Journal of Applied Ecology

British Ecological Society

Journal of Applied Ecology 2016, **53,** 1215–1224 doi: 10.1111/1365-2664.12606

Optimizing disturbance management for wildlife protection: the enforcement allocation problem

Kiran L. Dhanjal-Adams[1]*, Karen Mustin[1], Hugh P. Possingham[1,2] and Richard A. Fuller[1]

[1]*School of Biological Sciences, Centre for Biodiversity and Conservation Science, University of Queensland, Brisbane, Qld 4072, Australia; and* [2]*Division of Ecology and Evolution, Imperial College London, Silwood Park Campus, Berkshire, UK*

Summary

1. To ensure public compliance with regulations designed to protect wildlife, many protected areas need to be patrolled. However, there have been few attempts to determine how to deploy enforcement effort to get the best return on investment. This is particularly complex where repeated enforcement visits may result in diminishing returns on investment. Straightforward quantitative methods to solve such problems are not available to conservation practitioners.

2. We use structured decision-making to find the most cost-effective allocation of patrol effort among sites with a limited budget. We use the case study of declining migratory shorebirds in Moreton Bay, Australia, to determine where and when Marine Park personnel could reduce disturbance using two different scenarios: (i) where a fixed subset of sites is chosen for management each year and (ii) where different sites are visited during each patrol. The goal is to maximize the number of undisturbed birds for a given budget.

3. We discover that by prioritizing enforcement based on cost-effectiveness, it is possible to avoid inefficient allocation of resources. Indeed, 90% of the maximum possible benefit can be achieved with only 25% of the total available budget.

4. Visiting a range of enforcement sites at varying rates yields a greater return on investment than visiting only a fixed number of sites. Assuming an exponential reduction in disturbance from enforcement, the greatest benefit can be achieved by patrolling many sites a small number of times. Assuming a linear reduction in disturbance from enforcement, repeatedly patrolling a small number of sites where return on investment is high is best. If we only prioritize sites where wildlife is disturbed most often, or where abundance is greatest, we will not achieve an optimal solution. The choice of patrol location and frequency is not a trivial problem, and prudent investment can substantially improve conservation outcomes.

5. *Synthesis and applications*. Our research demonstrates a straightforward objective method for allocating enforcement effort while accounting for diminishing returns on investment over multiple visits to the same sites. Our method is transferable to many other enforcement problems, and provides solutions that are cost-effective and easily communicable to managers.

Key-words: Australia, Charadriiformes, decision theory, illegal activities, law enforcement, Moreton Bay, optimal planning, patrolling, shorebird, wildlife protection

Introduction

Effective enforcement is often needed to ensure that protected areas achieve successful conservation outcomes (Rowcliffe, de Merode & Cowlishaw 2004; Keane *et al.* 2008). Reductions in enforcement levels have repeatedly been shown to result in increases in illegal activities harmful to wildlife, both in marine (Walmsley & White 2003) and in terrestrial environments (Hilborn *et al.* 2006). Enforcement techniques such as fines, sanctions and patrols can be effective in dealing with illegal activities (Kahler & Gore 2012), and the efficacy of enforcement improves when the probability of detecting illegal activities increases (Leader-Williams & Milner-Gulland 1993). Managers therefore often target enforcement where threats are predicted to occur (Campbell & Hofer 1995), with less regard for cost, or for the expected benefit to biodiversity. However, equipment,

*Correspondence author. E-mail: kiran.dhanjal.adams@gmail.com

training and salaries for enforcement patrols over large areas can be expensive and budgetary constraints often limit the quality or quantity of enforcement (Keane *et al.* 2008). Given that the effectiveness of repeated enforcement in a single location can decrease over time as perpetrators desist or transfer their activities elsewhere, and therefore that continued enforcement once threats have been mitigated can result in misspent funds, it follows that there exists an optimal number of visits which ensures cost-effective resource allocation for diminishing returns on investment (Jachmann 2008).

Structured decision-making enables managers to allocate resources among actions in a transparent and rational manner (Naidoo *et al.* 2006; Shwiff *et al.* 2013) and can therefore be used to determine cost-effective enforcement options. Most enforcement allocation studies have assessed the budgetary requirements for reducing illegal activities to a level that does not significantly impact conservation objectives (Leader-Williams, Albon & Berry 1990; Jachmann 2008). However, there have been few attempts to determine how enforcement effort might be optimally allocated over both time and space. When optimized, targeted enforcement actions reduce patrol effort and hence cost, while continuing to achieve conservation targets (Linkie, Rood & Smith 2010; Plumptre *et al.* 2014), or deliver greater conservation outcomes for the same budget. However, many optimization methods are data-hungry or require complex models (Linkie, Rood & Smith 2010; Plumptre *et al.* 2014), meaning that easily accessible and reproducible methods to prioritize enforcement based on limited data are not yet easily reproducible or accessible to managers.

Here, we outline a simple method to allocate enforcement among sites subject to disturbance through recreational use, using data readily available to managers: number of infractions, average number of target species observed during patrols, and enforcement cost. We apply a structured decision-making framework to the problem of allocating patrol effort within a protected area with the aim of maximizing benefits to wildlife. We use enforcement of disturbance management for migratory shorebirds in Moreton Bay Marine Park, Australia, as a case study. We explore two enforcement strategies, first where a fixed set of sites is patrolled throughout a season, and second where different sites are visited during each patrol. The method we develop is transferable to other systems and is general enough to be modified for management of a wide range of threats, not just disturbance. For small data sets, this optimization can be solved using non-specialist software such as Microsoft Excel by simply comparing all possible scenarios, although larger problems will require more specialist optimization software and programming.

Materials and methods

We use enforcement of shorebird disturbance patrols in Moreton Bay as our study system. In the following sections, we describe a method of allocating enforcement effort between sites by (i) defining our study system, (ii) determining the benefits of enforcement, (iii) outlining enforcement cost, (iv) mathematically formulating and solving the enforcement allocation problem and (v) carrying out a sensitivity analysis.

STUDY SYSTEM

Moreton Bay Marine Park, Australia, is situated at 27·25° S 153·25° E and covers an area of 3400 km^2 (Fig. 1), providing internationally important feeding and roosting habitat for migratory shorebirds. The park is managed as a multi-use marine protected area by the Department of Environment Heritage Protection (EHP) and the Department of National Parks, Recreation, Sport and Racing (NPRSR). Queensland Parks and Wildlife Service (QPWS) is the business unit responsible for the day-to-day management of the marine park, regulating vessel size, speed, anchoring, bait gathering, crabbing, spear fishing, line fishing, trawling, netting, tourism, personal water crafts, vehicles on beaches, dog-walking and other forms of recreation on the foreshore (Queensland Government 2008).

Some of the human activities occurring in the park are known to cause disturbance to shorebirds (Olds 2005, Queensland Government 2010), defined here as 'the response of birds to a stimulus such as the presence of a person' (Weston *et al.* 2012b). Indeed, penalties apply for violations of the following provisions under the 1997 *Marine Parks (Moreton Bay) Zoning Plan*: (i) 'a person must not disturb shorebirds or their habitats', (ii) 'dogs must be controlled when near shorebirds' and (iii) 'vehicles must be driven away from/around feeding or roosting shorebirds'. Fur-

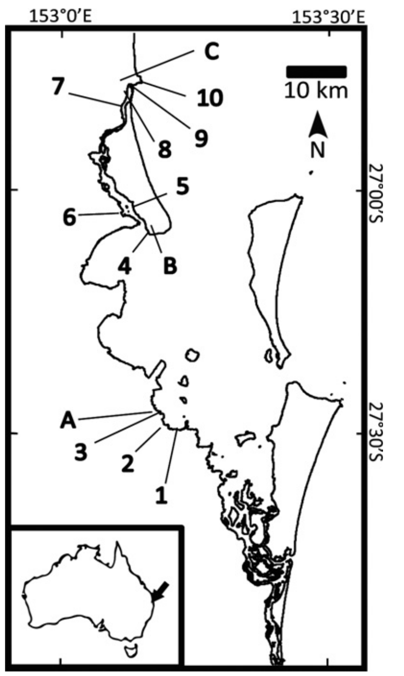

Fig. 1. Study area: Moreton Bay in south-east Queensland, Australia. A, B and C represent patrol bases where patrols originate: **A** = Manly, **B** = Bribie Island and **C** = Caloundra. Numbers 1 to 10 represent the potential patrol sites where **1** = Wellington point, **2** = Thorneside, **3** = Manly Harbour, **4** = Buckley's Hole, **5** = Kakadu Beach, **6** = Toorbul, **7** = Bell's Creek, **8** = Caloundra Sandbank, **9** = Caloundra Bar and **10** = Wickham Point.

thermore, migratory shorebirds are protected in Moreton Bay by state law (1992 *Queensland Nature Conservation act*), national law (1999 *Environment Protection and Biodiversity Conservation Act*) and international law (1971 *Ramsar Convention*, 1979 *Bonn Convention*, 1974 *Japan-Australia Migratory Bird Agreement*, 1986 *China-Australia Migratory Bird Agreement* and 2007 *Republic of Korea-Australia Migratory Bird Agreement*).

Repeated disturbance to shorebirds can prevent individuals from gaining the necessary weight to complete migration. For many species, pre-migration lipid reserves must reach roughly 50% of total body mass before departure (Blem 1990). Shorebirds feed in the intertidal zone and roost during high tide, when large numbers concentrate in to a small area. Disturbances at roost sites can therefore impact all roosting individuals simultaneously. Indeed, shorebirds are highly responsive to anthropogenic stimuli and thus are readily disturbed (Glover *et al.* 2011). Short-term disturbance includes increased levels of stress and behavioural changes (Landys, Ramenofsky & Wingfield 2006). Long-term disturbance includes chronic avoidance of disturbed habitat and abandonment of otherwise suitable habitat as individuals move to less disturbed areas (Nudds & Bryant 2000), increasing density and therefore competition between individuals at undisturbed sites (Dolman & Sutherland 1997).

With a multitude of factors for QPWS to manage in addition to shorebirds, funding and time allocated to shorebird disturbance enforcement are limited, yet the abundance of some migratory shorebird species has decreased by almost 80% in Moreton Bay between 1995 and 2009 (Wilson *et al.* 2011). Though many other factors may be driving declines in migratory shorebird numbers, anthropogenic disturbance represents an immediate and manageable impact on shorebirds which should be minimized where possible. Furthermore, the human population surrounding Moreton Bay has been estimated to increase from 4·5 million people in 2011 to 7·1 million by 2036 (Queensland Government 2013). Migratory shorebirds are therefore likely to be under increasing pressure from anthropogenic disturbances and in urgent need of cost-effective enforcement strategies. Indeed, simple and implementable solutions exist for reducing disturbance to shorebirds, such as education (Antos, Weston & Priest 2006), establishing a local culture of compliance (Williams *et al.* 2009), keeping dogs on leashes (Williams *et al.* 2009) and limiting access to important feeding or roosting areas (Weston *et al.* 2012a).

ENFORCEMENT BENEFIT

Cost-effective decision-making requires a measurable benefit. We therefore quantified the benefit of enforcement as the number of birds freed from disturbance by enforcement patrols. To do so, we used volunteer-collected data on shorebird numbers and disturbance rates in Moreton Bay. It is important to note however that volunteer-monitored data are not always available, and that different data may be more appropriate elsewhere, such as data collected during patrols on numbers of infractions and/or average abundances of target species.

We collated data from systematic bird count surveys conducted by volunteers from the Queensland Wader Study Group (QWSG; Milton & Driscoll 2006). About 40 sites were counted simultaneously by QWSG observers each month, with counts carried out within 2 h of the high tide to include roosting individuals (Zharikov & Milton 2009). Disturbances were systematically recorded from 2009 onwards. We therefore use data on disturbance rates at roost sites between 2009 and 2012, and bird numbers between 1992 and 2012, both during the months of December through to February when shorebirds are most abundant in Moreton Bay (Wilson *et al.* 2011). We selected all 10 sites experiencing forms of disturbance that could be enforced under the regulations outlined above. For each site we calculated the average number of disturbances observed during a bird count. We also assumed that all counts were carried out with equal detection error, and used the average numbers of birds present in the roost for 19 shorebird species (see Table S1, Supporting information for full list of species).

ENFORCEMENT COST

Cost-effective decision-making requires information about management costs. We estimated a ranger's salary at \$2414·70 fortnightly (search term 'ranger' on the smartjobs website of the Queensland Government 2014). Assuming 38 h of work per week (as per http://www.fairwork.gov.au/about-us/policies-and-guides/fact-sheets/minimum-workplace-entitlements/maximum-weekly-hours), hourly salaries were estimated at \$31·77. We used the maximum possible salary so as not to underestimate the budget. We assumed that patrols were always carried out by two rangers and that staff on-costs were 25% (Ban *et al.* 2011). Assuming a 2·6-L engine, we estimated vehicle costs at \$0·75 per kilometre (Australian Taxation Office 2014). Using Google maps (https://maps.google.com.au/), we estimated the distance by road from the main marine parks office to each management site, in addition to travel time. Finally, we assumed enforcement was always carried out with teams of two staff members working for 2 h at each site; thus:

$$C_i = N \times S \times 1 \cdot 25 \times (T_i + E) + P \times D_i \qquad \text{eqn 1}$$

where C_i is the cost of patrolling site i, N is the number of rangers, S is the hourly salary of one ranger, T_i is the time spent travelling to site i and E is the time spent enforcing each site, P is the price per kilometre of travel and D_i is the distance in kilometres to each site i from the ranger base (Appendix S1).

OPTIMIZING ENFORCEMENT

We optimized the enforcement visits over three different scenarios (Fig. 2): scenario 1, where patrol effort was fixed for all sites for the entire season, and where birds benefitted from a fractional reduction in disturbance rate as a result of enforcement at each site; scenario 2, where patrol effort could vary across sites during the season, and where birds benefitted from an exponential reduction in disturbance as a result of enforcement at each site; and scenario 3, where patrol effort could vary across sites during the season, and where birds benefitted from a linear reduction in disturbance as a result of enforcement at each site. Scenario 2 therefore represents a scenario where enforcement is highly effective in the beginning, but less so at the end; while scenario 3 represents a scenario where enforcement is not effective immediately, but increases in effectiveness incrementally through repeated visits. We also compared scenario 1 with prioritizing sites by ranking them based only on cost, number of birds, number of disturbances or score (calculated using the average rank for cost, number of birds and number of disturbances). We assumed that sites were patrolled a maximum of

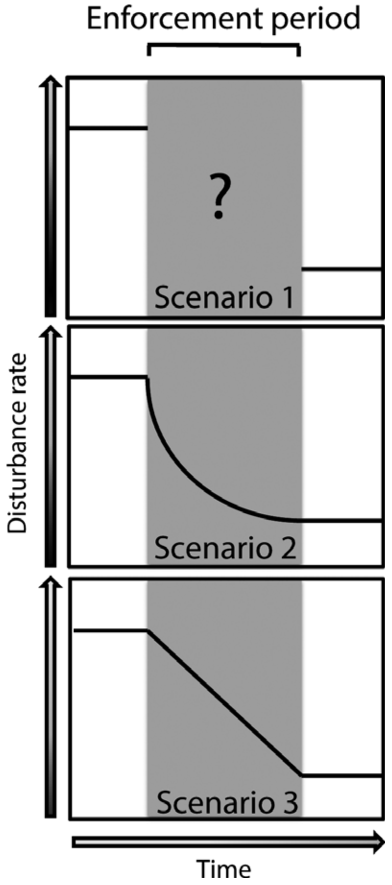

Fig. 2. Comparison among disturbance reduction scenarios. The period of enforcement is represented by the grey shading. In scenario 1, we assume no knowledge (hence the use of '?' in the figure) of the shape of the relationship between enforcement effort and disturbance rate and simply that a site can either be patrolled five times, or not (eqn 2), and that a fractional reduction in disturbance occurs if the site is patrolled. For scenarios 2 and 3 (eqns 3 and 4), we assume that sites can be patrolled a different number of times and that the benefit depends on the number of visits. We assume an exponential decrease in disturbance from repeated enforcement visits in scenario 2, and a linear decrease in scenario 3.

five times throughout the non-breeding season and that the patrol effort resulted in a 20% decrease in disturbance rate (Appendix S1). We also assumed that disturbance from enforcement was minimal, as patrols were land-based, and shorebirds were present on the foreshore.

The details of each scenario, and the algorithms used to implement them are provided in the following sections. All optimizations were implemented in MICROSOFT EXCEL (Appendix S2) and MATLAB 2014a (MathWorks Inc. 2014).

Fixed patrol effort over time, fixed disturbance reduction

In this scenario, it is assumed that: (i) each site can be either managed or unmanaged for the entire season each year, (ii) the benefit of managing sites is dependent on the number of birds present at that site before management, (iii) the benefit of managing sites is dependent on the level of disturbance prior to management and (iv) birds do not move between sites as a result of disturbance.

Our objective was to maximize the number of birds being freed from disturbance through enforcement in Moreton Bay, and our control variable was whether or not a site was managed in that year, such that:

$$\text{Max} \sum_{i=1}^{M} x_i \sum_{j=1}^{N} d_{i,j,0}\gamma_{i,j}N_{i,j}w_j \text{ subject to } \sum_{i=1}^{M} x_i C_i \leq B, \qquad \text{eqn 2}$$

where $x_i \in \{0, 1\}$ represents the decision whether or not to manage site i, C_i is the cost of visiting site i, $d_{i,j,0}$ is the number of disturbances at site i experienced by species j before management, $\gamma_{i,j}$ is the fractional reduction in disturbance at site i for species j due to management, $N_{i,j}$ is the number of birds of species j at site i, and w_j represents the relative importance given to species j. Throughout our case study, we assume all species have an equal importance of 1, but the weight can be modified for other studies (to represent, for example, a conservation status). We also assume that the initial disturbance rate $d_{i,j,0}$ is constant for all species and that $\gamma_{i,j}$ the fractional reduction in disturbance is identical for all species across all sites.

Different sites patrolled over time, exponential disturbance reduction from multiple visits

In this scenario, it is assumed that: (i) each site can be visited a number of times over the season each year such that $V_i \in \{0, \ldots, V_{\max}\}$, (ii) the benefit of visiting sites multiple times is proportional to the number of birds present at that site, (iii) the benefit of visiting sites increases logarithmically with the number of visits and (iv) birds do not move between sites as a result of disturbance.

Our objective was to maximize the number of birds being freed from disturbance through enforcement in Moreton Bay, and our control variable was the number of visits to each site, such that:

$$\text{Max} \sum_{i=1}^{M} \sum_{j=1}^{N} d_{i,j,0}\gamma_{i,j}(1 - e^{\frac{-6{\cdot}9}{V_{\max}}V_i})N_{i,j}w_j \text{ subject to } \sum_{i=1}^{M} V_i C_i \leq B, \qquad \text{eqn 3}$$

where $V_i \in \{0, \ldots, V_{\max}\}$ represents the number of visits to site i, C_i is the cost of visiting site i, $d_{i,j,0}$ is the number of disturbances at site i experienced by species j before management, $\gamma_{i,j}$ is the fractional reduction in disturbance at site i for species j due to enforcement, $N_{i,j}$ is the number of birds of species j at site i, and w_j represents the relative importance given to species j. Because we expect the amount of disturbance being enforced to increase to 99·9% of $\gamma_{i,j}$ over $V_{\max}$ visits, we have $\gamma_{i,j}(1 - e^{-\frac{-\ln(1-0{\cdot}999)}{V_{\max}}V_i})$; thus, $\ln(0{\cdot}001) = -6{\cdot}9$ in eqn 3.

Different sites patrolled over time, linear disturbance reduction from multiple visits

In this scenario, it is assumed that: (i) each site can be visited a number of times over the season each year such that $V_i \in \{0, \ldots, V_{\max}\}$, (ii) the benefit of visiting sites multiple times is linearly proportional to the number of birds present at that site as well as (iii) the number of visits and (iv) birds do not move between sites as a result of disturbance.

Our objective was to maximize the number of birds being freed from disturbance through enforcement in Moreton Bay, and our control variable was the number of visits to each site, such that:

$$\text{Max}\sum_{i=1}^{M}\sum_{j=1}^{N} d_{i,j,0}\left(\text{Max}\left[1,\frac{\gamma_{i,j}}{V_{\max}}V_i\right]\right)N_{i,j}w_j \text{ subject to } \sum_{i=1}^{M} V_iC_i \leq B, \quad \text{eqn 4}$$

where $V_i \in \{0, \ldots, V_{\max}\}$ represents the number of visits to site i, C_i is the cost of visiting site i, $d_{i,j,0}$ is the number of disturbances at site i experienced by species j before management, $\gamma_{i,j}$ is the fractional reduction in disturbance at site i for species j due to enforcement, $N_{i,j}$ is the number of birds of species j at site i, and w_j represents the relative importance given to species j.

SENSITIVITY ANALYSIS

To control for variability in travel costs, and to determine whether conclusions were robust, all optimization scenarios were run with three separate starting points for patrols: two randomly selected locations within 1 km of a roost to determine whether proximity influenced the prioritization (Caloundra and Bribie), in addition to the current patrol base location (Manly) as seen in Fig. 1. We also tested two disturbance reduction scenarios, one where disturbance was reduced by 20% due to management and one where disturbance was reduced by 80%; thus, $\gamma_{i,j} \in \{0{\cdot}2, 0{\cdot}8\}$. The 20% reduction represents the observed reduction rate from our case study (Appendix S1). The 80% reduction represents an extreme case, where management is highly effective, and is used to explore model behaviour. These two scenarios therefore illustrate how prioritizations can differ according to efficiency. Finally, for all simulations, $V_{\max}$ was set to 5, because QPWS patrols each shorebird site on average once a month, between the months of November and March.

Results

It is possible to achieve 90% of the total benefit to shorebirds, within a budget of $1000 AUD using the Manly patrol base, $2500 with Bribie and $2700 with Caloundra (Figs 3 and S1). Additional budget beyond this did not significantly increase management benefit along the efficiency frontier (which can be defined here as the greatest benefit for a given budget, and is represented by the lines in Fig. 3).

Scenarios 2 and 3 represent exponential and linear disturbance reductions, respectively. Across all three patrol stations (Manly, Caloundra and Bribie), these two scenarios produced more cost-effective solutions for smaller budgets than scenario 1, the fractional disturbance reduction (Figs 3 and S1). Indeed, scenarios 2 and 3 allowed combinations of single enforcement visits at multiple sites, unlike scenario 1 which assumed five visits to the same site. Overall, at low budgets, the optimal solution was to repeatedly visit the most cost-effective site, and the cost of repeatedly carrying out enforcement did not outweigh the high benefit (Appendix S2). However, with an increasing budget, the optimal solution included an increasing number of visits to additional sites complementing those already being visited (Appendix S2). Overall, the greatest benefit could be achieved by carrying out enforcement at sites with a large number of birds experiencing a large number of disturbances (Fig. S2). Either metric (cost, number of birds or number of disturbances) in isolation delivered less efficient outcomes (Table 1 and Fig. S2). Cost-effective sites are therefore not intuitive and benefit can be increased by including information on all factors impacting the system, including the number of birds present, the disturbance rate and the cost of enforcement (Fig. S2).

By ranking sites according to the number of times they were selected as part of the optimal solution for every dollar spent, we found that the results across scenarios were surprisingly similar (Figs 4 and S3, and Tables 2, S2 and S3). However, there was a marked difference between scenario 1 and scenarios 2 and 3. Indeed, some sites which were selected in scenarios 2 and 3 were not selected as part of the optimal solution for scenario 1. This is because scenarios 2 and 3 allow multiple sites to be patrolled, and scenario 1 does not. In addition, we found that all scenarios were identical for both disturbance reduction scenarios ($\gamma_{i,j} \in \{0{\cdot}2, 0{\cdot}8\}$). Uncertainty in the effectiveness of enforcement, over repeated visits, as a strategy to reduce disturbance did not therefore impact the optimal solution.

Discussion

Using structured decision-making, we discover simple rules of thumb that can be used to prioritize enforcement effort across a landscape, while accounting for both diminishing returns on investment and uncertainty in management outcomes. Indeed, in our case study, it was possible to achieve 90% of the maximum possible benefit with a relatively small budget by repeatedly reducing shorebird disturbance at the most cost-effective sites (Figs 3 and S1). However, with an increasing budget, the optimal solution was complemented by an increasing number of enforcement visits to an increasing number of less cost-effective sites (Appendix S2). Crucially, basing enforcement activity solely on the amount of disturbance, or the number of birds present, yielded very inefficient outcomes (Table 1 and Fig. S2).

We observed a large number of suboptimal solutions under medium-to-large budgets, many of which provided negligible benefits, thus increasing the probability of poor investment in enforcement (Figs 3 and S1). These results are unusual: past research has found a strong positive correlation between benefits and costs, with the relative variability of cost greater than that of benefit (Ferraro 2003). Here, we observe highly variable benefits, because there is a high level of variability in shorebird numbers and disturbance rates among sites. This is a common enforcement scenario. In addition, we find no correlation between benefit and cost because benefit is calculated using bird numbers and level of disturbance while cost is calculated using duration of enforcement, travel time and travel distance.

Interestingly, by ranking the number of times sites were selected as part of the optimal solution for every dollar

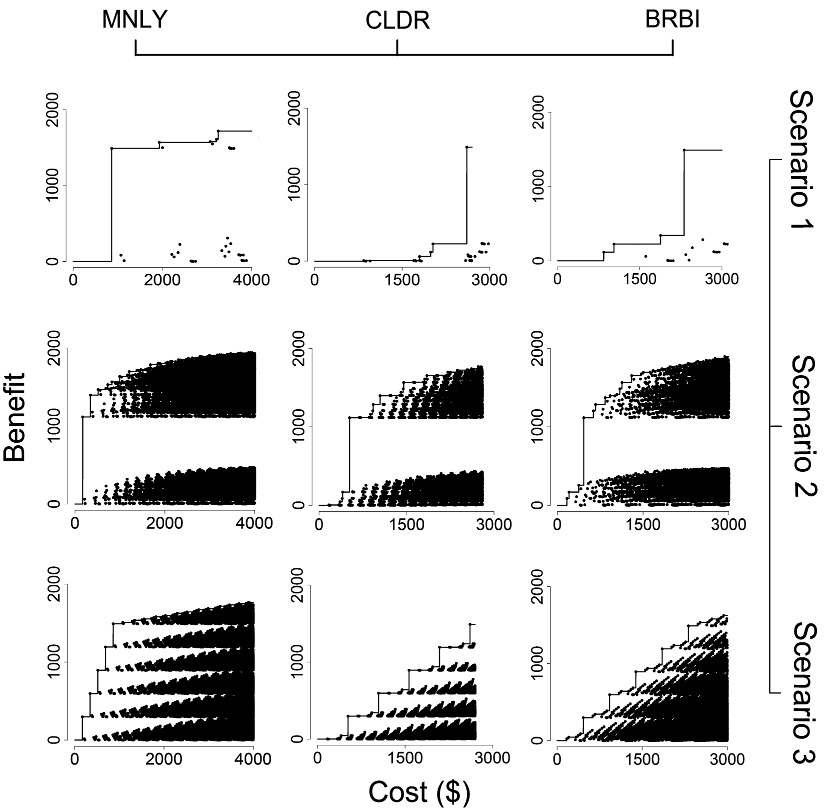

Fig. 3. Trade-offs between the cost of enforcing patrols and the benefit to shorebirds of reducing disturbance by 20%. Benefit is measured as the number of birds released from disturbance as a result of enforcement. Scenario 1, where birds benefitted from a fixed disturbance reduction of as a result of enforcement at each site; scenario 2, where patrol effort could vary across sites and where birds benefitted from an exponential reduction in disturbance; and scenario 3, where patrol effort could vary across sites and where birds benefitted from a linear reduction in disturbance. For each scenario, we plotted trade-off curves for three different patrol stations where rangers could be based: MNLY = Manly, CLDR = Caloundra and BRBI = Bribie. Lines indicate the optimal solution.

Table 1. Relative ranking of sites according to different prioritization strategies: cost-effectiveness (scenario 1), cost, number of birds, number of disturbances and score across sites for patrol stations

	Cost-effectiveness			Management cost			Number of birds			Number of disturbances			Scoring system		
Site code	M	C	B	M	C	B	M	C	B	M	C	B	M	C	B
Manly Harbour	1	1	1	1	8	8	1	1	1	1	1	1	1	1	3
Kakadu Beach	2	2	2	6	7	2	3	3	3	4	4	4	4/5	3/4/5	2
Thorneside	3	5	5	2	9	9	6	6	6	2	2	2	2	6	5/6
Buckley's Hole	4	3	3	5	6	1	4	4	4	3	3	3	3	2	1
Toorbul	5	4	4	4	5	3	2	2	2	7	7	7	4/5	3/4/5	4
Wellington Point	6	7	6	3	10	10	5	5	5	8	8	8	6	10	8/9
Caloundra Bar	7	6	7	7	1	4	7	7	7	6	6	6	7	3/4/5	5/6
Bell's Creek	8	9	9	10	4	7	9	9	9	9	9	9	10	9	10
Sandbank Caloundra	9	8	9	8	2	5	8	8	8	10	10	10	9	8	8/9
Wickham Point	10	10	10	9	3	6	10	10	10	5	5	5	8	7	7

M, Manly; C, Caloundra; B, Bribie. A rank of 1 represents a high enforcement priority (i.e. highly cost-effective, cheap to manage, large numbers of birds or highly disturbed), while a rank of 10 represents a low enforcement priority (i.e. less cost-effective, expensive to manage, small numbers of birds or small numbers of disturbances). The rank of the scoring system was calculated using the average of the rank of cost, number of birds and number of disturbances.

spent, it was possible to observe that scenarios 2 (exponential) and 3 (linear) were very similar, relative to scenario 1 (proportional; Tables 2, S2 and S3). Visiting a range of enforcement sites at varying rates yielded a greater return on investment than visiting only a fixed number of sites. Single visits to less cost-effective sites can therefore be used to complement more cost-effective solutions (Appendix S2). For example in Table 2, for scenario 1 it is more beneficial to visit Thorneside more often than Kakadu Beach, while for scenarios 2 and 3 it is more beneficial to visit Kakadu Beach more often than Thorneside. This is because Kakadu Beach is more expensive than Thorneside, but offers a greater benefit, achieving a greater return on investment under variable visitation rates. Furthermore, scenario 2 assumes an exponential decrease in disturbance rate, where enforcement is highly effective in the beginning, but less so at the end. The benefit of managing once for scenario 2 is therefore much greater than for scenario 3, where enforcement effectiveness increases incrementally. Assuming diminishing

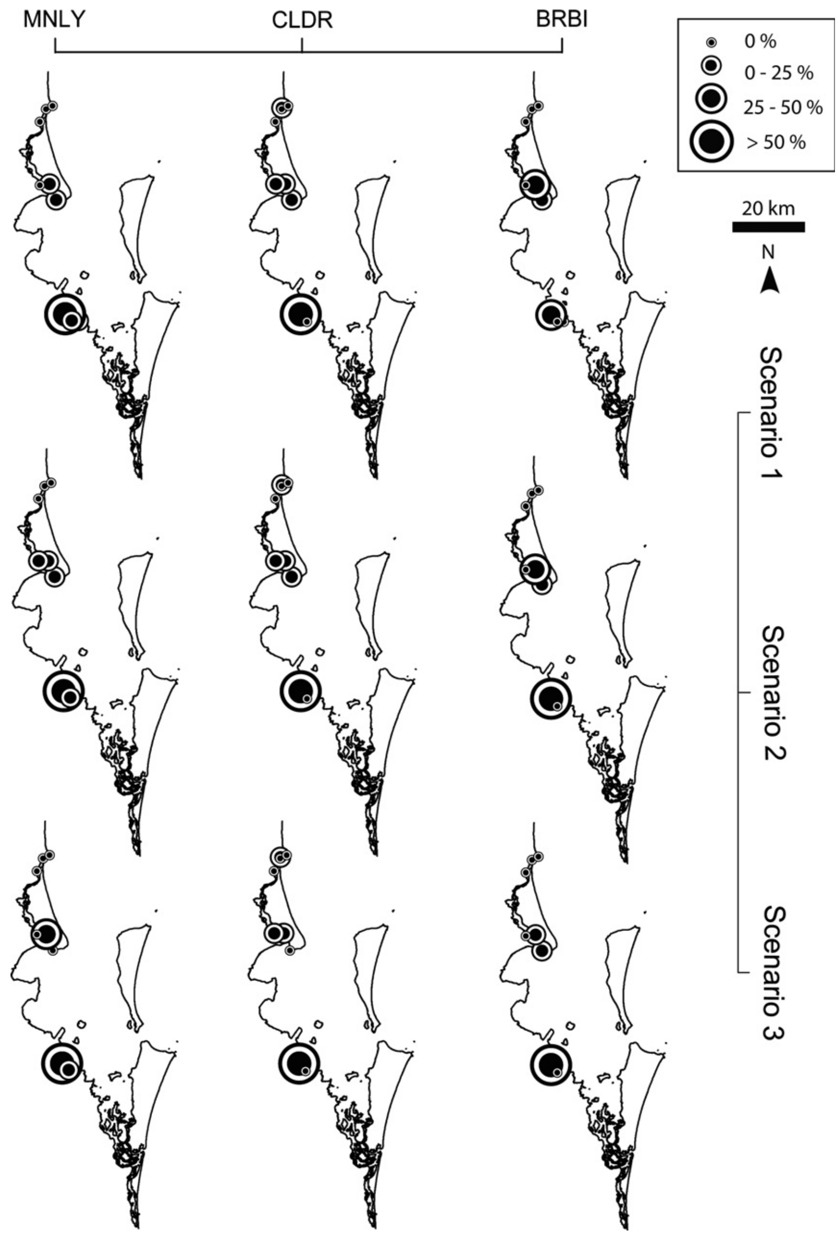

Fig. 4. The frequency at which sites are selected as part of an optimal solution for every dollar spent, expressed as a percentage, for each scenario at each patrol station for a disturbance reduction of 20%. The budget is limited for all scenarios to $0–4000 for patrol station Manly (MNLY), $0–2700 for patrol station Caloundra (CLDR) and $0–3000 for patrol station Bribie (BRBI). The differences in budget reflect the number of solutions: the number of solutions under $2700 at Caloundra is the same as the number of solutions under $3000 at Bribie, and $4000 at Manly.

returns on investment in scenario 2, it is more beneficial to patrol many sites a small number of times. For scenario 3 on the other hand, it is more important to find the sites with the greatest return on investment and repeatedly patrol them.

When comparing 20% and 80% disturbance reduction scenarios, the optimal solutions remained identical within each scenario (Tables 2, S2 and S3). Uncertainty in the effectiveness of enforcement at reducing disturbance over repeated visits did not impact the optimal solution found within each of these scenarios. It is therefore possible to identify robust solutions for a given budget despite uncertainty. These findings echo previous work indicating that management actions can be less sensitive to uncertainty than management outcomes (McCarthy, Andelman & Possingham 2003). Indeed, acting despite uncertainty is more likely to deliver better outcomes than not acting at all (McDonald-Madden *et al.* 2011).

Failing to account for both cost and benefit together can result in misspent funds, particularly with small budgets. For instance, there are a number of enforcement sites such as Thorneside that are highly cost-effective to enforce (patrol station Caloundra and Bribie in Table 1), yet also relatively expensive to visit. The benefit of carrying out enforcement at these sites therefore made the higher cost worthwhile. Similarly, there are a number of enforcement sites such as Caloundra Bar which are cheap to patrol (patrol station Caloundra in Table 1), yet are not cost-effective to enforce because of the low possible benefit. The intricacies of such trade-offs cannot be reflected by scoring sites based solely on cost, bird number or disturbance number (Table 1; Fig. S2). Cost-effectiveness analysis therefore offers a simple, transparent and

Table 2. Frequency at which sites are selected as part of optimal solutions, where the budget is limited to $4000 and Manly is the patrol base

Site	20% disturbance reduction			80% disturbance reduction		
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Manly Harbour	3139	13 300	17 419	3139	13 300	17 419
Thorneside	1280	3965	4239	1280	3965	4239
Kakadu Beach	751	4569	7950	751	4569	7950
Wellington Point	140	522	0	140	522	0
Buckley's Hole	40	3008	0	40	3008	0
Bell's Creek	0	0	0	0	0	0
Caloundra Bar	0	0	0	0	0	0
Sandbank Caloundra	0	0	0	0	0	0
Toorbul	0	1887	0	0	1887	0
Wickham Point	0	0	0	0	0	0

rational manner of allocating patrol effort between sites which cannot be achieved by ranking sites based on scores for particular criteria (Joseph, Maloney & Possingham 2009). Furthermore, it enables an optimal solution to be found among thousands of possible combinations of site visits.

We observed a logarithmic increase in the benefit of the optimal solution for every dollar spent (Figs 3 and S1). A small increase in spending therefore resulted in a large increase in benefit under small budgets (Figs 3 and S1). Our methods, which aimed at maximizing the number of birds being freed from disturbance through enforcement, yielded highly cost-effective solutions. Therefore, the greatest benefit could be achieved by carrying out enforcement at sites with a large number of birds experiencing disturbances (Table 1 and Fig. S2). If enforcement was carried out at sites with few birds experiencing high levels of disturbance, the overall shorebird population would not benefit from the reduction in disturbance from enforcement at that site. These simple rules of thumb are highly transferable to other enforcement scenarios, whereby the most cost-effective sites for enforcement are the cheapest sites with the greatest number of target species in combination with the greatest number of illegal wildlife activities.

The methods we develop here could easily complement an adaptive management framework (Chadès *et al*. 2012), whereby priorities are set using our methods, illegal activities are then monitored and enforcement is evaluated so that priorities can be reset for the following season using the same method. Indeed, it is not unreasonable to expect illegal wildlife activities to become displaced and change in response to the enforcement itself, such that a continually evolving arms race is needed to keep up with the changing pattern of disturbance, and to ensure previously undisturbed sites do not become disturbed (Keane *et al*. 2008). In some cases, target species might also change behaviour in response to the changing impact of wildlife activities.

Our methods could further be modified to allow for multiple sites to be visited per patrol by solving the travelling salesman problem (Larrañaga *et al*. 1999), finding the shortest route between a set of sites. By modifying this problem to minimize cost and maximize benefit simultaneously, and by adding a decision variable to limit the number of sites patrolled, it would be possible to determine the optimal route through the most cost-effective sites.

It is worth bearing in mind that enforcement is not always the most cost-effective solution for achieving long-term conservation goals, nor is it the only tool available to conservation practitioners (Steinmetz *et al*. 2014). In our case study for instance, the sparse availability of options for dog-walking (Cutt *et al*. 2008) means that dog owners might take the risk of exercising dogs on the foreshore contrary to regulations. Better dog-walking facilities, such as dog off-leash areas that are situated away from threatened wildlife, are likely to benefit not only dog-walkers in urban areas (Cutt *et al*. 2008), but also shorebirds. In addition, the lack of awareness that shorebirds are present on beaches (Antos, Weston & Priest 2006) and of how migration and feeding ecology are impacted by disturbances might be important in shaping dog-walkers' attitudes towards disturbing shorebirds (Williams *et al*. 2009). Raising awareness and better infrastructure could therefore complement enforcement in a variety of management scenarios.

The goal of our research was to propose a simple and objective method of allocating enforcement effort over space and time, which accounted for both diminishing returns on investment and uncertainty in enforcement outcome. We find that as a general rule of thumb, the most cost-effective sites for enforcement are the cheapest sites with the greatest number of target species in combination with the greatest number of illegal wildlife activities. By using cost-effectiveness analyses, our methods are easily transferable to other case studies, transparent and therefore easily communicable to managers.

Acknowledgements

This research was supported by an Australian Research Council Linkage Grant LP100200418, cofunded by the Queensland Department of Environment and Heritage Protection, the Commonwealth Department of the Environment, the Queensland Wader Study Group and the Port of Brisbane Pty Ltd. We acknowledge support from the Australian Government's

National Environmental Research Program, the Australian Research Council Centre of Excellence in Environmental Decisions and the University of Queensland. Additional support was provided to K.L.D-A by the Goodman Foundation and by Birdlife Australia's Stuart Leslie Award. H.P.P was supported by an ARC Laureate Fellowship.

Data accessibility

Data are uploaded as online Supporting Information.

References

Antos, M.J., Weston, M.A. & Priest, B. (2006) Factors influencing awareness of community-based shorebird conservation projects in Australia. *Applied Environmental Education & Communication*, **5**, 63–72.

Australian Taxation Office (2014) Method 1 – cents per kilometre. Available at: https://www.ato.gov.au/Business/Deductions-for-business/Motor-vehicle-expenses/Calculating-your-deduction/Method-1—cents-per-kilometre/ (accessed 25 October 2014).

Ban, N.C., Adams, V., Pressey, R.L. & Hicks, J. (2011) Promise and problems for estimating management costs of marine protected areas. *Conservation Letters*, **4**, 241–252.

Blem, C. (1990) Avian energy storage. *Current Ornithology*, **7**, 59–113.

Campbell, K. & Hofer, H. (1995) People and wildlife: spatial dynamics and zones of interaction. *Serengeti II*, 534–570.

Chadès, I., Carwardine, J., Martin, T.G., Nicol, S., Sabbadin, R. & Buffet, O. (2012) MOMDPs: a solution for modelling adaptive management problems. *Twenty-Sixth AAAI Conference of the Association for the Advancement of Artificial Intelligence (AAAI-12)*, July 22–26, Toronto, Canada.

Cutt, H.E., Giles-Corti, B., Wood, L.J., Knuiman, M.W. & Burke, V. (2008) Barriers and motivators for owners walking their dog: results from qualitative research. *Health Promotion Journal of Australia*, **19**, 118–124.

Dolman, P.M. & Sutherland, W.J. (1997) Spatial patterns of depletion imposed by foraging vertebrates: theory, review and meta-Analysis. *Journal of Animal Ecology*, **66**, 481–494.

Ferraro, P.J. (2003) Assigning priority to environmental policy interventions in a heterogeneous world. *Journal of Policy Analysis and Management*, **22**, 27–43.

Glover, H.K., Weston, M.A., Maguire, G.S., Miller, K.K. & Christie, B.A. (2011) Towards ecologically meaningful and socially acceptable buffers: response distances of shorebirds in Victoria, Australia, to human disturbance. *Landscape and Urban Planning*, **103**, 326–334.

Hilborn, R., Arcese, P., Borner, M., Hando, J., Hopcraft, G., Loibooki, M., Mduma, S. & Sinclair, A.R.E. (2006) Effective enforcement in a conservation area. *Science*, **314**, 1266.

Jachmann, H. (2008) Monitoring law-enforcement performance in nine protected areas in Ghana. *Biological Conservation*, **141**, 89–99.

Joseph, L.N., Maloney, R.F. & Possingham, H.P. (2009) Optimal allocation of resources among threatened species: a Project Prioritization Protocol. *Conservation Biology*, **23**, 328–338.

Kahler, J.S. & Gore, M.L. (2012) Beyond the cooking pot and pocket book: factors influencing noncompliance with wildlife poaching rules. *International Journal of Comparative and Applied Criminal Justice*, **36**, 103–120.

Keane, A., Jones, J.P.G., Edwards-Jones, G. & Milner-Gulland, E.J. (2008) The sleeping policeman: understanding issues of enforcement and compliance in conservation. *Animal Conservation*, **11**, 75–82.

Landys, M.M., Ramenofsky, M. & Wingfield, J.C. (2006) Actions of glucocorticoids at a seasonal baseline as compared to stress-related levels in the regulation of periodic life processes. *General and Comparative Endocrinology*, **148**, 132–149.

Larrañaga, P., Kuijpers, C.M.H., Murga, R.H., Inza, I. & Dizdarevic, S. (1999) Genetic algorithms for the travelling salesman problem: a review of representations and operators. *Artificial Intelligence Review*, **13**, 129–170.

Leader-Williams, N., Albon, S. & Berry, P. (1990) Illegal exploitation of black rhinoceros and elephant populations: patterns of decline, law enforcement and patrol effort in Luangwa Valley, Zambia. *Journal of Applied Ecology*, **27**, 1055–1087.

Leader-Williams, N. & Milner-Gulland, E.J. (1993) Policies for the enforcement of wildlife laws: the balance between detection and penalties in Luangwa Valley, Zambia. *Conservation Biology*, **7**, 611–617.

Linkie, M., Rood, E. & Smith, R. (2010) Modelling the effectiveness of enforcement strategies for avoiding tropical deforestation in Kerinci Seblat National Park, Sumatra. *Biodiversity and Conservation*, **19**, 973–984.

MathWorks Inc. (2014) *Matlab*. MathWorks Inc, Natick, MA, USA.

McCarthy, M.A., Andelman, S.J. & Possingham, H.P. (2003) Reliability of relative predictions in population viability analysis. *Conservation Biology*, **17**, 982–989.

McDonald-Madden, E., Chadès, I., McCarthy, M.A., Linkie, M. & Possingham, H.P. (2011) Allocating conservation resources between areas where persistence of a species is uncertain. *Ecological Applications*, **21**, 844–858.

Milton, D. & Driscoll, P. (2006) An assessment of shorebird monitoring in Queensland by the Queensland Wader Study Group. *Stilt*, **50**, 242–248.

Naidoo, R., Balmford, A., Ferraro, P.J., Polasky, S., Ricketts, T.H. & Rouget, M. (2006) Integrating economic costs into conservation planning. *Trends in Ecology and Evolution*, **21**, 681–687.

Nudds, R.L. & Bryant, D.M. (2000) The energetic cost of short flights in birds. *Journal of Experimental Biology*, **203**, 1561–1572.

Olds, J. (2005) *Shorebird Management Strategy: Moreton Bay*. Environmental Protection Agency, Brisbane, Qld.

Plumptre, A.J., Fuller, R.A., Rwetsiba, A., Wanyama, F., Kujirakwinja, D., Driciru, M., Nangendo, G., Watson, J.E.M. & Possingham, H.P. (2014) Efficiently targeting resources to deter illegal activities in protected areas. *Journal of Applied Ecology*, **51**, 714–725.

Queensland Government (2008) *Marine parks (Moreton Bay) zoning plan 2008*. Marine Parks Act 2004, Subordinate Legislation 2008 No. 343. Available at: https://www.legislation.qld.gov.au/LEGISLTN/SLS/2008/08SL343.pdf (accessed 8 December 2014).

Queensland Government (2010) *Moreton Bay Marine Park User Guide*. Queensland Government Environmental Protection Agency, Brisbane, Qld.

Queensland Government (2013) *Queensland Government Population Projections: 2013 Edition*. Queensland Government Statistician's Office, Queensland Treasury and Trade, Brisbane, Qld, Australia.

Queensland Government (2014) Smart jobs and careers. Available at: https://smartjobs.qld.gov.au/jobtools/jncustomsearch.jobsearch?in_organid = 14904 (accessed 25 October 2014).

Rowcliffe, J.M., de Merode, E. & Cowlishaw, G. (2004) Do wildlife laws work? Species protection and the application of a prey choice model to poaching decisions. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, **271**, 2631–2636.

Shwiff, S.A., Anderson, A., Cullen, R., White, P.C.L. & Shwiff, S.S. (2013) Assignment of measurable costs and benefits to wildlife conservation projects. *Wildlife Research*, **40**, 134–141.

Steinmetz, R., Srirattanaporn, S., Mor-Tip, J. & Seuaturien, N. (2014) Can community outreach alleviate poaching pressure and recover wildlife in South-East Asian protected areas? *Journal of Applied Ecology*, **6**, 1469–1478.

Walmsley, S. & White, A. (2003) Influence of social, management and enforcement factors on the long-term ecological effects of marine sanctuaries. *Environmental Conservation*, **30**, 388–407.

Weston, M.A., Dodge, F., Bunce, A., Nimmo, D.G. & Miller, K.K. (2012a) Do temporary beach closures assist in the conservation of breeding shorebirds on recreational beaches? *Pacific Conservation Biology*, **18**, 47–55.

Weston, M.A., McLeod, E.M., Blumstein, D.T. & Guay, P.-J. (2012b) A review of flight-initiation distances and their application to managing disturbance to Australian birds. *Emu*, **112**, 269–286.

Williams, K.J.H., Weston, M.A., Henry, S. & Maguire, G.S. (2009) Birds and beaches, dogs and leashes: dog owners' sense of obligation to leash dogs on beaches in Victoria, Australia. *Human Dimensions of Wildlife*, **14**, 89–101.

Wilson, H.B., Kendall, B.E., Fuller, R.A., Milton, D.A. & Possingham, H.P. (2011) Analyzing variability and the rate of decline of migratory shorebirds in Moreton Bay, Australia. *Conservation Biology*, **25**, 758–766.

Zharikov, Y. & Milton, D.A. (2009) Valuing coastal habitats: predicting high-tide roosts of non-breeding migratory shorebirds from landscape composition. *Emu*, **109**, 107–120.

Received 9 June 2015; accepted 22 December 2015
Handling Editor: Akira Mori

Supporting Information

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

Table S1. Optimization model parameter inputs: species, cost and disturbance rate.

Table S2. Frequency at which sites are selected as part of an optimal solution for every dollar spent. The budget is limited to $2700 for all scenarios and Caloundra is the patrol base.

Table S3. Frequency at which sites are selected as part of an optimal solution for every dollar spent. The budget is limited to $3000 for all scenarios and Bribie is the patrol base.

Fig. S1. Trade-offs between the cost of enforcing patrols and the benefit to shorebirds of reducing disturbance by 80%.

Fig. S2. Comparison between benefits (i.e. number of birds freed from disturbance) in eqn 1 when ranking sites according to (i) cost-effectiveness, (ii) cost, (iii) bird number or (iv) disturbance rate, for patrol station a) Manly, b) Caloundra and c) Bribie.

Fig. S3. The relative frequency at which sites are selected as part of an optimal solution for every dollar spent, expressed as a percentage, for each scenario at each patrol station for a disturbance reduction of 80%.

Appendix S1. Benefits of management.

Appendix S2. Worksheet outlining how to prioritize enforcement using scenario 1.