Prioritization of Marine Turtle Management Projects: A Protocol that Accounts for Threats to Different Life History Stages

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Abstract
Project prioritization protocols are an important tool for allocating conservation resources efficiently, and have been applied to a range of species and ecosystems. Current approaches are inadequate when applied to species with distinct threats impacting different and/or multiple life history stages, such as sea turtles. We develop a model that integrates the benefit of any management project on a population by way of its expected population growth rate, including projects targeting different and/or multiple life history stages. To illustrate its utility, we prioritize projects for investment relevant to Australia’s eastern population of Flatback turtle (Natator depressus). We rely upon expert elicitation to estimate individual benefit parameters, feasibility, and cost, and calculate the cost-effectiveness of each project. The most cost-effective project was not the most feasible, cheapest, or most beneficial. Our approach will help managers make efficient decisions that account for the full range of threats operating on a population.

Introduction
Funding to address the plight of threatened species is grossly inadequate (James et al. 1999; Balmford et al. 2003, 2015). In response, strategic approaches that optimally allocate resources among threatened species projects are increasingly being developed and applied around the world (Master 1991; Joseph et al. 2009; Arponen 2012). However, these approaches do not address distinct threats operating at different and/or multiple life history stages, a critical step for identifying effective management strategies for some species, like marine turtles. There are multiple current and emerging threats to marine turtles, but it is not always clear which threats should be a priority for management (Wallace et al. 2010; Mazaris et al. 2014).

All species of marine turtles have the same general life cycle and spend time both on the beach, as an egg, newly emerged hatchling or nesting female, and in the ocean for the remainder of its life (Figure 1). Threats to marine turtles vary across regions and species, but include fisheries impacts (i.e., incidental capture by fisheries targeting other species), direct take (e.g., excessive loss of eggs to predators and human consumption of eggs and/or turtles), coastal development, pollution, pathogens, and climate change (Wallace et al. 2010; Fuentes et al. 2012; Limpus et al. 2013). Each threat operates on different, and sometimes multiple, life history stages and the

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Figure 1 Lifecycle of a Flatback turtle and associated parameters from our model that estimates the benefit of investing in projects that address threats to different and/or multiple stages in the lifecycle. The images representing three example threats from our case study (fishing, predation of eggs by foxes, and light) are drawn near the parameters that they influence. For example, light pollution impacts the number of clutches laid by an adult female (na) and fraction of hatchings that reach the sea (fs). Individual parameters described in the methods.

relative reproductive value differs across these stages (Bolten et al. 2011). Thus, effective management of marine turtles must consider the full range of threats operating on a population (Chaloupka 2003a; Dethmers et al. 2006; Wallace et al. 2010, 2011).

Conservation funding for turtles, and any species, is inherently limited, thus we should prioritize our investments for their management (James et al. 1999; Balmford et al. 2003). Optimal allocation of funding to different management projects can be determined by considering a project’s benefits, costs, and the likelihood of management success, a parameter that captures operational, legal, political, and social factors (Marsh et al. 2007; Joseph et al. 2009; Carwardine et al. 2012; Fuentes et al. 2015). Yet, such an approach is rarely, if ever, used in marine turtle management. Existing approaches are focused on prioritizing threats, not management projects (see Bolten et al. 2011), or focused on threats to a single life history stage, overlooking the importance of prioritizing management projects that mitigate threats to different and/or multiple life history stages in a turtle’s life (Fuentes et al. 2015). The lack of prioritization approaches is, in part, due to difficulties associated with determining the benefits of a project to different and/or multiple life history stages.

We present a prioritization protocol that can guide decisions about what and where to invest to most cost-effectively protect marine turtles. Novel to our approach is the implementation of a benefit function that can consider the effect of any management project on a turtle population, including projects that address a range of threats to multiple life history stages. The benefits to different life stages are integrated through a formula for the population growth rate. Using information on the benefit, cost, and feasibility of a range of management projects, we apply our prioritization approach to a selection of conservation projects (i.e., management action in a specific place) relevant to Queensland, Australia’s eastern population of Flatback turtles. Without the proposed optimal resource allocation strategy, we risk wasting limited funding for conservation and, more critically, the endangerment of marine turtles.

Methods

Our prioritization approach for marine turtles is based on decision science (Keeney 1982; Bell et al. 1988). Here, we describe the seven general steps of our approach, and discuss how we applied each to our example application for Australia’s East Coast population of Flatback turtles, a vulnerable species under both the Queensland and Federal conservation legislation (Limpus et al. 2013). This particular population represents a modest sized but distinct breeding population for the species, with a majority of its nesting occurring on the continental islands and...
adjacent mainland beaches between 19 and 24° S (Limpus et al. 2013).

For each step, we compiled information from the literature and from people knowledgeable about Flatback turtles in Queensland, Australia. Expert information was obtained both in person through workshops and in writing through an email-based questionnaire. Eleven experts in the biology and/or management of Flatback turtles were invited to participate. Eight of 11 experts participated in an email survey with three review rounds (Table S1).

**Step 1: define conservation objective**

The first step is to define a quantifiable outcome-based objective aimed at maintaining or improving the state (e.g., health) of the species. Our objective was to maximize the average expected number of sexually mature offspring a female turtle produces in her lifetime. We use a timeframe of 2014–2050 as it roughly represents two generations based on the following estimates: (1) the lifetime of a female Flatback turtle is about 30.5 years (Parmenter & Limpus 1995); (2) the reproductive half-life is 10.1 years (Parmenter & Limpus 1995); and (3) females are sexually mature around 15–20 years of age (Limpus 2009; Chaloupka, personal communication). The species and objective were chosen in a workshop focused broadly on conservation prioritization in the Great Barrier Reef (GBR), attended by 20 scientists and managers from 15 different organizations (Supplementary Information). The eastern Australian Flatback population was chosen as it is endemic to Australia, primarily restricted to the GBR World Heritage Area, and is listed as vulnerable on Queensland and Australian legislation (Limpus et al. 2013).

**Step 2: identify threats**

List current and future threats to the turtle species under consideration that can be managed locally. As many global threats cannot be managed at the local scale, we excluded them. For each threat, the life history stage(s) impacted should be identified for use in step 4.

**Step 3: list management projects**

Identify management projects (i.e., management action in a place) that can mitigate each threat. To illustrate the utility and flexibility of our approach for a broad range of projects, we choose a subset of six projects from a larger list identified by experts that represent a range of threats operating on different life history stages in different places in Queensland. We only considered projects where sufficient information were available to estimate project costs (step 5) and feasibility (step 6).

**Step 4: estimate benefit of projects**

Estimate the benefit of each project at achieving the objective. The potential benefit of a project is the difference between its benefit with and without implementation (Joseph et al. 2009; Carwardine et al. 2012),

\[
B_i = R_i' - R_i,
\]

where \( R_i' \) is the benefit parameter under project \( i \) over the time period. \( R_i \) represents what will happen if the project is not implemented. The benefit measure, \( R' \), is an estimate of the average expected number of mature offspring a female turtle produces. The value \( R' \) is determined logically from all stages in the species’ life cycle (Figure 1):

\[
R' = w \left[ \frac{n_i n_s f_0 f_1 f_2 n_s s_0 n_0 s_1}{(1 - s_1) T_i} \right],
\]

where \( n_i \) is the mean number of eggs laid by an adult female in a nesting event, \( n_s \) is the number of clutches laid by an adult female per year, \( f_0 \) is the fraction of clutches that hatch and emerge onto the sand, \( f_1 \) is the fraction of hatchlings that reach the edge of the ocean, \( f_2 \) is the fraction of \( f_1 \) that reach the open ocean, \( s \) is the sex ratio of females to males (e.g., 0.45 if 45% are females), \( s_0 \) is the first year survival rate of hatchlings in the ocean, \( s_1 \) is the annual benthic juvenile survival rate, \( s_2 \) is the annual subadult survival rate, \( n_i \) is the number of years, on average, a turtle is a small subadult, \( n_f \) is the number of years, on average, a turtle is a large subadult, \( n_s \) is the annual adult survival rate, and \( T_i \) is the mean number of years between a female returning to nest (i.e., the “return” time).

If the project does not benefit the entire population, a weighting value, \( w \), is used to indicate the fraction of turtles in the population that benefits from the project. For each project, Limpus (coauthor, personal communication) estimated the fraction of the population that benefits from the project based on his mark and recapture and nesting databases (Table S3). The weighting value could be estimated from other types of data or expert opinion, depending on what is available. Benefit parameters were informed by the literature and experts (Table S3). By increasing individual parameters of \( R' \) by the same proportion, one parameter at a time, we assessed the sensitivity of \( B_i \) to each parameter.

**Step 5: calculate cost of projects**

This step requires information about the cost of each project over its lifetime, including start-up costs and
annual costs. For annual costs incurred over multiple years \((N)\), we determined the present value \((C_i)\) of a series of equal payments over a number of years at the time of cash flow \((t)\) using a discount rate, \(r\), of 2%, such that

\[
C_i = \sum_{i=1}^{N} \frac{C_{\text{annual}}}{(1 + r)^i}
\]

As experts were reluctant to estimate project costs, we estimated project costs using a variety of data, including costs of past management projects (Supplementary Information). For each project, we use the lower, upper, and midpoint costs in the prioritization.

**Step 6: estimate feasibility**

The sixth step requires an estimation of project feasibility \((F_i)\), which includes the probability that it will be successfully implemented and effective, considering operational, legal, political, and social factors, but not management cost (Joseph et al. 2009). For each project, quantitative estimates were elicited from experts using the four-point estimation method described in McBride et al. (2012), which requires each expert to indicate low, high, and “best guess” estimates (between 0% and 100%) and their confidence in the estimate (0–100%). We calculated normalized values using linear extrapolation (Bedford & Cooke 2001) to absolute lower \((\alpha)\) and upper bounds \((\beta)\) within which 100% of all estimates might be expected to fall, such that

\[
\alpha_{abs} = \gamma - (\gamma - \alpha) \left( \frac{c}{\rho} \right) \\
\beta_{abs} = \gamma + (\gamma - \alpha) \left( \frac{c}{\rho} \right)
\]

where \(c\) is the required possibility level (100%), \(\rho\) is the expert’s stated confidence, and \(\gamma\) is their best guess. We use the lower, upper, and midpoint of these in the prioritization. For each project, typically 3–6 experts responded (Table S1).

**Step 7: prioritize projects**

Estimate the cost-effectiveness \((CE)\) of each project, \(i\), defined by:

\[
CE_i = \frac{B_i F_i}{C_i}
\]

Cost-effective projects are the most effective per dollar spent, and are a priority for investment. We rank projects according to cost-effectiveness using midpoint, low, and high cost and feasibility estimates (Table 1, 2). We also compare rankings using our approach with prioritization approaches based on a single parameter (B, F, or C).

**Results**

Experts listed 18 threats (step 2) and over 50 actions (step 3) specific to the turtle population to address the objective (Table S2). The threats can be grouped into the following categories: fishing (e.g., bycatch in nets), clutch depredation (e.g., by foxes), nest destruction (e.g., vehicle traffic on beaches), marine debris, coastal/port development, light pollution, land based run-off, boat strikes, and climate change. Of the actions identified, some were relevant to the entire region, whereas others were only relevant to particular places within the region, and not all experts specified this information. As we required this information about projects, we selected a subset of actions and applied them to specific places, resulting in six projects (Table 2). Some of the projects selected, such as predator management, included several, more specific actions, from the broader list, such as baiting, trapping, shooting, and excluding different types of predators from nests.

We considered a range of cost and feasibility estimates for most projects (Table 2). For an individual project, the highest cost estimate was 2.6–4.4 times larger than the lowest cost estimate. The largest range was for the project “Reduce the glow” as costs that considered both with and without savings on the electricity bill were estimated (Supplementary Information). We relied upon experts’ best guess for the individual parameters within the benefit function (Table S3) that required expert input (Table 2). A basic sensitivity analysis of the benefit function revealed that \(R\) is most sensitive to survival rates, \(s_o\), \(s_i\), and \(s_s\), respectively.

Using the project benefit, midpoint feasibility, and midpoint cost, we calculate the cost-effectiveness of each project and rank them in order of their priority (Table 1). We also rank each project according to the low and high values for both cost and feasibility (Table 2) and find that the three highest ranked projects remain constant across all three cost-effectiveness rankings (Table 1). The total cost of funding the top three projects based on midpoint costs is approximately AUD $146 million; we use this budget to determine which projects would be funded if ranked by benefit, cost, or feasibility alone.

We found little concordance among ranks produced using cost-effectiveness and other approaches (e.g., rankings based on individual parameters, such as cost) (Table 1). For example, if the prioritization is based solely on benefit or feasibility, only one project (C: reduce runoff) would be fully funded with the same budget ($146 million) that funded three projects using cost-effectiveness. Similarly, if the prioritization is based solely on cost, a budget of $146 million would fund four projects (A, B, D, and F), but the project benefit would be only
Table 1  Comparison of priorities determined using different approaches

| Project               | Rank, CE midpoint | Rank, CE low | Rank, CE high | Rank, B | Rank, cost midpoint | Rank, feasibility midpoint |
|-----------------------|-------------------|--------------|---------------|---------|---------------------|----------------------------|
| Reduce glow           | 6                 | 5            | 6             | 5       | 4*                  | 3                          |
| Manage predators      | 1*                | 1*           | 1*            | 4       | 2*                  | 2                          |
| Reduce runoff         | 2*                | 2*           | 2*            | 1*      | 5                   | 1*                         |
| Protect land          | 5                 | 6            | 4             | 3       | 3*                  | 6                          |
| Buyout fisheries      | 4                 | 4            | 5             | 2       | 6                   | 4                          |
| Shade nests           | 3*                | 3*           | 3*            | 6       | 1*                  | 5                          |

We compare rankings on the basis of (1) cost-effectiveness (midpoint cost and feasibility); (2) cost-effectiveness (low cost and feasibility); (3) cost-effectiveness (high cost and feasibility) (4) benefit; (5) cost (midpoint); and (6) feasibility (midpoint). Higher cost-effectiveness, benefit, and feasibility, and lower cost, were assigned a higher rank. Full project names are detailed in Table 2. *Project fully funded using a fixed budget of $146 million AUD, based on midpoint costs for all projects and approaches.

Table 2  Benefit, cost, and feasibility estimates for six example management projects used to demonstrate our prioritization approach

| Project                                                                 | Benefit | Cost range (millions AUD) | Feasibility range |
|------------------------------------------------------------------------|---------|---------------------------|------------------|
| A: Reduce the glow during nesting season w/in 20 km of Woongarra Coast  | 0.017   | 10.7–47.1                 | 46.7–79.8        |
| B: Manage (trap, bait, and shoot) foxes, feral pigs, and dogs at Curtis Island | 0.050   | .814–2.81                 | 58.5–82.2        |
| C: Reduce suspended sediment from Fitzroy river by 20% by 2020          | 3.42    | 61.6–225.7                | 63.1–90.9        |
| D: Protect freehold and lands lease land (295 km²) from coastal development on Curtis and Facing Islands | 0.076   | 28.4                      | 16.7–46.0        |
| E: Buyout 50% of trawling and gillnet fishing licenses in GBR            | 0.462   | 100.0–258.4               | 24.7–48.0        |
| F: Artificially shade 1,000 nests at Wild Duck Island                   | 0.007   | 0.610                     | 19.2–49.5        |

17% of the benefit when cost-effectiveness is used to prioritize.

Discussion

The field of decision science provides information and tools to ensure that conservation prioritizations deliver objective, defensible, and efficient decisions. Cost-effectiveness analyses are increasingly being used to inform conservation problems, ranging from threatened species management (Joseph et al. 2009; Carwardine et al. 2012) to coral reef conservation (Klein et al. 2010) to marine water quality improvement (Star et al. 2013; Beher et al. 2016). This article makes a substantial contribution to the field as it presents a demographically motivated benefit function that can be used in cost-effectiveness analyses that is able to account for threats to a species that operate on different and/or multiple life history stages. Our benefit function addresses one of several possible objectives relevant to turtle conservation; other objectives may require the development of a different benefit function for use in prioritization.

The purpose of this article is to present a novel prioritization approach, not to instruct management for Flatback turtles. Although we considered plausible management projects for Flatback turtles, a more extensive assessment that considers more threats and projects would be required to inform decisions in a particular location or for a specific population. We acknowledge that cost estimations may not represent the true costs of implanting each project, which may require more resources and/or implementation for a longer time period. The selection of projects that we feature here does not necessarily represent the most important or relevant projects for Flatback turtles—they were chosen to demonstrate how our demographic benefit function can be applied to projects at different scales, in different places, and at different and multiple life history stages. Regardless the result that the highest ranking project using our approach (manage predators) was not the project with the largest benefit, smallest cost or highest feasibility highlights the importance of considering three critical factors in a cost-effectiveness analysis to prioritize conservation decisions when limited resources are available.

Our approach relies on data elicited from experts, as empirical data to inform all aspects of our approach were unavailable. Although using expert opinion is common in conservation (Joseph et al. 2009; Game et al. 2011;
Carwardine et al. 2012; McBride et al. 2012), our model used to predict the benefit of projects is particularly reliant upon expert opinion as empirical data (Figure 1). We initially planned to obtain expert opinion solely through an email questionnaire, following guidance from McBride et al. (2012). However, the responses to the questionnaire were incomplete and inadequate to test our prioritization approach. We followed up on the questionnaire through in-person workshops and phone conversations. We suggest that future applications requiring expert elicitation be done in person, but acknowledge that this approach can introduce biases and be more costly than email questionnaires (McBride et al. 2012). Further, in some steps (e.g., step 6, estimate feasibility), we asked experts to estimate a range of values as way of capturing their uncertainty. However, we do not know about the uncertainty of information gathered in step 4 (estimate benefit) and suggest that it be better understood in future applications of our prioritization approach.

Although the collection of empirical data to inform our approach is possible, it will be costly and will take several years, likely decades, to gather. The risk of waiting for empirical data is that the species could decline to critically low numbers (Martin et al. 2012). It is important that decisions be made with data from experts, validated, and then adapted as new information becomes available (Holling 1978; Walters 1986). Conducting a value of information analysis (Runge et al. 2011; Canessa et al. 2015) on our approach would determine whether it is worth the time and money to gather new data relative to acting now and investing all our resources in that action. A sensitivity analysis revealed that $R$ is most sensitive to survival rates. As survival rates are often uncertain for many migratory species, an analysis (e.g., using information-gap theory) investigating the impact this uncertainty has on the outcome is an area of further research (Regan et al. 2005). However, this does not mean that investment in reducing uncertainty in those parameters represents the best investment. A rigorous sensitivity analysis of project ranks with respect to new information, where all 13 parameters are systematically and/or simultaneously varied according to the cost of information gain, would be useful in helping managers make robust decisions (Wilson et al. 2015). Improving data for decision-making is not worthwhile unless there is some chance that it will change the management decision (Grantham et al. 2008).

Our demographic benefit function assumes a closed population, where immigration and emigration do not occur. Although the East Coast population of Flatback turtles is essentially restricted to the GBR World Heritage Area, this spatial restriction does not occur for all turtle species (Bolten 2003; Plotkin 2002). To apply our approach to other turtle species with broader geographic ranges, the parameters in the benefit function that impact the posthatching through subadult stages would need to be modified to account for within species spatial variation. Similar modifications to the benefit function would be required to apply our approach to the prioritization of projects to multiple species (Joseph et al. 2009). However, because the breeding and/or foraging distributions of many marine turtle stocks can span international boundaries, the development of these steps and implementation of the results would likely require coordination and participation by multiple countries. This would be possible because the distribution of turtles and their stock boundaries is often reasonably well known (Wallace et al. 2010; Fitzsimmons & Limpus 2014). Plus, although effective conservation of international species is a difficult challenge faced by many conservation initiatives (Beger et al. 2015; Runge et al. 2015), there are several regional marine turtle conservation instruments (e.g., Indian Ocean—Southeast Asian Memorandum of Understanding for the Conservation and Management of marine turtles and their habitats) that could serve as starting points for discussion and collaboration.

Other population models, such as demographically structured population model (Chaloupka 2003b) or stage-structured (or age-structured) matrix population models (Wallace et al. 2008), have also been used to estimate a project’s benefit. These alternative models have their merits as they can account for initial conditions and deliver population growth rates and projections through time. However, they require considerably more information about marine turtle demography than can be accounted here for in this particular study for flatbacks. Our model is simple and is set up in an Excel spreadsheet so that it is accessible to natural resource managers with a range of technical expertise and a basic understanding of demography. We believe that this article will help resource managers to make efficient decisions that account for the full range of threats operating on a turtle population, and ultimately help contribute toward the conservation of threatened marine turtles.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web site.

Table 1. Experts from different backgrounds and industries informed steps 2–6 in our study through an email-based questionnaire (indicated with an asterisk, *) and/or in person, over the phone or in a workshop (indicated with a cross, +).

Table 2. Actions identified by experts to address general threats to Flatback turtles in Queensland.

Table 3. Individual parameters used to estimate the benefit, \( B_i \), of the six example projects used in the case-study.

Table 4. Start-up and annual costs of managing pests on Curtis Island for the Queensland Parks and Wildlife Services.

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