis squatarola*)	119	119 [a]	National	Marine, Migratory	80,000*	LC	LC
Grey-tailed Tattler (*Tringa brevipes*)	2,430	2,430 [a]	**International (3.5%)**	Marine, Migratory	70,000*	NT	LC
Latham's Snipe (*Gallinago hardwickii*)	24	24 [d]	Below thresholds	Marine, Migratory	30,000*	LC	LC
Lesser Sand Plover (*Charadrius mongolus*)	1,915	1,929 [b]	**International (1.1%)**	EN, Marine, Migratory	180,000–275,000*	LC	E
Little Curlew (*Numenius minutus*) [e]	0	0 [d]	Vagrant	Marine, Migratory	110,000*	LC	LC
Long-toed Stint (*Calidris subminuta*)	0	2 [d]	Vagrant	Marine, Migratory	230,000*	LC	LC
Marsh Sandpiper (*Tringa stagnatilis*)	170	245 [d]	National	Marine, Migratory	130,000*	LC	LC
Oriental Plover (*Charadrius veredus*)	0	1 [d]	Vagrant	Marine, Migratory	230,000*	LC	LC
Pacific Golden Plover (*Pluvialis fulva*)	827	827 [b]	**National**	Marine, Migratory	120,000*	LC	LC
Pectoral Sandpiper (*Calidris melanotos*)	0	3 [d]	Vagrant	Marine, Migratory	1,220,000–1,930,000*	LC	LC
Red Knot (*Calidris canutus*) [f]	17	992 [a]	**National**	EN, Marine, Migratory	110,000*	NT	E
Red-necked Stint (*Calidris ruficollis*)	5,412	5,412 [c]	**International (1.1%)**	Marine, Migratory	475,000*	NT	LC

Table S2 *continued*

Species name	Summer maximum	Annual maximum	Importance	EPBC status	Population estimate	IUCN status	Qld (NC Act)
Ruddy Turnstone (*Arenaria interpres*)	213	213 [b]	**National**	Marine, Migratory	30,000*	LC	LC
Ruff (*Calidris pugnax*)	0	2 [d]	Vagrant	Marine, Migratory	25,000–100,000*	LC	LC
Sanderling (*Calidris alba*)	122	122 [b]	National	Marine, Migratory	30,000*	LC	LC
Sharp-tailed Sandpiper (*Calidris acuminate*)	1,550	1,550 [a]	**International (1.8%)**	Marine, Migratory	85,000*	LC	LC
Terek Sandpiper (*Xenus cinereus*)	691	691 [a]	International (1.4%)	Marine, Migratory	50,000*	LC	LC
Wandering Tattler (*Tringa incana*)	3	9 [d]	Below thresholds	Marine, Migratory	10,000–25,000*	LC	LC
Whimbrel (*Numenius phaeopus*)	1,364	1,364 [c]	**International (1.8%)**	Marine, Migratory	65,000*	LC	LC
Wood Sandpiper (*Tringa glareola*)	0	1 [d]	Vagrant	Marine, Migratory	130,000*	LC	LC
Total	**35,446**	**36,660**					

[a] from only complete count of Moreton Bay (Milton 2008)

[b] from last 5 years

[c] estimated from summed average roost counts

[d] maximum count from QWSG database

[e] reported once prior to 2008

[f] peak numbers occur in October during southward migration

* Hansen *et al.* 2016

† IUCN

Bold = regularly meets this threshold

Table S3

Whitney-U test results comparing paired mean roost abundance for roosts throughout Moreton Bay, before and after severe weather events in 2011, 2013, and 2017 in either the short-term (2 months) or long-term (summer).

Species	Event	Mean count (before)	Mean count (after)	Mean difference	Wilcoxon *n*	Wilcoxon *p*-value
Bar-tailed Godwit	2011 Flood (long-term)	204	230	26	34	0.462
	2011 Flood (short-term)	206	245	39	24	0.673
	2013 Flood (long-term)	267	225	-42	29	0.221
	2013 Flood (short-term)	401	240	-161	21	0.368
	2017 Cyclone (long-term)	287	260	-28	32	0.350
Curlew Sandpiper	2011 Flood (long-term)	170	215	45	7	0.813
	2011 Flood (short-term)	100	7	-93	5	0.312
	2013 Flood (long-term)	142	92	-51	10	1.000
	2013 Flood (short-term)	394	128	-266	4	0.250
	2017 Cyclone (long-term)	222	247	25	7	0.675
Far Eastern Curlew	2011 Flood (long-term)	62	56	-6	27	0.170
	2011 Flood (short-term)	62	64	1	19	0.983
	2013 Flood (long-term)	63	53	-10	21	0.444
	2013 Flood (short-term)	76	45	-31	14	0.241
	2017 Cyclone (long-term)	66	65	-2	26	0.600
Great Knot	2011 Flood (long-term)	50	78	27	13	0.244
	2011 Flood (short-term)	102	114	12	8	0.933
	2013 Flood (long-term)	91	69	-22	11	0.175
	2013 Flood (short-term)	106	49	-57	11	0.919
	2017 Cyclone (long-term)	43	30	-13	18	0.154
Greater Sand Plover	2011 Flood (long-term)	23	60	37	4	0.375
	2011 Flood (short-term)	15	13	-2	2	1.000
	2013 Flood (long-term)	133	34	-99	2	0.500
	2013 Flood (short-term)	149	52	-97	2	0.500
	2017 Cyclone (long-term)	62	33	-29	3	0.500
Grey-tailed Tattler	2011 Flood (long-term)	109	135	26	11	0.415
	2011 Flood (short-term)	100	104	4	5	0.855
	2013 Flood (long-term)	107	123	16	12	0.476
	2013 Flood (short-term)	146	203	58	6	0.563
	2017 Cyclone (long-term)	193	169	-24	7	0.219
Lesser Sand Plover	2011 Flood (long-term)	198	489	291	3	0.750
	2011 Flood (short-term)	71	5	-66	2	0.500
	2013 Flood (long-term)	411	244	-167	4	0.625
	2013 Flood (short-term)	334	147	-186	5	0.584
	2017 Cyclone (long-term)	176	168	-8	7	0.813
Pacific Golden Plover	2011 Flood (long-term)	47	42	-4	11	1.000
	2011 Flood (short-term)	12	23	11	8	0.272
	2013 Flood (long-term)	43	31	-12	11	0.320

Table S3 *continued*

Species	Event	Mean count (before)	Mean count (after)	Mean difference	Wilcoxon *n*	Wilcoxon *p*-value
Pacific Golden Plover	2013 Flood (short-term)	69	42	-27	6	1.000
	2017 Cyclone (long-term)	48	63	15	13	0.556
Red-necked Stint	2011 Flood (long-term)	274	233	-41	15	0.252
	2011 Flood (short-term)	113	53	-60	10	0.236
	2013 Flood (long-term)	178	292	114	16	0.029
	2013 Flood (short-term)	333	496	164	9	0.910
	2017 Cyclone (long-term)	308	344	36	18	0.932
Sharp-tailed Sandpiper	2011 Flood (long-term)	57	49	-9	16	0.485
	2011 Flood (short-term)	81	2	-79	4	0.125
	2013 Flood (long-term)	55	50	-5	15	0.561
	2013 Flood (short-term)	147	132	-15	6	0.563
	2017 Cyclone (long-term)	57	89	33	16	0.860
Whimbrel	2011 Flood (long-term)	38	35	-2	28	0.674
	2011 Flood (short-term)	43	39	-4	14	0.315
	2013 Flood (long-term)	33	27	-6	23	0.211
	2013 Flood (short-term)	36	23	-13	13	0.505
	2017 Cyclone (long-term)	46	39	-7	21	0.032

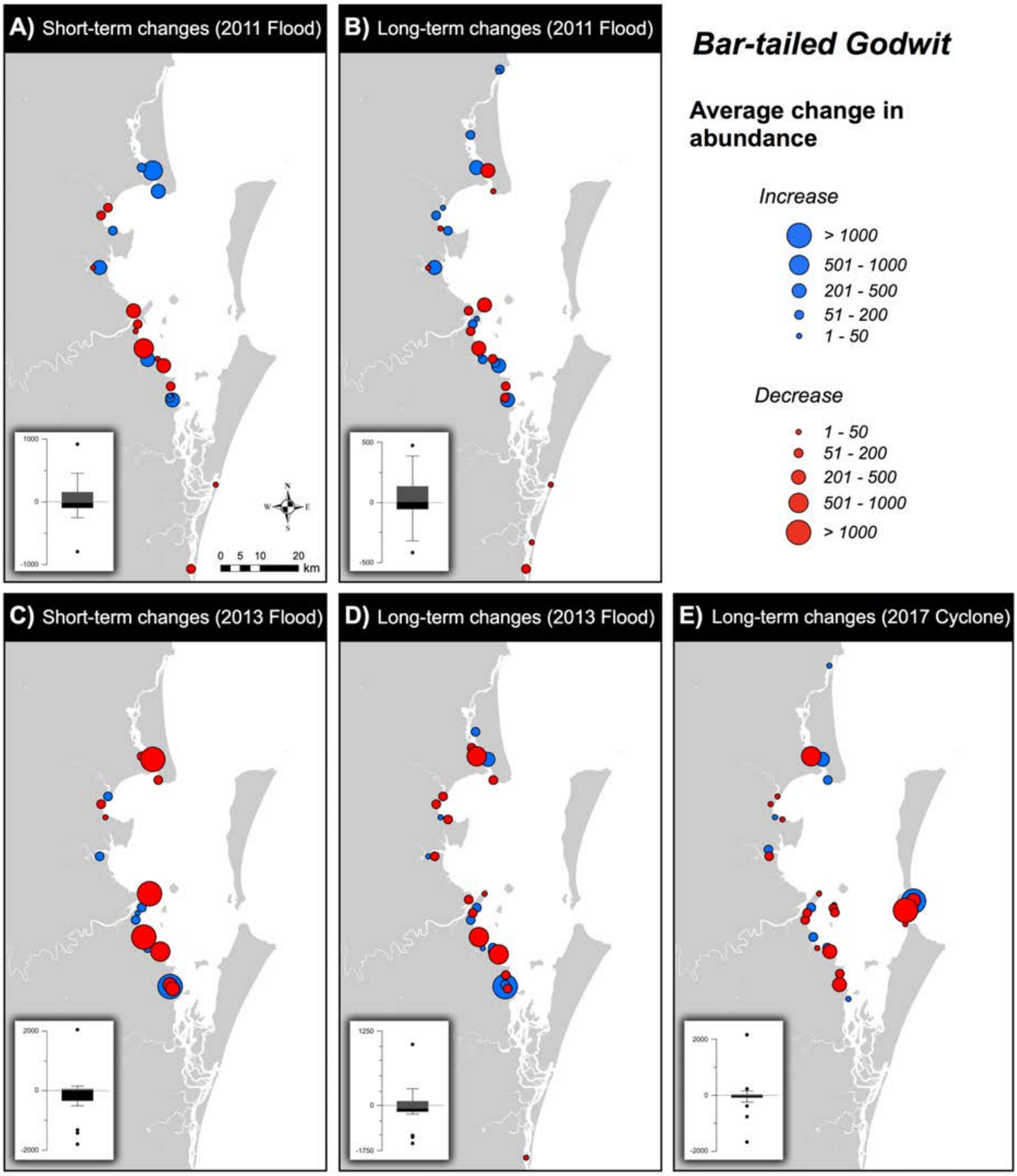

Figure S1

Changes in Bar-tailed Godwit abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Changes in the abundance of Bar-tailed Godwit were not obviously related to the severe weather events of 2011, 2013, or 20187. While there was substantial variation in abundance at individual roosts before or after the severe weather event, patterns were not obviously consistent in multiple severe weather events and were similar to a previous report (Clemens *et al.* 2012) which noted a slight increase in birds immediately after the 2011 severe weather events and some evidence of movement away from those areas closest to the Brisbane River. Despite 25+ year declines in the whole bay, long-term changes in abundance at individual roosts suggest some roosts have been more or less favoured over the decades (Clemens *et al.* 2012).

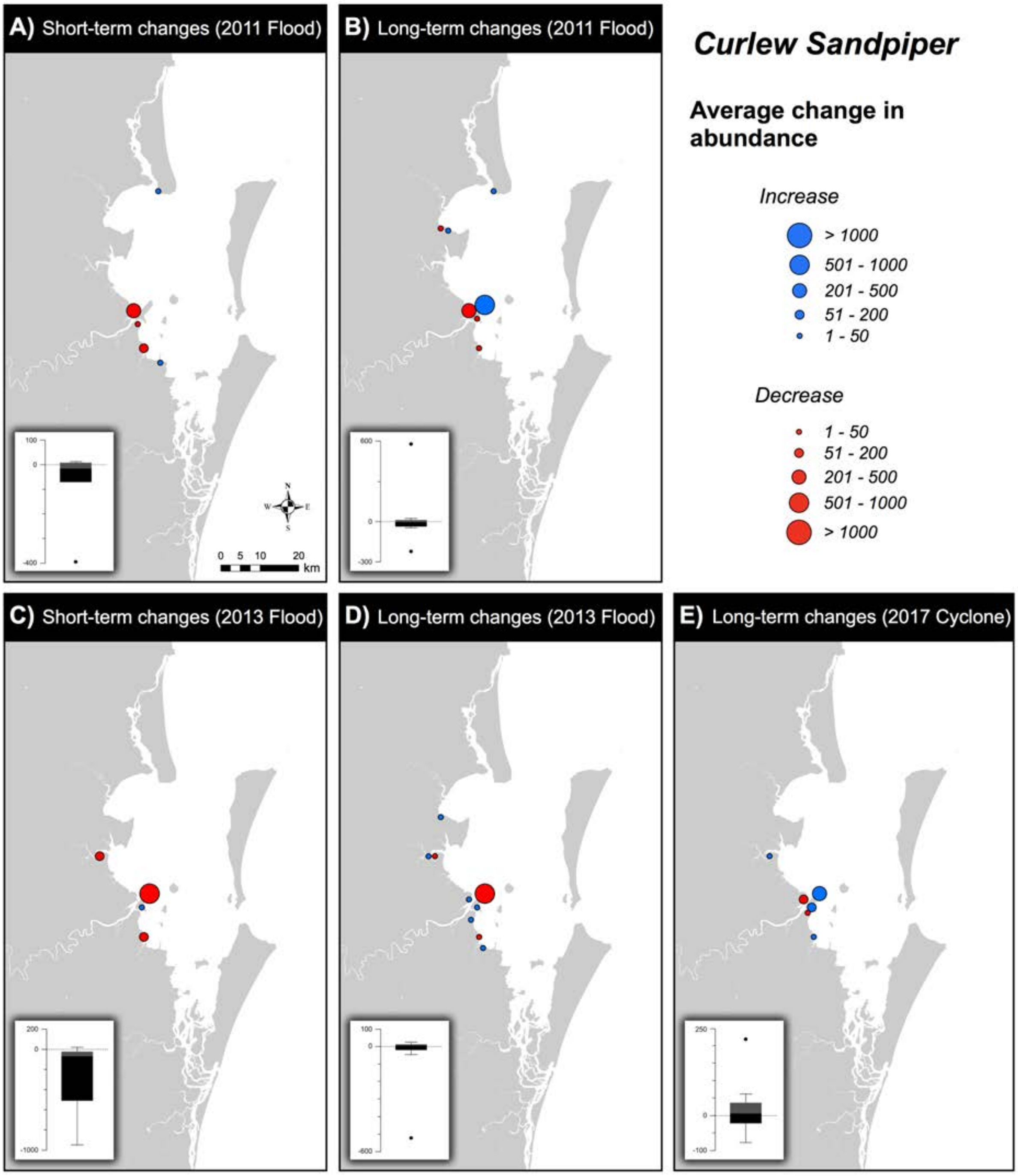

Figure S2

Changes in Curlew Sandpiper abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Changes in Curlew Sandpiper abundance were not consistent in the immediate or long-term periods compared in this report and were not obviously related to the three severe weather events. Large numbers of Curlew Sandpipers did disappear from Moreton Bay in the month following the 2011 severe weather event, and have increased over the last couple of decades at the port despite decreasing at most other roosts and throughout the bay significantly (Clemens *et al.* 2012).

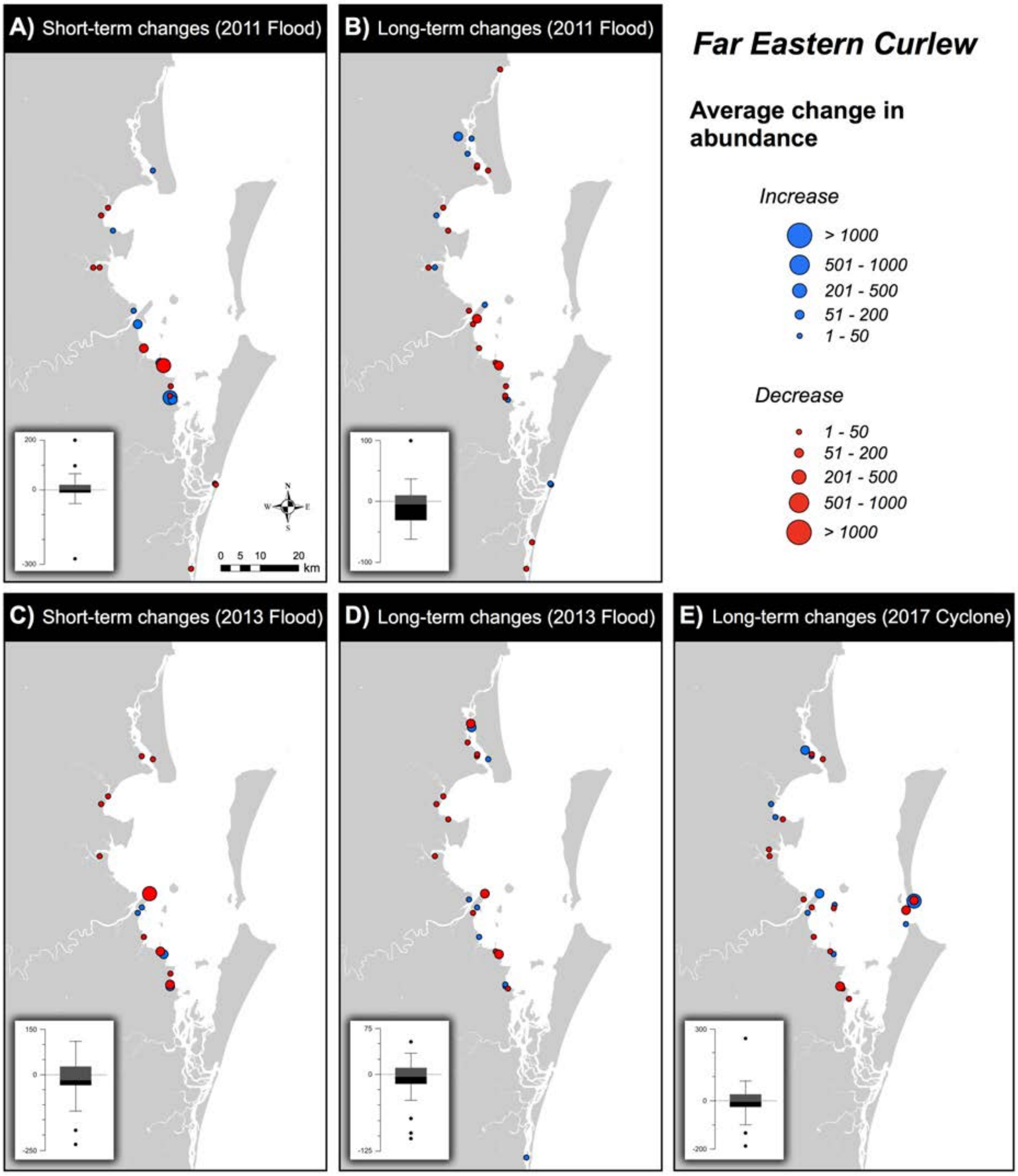

Figure S3 Changes in Far Eastern Curlew abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Changes in the abundance of Far Eastern Curlew do not appear to be strongly related to severe weather events. Declines in Far Eastern Curlew are evident throughout the bay over the last couple of decades but show increases at some roosts and declines in others (Clemens *et al.* 2012) which are not yet explained. Whitney-U tests indicate significant declines in the short and longer-term after 2013, but declines were not indicated in other severe weather events and are therefore likely related to other variables.

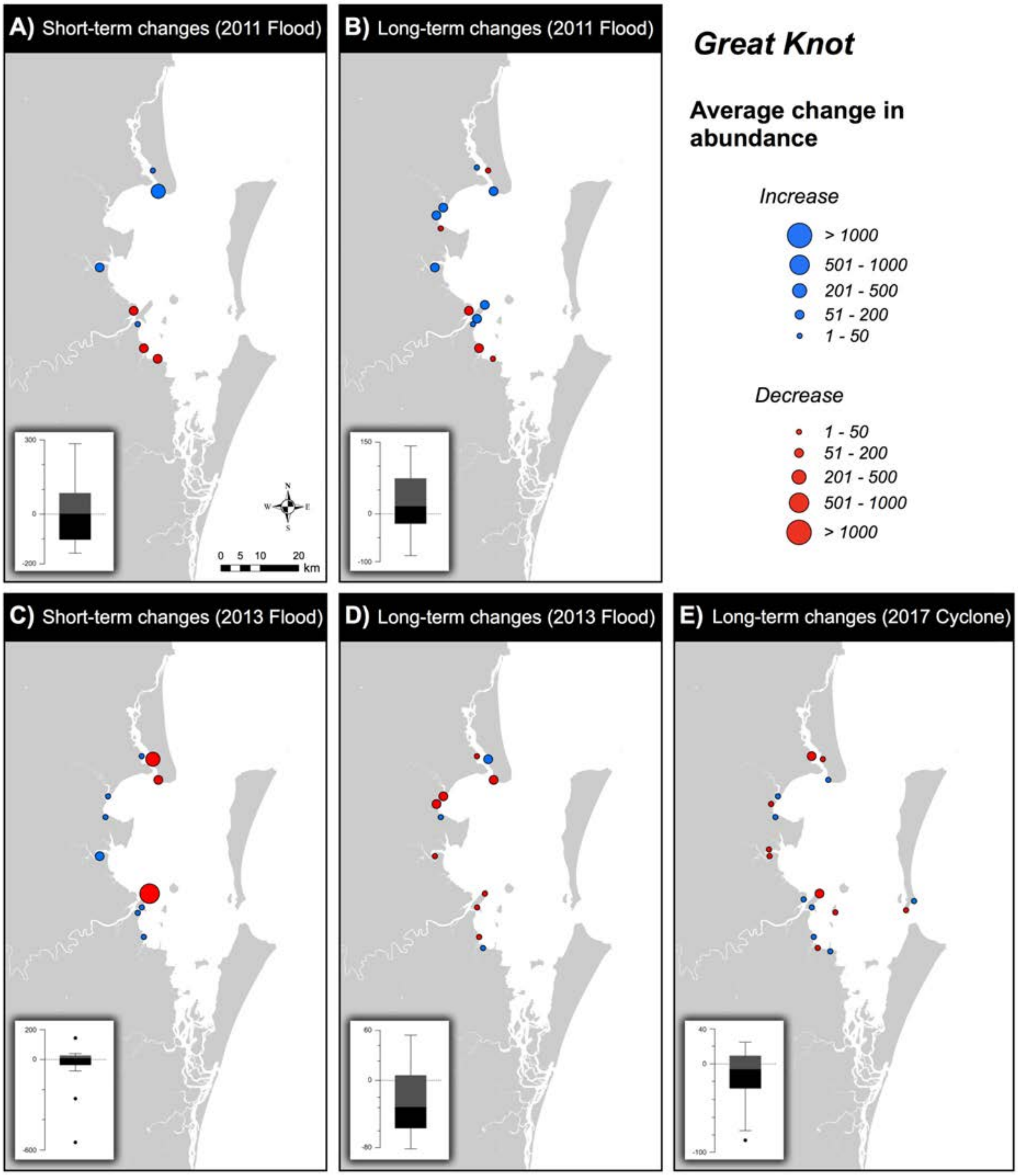

Figure S4

Changes in Great Knot abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Changes in Great Knot abundance do not appear to be related to recent severe weather events. In the month following the 2011 severe weather event large numbers of Great Knot left the area near the Brisbane River and appeared to the north near Bribie Island (Clemens *et al.* 2012). Whitney-U tests indicate significant declines in the longer-term after 2013, but such declines were not indicated in other severe weather events and so were likely related to other factors.

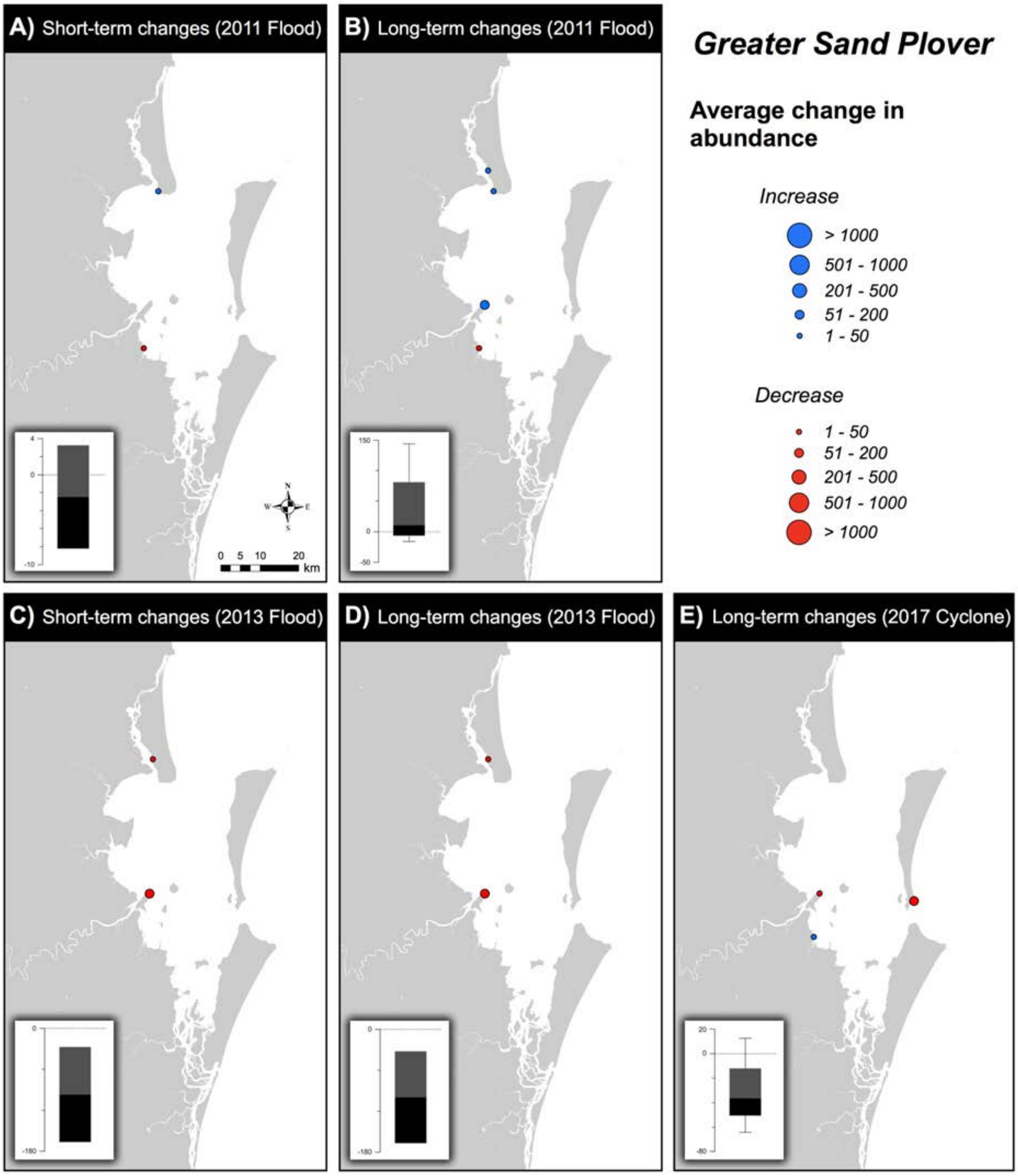

Figure S5 Changes in Greater Sand Plover abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Greater Sand Plover are not recorded in large numbers in Moreton Bay, but have been declining over the last twenty years throughout the bay (Clemens *et al.* 2012). Declines in the longer-term after the 2013 severe weather event were significant but were not consistent across severe weather events or roost areas, so appear to relate to something else occurring in 2013.

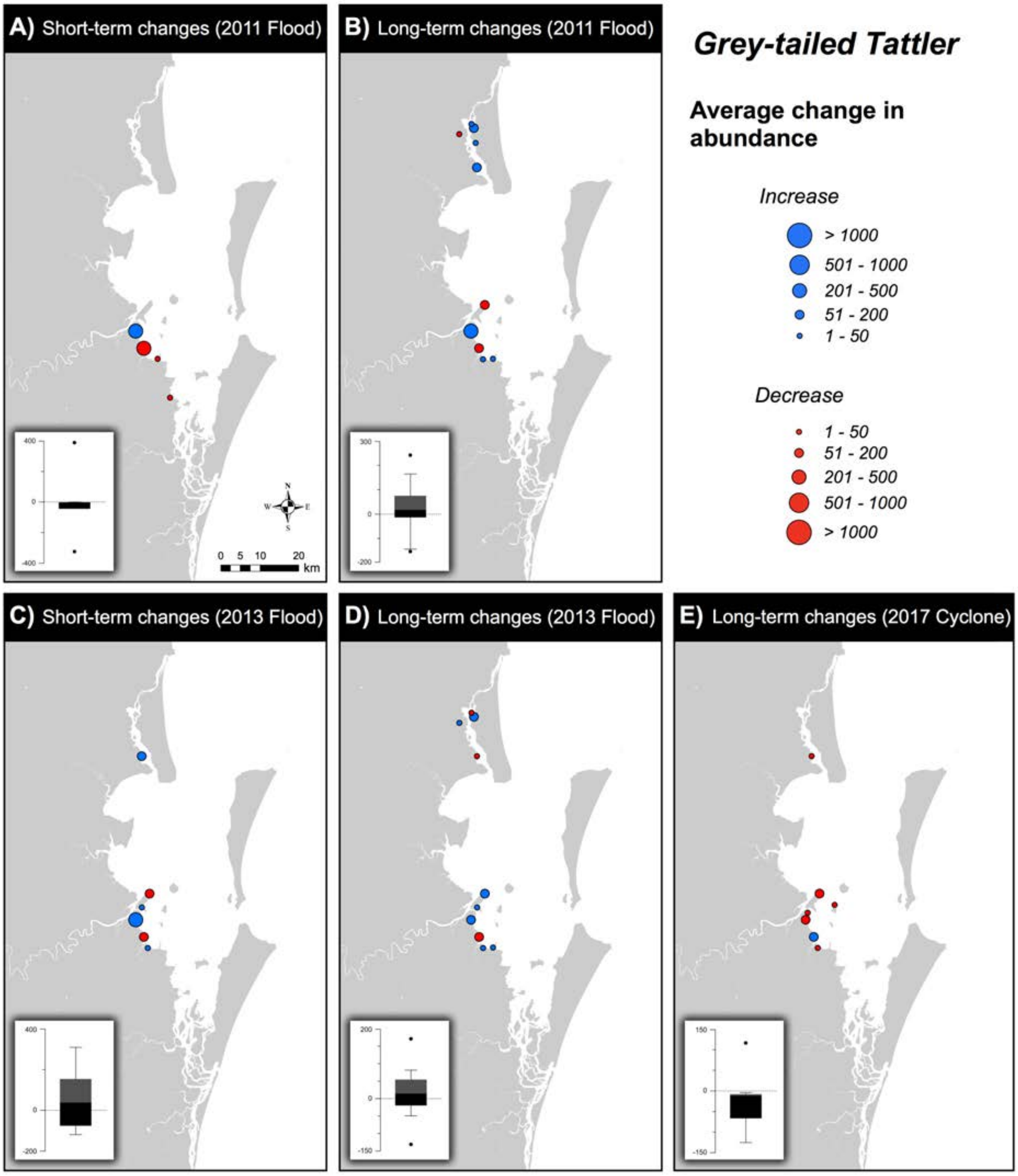

Figure S6 Changes in Grey-tailed Tattler abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Grey-tailed Tattler show no patterns in changes in abundance that are consistent. In part the lack of patterns may relate to variable chances of finding these birds in the mangroves they roost.

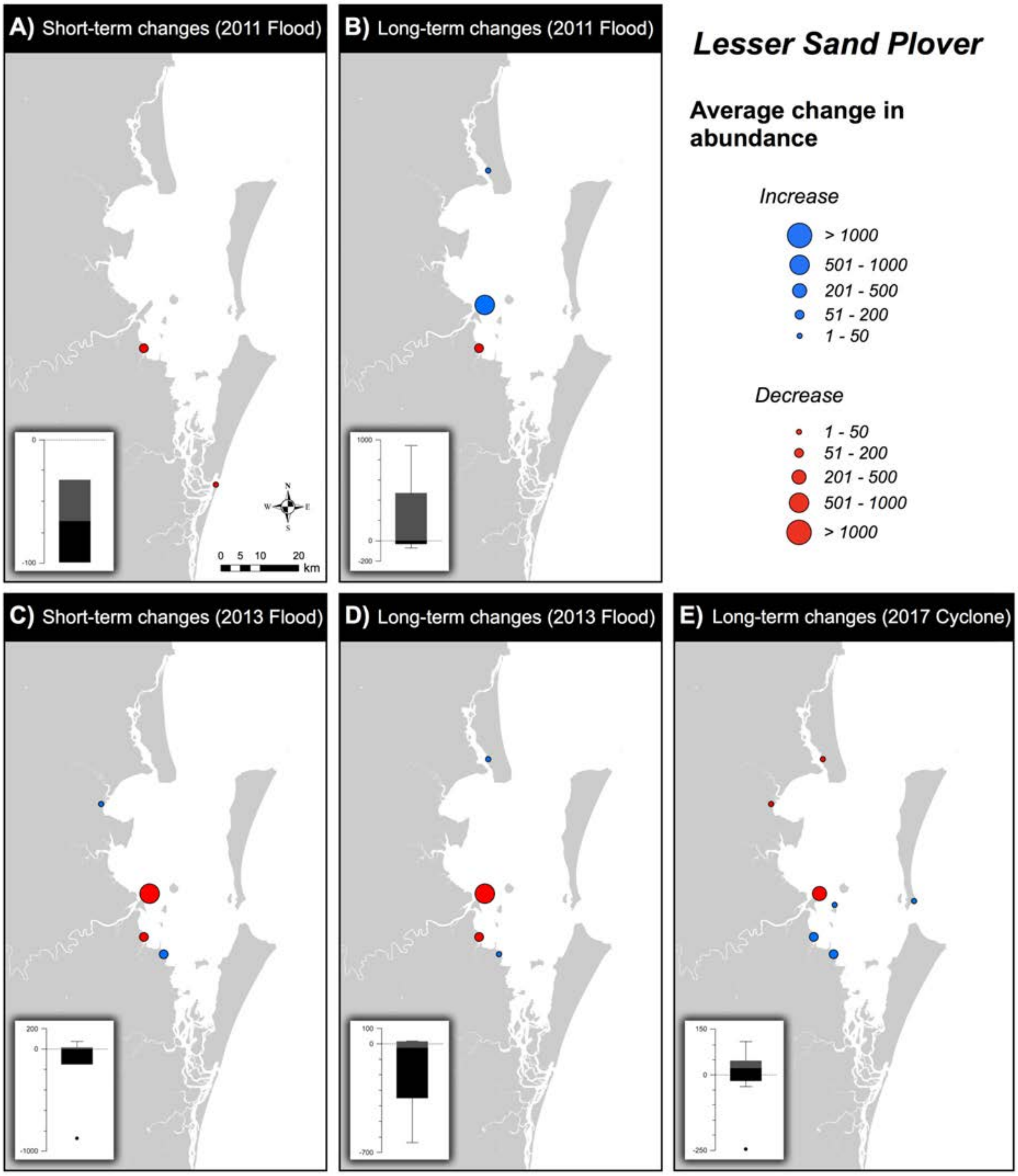

Figure S7 Changes in Lesser Sand Plover abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. No clear patterns were consistently observed in the number of Lesser Sand Plover after severe weather events. Significant increases in counts were observed in the longer-term after the 2011 severe weather event, but that increase does not appear to be related to the severe weather event.

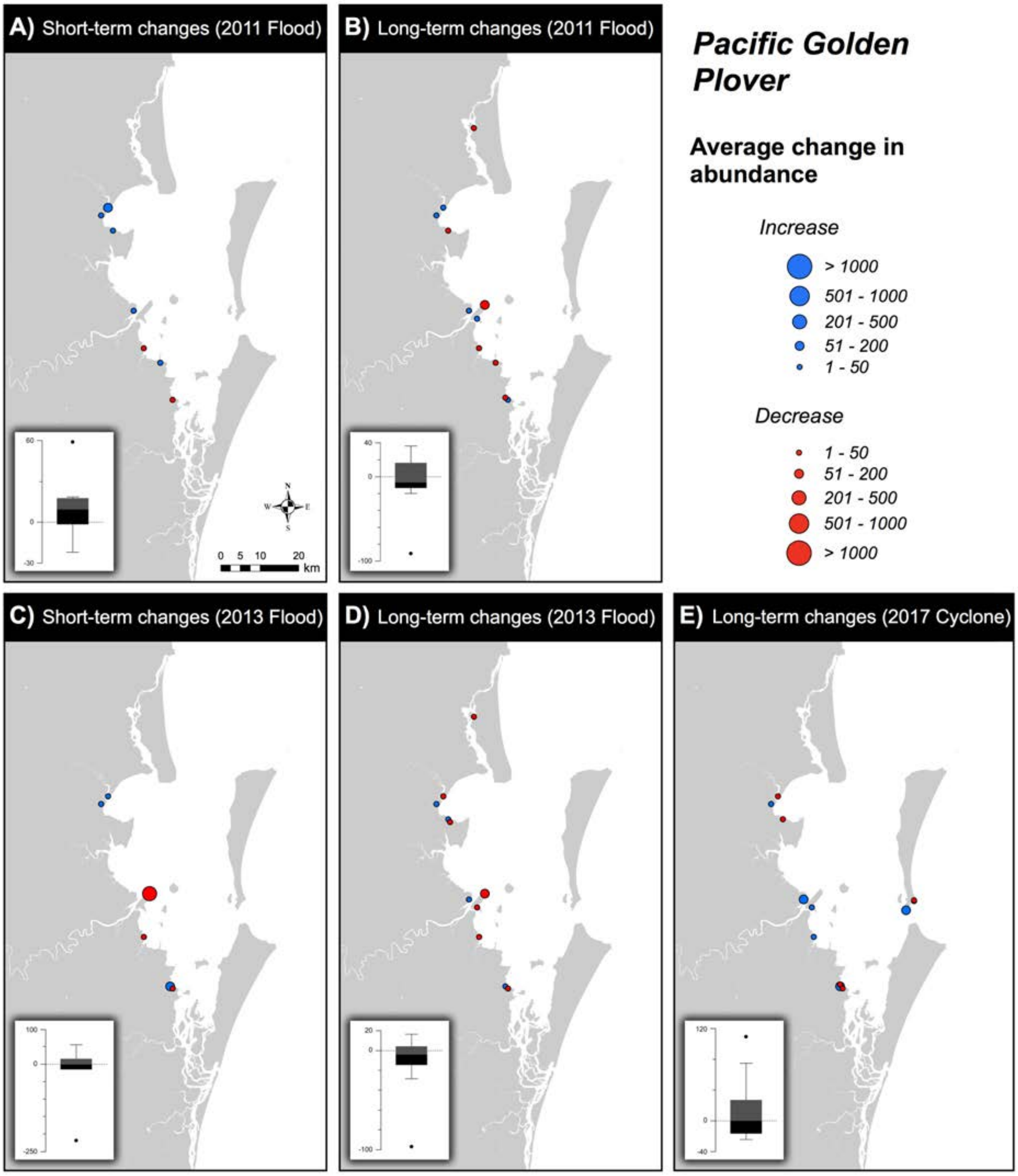

Figure S8 Changes in Pacific Golden Plover abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. No clear patterns were apparent in the changes in abundance after recent severe weather events in Pacific Golden Plover.

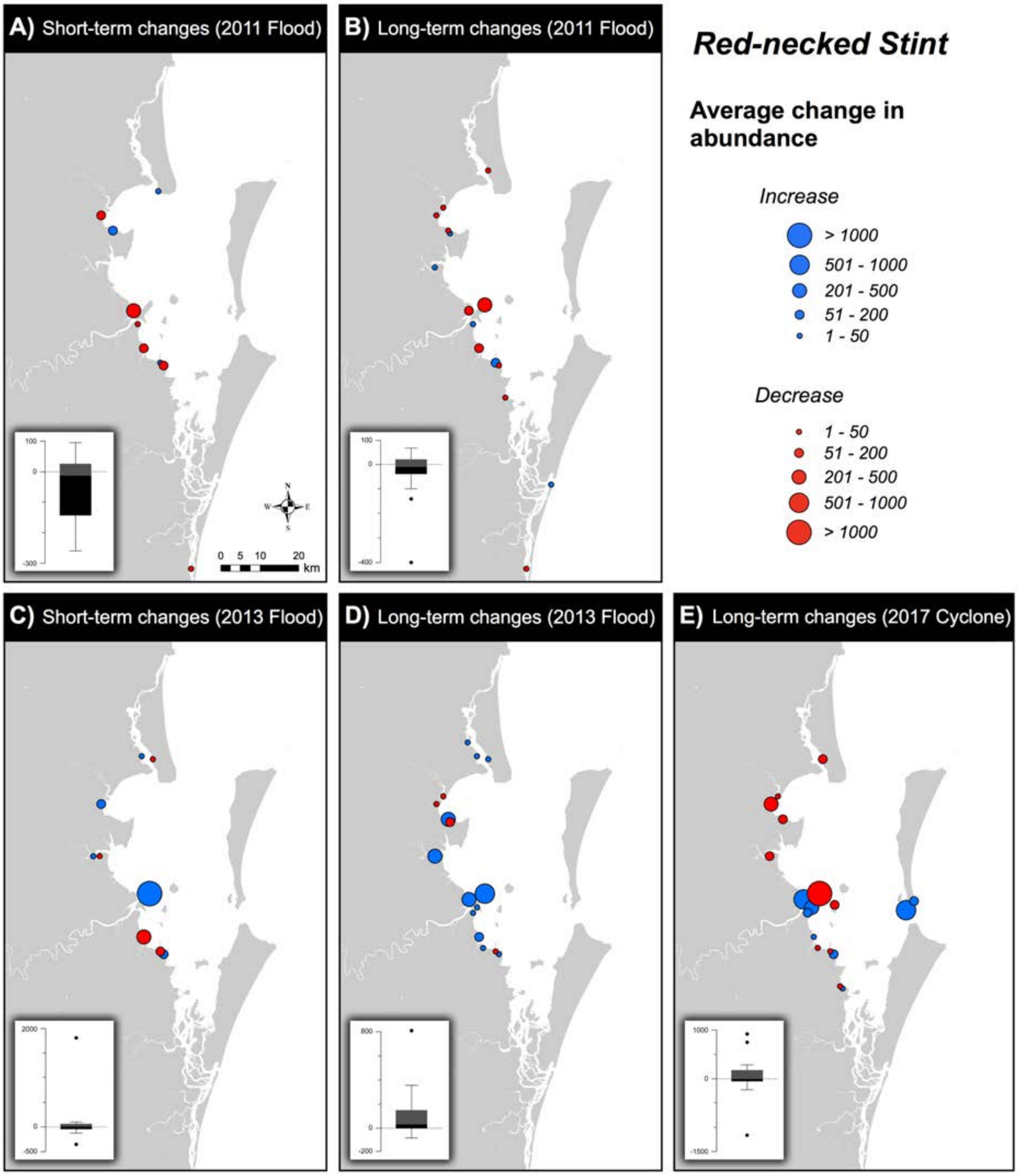

Figure S9

Changes in Red-necked Stint abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Large numbers of Red-necked Stint left Moreton Bay in the month after the 2011 event (Clemens *et al.* 2012), but those decreases were less obvious when the two summer months following the severe weather events were compared. Those decreases were not repeated in the 2013 or 2017 events. The latter events were not as large as the 2011 event and it is possible the movement away from coastal areas in large numbers occurs more readily in only the largest severe weather events.

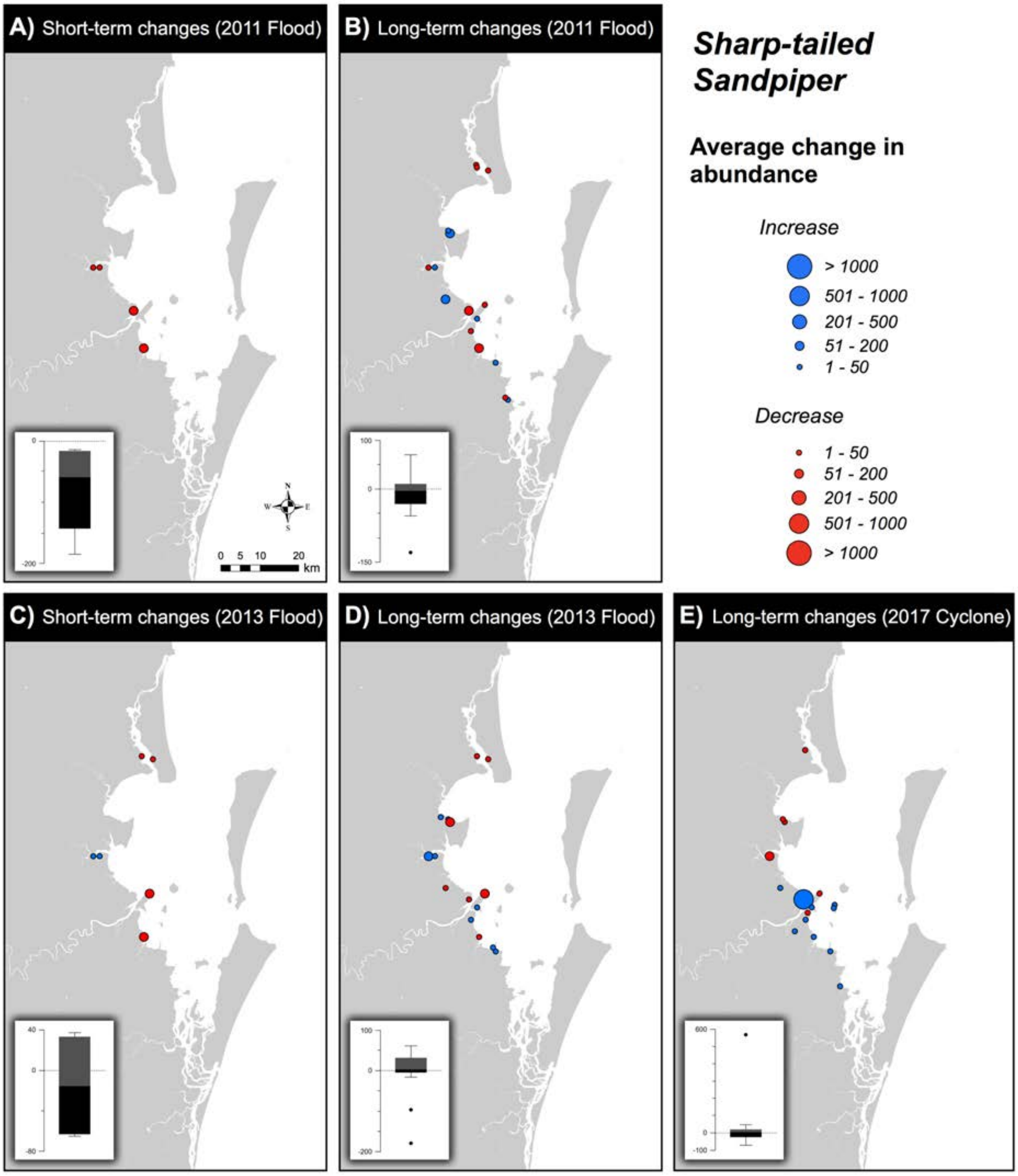

Figure S10 Changes in Sharp-tailed Sandpiper abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Sharp-tailed Sandpiper numbers reduced immediately after the 2011 severe weather event (Clemens et al 2012), but those decreases were not repeated in later severe weather events. It is possible that if the later severe weather events had been large enough to also flood inland areas of Australia, more Sharp-tailed Sandpipers would have left the coastal areas of Moreton Bay.

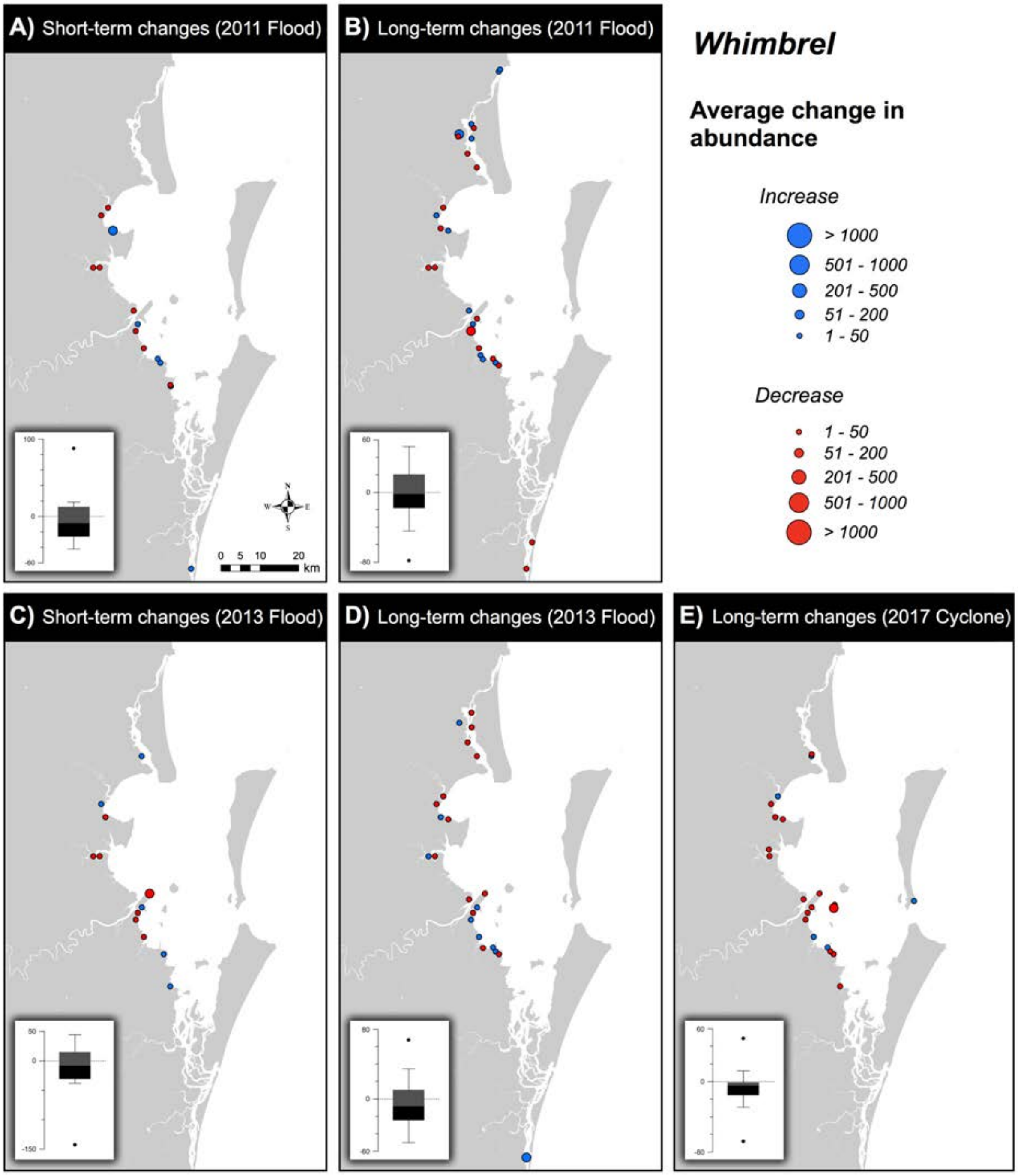

Figure S11 Changes in Whimbrel abundance in the two summer months immediately before and after, and between the previous and subsequent summer to the three severe weather events. Whimbrel have decreased significantly in Moreton Bay over the last couple of decades (Clemens et al. 2012), but there are no clear patterns in abundance after recent severe weather events. The variation in counts of Whimbrel at individual roosts might relate in part to the difficulty in finding them when roosting among the mangroves.