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Reconciling recreational use and conservation values in a coastal protected area

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Summary

1. Protected areas often need to provide recreational opportunities whilst conserving biodiversity. Recreation brings important benefits to human well-being, and allowing people to experience nature in protected areas can also provide revenue and support for conservation objectives. However, not all recreational activities are compatible with environmental management goals.
2. Here, we show how a coastal protected area can be zoned to satisfy both recreational and conservation objectives.
3. We collected empirical data on the effect of recreational disturbance to foraging shorebirds in Moreton Bay Marine Park, Queensland, Australia, and calculated the benefit of alternative protected area zone types on shorebird representation using a zero-inflated negative binomial model. The predictions from this model were used to optimize a zoning plan in a linear programming framework that balances recreational use with shorebird conservation. Costs reflect foregone recreational opportunity, thereby facilitating solutions that minimize restrictions on recreational use of the coastline.
4. We discover a consistent negative effect of recreational use of the foreshore on shorebird occupancy and abundance and show that, despite this, zoning can be used to achieve shorebird representation targets with only a small cost to recreational opportunity.
5. When dog recreation is permitted at all sites, a 91% shorebird representation target can be met, indicating that *de facto* patterns of recreation were rather well segregated from areas used by shorebirds. By restricting dog recreation to five sites and allowing people to access all other foreshore sites, shorebird representation increased to 97%.
6. *Synthesis and applications*. Our approach of calculating the contribution of each zone type towards conservation objectives results in zoning plans with robust estimates of conservation benefit that can be readily implemented by managers. Specifically, we estimated the effects of removing people and domestic dog recreation within each intertidal site on shorebird abundance to inform coastal zoning plans. Incorporating cost as foregone recreational opportunity results in zoning plans that minimize the number of people required to make a behavioural change. Compliance to zone types is often ultimately voluntary so integrating the current intensity of recreational use is more likely to generate workable zoning plans.

Key-words: coastal ecosystems, conservation planning, disturbance, dogs, ecosystem services, optimization, recreational use, shorebirds, social impact, zoning

Introduction

Recreational use of protected areas is widespread and increasing in many countries (Balmford *et al*. 2009). Recreational opportunity is an important ecosystem service because people derive many benefits from experiencing nature (Keniger *et al*. 2013), and allowing people into protected areas can generate public support and revenue for conservation activities (Powell & Ham 2008). However, not all recreational activities are compatible with the conservation objectives of a protected area (Reed & Merenlender 2008; Kangas *et al*. 2010), and in such situations managers must decide how to plan for human uses whilst minimizing impacts on biodiversity.

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Where human use and biodiversity value coincide, conservation conflicts can easily arise (Redpath *et al.* 2013). Conflicts typically occur with respect to land-use disputes whereby people or certain activities are excluded from natural areas in an effort to meet conservation requirements (Redpath *et al.* 2013). To accommodate conflicting objectives, managers can adopt conservation planning approaches that are transparent and systematic, with explicit recognition of trade-offs (Margules & Pressey 2000). One method of addressing the conflict between recreational users and conservation managers is to implement zoning, so that conflicting uses can be spatially segregated (Klein *et al.* 2009).

Reserve selection optimization techniques, such as integer linear programming (ILP), can be used to prioritize a set of management actions across space to meet conservation targets whilst minimizing costs (Beyer *et al.* 2016). Costs are typically the financial burden of implementing zoning plans (Naidoo *et al.* 2006; Ban & Klein 2009) including acquisition (Carwardine *et al.* 2008), enforcement (Davis *et al.* 2014) and opportunity costs reflecting lost revenue (Klein *et al.* 2009; Ruiz-Frau *et al.* 2015). Few studies have explicitly considered costs associated with the restriction of non-consumptive recreational activities which do not have an easily measured direct opportunity cost. Where human impacts have been considered, they tend to be summed across multiple user groups resulting in zoning plans which are not cost-effective and difficult to manage (Ban & Klein 2009).

Here, we apply an optimization method to zone the recreational use of Moreton Bay, a major coastal protected area in Australia. Recreational use of the foreshore results in disturbance to shorebirds, several of which are threatened with extinction nationally or globally, and represent one of the reasons why the park was designated (EPA 2005). Human recreational use of natural areas can incur immediate behavioural costs to birds including increased energy expenditure and loss of foraging time as a result of anti-predator behaviours (Fitzpatrick & Bouchez 1998; West *et al.* 2002; Yasué 2005; Goss-Custard *et al.* 2006). In some cases, temporary or permanent avoidance of suitable habitat can occur (Meager, Schlacher & Nielsen 2012; Lafferty, Rodriguez & Chapman 2013; Martín *et al.* 2015), ultimately reflected in lower local abundance, physiological condition or reproductive success (Gill 2007; Steven, Pickering & Castley 2011; Weston *et al.* 2012b).

Peak abundance of shorebirds in Moreton Bay occurs in the summer when the migratory species are present, which is also a time when recreational use of the foreshore is at its highest (Williams *et al.* 2009). This creates potential for spatial and temporal overlap between shorebirds and people that could result in conservation conflict. Intentionally causing disturbance to migratory shorebirds listed under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC 1999) is illegal in Australia. Penalties apply to persons who cause undue disturbance to shorebirds and their habitats, and in particular, domestic dogs must be kept under control at all times (Queensland Government 2008). Compliance with and enforcement of legislation is currently inadequate, with domestic dogs commonly observed off-leash on intertidal areas within the Marine Park (Kyne 2010; Milton *et al.* 2011; Meager, Schlacher & Nielsen 2012) and other coastal areas around Australia (Dowling & Weston 1999; Williams *et al.* 2009).

Designation of legally dedicated recreational areas is one approach to satisfying demand for recreation, and if such areas can be situated in a way that minimizes overlap with shorebirds, effective multi-use of the protected area might be achieved. Here, we develop models of shorebird occupancy and abundance based on empirical data (shorebird and recreational use surveys) and use these to build a zoning plan that balances human and domestic dog recreation with shorebird protection in Moreton Bay. We find a consistent negative effect of recreational use on shorebird abundance and show that, despite this, zoning can be used to achieve high levels of shorebird representation with only a small cost to recreational opportunity.

Materials and methods

STUDY AREA

Moreton Bay is a large subtropical embayment on the Pacific coast of Australia (Zharikov *et al.* 2005) (Fig. 1). It is operated as a state Marine Park and is broadly zoned into Marine National Park, Conservation Park, Habitat Protection and General Use zones under the Marine Parks (Moreton Bay) Zoning Plan 2008. Moreton Bay is an important site for migratory shorebirds in Queensland, supporting up to 40 000 shorebirds over summer (Bamford *et al.* 2008), although the numbers of many migratory species are decreasing rapidly (Wilson *et al.* 2011). There is concern among the conservation community that recreational disturbance is negatively affecting shorebird roosting and foraging sites in Moreton Bay, with one of the most frequent causes being people walking domestic dogs (Kyne 2010; Milton *et al.* 2011; Meager, Schlacher & Nielsen 2012).

We divided a section of the mainland coastline of Moreton Bay into 85 stretches of foreshore (hereafter 'planning units'), each approximately 600 m in length (Fig. 1), reflecting the size of current management areas. Planning units were grouped into five geographically coherent management regions: Deception Bay, Redcliffe, Sandgate, Nudgee and Wynnum/Manly/Lota (Fig. 1).

DATA COLLECTION

Observers visited each planning unit 9–11 times (total 812 surveys) in November and December 2014, identifying and counting migratory shorebirds. The survey team consisted of one to six individual observers who were all proficient in shorebird identification. Observers stood on the landward side of the high tide mark to count birds, people and dogs (leashed or off-leash) from a distance using a telescope where necessary, minimizing the chance of observers themselves causing disturbance to the birds. Counts were conducted within 2 h each side of low tide, when the tidal flats are

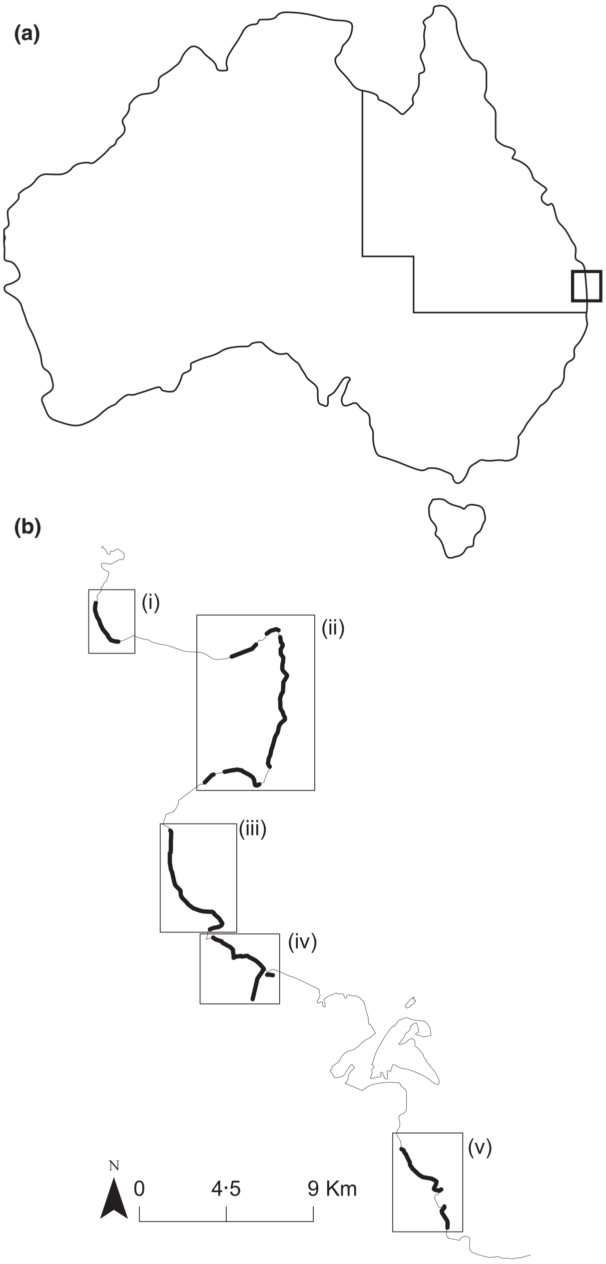

Fig. 1. (a) Moreton Bay study area in south-east Queensland, Australia. (b) There are 85 intertidal planning units in this study (not shown in these maps) numbered consecutively from north to south, and distributed across five regions: (i) Deception Bay, (ii) Redcliffe Peninsula, (iii) Sandgate, (iv) Nudgee, (v) Wynnum, Manly and Lota Foreshore.

most exposed, and visits were made to each planning unit at various times of day, and on weekends and weekdays. These data were used to model the relationship between the level of disturbance and the occupancy and abundance of shorebirds in each planning unit. Shorebird and recreationalist data can be found in Table S1 in Supporting Information.

ZONING

Three zone types were considered, each embodying different access restrictions to people and domestic dogs along the foreshore, thus providing different levels of protection to shorebirds. The *Unrestricted Access Zone* allows access by people and domestic dogs, the *Partial Reserve Zone* permits people in the intertidal zone, but prohibits dog access, and the *Conservation Reserve Zone* prohibits both people and domestic dog access to the intertidal zone. Zoning plans were constructed for three management scenarios, reflecting differing approaches to the designation of dog recreation areas, and considering the potential effects of future increased recreational use. Scenario 1 allows any planning unit to be selected as an Unrestricted Access Zone such that there is no restriction on the number of sites in which dog recreation is permitted as part of the zoning plan. Scenario 2 restricts the selection of sites supporting dog recreation to one planning unit within each of the five study regions, reflecting the possibility that many people prefer most areas of the foreshore to be dog-free to enhance their own recreational experience. Scenario 3 extends Scenario 2 by considering how the zoning plan would change if recreational use doubled. A comparison between scenarios 2 and 3 provides insight into how robust planning solutions might be in the context of future increased levels of recreational use.

MODELLING SHOREBIRD NUMBERS

A zero-inflated negative binomial (ZINB) model was used to relate habitat covariates and counts of dogs and humans to the occurrence (or 'occupancy') and abundance of migratory shorebirds. The abundance component relates counts of shorebirds as a function of one set of covariates using a negative binomial distribution, and a zero-inflated component with a binary distribution that predicts the additional (inflated) probability of a zero count (no occupancy of a site by shorebirds) based on another set of covariates. Such models are useful where there is a high frequency of zero counts among surveys and overdispersion in the raw count data (Zuur *et al.* 2009). Many shorebird species in Moreton Bay occur only in small numbers and few sites, so we were unable to make zoning decisions based on species-specific models. Instead, counts from all species were pooled. Habitat predictors considered in these models were the width of the intertidal zone from the low to high tide mark (km), and distance between the centre of the planning unit and the nearest roosting location (km) as these have previously shown to influence shorebird distribution (Rosa, Palmeirim & Moreira 2003; Zharikov & Milton 2009; Lafferty, Rodriguez & Chapman 2013). The count of dogs and people were included as they elicit significant disturbance responses in shorebirds (Burger *et al.* 2007; Lafferty, Rodriguez & Chapman 2013). A site factor was also evaluated to determine whether there was site-level variation in the counts of shorebirds that was not adequately accounted for by the other covariates.

Akaike's information criterion (AIC) was used to rank nine competing models (Table 1), with a decrease in AIC of $\geq$2 considered a substantial improvement (Burnham & Anderson 2002). The fitted coefficients from the highest ranked model were used to calculate expected shorebird abundance at each planning unit for each of the three zone types. At some sites, no dogs and/or people were observed on any of the visits. Although recreational use levels were low at such sites, they were unlikely to be zero and, to ensure a minimal use, the people and dog count covariates were incremented by 3 and 1, respectively (because the ratio of people to dogs among all surveys was approximately 3:1). This was necessary to estimate the benefit of zoning at each site. For projected increase in future use (Scenario 3), these covariates were doubled. To predict the effect of removing dogs in Partial Reserve Zones, the dog covariate was set to 0, and to predict the effect of removing both dogs and people in Conservation Reserve Zones, both people and dog covariates were set to 0.

All statistical analyses were conducted using R software (R Development Core Team 2015), fitting the ZINB model with the pscl package (Zeileis, Kleiber & Jackman 2007).

ALLOCATING ZONE TYPES TO PLANNING UNITS

We formulated the problem of balancing human recreational and shorebird use of the foreshore as a reserve selection problem, ensuring a minimum level of representation of conservation features was achieved whilst minimizing some measure of cost. Here, the conservation feature is shorebird abundance and minimum representation targets were set as percentages of the estimated maximum number of shorebirds that could be achieved if there was no disturbance at any site, as predicted from the highest ranked ZINB model. The cost of zoning solutions was measured as foregone recreational opportunity, encouraging solutions that minimize restrictions on the recreational use of the bay. Recreational opportunity at each planning unit was quantified as the mean number of people and dogs observed among all field visits, incremented as described above. Without this adjustment, the optimization algorithm would have allocated many more Conservation Reserve Zones as there would have been zero cost for so doing at some sites. The cost of assigning a planning unit to an Unrestricted Access Zone is zero as it does not incur any loss of recreational use of the foreshore. Partial Reserve Zones incur opportunity costs equal to the average count of dogs observed at each planning unit. Conservation Reserve Zones incur the opportunity cost of the average count of dogs at each planning unit plus the average count of people at each planning unit. Thus, the total cost of a zoning solution is the sum of the costs of allocating Partial Reserve Zones and Conservation Reserve Zones across all planning units in the study region.

The problem was solved using the following ILP model:

$$\text{Minimize} \quad \sum_{i=1}^{N}\sum_{k=1}^{Z} c_{ik}x_{ik}$$

$$\text{Subject to} \quad \sum_{k=1}^{Z} x_{ik} = 1, i \in N$$

$$\sum_{i=1}^{N}\sum_{k=1}^{Z} r_{ik}x_{ik} \geq T$$

$$\sum_{i \in R_j} x_{ik} = M_k, k = m, j \in 1\ldots5$$

$$x_j \in \{0, 1\}, i \in N$$

where N and Z refer to the number of planning units and zone types, respectively, x_{ik} is a binary decision variable that is 1 when unit i is assigned to zone k and 0 otherwise and c_{ik} is the cost of planning unit i when assigned to zone k. Thus, the costs associated with selecting a planning unit vary among the different zone types and planning units.

The first constraint ensures that each planning unit is assigned to exactly one zone. The second constraint r_{ik} represents the value of planning unit i when assigned to zone k (the expected shorebird abundance under each zone type, as described in *Modelling Shorebirds Numbers*). Thus, summed over all planning units and zones, this constraint ensures that the minimum representation target, T, is met. The third constraint ensures that there is exactly one (M_k) of zone type m in each of the five regions (R). The final constraint ensures that the decision variables are binary integers.

In the three scenarios investigated, the first removes constraint 3 so that Unrestricted Access Zones can be freely allocated in the planning solutions. The second and third scenarios include constraint 3 so that at least one Unrestricted Access Zone (k = 1) is present within each region. Exact solutions to this ILP problem were found using Gurobi (Gurobi Optimization Inc 2015).

Results

Migratory shorebirds were present in the area in large numbers and high richness, with 17 species observed in total, and an average of 2604 individuals present on the intertidal habitats during low tide (Table S2). Two species accounted for more than half of total shorebird abundance, with bar-tailed godwit *Limosa lapponica* and curlew sandpiper *Calidris ferruginea* representing 32% and

Table 1. Rankings of nine zero-inflated negative binomial mixture models of shorebird occupancy and abundancy at 85 sites in Moreton Bay

Negative binomial count portion	Zero-inflated binomial portion	ΔAIC
Site + dog + people	Width + people + dog	0
Site + dog + people	Width + people + dog + roost	0·7
Site + dog + people	People + dog	11·1
Site + dog + people	People + dog + roost	19·6
Width + roost + dog + people	Width + people + dog + roost	434·9
Width + roost + dog + people	People + dog + roost	650·9
Width + roost + dog + people	People + dog	659·6
Intercept only	Intercept only	1227·3

Covariates included the width of the foreshore (width), the distance to the nearest roost site (roost), the number of dogs (dog) and people (people) observed at each site and a factor representing site identities (site). Rankings were based on differences in Akaike information criteria (ΔAIC). The first model in the list is the top-ranked model.

20% of the total shorebird count, respectively, whilst seven species contributed <1·0% of the total shorebird count (Table S2).

An average of 174 people used the intertidal flats within the study region at any one time during each low tide. Accompanying these people, there were on average 72 dogs, of which 84% were unrestrained, potentially posing a substantial source of disturbance to the shorebirds. People and dogs were widespread along the coastline, using 76 and 58 of the total 85 planning units in the study region, respectively, such that only 10% of the study region was free from recreational use during the field surveys. Planning units used by people supported 78% of the total shorebird abundance, and planning units used by dogs supported 65% of the total shorebird abundance, indicating strong potential for people and dogs to impact large numbers of birds.

The presence of dogs and people on the foreshore significantly increased the probability of shorebirds not occupying a planning unit, with the presence of dogs having more than twice the effect of people (Table 2). As well as shorebirds being less likely to be present when dogs are present, shorebird counts within a planning unit also significantly declined as dog numbers increased, although there was no significant effect of the number of people on shorebird abundance (Table 2). These results suggest that dogs exert a greater effect on shorebird abundance than people as they not only reduce the probability of birds occupying a planning unit, they also reduce the count of birds within a planning unit to a greater extent than people alone. The probability of shorebirds not occupying a site significantly decreased with increasing foreshore width (Table 2), and the significant site effect (Table S3) signifies unexplained variation among sites in their importance to shorebirds. Observed and predicted counts (log scale) were highly correlated ($r = 0{\cdot}91$), indicating reasonable model performance.

Table 2. Parameter estimates and standard errors for the highest ranked zero-inflated negative binomial model of shorebird occupancy and abundance within the Moreton Bay study region

	Est	SE	*Z* value
Zero-inflated model coefficient			
Intercept	−1·21	0·63	−1·91
People	0·07	0·03	2·61***
Dog	0·15	0·08	2·03*
Width	−15·5	6·23	−2·49**
Count model coefficient			
Intercept	4·33	0·27	16·23***
Dog	−0·03	0·02	−1·97*
People	−0·001	0·001	−0·71
Log(theta)	0·47	0·08	6·12***

The model consists of an abundance component that models counts of shorebirds as a function of one set of covariates using a negative binomial distribution, and a zero-INFLATED component with a binary distribution that predicts the additional (inflated) probability of a zero count (no occupancy of a site by shorebirds). The dispersion parameter log(theta) differs significantly from 0 in this model, indicating overdispersion in the count data. Values for the site factor are omitted from this table for brevity, but are included in Table S2.
Significance codes: 0 '***' 0·001 '**' 0·01 '*' 0·05.

CONSERVATION ZONING

Scenario 1: dog recreation not spatially restricted

This scenario allows any planning unit to be allocated to the Unrestricted Access Zone that permits both people and dog access to the intertidal zone. The cost of allocating a planning unit to the Unrestricted Access Zone is zero because no recreational activities are excluded from the foreshore; thus, Unrestricted Access Zones are strongly favoured when shorebird targets are low. When all planning units are allocated to the Unrestricted Access Zone, the highest shorebird conservation target achievable is 91% (Fig. 2). As the shorebird target is increased, a greater proportion of planning units are allocated as Partial Reserve Zones and Conservation Reserve Zones to ensure shorebird targets are met (Fig. 2). Scenario 1 only slightly reduces recreational opportunity relative to no zoning, and Conservation Reserve Zones are needed to protect the planning units that are especially important for shorebirds, particularly at the highest shorebird target levels (Fig. 2).

Scenario 2: dog recreation restricted to five planning units

Limiting the number of Unrestricted Access Zones to five planning units, one within each region, allows a shorebird representation target of 97% to be met without the need to designate any Conservation Zones that restrict people from the foreshore (Fig. 2), potentially resulting in an attractive solution for decision-makers. Scenario 1 allocates more planning units to the Conservation Reserve Zone than Scenario 2 for every shorebird target (Fig. 2), indicating that Scenario 2 solutions are less restrictive on people, but more restrictive on dog recreation than Scenario 1 solutions.

Scenario 3: future recreational growth

Scenario 3 (recreational use doubled) allocated a greater proportion of planning units to the more restrictive zones in comparison with Scenario 2, to ensure representation targets were met (Fig. 2). Conservation Reserve Zones were also adopted at lower shorebird targets in Scenario 3 than Scenario 2; in Scenario 2, the highest conservation target attainable without the use of Conservation Reserve Zones is 97%, but in Scenario 3 this dropped to 95% (Fig. 2). This is because stronger conservation measures are needed to compensate for the increase in recreational activity, which results in a decrease in shorebird occupancy and abundance among planning units.

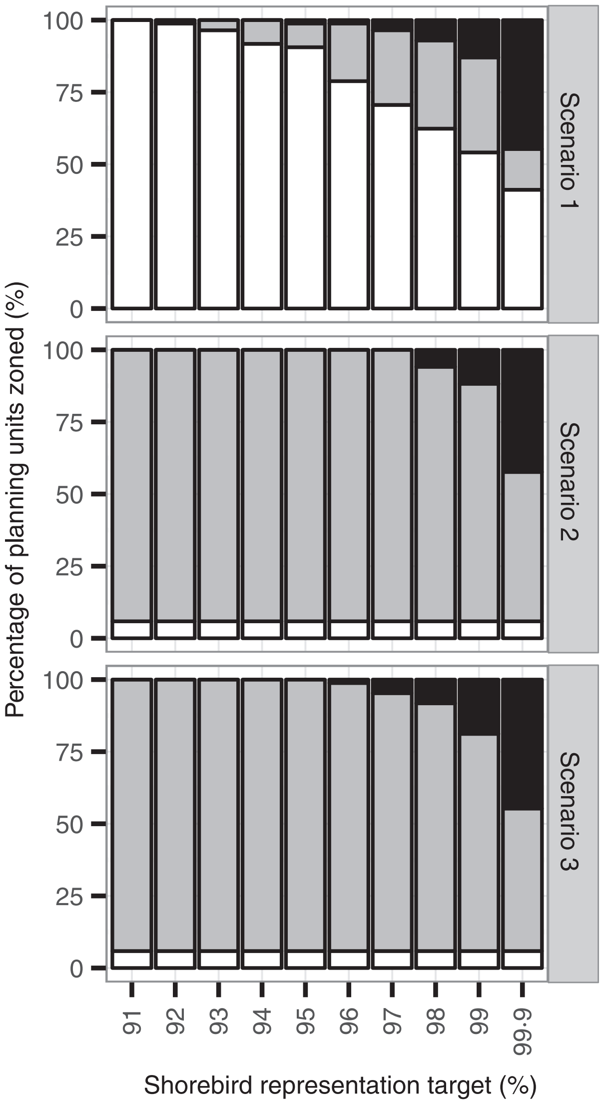

Fig. 2. The percentage of planning units allocated to each zone type (Conservation Reserve Zone, black; Partial Reserve Zone, grey; Unrestricted Access Zone, white) for each shorebird representation target for the three planning scenarios.

Nestedness of zoning plans

The planning units allocated as Conservation Reserve Zones were highly conserved across the scenarios and shorebird target levels, indicating a high degree of nestedness in the solutions (Table S4). Planning for the highest shorebird representation target of 99·9% produced an almost identical spatial pattern of allocation of Conservation Reserve Zones across three scenarios (Table S4), prohibiting all recreational activities in 44·7% of the foreshore in scenarios 1 and 3, and 42·4% in Scenario 2 (Fig. 2).

Discussion

Our results show that even when recreational use of a protected area has a demonstrated effect on its ecological values, a conservation conflict can readily be avoided through conservation zoning. In our present case study, the resolution can be achieved without the need for any strict Conservation Reserve Zones, which are often not practical or effective in protected areas near dense human habitation (Maguire, Rimmer & Weston 2013). Although people and dogs significantly reduced the number of shorebirds using a planning unit, a high percentage (91%) of shorebird representation is achievable when the entire foreshore is zoned as Unrestricted Access. This is perhaps a result of a natural separation of the two activities, with three of the planning units with over 500 shorebirds having low recreational use (planning units 6, 7, and 85; Table S4). Managers may find it more difficult to plan for situations where the spatial overlap of good quality sites for people and conservation is high, and when human recreation has a strong negative impact on conservation features. In such situations, zoning solutions could be assessed using trade-off analysis to provide guidance on appropriate conservation decisions and their impacts on recreational use (White, Halpern & Kappel 2012).

A recent study on beach resource management in south-east Queensland's coastal areas showed that the majority of respondents supported the idea of designated dog recreation areas, complemented with exclusion of dogs from some areas (Windle & Rolfe 2014). Our results show that by restricting dog exercise locations to those sites already most heavily used can increase shorebird representation from 92% in Scenario 1 to 97% in Scenario 2 without the need for any Conservation Reserve Zones that restrict access to the foreshore. This is because the presence of dogs on the foreshore has a much greater negative effect on shorebird occupancy and abundance than the presence of people alone, and if the former are carefully restricted, there is no need for the latter to be. We assumed that impacts on birds scale positively with increasing numbers of dogs; however, there is unexplained variance in this relationship which invites further investigation. It is possible for a single dog to have greater than average impact, and for dogs to have different scales of impact, such as observed between on- and off-leash dogs (Kyne 2010). Unrestricted Access Zones in this study were conceptualized as dog off-leash exercise areas, which are in higher demand than dog on-leash areas, perhaps because of perceived benefits of off-leash exercise for dogs (Williams *et al.* 2009). Preference for walking dogs off-leash is reflected in both our field data, with 84% of dogs being unrestrained, and previous work by others (Kyne 2010; Milton *et al.* 2011; Lafferty, Rodriguez & Chapman 2013; Maguire, Rimmer & Weston 2013).

Zoning can be used to manage multiple competing uses and objectives of protected areas more effectively (Halpern *et al.* 2008; Klein *et al.* 2009; Makino *et al.* 2013; Davis *et al.* 2014). Different management actions among zones afford varying degrees of protection to biodiversity dependent on the degree of restriction of human use and activities (Makino *et al.* 2013). It is often assumed that zones excluding people will confer the greatest benefit to conservation objectives, and zones which allow unrestricted access contribute the least to conservation objectives (Makino *et al.* 2013). Based on field data we found, however, that the presence of people was not necessarily incompatible with shorebird conservation, provided that dogs were excluded from those sites. This observation is supported by other work showing that shorebirds respond to the presence of people with dogs at greater distances and intensities than people alone (Lord *et al.* 2001; Burger *et al.* 2007; Glover *et al.* 2011). Quantitative predictions of the effects of people and dog recreation on shorebird occupancy and abundance facilitate identifying conservation solutions that minimize impacts on other stakeholders.

A good zoning plan is robust to future changes in threats (Pressey *et al.* 2007). This is especially relevant for the present analysis, where the residential population of Greater Brisbane is growing rapidly, with a mean annual rate of population increase of 1·7% in 2013–2014 (Australian Bureau of Statistics 2015). In Scenario 3, where recreational use was double the current amount, the spatial allocation of Unrestricted Access Zones and Conservation Reserve Zones occurred in a similar pattern to that of Scenario 2, but Conservation Reserve Zones were needed at lower conservation targets in Scenario 3. This is because high recreational use requires the designation of areas free from human influence to offset the negative effect of increased recreational use. Future work could consider changes in the distribution of recreational use resulting from zoning. Another key consideration is whether the zone allocation should remain fixed over time, which is dependent on the spatial use of the foreshore by people and birds. Whilst some species of shorebird show high feeding site fidelity in Moreton Bay, the site fidelity for many species remains unknown (Coleman & Milton 2012). Ongoing monitoring of recreationalist and shorebird distributions in Moreton Bay could be used to evaluate current zones, validate the shorebird abundance model and to provide a baseline for adaptive management (Ferrier & Wintle 2009). Another consideration is the use of temporary or seasonal zoning rather than permanent zoning, which could be an interesting avenue for future work.

Non-compliance to zoning restriction can of course undermine the conservation benefit, and the success of management actions such as concentrating dog exercise into specified areas ultimately relies on the public to adjust their current recreational behaviour by voluntary compliance (Burger & Niles 2013; Maguire, Rimmer & Weston 2013). However, careful zoning that minimizes the impact on recreational opportunity is likely to minimize non-compliance. Situations requiring major behavioural changes may require supplementary management actions such as signage and enforcement (Dowling & Weston 1999; Weston *et al.* 2012a; Rimmer, Maguire & Weston 2013), the establishment of social norms (Williams *et al.* 2009), or community education and engagement (Weston, Tzaros & Antos 2006; Glover *et al.* 2011). It remains unclear why compliance to some recreational management actions such as dog control is generally low (Dowling & Weston 1999; Williams *et al.* 2009; Kyne 2010), and a better understanding of how human perceptions mediate management effectiveness would increase knowledge on how to ensure compliance (Burger & Niles 2013; Maguire, Rimmer & Weston 2013, 2014; Adams, Pressey & Stoeckl 2014). Thus, it is essential that ongoing monitoring takes place to determine levels of compliance and to inform further management intervention.

In future work, it would be useful to consider the response of individual species of shorebird to different recreational uses, as previous studies have shown that shorebirds show species-specific responses to disturbances (Glover *et al.* 2011; Martín *et al.* 2015). Additionally, our study measured only the immediate redistribution of birds as a result of recreational use at small spatial scales (600-m length of foreshore) and did not capture any chronic effects of disturbance over a larger spatial and temporal scale. For example, we cannot account for the shorebirds that no longer use the study region as a result of the generally high level of disturbance over time. The relative contributions of threats operating in Moreton Bay and elsewhere along the birds' migratory flyway on population declines are also not fully understood (Bamford *et al.* 2008; Murray & Fuller 2015). However, threats in the non-breeding season could influence the ability of shorebirds to complete migration, as environments experienced by individuals in one season can carry over to influence demographic processes at other times of the year (Newton 2006).

With the majority of protected areas around the world open to human use, managers must find ways to balance access by people with protection of biodiversity. Here, we show how a perceived conflict between recreational use of the intertidal zone and protection of threatened migratory shorebirds can in fact be greatly reduced through appropriate land-use zoning. Zoning plans that explicitly consider existing levels of human use and provide solutions that minimize the need for behavioural change by people may garner support by a majority of stakeholders, naturally encouraging compliance with usage restrictions. Where there are perceived or apparent conflicts, empirical data can be used in a scientifically rigorous manner to create transparent, robust solutions.

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Data accessibility

All shorebird and recreationalist surveys are included in Table S1.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Table S1. Shorebird and recreationalist count data.

Table S2. Shorebird species observed within the Moreton Bay study region.

Table S3. Results from the highest ranked ZINB model of shorebird counts within the Moreton Bay study region.

Table S4. Results matrix for the allocation of the three zone types to each planning unit for the three planning scenarios.