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

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Abstract

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

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

Running heading: an artificial site is valuable to migratory shorebirds

Introduction

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

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

Shorebird declines have been occurring in Australia for over 30 years (Hansen 2011), with the greatest losses in southern Australia at the migration terminus for many species (Clemens *et al.* 2016; Hansen *et al.* 2015). Much less is known about trends in shorebirds that spend the non-breeding season in northern Australia, although local-scale increases have been reported in the Northern Territory (Clemens *et al.* 2016; Lilleyman *et al.* 2016b). Species that have increased in Darwin Harbour include the Far Eastern Curlew (*Numenius madagascariensis*) (Lilleyman *et al.* 2016b) which has been declining so rapidly at a national and flyway level

(Studds et al. 2017) that it has been listed as Critically Endangered under national legislation, and Endangered on the IUCN Red List (BirdLife International 2017). While the current habitat of Darwin Harbour in the Northern Territory is in excellent environmental condition (Munksgaard *et al.* 2018), there has been some coastal development, and there are also plans for further expansion of industry in this coastal setting.

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

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

Methods

Study area

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

Point and Nightcliff Rocks are rocky outcrops connected to a tidal bay where shorebirds feed. Spot on Marine is an open saltpan bordered by mangroves.

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

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

The sites were all chosen because monitoring data exist from an established program that covers the main roost sites in the area from East Arm Wharf to Buffalo Creek (Figure 1). Previous survey work in Darwin Harbour has shown that the East Arm Wharf roost site is the only available roost site for shorebirds when the tide is >7.6 m as available roosting space at all other survey sites is greatly reduced (Lilleyman et al. 2018).

[insert Figure 1]

Count data

We used data collected from shorebird high-tide roost surveys conducted at the five natural sites around Darwin Harbour between 2010 and 2018 from the BirdLife Australia Shorebirds 2020 national program and data collected by A. Lilleyman or G. O'Brien at East Arm Wharf to determine population trends at these sites. The surveys included were conducted by experienced shorebird counters and vetted by BirdLife Australia staff. Some roosts could be counted from a single point, and others were surveyed by walking along a stretch of beach. On average it took 75 minutes to count the birds at each roost at the natural sites and 96 minutes at East Arm Wharf. Time was recorded to calculate the tide height at the time of the count; we only included counts from surveys that were performed when tides were >6 m by which time most shorebirds had moved to roosts because their foraging habitat was covered by the sea.

Significance thresholds

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

Drivers of change: Disturbance

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

Statistical analyses

Model parameters and selection for population change estimates

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

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

Results

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

Overall population trends of shorebirds in Darwin Harbour

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

[insert Table 1]

[insert Figure 2]

[insert Figure 3]

[insert Figure 4]

Disturbance

We recorded 81 disturbances over 26 surveys at five sites within the Darwin Harbour region during the 2014 - 2016 austral summer months of which 92.6% were at the natural sites (Table

S3). Most disturbances (98.7%) were recorded at the two natural sandy-beach sites (Lee Point and Sandy Creek) which have historically supported the highest number of birds from across the surveyed sites in Darwin Harbour. Humans (with or without dogs) made up over 70% of disturbances across the sites with birds of prey causing <16% of total recorded disturbances. Humans (and humans with dogs) stayed within the flight-initiation distance zone of the shorebird flocks for 1 to 10 minutes. Whether or not a species was declining or increasing at the natural sites was not significantly correlated with flight-initiation distance (P = 0.881), with some of the flightiest species, such as Far Eastern Curlew and Common Greenshank, being among species with positive (but not significant) trends at the more disturbed sandy beach sites while other species with relatively high tolerance (i.e.: shorter FIDs), such as sand plovers, declined (Figure S1). Contrary to this, there was a significant relationship (P = 0.022) between the FID and population trends for shorebirds at the artificial site (Figure S2).

Discussion

Population trends of migratory shorebirds in Darwin Harbour

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

For species listed as threatened under Australian legislation, in Darwin Harbour we observed declines in Greater Sand Plover, Lesser Sand Plover, Bar-tailed Godwit and Curlew Sandpiper consistent with strong declines reported previously, but observed trends in Far Eastern Curlew and Great Knot at both natural and artificial sites (no significant declines and a significant increase, respectively) that are inconsistent with strong national declines reported previously (Studds et al. 2017), requiring explanation. While the Great Knot is globally listed as Endangered, another study found little evidence of decline (Clemens *et al.* 2016). At our study region the increase in Great Knot explained the increase in total shorebird abundance at the natural sites; when Great Knot was removed from the overall shorebird abundance analysis at the natural sites, the trend for the remaining shorebirds showed a significant decline. For the Far Eastern Curlew, East Arm Wharf is now particularly important: over 80% of the local Darwin Harbour population of Far Eastern Curlew roost there during the highest tides (Lilleyman et al. 2018), which is close to 1% of the global population of this species. While our current study, using a different statistical approach, did not find the same increase in Far Eastern Curlew detected by Lilleyman et al. (2016b), the lack of a steep decline is anomalous compared to global trends. Several hypotheses, (not mutually exclusive) that might explain these anomalous results are considered below: (1) birds are responding to local disturbance trends and regimes, (2) local increases, or failures to decline, are being driven by provision of habitat at East Arm Wharf that is suitable for roosting at all tides and superior to habitat available locally before this site was built, (3) populations of some species in Darwin Harbour are genuinely increasing because the provision of a new roost provides access to foraging areas that could not be exploited before.

Hypothesis 1: Disturbance causes local redistribution

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

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

The numbers of shorebirds now being recorded at East Arm Wharf have not previously been reported in surveys of Darwin Harbour in the vicinity of the wharf (Chatto 2012), suggesting there are now more individuals using this system as a whole or that there is a redistribution of shorebirds in the harbour. However, single-season radio-tracking studies, and regular searches for marked birds, showed little evidence of birds moving between the natural and artificial sites (Lilleyman, A. unpublished data), suggesting that the increase at the artificial sites was unlikely to be driven by relocation of birds from the natural sites. We are unable to tell whether the influx of birds comes from outside Darwin Harbour, or if the 'new' birds have relocated from undiscovered roosts of the southern/central harbour. Nevertheless, they could be the result of a longer-term transition of birds from the natural to the artificial site that are not picked up in mark recapture/tagging studies. We inspected demographic data from catching and marking studies and did not find that that either natural or artificial sites supported a higher proportion of juvenile birds, which could have been driving the local increases. Further research on marking and tracking birds in the region could help unravel this story.Some flexibility in roosting behaviour has been demonstrated for shorebirds in both the Darwin region (Lilleyman *et al.* 2016b) and elsewhere in the EAAF where loss of roost sites is widespread (Lee *et al.* 2017; Melville *et al.* 2015; Moores *et al.* 2016; Rogers *et al.* 2010; Round 2006), but the increases at East Arm Wharf do suggest it is increasingly being used as a roost site. It is possible that the East Arm Wharf site has become more attractive to shorebirds that forage nearby over time, resulting in a genuine increase in the local shorebird population. In particular, increased numbers at the East Arm Wharf roost may indicate that there is a long-standing shortage of suitable roosting habitat in Darwin Harbour, especially at the highest tides when saltpans are inundated and all but a few sites around the mangrove-lined harbour are under water. While shorebirds can, and sometimes do, roost in the branches of mangroves, the frequency of most species at open roosts suggests that this is not a favoured option. Many factors constrain shorebird populations in their non-breeding habitat, including food resources (Dias *et al.* 2006; van Gils *et al.* 2003), disease and parasite load (Aharon-Rotman *et al.* 2016), extreme heat loads (Battley *et al.* 2003), available space, commuting distances and disturbance rates at a site (Lilleyman *et al.* 2016a; Rogers *et al.* 2006) and predation (Johnston-González and Abril 2018). Yet if roost sites are a scarce resource, provision of the artificial roost site may be allowing more shorebirds to visit and exploit the resources of Darwin Harbour than was previously possible. This suitable roost site could be providing access to foraging areas that could not be exploited before due to high commuting distances between roosting at the natural roost sites and feeding grounds closer to where the artificial site is now located.

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

In managing a network of natural and artificial sites, it will be important to consider possible long-term changes in the environment. Over the longer term, artificial sites might be less vulnerable to sea-level rise than natural sites such as claypans. The sea level along the northern coast of Australia has already been rising at among the fastest rates in the world, driven partly by the thermal expansion of the large and relatively shallow Arafura Sea to the north (Valentine and Tan 2009) and, in the Darwin region, there has been expansion of mangroves on to areas that were previously bare salt-flats, and therefore suitable for roosting during some high tides (Williamson *et al.* 2011) so there is likely to be increasing pressure on what were traditional roost sites.

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

Conclusions

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

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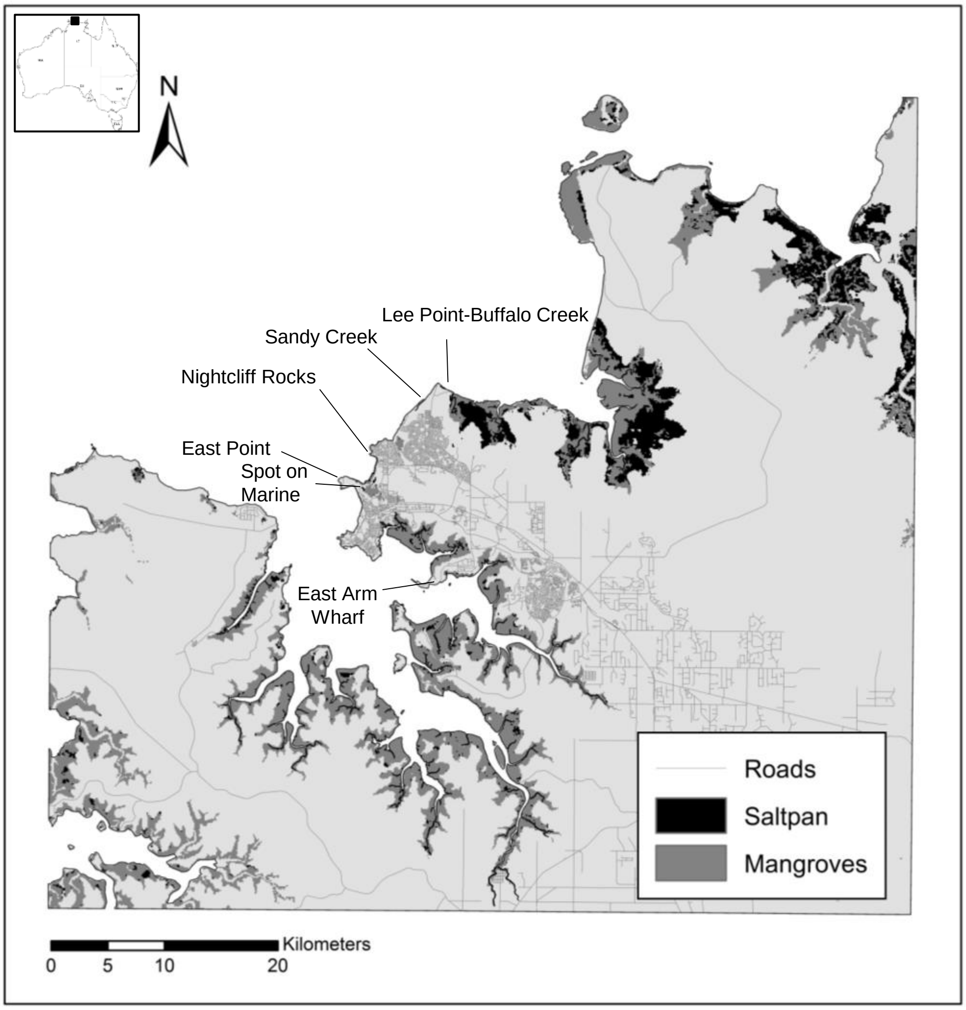

Figure 1. Map of migratory shorebird monitoring sites in Darwin Harbour, Northern Territory. Lee Point-Buffalo Creek, Sandy Creek, Nightcliff Rocks, East Point and Spot on Marine are natural roost sites; East Arm Wharf is artificial.

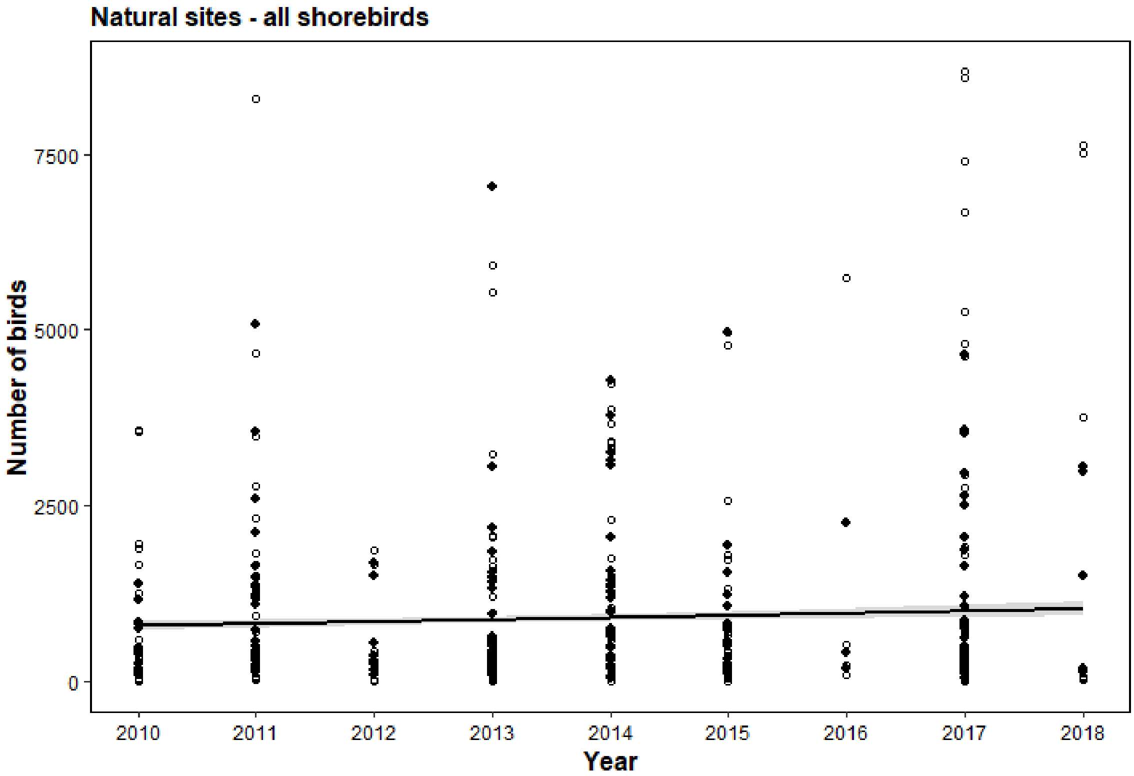

Figure 2. Modelled (black dots = estimated data, empty dots = raw count data) local annual population trends (species combined) based on a negative binomial GLM of all migratory shorebirds across an inter-connected suite of five natural sites in Darwin Harbour for the years 2010 - 2018.

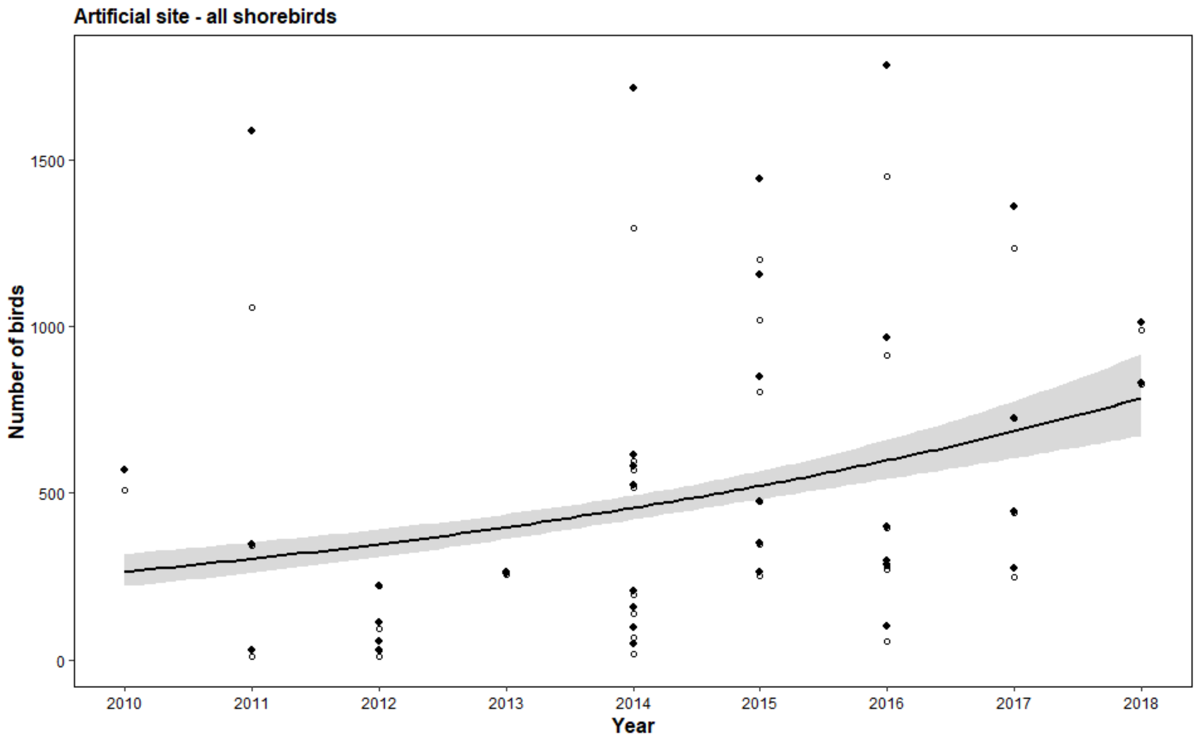

Figure 3. Modelled (black dots = estimated data, empty dots = raw count data) local annual population trends (species combined) based on a negative binomial GLM of all migratory shorebirds at East Arm Wharf, an artificial site in Darwin Harbour, for the years 2010 - 2018.

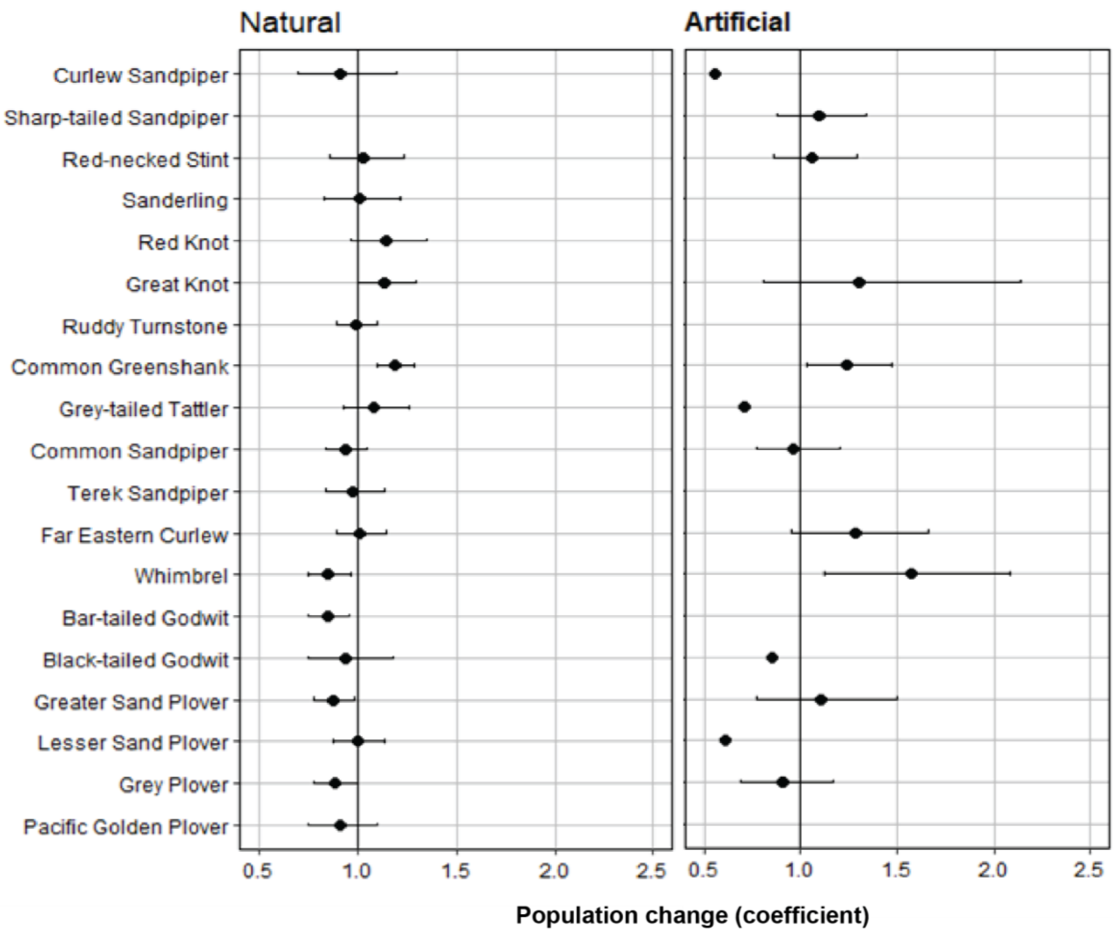

Figure 4. Annual population trends in non-breeding season counts for migratory shorebirds in Darwin Harbour at an artificial site and five inter-connected natural sites. Species to the left of the black vertical line (i.e. <1.0) decreased and species to the right of the vertical line (i.e. > 1.0) increased over the period studied.

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

Site class and species	Best model formulae	Estimated coefficient	P-value	% change per year	95% CI
Artificial site	**count ~ year**	**0.14**	**0.000**	**+14.5%**	**10.5-18.6**
Bar-tailed Godwit	count ~ year + decimal_effort + tide_height	-0.29	0.097	-24.80%	11 - 50.6
Black-tailed Godwit	count ~ year	-0.16	0.557	-14.7%	32.3-50.3

Common Greenshank	**count ~ year + tide_covered**	**0.21**	**0.007**	**+23.9%**	**3.4 - 47.1**
Common Sandpiper	count ~ year	-0.04	0.704	-3.8%	20.2-23.1
Curlew Sandpiper	**count ~ year + month**	**-0.58**	**0.000**	**-44.4%**	**29.5 - 57.7**
Far Eastern Curlew	count ~ year	0.25	0.131	+28.2%	4.6-66.0
Great Knot	count ~ year	0.26	0.086	+28.2%	19.2-78.6
Grey Plover	count ~ year	-0.10	0.495	-9.3%	17.0-31.5
Greater Sand Plover	count ~ year + tide covered	0.10	0.534	+10.8%	23.2-49.6
Grey-tailed Tattler	count ~ year	-0.34	0.122	-28.9%	11.0-58.2
Lesser Sand Plover	**count ~ year**	**-0.50**	**0.003**	**-39.5%**	**18.0-56.4**
Red-necked Stint	count ~ year	0.06	0.603	+6.1%	14.1-29.6
Sharp-tailed Sandpiper	count ~ year	0.09	0.493	+9.1%	11.8-33.5
Whimbrel	**count ~ year**	**0.45**	**0.014**	**+56.9%**	**12.3-108.9**
Natural sites	**Total ~ year + tide_covered**	**0.03**	**0.001**	**+3.30%**	**1.3 - 5.4**
Bar-tailed Godwit	**count ~ year + site + month**	**-0.16**	**0.003**	**+15.20%**	**4.4. - 25**
Black-tailed Godwit	count ~ year + site + month	-0.06	0.547	+6.10%	**17.6 - 25**
Common Greenshank	**count ~ year + site + month**	**0.17**	**0.000**	**+18.80%**	**9.6 - 29**
Common Sandpiper	count ~ year	-0.07	0.165	-6.70%	4 - 16.2
Curlew Sandpiper	count ~ year	-0.09	0.548	-8.60%	**19.4 - 30.9**
Far Eastern Curlew	count ~ year	0.01	0.868	+0.90%	10.5 - 13.9
Great Knot	count ~ year	0.13	0.076	+13.40%	0.3 - 29.2
Greater Sand Plover	**count ~ year + decimal_effort + tide_height**	**-0.14**	**0.041**	**-12.70%**	**1.9 - 22.5**
Grey Plover	**count ~ year + decimal_effort + tide_height**	**-0.13**	**0.035**	**-12.00%**	0.5 - 22.3
Grey-tailed Tattler	count ~ year	0.08	0.278	+7.90%	7.3 - 26
Lesser Sand Plover	count ~ year	0.00	0.950	-0.50%	13 - 136
Pacific Golden Plover	count ~ year + tide_covered	-0.09	0.315	-8.70%	10.1 - 24.8
Red Knot	count ~ year	0.13	0.167	+14.10%	3.7 - 35.3
Red-necked Stint	count ~ year	0.02	0.776	+2.30%	14.5 - 23.3
Ruddy Turnstone	count ~ year + decimal_effort + tide_height	-0.01	0.917	-0.70%	10.1 - 10.7
Sanderling	count ~ year + decimal_effort + tide_height	0.01	0.933	+0.90%	16.8 - 21.8
Terek Sandpiper	count ~ year	-0.03	0.741	-2.70%	13.8 - 16.5
Whimbrel	**count ~ year + decimal_effort + tide_height**	**-0.16**	**0.004**	**15.00%**	3.4 - 25.3

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