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ORIGINAL PAPER

Estimating realistic costs for strategic management planning of invasive species eradications on islands

Amelia S. Wenger · Vanessa M. Adams · Gwenllian D. Iacona · Cheryl Lohr · Robert L. Pressey · Keith Morris · Ian D. Craigie

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Abstract Environmental managers regularly face decisions about how to counteract threats. These decisions require an understanding of both the conservation benefits and economic costs of candidate actions. However, transparent frameworks for how to accurately calculate costs for management are rare. We worked with island managers in Australia to develop eradication protocols for six invasive species-four mammals and two weeds. We used the protocols to create an accounting framework for invasive species eradications to produce realistic cost estimates for eradications across multiple locations. We also used our models to test common cost assumptions: (1) that costs scale linearly with area, (2) that terrain does not influence costs, and (3) that eradication costs stay constant through time. By explicating testing assumptions, we found that costs largely scaled linearly with area, that terrain influences costs, and that costs decline as populations decline in response to ongoing management. Estimated mammal eradication costs were driven in large part by the area of an island and the cost of transport. However, when area alone was used as a proxy for costs, the calculated costs deviated from our modelled costs by 40–56%. Weed

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A. S. Wenger (✉) · R. L. Pressey · I. D. Craigie
ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia
e-mail: amelia.wenger@gmail.com

R. L. Pressey
e-mail: bob.pressey@jcu.edu.au

I. D. Craigie
e-mail: craigie.ian@gmail.com

A. S. Wenger
School of Earth and Environmental Sciences, University of Queensland, St. Lucia, QLD 4072, Australia

V. M. Adams
School of Biological Sciences, University of Queensland, St. Lucia, QLD 4072, Australia
e-mail: v.adams@uq.edu.au

G. D. Iacona
ARC Centre of Excellence for Environmental Decisions, Centre for Biodiversity and Conservation Science, School of Biological Sciences, University of Queensland, St. Lucia, QLD 4072, Australia
e-mail: g.iacona@uq.edu.au

C. Lohr · K. Morris
Animal Science Program, Science and Conservation Division, Western Australia Department of Biodiversity, Conservation and Attractions, Woodvale, WA 6026, Australia
e-mail: Cheryl.lohr@dpaw.wa.gov.au

K. Morris
e-mail: Keith.Morris@dpaw.wa.gov.au

eradication cost estimates were driven by the size and density of an infestation as well as the terrain of the island, with the effect of terrain becoming more pronounced as area to be treated increased. We provide a method to calculate realistic costs across several sites, which can be used to guide strategic management decision-making, including prioritisation, and on-ground management actions.

Keywords Conservation planning · Invasive species management · Prioritisation · Conservation costs · Island management

Introduction

Biodiversity loss continues at an alarming rate (Butchart et al. 2010; Vitousek et al. 1997) and invasive species are one of the primary threats to biodiversity persistence (Butchart et al. 2010; Duncan et al. 2013; Ehrenfeld 2010). Island ecosystems have a disproportionate share of global terrestrial biodiversity but have suffered heavily from introductions of invasive species (Brooke et al. 2007; Courchamp et al. 2003; Kier et al. 2009; Medina et al. 2011). The high biodiversity value of islands is largely a result of their isolation, but this also makes them candidates for successful invasive species eradications, restoration, and protection from the arrival of threats (Brooke et al. 2007; Helmstedt et al. 2016; Towns and Ballantine 1993). While there are many examples globally of successful eradications and subsequent recoveries of native species (Clout 2001; Courchamp et al. 2003; Jones et al. 2016), failures of eradication campaigns still occur (Holmes et al. 2015b; Simberloff 2009). Two of the most commonly identified reasons for eradication failure are poor planning and insufficient funding (Broome et al. 2002; Keitt et al. 2015; Myers et al. 2000; Simberloff 2009; Simberloff et al. 2005). These problems are confounded because good planning is impossible without a knowledge of how much the intervention should cost.

The costs associated with invasive species control or removal must be carefully estimated to ensure the most cost-effective approach is implemented and the medium- to long-term implications for budgets and native species are well understood (Adams and Setterfield 2016; Firn et al. 2015). Otherwise, identified priorities for action may be misleading. Unfortunately, apart from general guidelines (Keitt et al. 2015; Simberloff 2009), there is limited literature detailing how to plan and budget for invasive species management, especially across multiple sites. A detailed and fine-resolution cost accounting model is necessary for future research to incorporate realistic costs of management into strategic planning for on-ground actions to manage invasive species across many different sites (Donlan and Wilcox 2007; Donlan et al. 2015).

Due to the complexities of costing out diverse management actions across many sites, several authors exploring costs in invasive species management or restoration activities have relied on either simple estimates of costs, costs extrapolated from other regions, or proxies for cost data, including area, remoteness, and landscape condition (Evans et al. 2015; Holmes et al. 2015a; Lohr et al. 2015; Martins et al. 2006; Murdoch et al. 2007; Wilson et al. 2007). Additionally, the assumption is often made that the costs of reducing invasive species are constant over time, even though reductions in density or abundance of those species in response to management will occur (Armsworth 2014; Donlan et al. 2015; Evans et al. 2015; Holmes et al. 2015a). Finally, in the conservation planning literature, many authors use low-resolution (continental or global scale) hypothetical cost models to conduct theoretical exercises about how incorporating cost information can influence conservation decisions; often with the caveat that costs should not be taken as realistic estimates (Cunningham et al. 2004; Helmstedt et al. 2016).

The use of hypothetical costs or cost proxies means that conservation decisions based on the resulting estimates could be inaccurate (Armsworth 2014; Donlan and Wilcox 2007) and contribute to the research-implementation gap noted in two-thirds of conservation assessments (Knight et al. 2008). When assumptions are violated at the high resolution at which management actions occur, cost estimates based on them will inflate or deflate the actual cost of undertaking management (Armsworth 2014; Sutton and Armsworth 2014). If poorly estimated costs result in projects being underfunded, this will lead to interruptions in management due to insufficient funds (Simberloff 2009). For certain management actions, this would lead not only to a waste of limited resources but also to failure to meet conservation objectives

(Myers et al. 2000). Inaccurate costs will also lead to mistakes in identifying priorities for actions in space and time. Despite the potential for assumptions about costs to substantially alter planning outcomes, explicit tests of these assumptions are rare in the literature.

In this study we developed a framework for comprehensively estimating management costs that are appropriate for informing invasive species management planning. The framework was developed in collaboration with managers who would be relying on the cost models embedded in a new decision-support tool to allocate priorities for management actions. First, we drew on best-practice in invasive species management to develop species-specific eradication protocols. Second, we formulated comprehensive cost models for each step of the eradication protocols. We used our models to estimate the costs of invasive species management across 601 islands in Western Australia, as a case study. We then tested common assumptions about costs found in the conservation literature. Our framework outlines common invasive management activities undertaken at different points across the management cycle (e.g. pre-eradication planning, eradication implementation). It therefore relates directly to the management work planning with which on-ground managers are familiar. This means that the framework translates across island contexts and can be used to estimate invasive species eradication costs relating to specific invasive species eradication projects.

Methods

Study region

Our study region was a large group of islands off the Pilbara coast of Western Australia. The region has 601 islands in a 30,000 km^2 marine expanse. The islands have a total area of 68,780 ha, ranging in size from 0.002 to 23,569 ha, with most (591) smaller than 1000 ha. The Pilbara islands support several threatened species. Currently, there are 89 islands known to have at least one of the invasive species examined here, with more expected as the region continues to develop (Lohr et al. 2017). There has been renewed focus on management in the region due to several large scale industrial projects over the past several years. The cost data generated in this study will be used to prioritise management actions on the Pilbara Islands as part of a collaborative project between James Cook University and the Western Australian Department of Parks and Wildlife, hereafter “Parks and Wildlife”. The project is also developing conservation planning decision-support software to prioritise invasive species eradications that maximise conservation benefit for a limited budget (Brotankova et al. 2015), which will use the cost model we describe here.

Identification of management needs and actions

Over the course of three expert workshops held in Western Australia in November 2014, April 2015, and March 2016, eradication protocols for invasive species eradication were developed to provide a useful tool to managers wishing to cost out on-ground invasive species eradication programs to inform budget requests and to strategically plan eradication campaigns. Workshop participants included personnel from Parks and Wildlife and consultants with experience in the region’s biodiversity and threatening processes. During the workshops, we identified six invasive species that are serious threats for native priority species. The invasive that were identified through this process were black rats (*Rattus rattus*), house mice (*Mus musculus*), cats (*Felis catus*), foxes (*Vulpes vulpes*), buffel grass (*Cenchrus ciliarus*), and bellyache bush (*Jatropha gossypiifolia*).

Workshop participants then identified applicable eradication protocols (Table 1), defined here as specific sequences of actions that could be used to eradicate invasive species, including step-by-step description of best-practice from the planning stages to a declaration of a successful eradication. Each step was treated as an action. Managers estimated both the time requirements for each action and the frequency with which each action would occur. To augment and refine the eradication protocols, we also searched published and grey literature, including government reports and invasive species databases, to compile information about best management practices for eradication of each invasive species.

Our goal in developing the framework was to provide a strategy for estimating costs that provided enough detail to guide priorities in field management but was general enough to be easily calculated by managers and transferable to other management decisions that require more accurate cost information.

Table 1 Management eradication protocols for invasive species

Eradication protocol	Actions	Days required (not including time in transit)	Minimum personnel required	Number of trips required per year	Years committed	Start year	Transport	Travel costs (average cost of action)	Labour costs (average cost of action)	Consumable costs (average cost of action)
Cat eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel	$51,926	$7422	NA
Cat eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None	NA	$24,000	
Cat eradication	Aerial baiting	Number of days required to bait island	1	1	1	1	Fixed wing	$714	$528	$84
Cat eradication	Trapping	Fixed rate (see Online Resource 1 for details)	5	1	1	1	Charter vessel	$39,244	$57,666	Not calculated
Cat eradication	Post-eradication monitoring	Terrain penalty × person days per ha × island size	2	1	2	2	Charter vessel	$103,852	$14,844	NA
Total costs								$195,736	$104,460	$84
Rat eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel	$51,926	$7422	NA
Rat eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None	NA	$24,000	NA
Rat eradication	Aerial baiting	Number of days required to bait island	1	2	1	1	Helicopter	$1586	$1650	$5512
Rat eradication	Post-eradication monitoring	Terrain penalty × person days per ha × island size	2	1	2	2	Charter vessel	$103,852	$14,844	NA
Total costs								$157,364	$47,916	$5512
Mouse eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel	$51,926	$7422	NA
Mouse eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None	NA	$24,000	NA
Mouse eradication	Aerial baiting	Number of days required to bait island	1	1	1	1	Helicopter	$1750	$1588	$11,028
Mouse eradication	Post-eradication monitoring	Terrain penalty × person days per ha × island size	2	1	2	2	Charter vessel	$103,852	$14,844	NA
Total costs								$157,528	$47,854	$11,028
Fox eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel	$51,926	$7422	NA
Fox eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None	NA	$24,000	

Table 1 continued

Eradication protocol	Actions	Days required (not including time in transit)	Minimum personnel required	Number of trips required per year	Years committed	Start year	Transport	Travel costs (average cost of action)	Labour costs (average cost of action)	Consumable costs (average cost of action)
Fox eradication	Aerial baiting	Number of days required to bait island	1	1	1	1	Fixed wing	$714	$528	$84
Fox eradication	Shooting	Fixed rate (see Online Resource 1 for details)	2	1	1	1	Charter vessel	$39,244	$26,865	Not calculated
Fox eradication	Post-eradication monitoring	Terrain penalty × person days per ha × island size	2	1	2	2	Charter vessel	$103,852	$14,844	NA
Total costs								$195,736	$73,659	$84
Buffel grass eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel	Calculations are infestation size dependent. See Sect. ''Assumption two—eradication costs will remain the same regardless of the terrain on which it occurs'' for more details.		
Buffel grass eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None			
Buffel grass eradication	Hand spraying	Terrain penalty × person days per ha at density level × infestation size	2	7	4	1	Charter vessel			
Buffel grass eradication	Post-eradication monitoring	Terrain penalty × person days per ha × infestation size	2	1	2	5	Charter vessel			
Buffel grass eradication	Revegetation office planning	0.3 FTE	1	0	1	5	None			
Buffel grass eradication	Revegetation	Infestation size × person days per ha	2	1	1	5	Charter vessel			
Bellyache bush eradication	Pre-eradication field planning	Terrain penalty × person days per ha × island size	2	1	1	1	Charter vessel			
Bellyache bush eradication	Pre-eradication office planning	0.3 FTE	1	0	1	1	None			
Bellyache bush	Hand spraying	Terrain penalty × person days per ha at density level × infestation size	2	2	6	1	Charter vessel			
Bellyache bush eradication	Post-eradication monitoring	Terrain penalty × person days per ha × infestation size	2	1	2	5	Charter vessel			
Bellyache bush eradication	Revegetation office planning	0.3 FTE	1	0	1	5	None			
Bellyache bush eradication	Revegetation	Infestation size × person days per ha	2	1	1	5	Charter vessel			

Each eradication protocol details the specific sequence of actions to conduct eradications of the listed invasive species. Terrain penalty refers to the incorporation of island terrain into estimates of time required to traverse an island

The cost estimates we calculate are specific to the location, but the process of getting them is what we have made transparent and comparable across studies. As such, we defined actions within eradication protocols including: (1) pre-eradication field planning, (2) pre-eradication office planning, (3) the eradication activity (e.g., aerial baiting, hand spraying), and (4) post-eradication monitoring. Weed eradication had two additional actions: (5) revegetation office planning, and (6) revegetation. We defined six eradication protocols (Table 1), two for invasive plants, and four for invasive mammals. Our eradication protocols strongly aligned with reported management approaches reported within the literature, emphasising the transferability of our framework and protocols across contexts (Algar et al. 2002; Armstrong 2004; Bell 2002; Broome et al. 2002, 2014; Campbell et al. 2011; Dixon et al. 2002; Keitt et al. 2015; Marshall et al. 2012; McLeod et al. 2011; Nogales et al. 2004; Tjelmeland et al. 2008). The framework we have developed here can be modified to suit different scenarios, since it demonstrates a method to breakdown costs into clearly defined components.

Estimating the costs of actions

The cost models we developed follow an accounting framework with each of the broad cost components being broken down into parameters that would be found on an itemised budget. All equation variables are defined in Table 2. The relationship between cost components, actions, and eradication protocols are outlined in Fig. 1.

We categorised costs into four broad components: travel costs (T), labour time (L), consumables (C), and equipment (E). For each expenditure, we engaged in extensive consultation with contractors in the region to obtain accurate and realistic costs. While the eradication protocols of how managers undertake eradications are based on expert information and best practice in the literature, the costs are based on actual quotes received from contractors who provide services in the regions, companies that sell consumables, and salary rates within the Department of Parks and Wildlife. Full details on the sources of all of the costs are found in Table 3. For all of the different cost equations, we used an accounting framework consistent with how managers and contractors would generate quotes for the costs of specific management activities. In order to ensure we were incorporating the correct information needed to calculate accurate costs and develop a budget, the equations for each of the four components were reviewed by the relevant personnel, and modified as needed. Detailed information is provided in the Online Resource 1. The total cost of each action (A_s) was the sum of the four broad cost components, multiplied by number of trips per year (X) and number of years required (Y):

$$A_{S=}(T + L + C + E)XY \tag{1}$$

The overall equation for the cost of each eradication protocol (A) was the sum of its component actions (Fig. 1):

$$A = \sum A_s \tag{2}$$

Travel costs

Travel costs were split by types of transport because their respective costs can differ markedly. The options for our study region were flying (F) or boating (B), resulting in T = F + B:

The costs of flying (helicopter and fixed-wing airplane) were calculated as:

$$F = 2F_c\left(\frac{D_b}{S_f}\right) + F_c\left\{\frac{\left(\frac{I_s}{t}\right)}{S_a}\right\} + 2F_c\left(\frac{D_i}{S_f}\right) \times \left(\frac{1}{R}\right) \times \left\{\frac{\left(\frac{I_s}{t}\right)}{S_a}\right\} \tag{3}$$

The flying cost depended on an hourly helicopter/plane charge (F_c), the distance from the aircraft base to the operations centre for the eradication (D_b), distance from operations centre to management site (D_i), the travel speed of the helicopter/plane (S_f), the maximum running time of the aircraft (R), working speed of aircraft (S_a), size of area to be treated (I_s), and distance between transects (t). The first term indicates the cost of bringing the aircraft from its base to the operations centre. The second term is the cost of implementing an aerial action across an entire island. The third term is the cost of transit between the base of operations and the island, multiplied by the number of trips required to bait the island which has to be greater than or equal to 1.

The total time required for a charter vessel (B_t) was calculated as:

Table 2 The definition of variables used in cost equations and common sources of the information in parentheses where applicable

Variables	Unit	Definitions
A	NA	Eradication protocol
A_s	NA	Action
A_m	litres/ha; grams/ha	Application rate (chemical manufacturer information sheets)
A_t	NA	Terrain penalty (freely available digital elevation model)
B	Dollars	Cost of hiring charter vessel (charter vessel operator)
B_c	Dollars/day	Daily rate of charter vessel (charter vessel operator)
B_t	Days	Time required for charter vessel (calculated with equations)
C	Dollars	Consumables
C_m	Dollars/litre Dollars/gram	Chemical cost per application rate (Chemical supply companies)
d	plant coverage/ha	Weed density (GIS or survey estimates)
D_b	Kilometres	Distance from aircraft base to operations centre for the eradication (aircraft operator and GIS)
D_i	Kilometres	Distance from operations centre to island (GIS)
E	NA	Equipment
F	Dollars	Costs of flying (aircraft operator)
F_c	Dollars/hr	Hourly aircraft charges (aircraft operator)
I_s	ha	Island size (GIS)
L	Hours; days	Labour time (calculated with equations)
L_d	Dollars/day	Daily labour rate (management agency)
P_d	NA	person days required per hectare (calculated with equations)
P_r	NA	Personnel required per trip (management agency)
R	Hours	Maximum running time of the aircraft (aircraft operator)
S_a	Km/hour	Speed of aircraft during baiting (extracted from literature and listed in Online Resource 1)
S_b	Km/hour	Speed of charter vessel (charter vessel operator)
S_f	Km/hour	Travel speed of aircraft (aircraft operator)
T	NA	Travel
t	Kilometres	distance between baiting transects (extracted from literature and listed in Online Resource 1)
X	NA	Action repeats per year (extracted from literature and listed in Table 1)
Y	NA	Number of years over which the action is required (extracted from literature and listed in Table 1)

$$B_t = 2\left(\frac{D_i}{S_b}\right) + \left(\frac{P_d}{P_r}\right) I_s \quad (4)$$

The transit time required depends on the distance from the base of operations to the management site (D_i), the speed of the charter vessel (S_b), size of area to be treated (I_s), and the person-days required to implement an action per hectare (P_d), and personnel used per trip (P_r). Table 1 shows the minimum personnel required for each action in the study region. The time requirements (B_t) and the daily rate of the charter vessel (B_c) were used to calculate the cost of hiring a charter vessel (B):

$$B = B_t B_c \quad (5)$$

Labour costs

The cost of labour when using a helicopter or plane to fly to an island was calculated as:

$$L = P_r L_d \left(2\frac{D_i}{S_f}\right) \times \left(\frac{1}{R}\right) \times \left\{\frac{\left(\frac{I_s}{t}\right)}{S_a}\right\} \quad (6)$$

This represents the personnel required per trip (P_r), the daily labour rate (L_d), and the number of trips required to implement an action across an entire site.

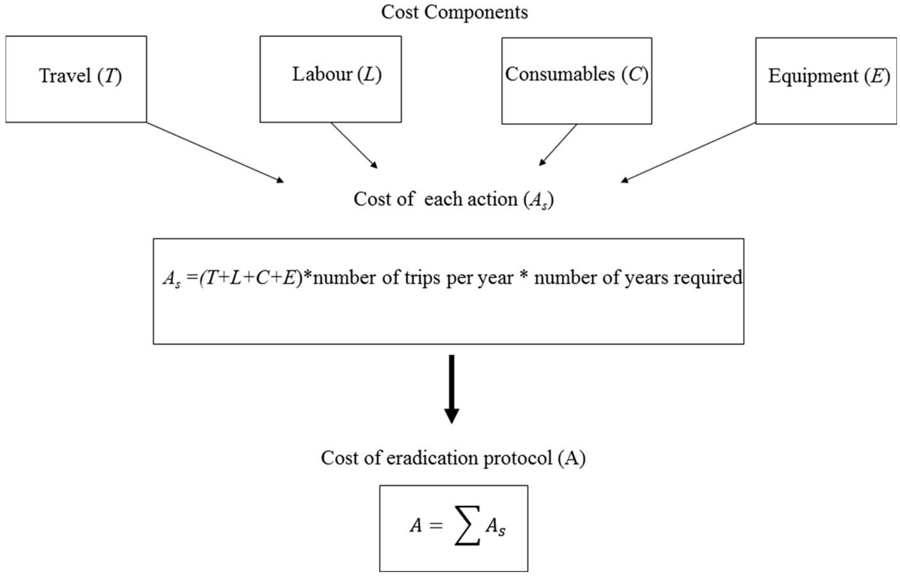


Fig. 1 Schematic diagram of the relationship between cost components, actions, and eradication protocols

Table 3 The source of cost information for budget items

Budget item	Source
Helicopter rates, travel speed, location of base, and running time	Charter helicopter company in the region that has been previously contracted to conduct work for the department
Airplane rates, travel speed, location of base, and running time	Charter airplane company in the region that has been previously contracted to conduct work for the department
Charter boat rates and travel speed	Charter boat company in the region that has been previously contracted to conduct work for the department
Daily labour rate	Department of Parks and Wildlife hourly rates for an individual conducting on the ground eradication work
Chemical costs and application rates	Chemical supply companies in the region. Bulk prices were obtained where possible; Application rates were obtained from management plans, literature sources, and chemical manufacturers' product use information sheets

The cost of labour when using a charter vessel was calculated as:

$$L = I_s L_d \left(\frac{P_d}{P_r}\right) + 2\left(\frac{D_i}{S_b}\right) P_r L_d \quad (7)$$

The cost of labour when undertaking pre-eradication field planning and post-eradication monitoring was calculated as:

$$L = I_s A_t L_d P_r P_d + 2L_d \left(\frac{D_i}{S_b}\right) P_r L_d \quad (8)$$

The daily rate for labour costs was provided by Parks and Wildlife. In order to calculate person days per hectare (P_d) we needed to determine how much time would be required to walk an island while undertaking an activity that required personnel to periodically stop. We used an internal Parks and Wildlife report about the time it took to hand bait a flat island in the study region (Bedout Island) to calculate the amount of surveillance that can be completed per person, assuming that the action of hand baiting would reasonably reflect the time to undertake pre-eradication field planning. The person-days per hectare (P_d) is estimated at 0.07 days, based on baiting on Bedout Island which took 3 person-days for 41.3 ha (Department of Conservation 1982). This strategy was endorsed by Parks and Wildlife personnel.

Additionally, we needed to consider how terrain would influence costs. Terrain can drive variations in invasive species eradication costs during any action that requires personnel on the island, including pre-eradication field planning for any invasive species eradication, treatment of weeds, re-vegetation, and post-eradication monitoring following any invasive species eradication (van Wilgen et al. 2016). Additionally, the effective area that needs to be treated changes depending on the terrain of an island, thus affecting the amount of herbicide or bait required. Therefore, to account for variations in terrain, we derived island surface area from 30 m Digital Elevation Model (DEM) using the ArcMap (v.10.2.1) extension tool DEM Surface Tools (Jenness 2006) and the Zonal Statistics as Table tool. We then calculated a surface area/planar area ratio which we used as a penalty rate (A_t). For two islands with the same planar area, but one is a flat cay and the other a rugged, rocky island, the second island could have, for example, 1.5 times the surface area and all area-related costs would be 50% greater than the first island.

The cost of labour when undertaking hand-spraying of weeds was calculated as:

$$L = I_s A_t L_d P_r (0.0193d + P_d) + 2L_d \left(\frac{D_i}{S_b}\right) P_r L_d \qquad (9)$$

The density of a weed infestation (d) was incorporated into estimates of necessary person-days per hectare needed to treat an infested area (I_s). To determine how density would influence timing, we used information from previous studies on time require for weed treatment to calculate a linear relationship between density of a grass species that was hand sprayed and person-days required to treat it (see Online Resource 1). The assumption of a linear relationship was based on in situ calculations performed by the Working for Water program in South Africa (South African Department of Environmental Affairs). This equation allowed us to vary management costs as weed density declined in response to management.

Consumable costs

The cost of consumables was calculated as:

$$C = A_m C_m I_s A_t \qquad (10)$$

The cost of consumables depends on the application rate (A_m; i.e., litres of herbicide per hectare or bait per hectare), the cost of chemicals per application unit (C_m, i.e., \$/litre), and site size. Weed density did not change the amount of herbicide required as it was indicated by the managers that pre-emergent herbicide would be sprayed in areas without visible weed growth. The costs and application rates are listed in Online Resource 2.

Equipment costs

Equipment costs were fixed for each action regardless of site size (Online Resource 1).

Number of trips per year and number of years required

For the mammal eradications, the literature and the advice from managers was clear on the time requirements. For the weed species, we used the time to maturation to determine the number of times in a year that a weed had to be treated. We used the duration of the seedbank to determine the number of years that treatment needed to continue in order to eradicate the species (Flint and Rehkemper 2002). The growth of buffel grass was triggered by rainfall events, therefore the number of field trips per year is based on the number of rainfall events per year. The daily rainfall data for the entire Pilbara region for 10 years was sourced from the Australian Bureau of Meteorology and the number of rainfall events above 20 mL were counted (www.bom.gov.au). This volume represented the amount of rain experts stated was needed to trigger weed growth. Multiple rainfall events within a week were considered one event. Information on plant maturation and seedbanks are listed in Online Resource 3.

Testing assumptions about costs

We explored how are cost estimates which are based on multiple cost components compare to cost estimates using three common assumptions made about conservation costs.

Assumption one—eradication costs scale linearly with area

The assumption that eradication costs scale linearly with area implies that island area is a sufficient proxy to capture any variability in transport, labour, or consumables that occur across islands of different size, terrain, and distance from the base of operations. To test this assumption, we used a generalised linear model to assess the significance of island area, terrain, and distance from base of operations in explaining variations in total cost of invasive fauna eradication across all islands as calculated by our comprehensive cost models. While this assumption could also be tested with weed eradication campaigns, we would have had to set weed infestation densities and extent. Given that mammal eradications require whole islands to be searched during pre-eradication field planning, baiting, and post-eradication monitoring, we could better assess the influence of island area on costs using mammal eradications as an example. The model was generated using the glm function in the R package lme4 (Bates et al. 2014). We tested this assumption with invasive fauna (rat, mouse, cat, and fox), because the costs of eradicating invasive flora depend on the size of the infestation, information that does not exist for our study region, whereas fauna eradications occur across whole islands. We then used the predicted linear fit of the relationship between island area and cost of eradication (i.e., the linear regression line) to estimate the theoretical cost of invasive fauna eradication across all islands based on area alone. Paired t-tests were then conducted to assess the variation between cost estimates that account only for island area and cost estimates using our comprehensive cost models that account for variations in transport, labour, and consumables costs.

Assumption two—eradication costs will remain the same regardless of the terrain on which it occurs

To test this assumption, we modelled the cost of one year of an eradication campaign for a buffel grass (*Cenchrus ciliaris*) infestation ranging from 1 to 25 hectares on two islands using our cost models: Island A, an island where surface area and planar area are equal (i.e. a completely flat island), and Island B, an island where the surface area to planar area ratio is 2. To compare how much the two scenarios deviated from each other we conducted a paired t test. The assumption tested here would equally apply to belly-ache bush and other weeds eradication through spraying. This assumption could similarly be tested with the on-island actions of mammal eradication protocols, however islands of similar sizes but different terrains would need to be compared.

Assumption three—reductions in weed density in response to management do not influence costs

To test the third assumption, we estimated the cost of a buffel grass eradication under two scenarios: (1) buffel grass density was not factored into calculations of person-days per hectare, meaning that weed density was assumed to remain constant throughout the treatment [i.e., we did not use Eqs. (10) and (2)] the declining buffel grass density as treatment proceeded was incorporated into calculations of person-days per hectare required to treat the buffel grass infestation (Eq. 10), which is a common real-world situation (Adams and Setterfield 2013; McMaster et al. 2014). For both scenarios, we assumed that the eradication was taking place on a low-lying cay with 20 ha of buffel grass at a starting density of 100%. For scenario 2, we assumed that buffel grass density declined linearly at a rate of 25% per year as treatment proceeded. The eradication protocol for buffel grass recommends treatment 7 times each year for 4 years. We assumed that each team still had to walk the entire infestation area for each treatment. We excluded pre-eradication planning and post-eradication monitoring costs because they would be the same for both scenarios. To compare how much the two scenarios deviated from each other we conducted a paired t-test.

Results

Management needs and actions

Cost of actions

The eradication costs estimated using our framework provided detailed data that could support eradication campaigns for the Pilbara islands. These data will be used in a later study to inform management priorities, but we provide summaries here of relevant cost comparisons. All reported costs refer to the 2016 value of Australian dollars (AUD). Average costs of each eradication are listed in Table 1. We report here only the cost of invasive fauna eradication.

Estimated rat eradication costs varied across islands from \$34,134 to \$2,512,717 (Fig. 2a). The primary cost component driving these costs was transport, which accounted for $70 \pm 0.4\%$ of the total costs (mean $\pm$ SE; Fig. 3a). Labour costs accounted for

28 ± 0.5% of the total costs. However, in some instances, the labour costs exceeded the transport costs (Fig. 3a). The cost of consumables, although ranging from $0.40 to $290,399, accounted for only 1.2 ± 0.15% of the estimated total costs, on average (Fig. 3a).

Despite mouse eradications requiring twice as much bait and double the transects during baiting as rat eradication (Bell 2002), mouse eradications were not estimated to be twice the overall cost of rat eradication, instead ranging from $34,272 to $2,808,776 across all islands (Fig. 2b). The percentages of total costs associated with transport, labour, and consumables were almost equal to those for rat eradication (Fig. 3b). The reason for such similarities were the costs of pre-eradication and post-eradication activities, which were the same between rat and mouse eradication, making up 98% of the total costs (Table 1).

Cat and fox eradications, which required more on-island time than rodent eradications, were estimated to be more costly than rodent eradications on average. Costs for cat eradication costs ranged from $91,088 to $2,286,816 across all islands (Fig. 2c), while fox

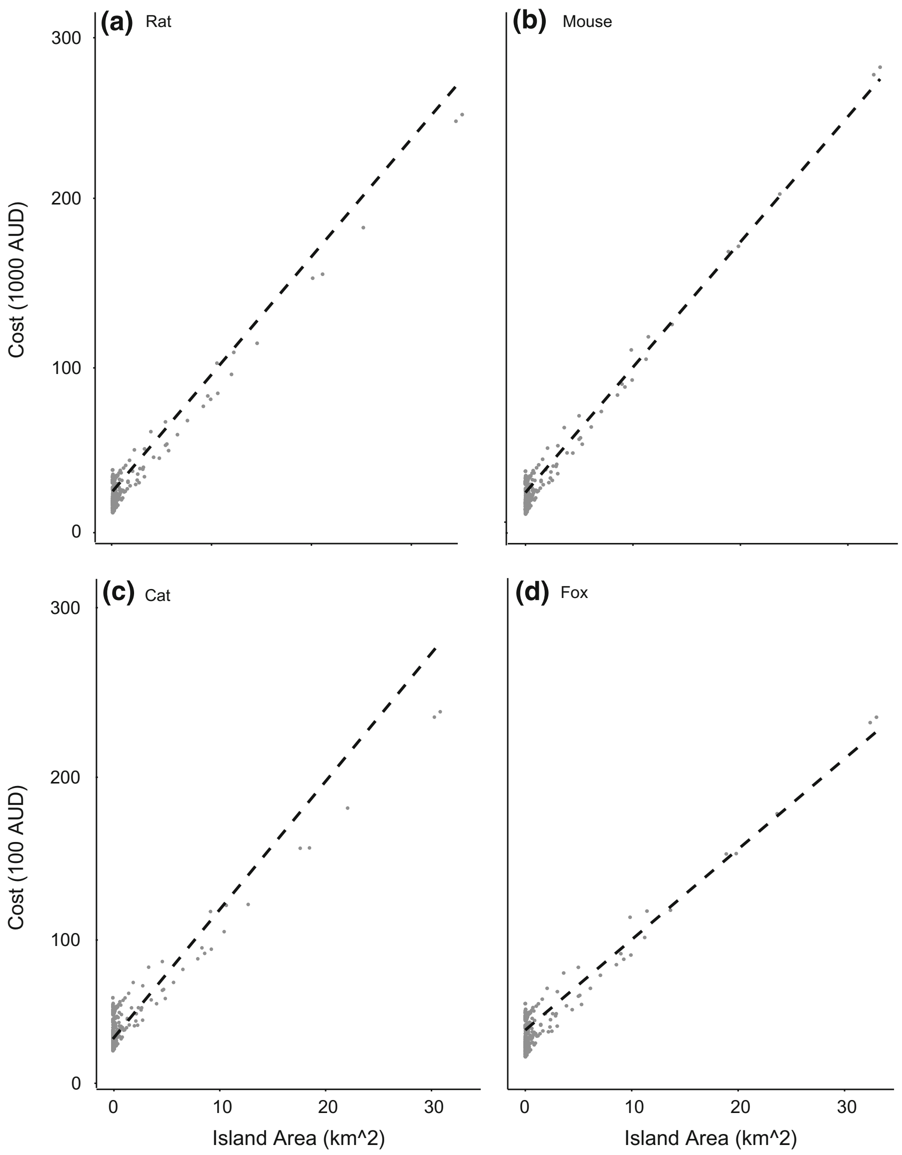
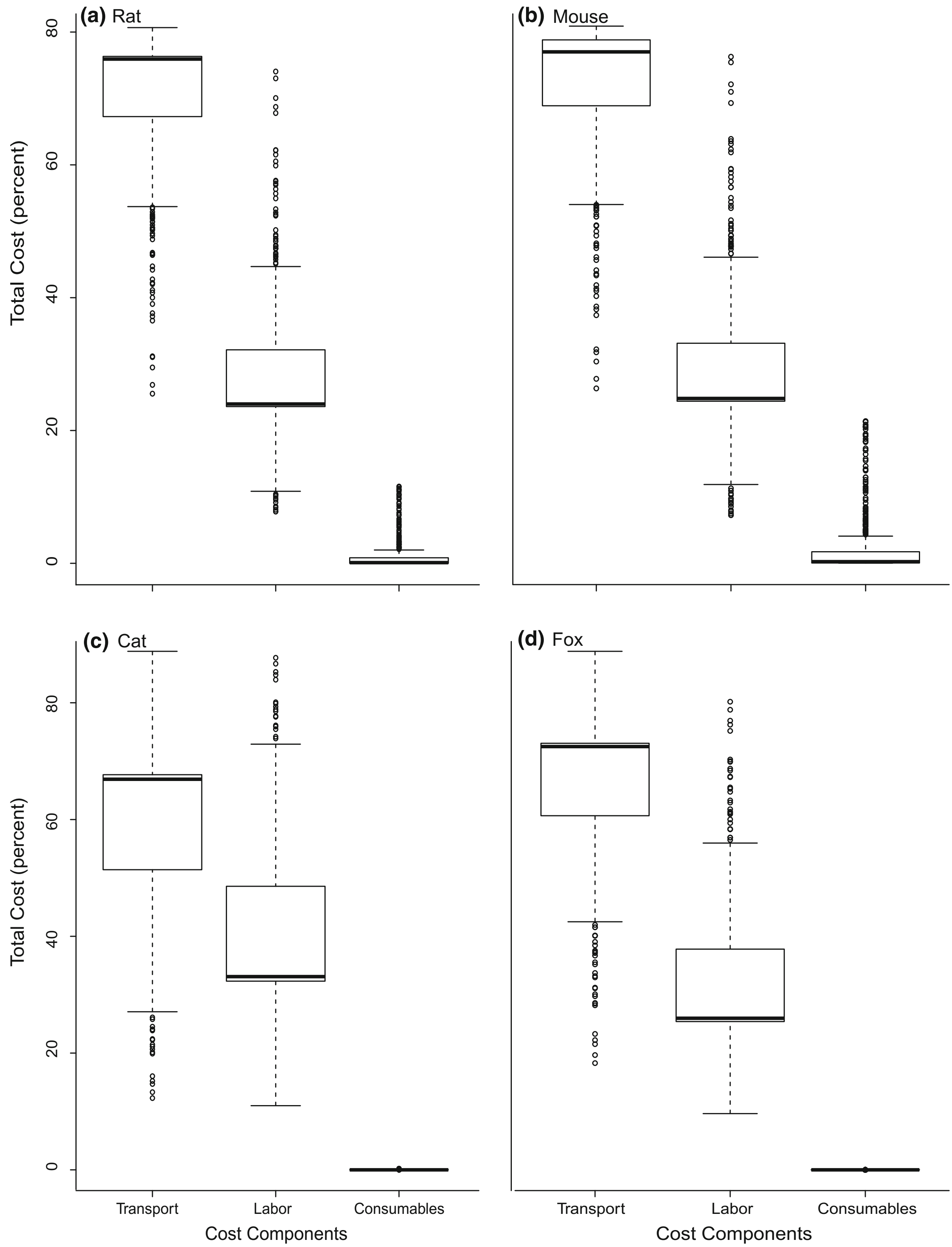


Fig. 2 The costs of eradicating vertebrate pests. **a** Rat eradication, **b** mouse eradication, **c** cat eradication, and **d** fox eradication on each island, which have a range of areas. The costs reflect the cost of the entire eradication protocol for each species for islands ranging from 0.002 to 23,569 ha. The dashed line shows the predicted costs in relation to area based on linear regressions


(a) Rat
(b) Mouse
(c) Cat
(d) Fox
Total Cost (percent)
0
20
40
60
80
Transport
Labor
Consumables
Cost Components

◀**Fig. 3** Cost components of eradicating vertebrate pests. The range of the proportional cost of transport, labour, and consumables for each of the 601 islands for **a** rat eradication, **b** mice eradication, **c** cat eradication, and **d** fox eradication

eradications ranged from \$60,286 to \$2,252,007 across all islands (Fig. 2d). Unlike rodent eradications, labour costs played a much larger role in the estimated costs of cat eradications. Transport accounted for 59% on average of the total costs of cat eradications and labour accounted for 40% (Fig. 3c). In contrast, even though cat and fox eradications had similar protocols, the lower labour requirements for shooting foxes as opposed to trapping cats meant that labour costs, on average, accounted for only 33% on average of the total costs of fox eradication (Table 1; Fig. 3d).

We could not calculate the time required for buffel grass and bellyache bush eradication on each island because weed infestation density and extent is unknown. However, when comparing just the costs of transport and the labour costs associated with transport, the estimated costs for buffel grass ranged from \$116,206 to \$21,575,000, while they ranged from \$70,195 to \$10,800,000 for bellyache bush. The costs of the charter vessel compared to the labour costs for pre-eradication office planning and labour costs during transit accounted for 79–99% of the costs for buffel grass and 65–99% of the costs for bellyache bush. The differences in costs between the two weeds was driven by the number of trips required per year and the years of treatment required (Table 1).

Testing assumptions about costs

Assumption one: that the cost of management scales linearly with the area over which it occurs

There was a significant relationship between the area of an island and the cost of eradication of rats, mice, cats, and foxes, explaining 88, 91, 76, and 76% of the variation in costs, respectively (Fig. 2). Terrain and distance from shore did not significantly drive cost estimates ($p > 0.05$ for all species). Furthermore, there were no significant differences between cost estimates based on area alone and estimations based on the comprehensive cost models developed in this study ($p > 0.05$ for all species), which accounted for several factors other than area. While statistically there were no differences, the deviations between the predicted costs and the modelled costs were large in dollar terms. The estimated costs based on area alone varied from \$130,000 less than the costs estimated by our formulas to \$130,000 more than the comprehensive costs for rats and mice and over \$170,000 for cats and foxes. These differences represented between 40 and 56% differences of total costs.

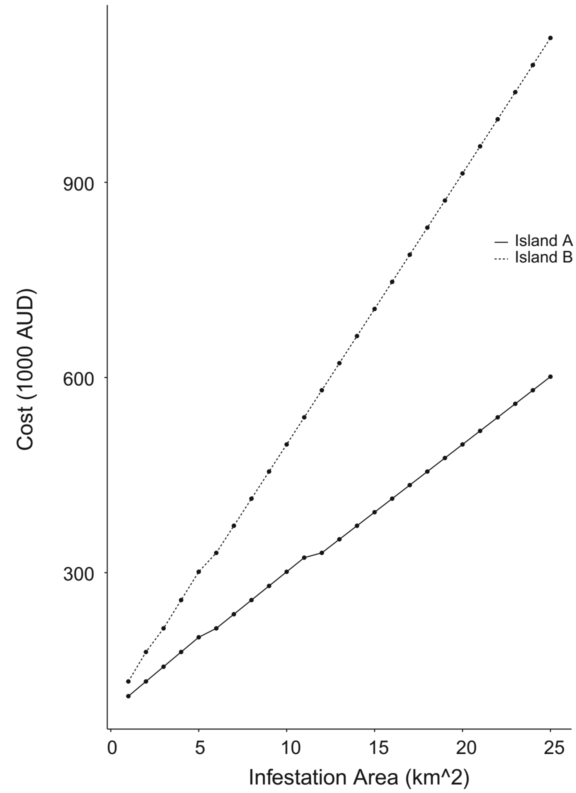


Fig. 4 Alternative eradication costs for a buffel grass infestation with increasing area on a flat island (Island A) and a rugged island (Island B)

Assumption two: costs will remain the same regardless of the terrain on which it occurs

Terrain ranged from a surface area to planar area ratio of 1:1 to 11.6:1. The mean and median ratios were 1.3:1 and 1.07:1, respectively. The cost of buffel grass eradication when island terrain was incorporated into the costing was significantly greater than when terrain was ignored ($p < 0.001$; Fig. 4). From a monetary perspective, the effect of terrain became more pronounced as the area to be treated increased. The difference between cost estimates to treat an

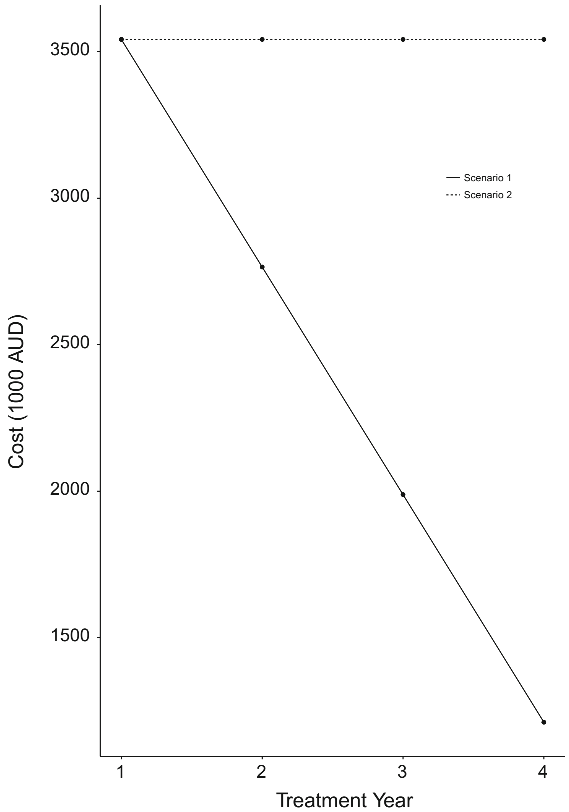


Fig. 5 Eradication costs for a 20 ha buffel grass eradication based on two assumptions. Scenario 1 costs recognise response to management as declines in density through time. Scenario 2 does not consider declines in density in response to management

infestation the size of one ha on a flat island versus a rugged island was $22,640, a 21% increase from the flat-island cost estimate. However, the difference in estimated costs when considering or ignoring terrain when treating a 25 ha infestation was $520,734, an 86% increase from the flat-island estimate (Fig. 4).

Assumption three: that reductions in species density or abundance in response to management to not influence costs

The changing person-days per hectare with reducing weed density (Fig. 5) resulted in progressively less time needed on the island to treat the weed infestation and thus a significant reduction in annual labour and transport costs ($p < 0.01$). This led to an overall estimated cost-savings of $4,660,950 when compared to the scenario assuming unchanging density of buffel grass.

Discussion

Biodiversity conservation managers regularly face decisions about what actions to perform to counteract threats. These decisions require an understanding of both the conservation benefits and economic costs of candidate actions. Accounting for costs of continuing management interventions is a necessity for good conservation planning (Armsworth 2014; Naidoo et al. 2006), yet fine-resolution estimates of management costs that are appropriate for conservation decision-making on the ground are often lacking. This study provides a framework, based on best management practices, expert advice, and real-world costs, for how to estimate costs of invasive species eradications over a range of landscapes at a resolution useful for field management. The breakdown of our framework into different cost components allows managers and conservation practitioners to better understand what factors are driving differences in invasive species eradication costs. Further, the models are readily adaptable to different management settings where eradication protocols are different but there are similar cost components. Although initial development of the formulation was time-intensive, the models enable calculations of realistic cost estimates that can inform annual management budgets and strategic planning, both necessary prerequisites for successful eradication campaigns (Broome et al. 2002; Keitt et al. 2015; Myers et al. 2000; Simberloff 2009; Simberloff et al. 2005).

The cost models are generic, requiring only minor adjustments to variables in other management settings. Importantly, populating the models with values for the variables was achieved during consultation with managers, contractors, and suppliers or by using freely available global datasets (i.e., the digital elevation model used to calculate terrain), indicating that the information required for the models can not only be easily obtained but will be available to most people working on real-world management with practitioners. Furthermore, given the eradication protocols were based on commonly used management interventions, translating them to new areas is likely to require less time than their initial development because managers would be primarily vetting and adapting protocols to ensure they reflect their local context and then adding in appropriate dollar figures for inputs. We argue that, although some of the information required may take time to source, an eradication attempt should not be made if the steps of the eradication and the costs associated with them are not adequately understood, because the likelihood of failure would be high (Holmes et al. 2015a, b).

The risk of budget-related eradication failure, as well as avoidable delays, applies also to easily derived proxies for costs, where discrepancies between proxies and actual costs are large (Keitt et al. 2015; Simberloff 2009; Simberloff et al. 2005). Our study demonstrated that while there is a strong statistical relationship between area and eradication costs, it does not adequately capture fine-scale variations in more comprehensively estimated costs across islands, resulting in both over- and underestimated costs of invasive species eradication. Large under-estimations have implications for both the success of projects being funded and the strategic allocation of funds to other management actions (Pressey et al. 2013). In some cases, area is probably an appropriate proxy for costs, but until we have a better understanding of the situations where this might apply, researchers should apply cost proxies with cau'tion. Our approach provides one strategy for sidestepping area-based assumptions to obtain better cost estimates.

While it is widely acknowledged that understanding and incorporating spatial variation in costs is critical for conservation planning (Adams et al. 2012; Burkhalter et al. 2016; Carwardine et al. 2008; Evans et al. 2015; Frazee et al. 2003), landscape terrain is rarely incorporated into cost calculations, despite its clear spatial variation and its ability to influence costs (van Wilgen et al. 2016). More rugged terrain has increased the cost of revegetation activities and in some cases has completely altered the protocol used for invasive species management, including opting for not conducting work on foot (Board 2009; Schirmer and Field 2002; van Wilgen et al. 2016). In our case, terrain variation resulted in a significant, non-linear increase in buffel grass management costs due to its influence on increased labour and transport requirements. Given that terrain was calculated using a freely available global digital elevation model, incorporating a terrain factor into cost calculations should become standard practice. The addition of terrain will further improve the accuracy and transparency of invasive species cost estimates, enabling managers to understand how costs could change in different landscapes, which will allow for better decision making about the best course of action and potential costs that could be incurred, and thus better allocation of management resources.

Temporal variation in costs, which has been neglected, should also be incorporated to further improve the accuracy of cost estimates (Cattarino et al. 2016). When accounting for changing weed density in response to treatment, we found that the overall costs of buffel grass eradication was 32% lower than when not accounting for the response of the weed to management. This finding is consistent with other studies that have incorporated temporal variations such as a species' response to management into cost estimates (e.g., Adams and Setterfield 2013, 2016; Cattarino et al. 2016). If conservation practitioners are undertaking a prioritisation exercise and have not considered temporal variability, there is the potential for misallocation of management resources, which could hinder the success of an eradication campaign (Simberloff 2009). An ability to shift resources in time in relation to expected density of pest species has been shown to provide optimal conservation outcomes (Adams and Setterfield 2015).

The two weed eradication protocols developed in this study highlight how the explicit incorporation of life-history information of the target species and abiotic conditions in the region are critical in ensuring proper budget allocation and can be used as a way to gauge if the proposed eradication protocol is logistically feasible. For instance, buffel grass spraying needs to occur 4–6 weeks after a rainfall event due to its short generation times, which in our study region means that spraying would likely be required seven times a year over four years. In contrast, bellyache bush only needs to be sprayed twice a year but over six years. These biological differences may not always be compatible with budgets or grant cycles, making eradication efforts infeasible. Additionally, the size of an infestation and the rate and mode of spreading (which we did not consider in our cost models) might lead to an exploration of alternative and most cost-effective eradication techniques (Campbell et al. 2015; McMaster et al. 2014) or to the acknowledgement that an eradication is unlikely to be successful (Rejmánek and Pitcairn 2002).

Similarly, the identification during pre-eradication planning of species interactions and the potential for non-target and secondary poisoning or ecosystem-level impacts can considerably influence eradication costs in several ways, including changing the eradication protocol that is used. Changes to protocols could vary from different baiting procedures to avoid lethal impacts to non-target species (Moro 2001) to temporary captivity and translocation (Howald et al. 2010). These examples underscore the importance of clearly understanding the scale of a problem, the biology of the target species, and the budget (and timeframe) required prior to the commencement of an eradication, otherwise, there is a high risk of failure (Gardener et al. 2010). The framework we have developed here can be modified to suit different scenarios, since it demonstrates a method to breakdown costs into clearly defined components.

The development of clear protocols for invasive species management allowed us to examine the influence of separate cost components on total costs. Since invasive species management is often very expensive (McConnachie et al. 2012), understanding the different cost components allows managers to explore potential cost savings. For instance, in our case, because management was occurring on offshore islands, transport costs, particularly the use of charter vessels, were the primary driver of overall costs. We costed management interventions on a single-island and single-species basis. However, this approach makes the traveling-salesman problem apparent: the potential for managers to achieve substantial cost savings by optimising management actions that could be achieved on a single trip to multiple islands (Bektas 2006). Furthermore, simultaneous invasive species eradications could also lead to substantial cost savings (Glen et al. 2013). As an example, although there is very limited information in our study region about how much previous eradication efforts cost, one estimate of concurrent cat and rat eradication in the Montebello Islands was estimated to cost 1.4 million AUD (budget estimate converted from 1994 AUD to 2016 AUD), although this number did not fully account for staff time (A. Burbidge pers comm.). If the eradications had been conducted separately, they would have cost 1.9 million AUD, according to our cost estimates. Simultaneous eradications of invasive species, particularly species that interact with each other, can also prevent unintended ecological consequences (Courchamp et al. 2003). By understanding where potential cost savings could occur, managers could thus incorporate this information into their strategic allocation of resources.

Similarly, labour costs accounted for a substantial portion of the overall costs. A number of management programs for invasive species have relied on convict and volunteer labour (Campbell and Carter 1999; Simberloff 2009; Simberloff et al. 2005). Management agencies could look into alternative sources of labour outside of agency employees to assist in eradication campaigns and potentially reduce overall costs. The examination of the influence of separate cost components on total costs highlights the importance of allocating resources to the planning phase of an eradication campaign, as we have done here. Thorough planning will reduce the risk of eradication failures and waste of management resources (Holmes et al. 2015b; Keitt et al. 2015; Simberloff 2009; Simberloff et al. 2005).

For the purposes of this study, we have chosen to ignore costs associated with environmental compliance and stakeholder engagement, although they can be substantial (Donlan and Wilcox 2007; Oppel et al. 2011). The islands in the study region are not inhabited, but they are used for recreation. Community engagement and approval where necessary to treat invasive species would necessarily be part of operationalising priority actions, including alerting visitors of potential associated risks (Oppel et al. 2011). In places where eradications are to take place in inhabited areas, there will also be several additional, and likely situation-specific, cost considerations that will be required. Glen et al. (2013) detail several possible circumstances that could arise in populated areas, which will likely increase costs, including the inability to aerial bait (Wilkinson and Priddel 2011), the presence of domesticated individuals of the target species, such as cats (Ratcliffe et al. 2010), and the presence of multiple landholders, which necessitates extensive engagement (Gardener et al. 2010). The transparency and flexibility of the eradication protocols and cost models developed here will enable managers and conservation practitioners to add in any additional costs that we did not consider. There will inevitably be some uncertainties in strategic planning that will have to be fine-tuned as managers move towards the implementation phase of a project (Pressey et al. 2013). The cost models developed here provide a transparent framework with which managers can explore budgetary uncertainties and improve the likelihood of successful eradication campaigns.

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References

Adams VM, Setterfield SA (2013) Estimating the financial risks of Andropogon gayanus to greenhouse gas abatement projects in northern Australia. Environ Res Lett 8:025018

Adams VM, Setterfield SA (2015) Optimal dynamic control of invasions: applying a systematic conservation approach. Ecol Appl 25:1131–1141

Adams VM, Setterfield SA (2016) Approaches to strategic risk analysis and management of invasive plants: lessons learned from managing gamba grass in northern Australia. Pac Conserv Biol 22:189–200

Adams VM, Pressey RL, Stoeckl N (2012) Estimating land and conservation management costs: the first step in designing a stewardship program for the Northern Territory. Biol Conserv 148:44–53

Algar D, Burbidge A, Angus G (2002) Cat eradication on Hermite Island, Montebello Islands, Western Australia. In: Turning the tide: the eradication of invasive species. pp 14–18

Armstrong R (2004) Baiting operations: western shield review-February 2003. Conserv Sci West Aust 5:31

Armsworth PR (2014) Inclusion of costs in conservation planning depends on limited datasets and hopeful assumptions. Ann N Y Acad Sci 1322:61–76

Bates D, Mächler M, Bolker B, Walker S (2014) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48

Bektas T (2006) The multiple traveling salesman problem: an overview of formulations and solution procedures. Omega 34:209–219. https://doi.org/10.1016/j.omega.2004.10.004

Bell BD (2002) The eradication of alien mammals from five offshore islands, Mauritius, Indian Ocean. In: Turning the tide: the eradication of invasive species IUCN SSC Invasive Species Specialist Group, Gland, Switzerland. pp 40–45

Board LHI (2009) Draft Lord Howe Island Rodent Eradication Plan. Lord Howe Island Board

Brooke MdL, Hilton G, Martins T (2007) Prioritizing the world's islands for vertebrate-eradication programmes. Anim Conserv 10:380–390

Broome K, Cox A, Empson R, Hutchinson W (2002) Eradication planning for invasive alien animal species on islands-the approach developed by the New Zealand Department of Conservation. In: Turning the tide: the eradication of invasive species: proceedings of the international conference on eradication of Island Invasives, vol 27. IUCN, p 85

Broome K, Cox A, Golding C, Cromarty P, Bell P, McClelland P (2014) Rat eradication using aerial baiting: current agreed best practice used in New Zealand (version 3.0) New Zealand Department of Conservation internal document, Wellington, New Zealand, 24 pp

Brotankova J, Randall M, Lewis A, Pressey B, Wenger A (2015) A genetic algorithm solver for pest management control in island systems. Artificial Life and Computational Intelligence. Springer, Germany, pp 273–285

Burkhalter JC, Lockwood JL, Maslo B, Fenn KH, Leu K (2016) Effects of cost metric on cost-effectiveness of protected-area network design in urban landscapes. Conserv Biol 30(2):403–412

Butchart SH et al (2010) Global biodiversity: indicators of recent declines. Science 328:1164–1168

Campbell C, Carter FD (1999) The Florida Department of Corrections involvement in exotic pest plant control Florida's garden of good and evil West Palm Beach. Exotic Pest Plant Council, Florida

Campbell K, Harper G, Algar D, Hanson C, Keitt B, Robinson S (2011) Review of feral cat eradications on islands Island Invasives: eradication and Management'(Eds CR Veitch, MN Clout and DR Towns) pp 37–46

Campbell KJ et al (2015) The next generation of rodent eradications: Innovative technologies and tools to improve species specificity and increase their feasibility on islands. Biol Conserv 185:47–58. https://doi.org/10.1016/j.biocon.2014.10.016

Carwardine J, Wilson KA, Watts M, Etter A, Klein CJ, Possingham HP (2008) Avoiding costly conservation mistakes: the importance of defining actions and costs in spatial priority setting. PLoS One 3:e2586

Cattarino L, Hermoso V, Bradford LW, Carwardine J, Wilson KA, Kennard MJ, Linke S (2016) Accounting for continuous species' responses to management effort enhances cost-effectiveness of conservation decisions. Biol Conserv 197:116–123

Clout M (2001) Where protection is not enough: active conservation in New Zealand. Trends Ecol Evol 16:415–416. https://doi.org/10.1016/S0169-5347(01)02225-X

Courchamp F, Chapuis J-L, Pascal M (2003) Mammal invaders on islands: impact, control and control impact. Biol Rev 78:347–383

Cunningham DC, Barry SC, Woldendorp G, Burgess MB (2004) A framework for prioritizing sleeper weeds for eradication 1. Weed Technol 18:1189–1193

Dixon I, Dixon K, Barrett M (2002) Eradication of buffel grass (Cenchrus ciliaris) on Airlie Island, Pilbara Coast, Western Australia. In: Turning the tide: eradication of invasive species International Union for the Conservation of Nature SSC Invasive Species Specialist Group, Gland, Switzerland and Cambridge, United Kingdom. pp 92–101

Donlan C, Wilcox C (2007) Complexities of costing eradications. Anim Conserv 10:154–156

Donlan CJ, Luque GM, Wilcox C (2015) Maximizing return on investment for island restoration and species conservation. Conserv Lett 8:171–179

Duncan RP, Boyer AG, Blackburn TM (2013) Magnitude and variation of prehistoric bird extinctions in the Pacific. Proc Natl Acad Sci 110:6436–6441

Ehrenfeld JG (2010) Ecosystem consequences of biological invasions. Annu Rev Ecol Evol Syst 41:59–80

Evans MC, Tulloch AI, Law EA, Raiter KG, Possingham HP, Wilson KA (2015) Clear consideration of costs, condition and conservation benefits yields better planning outcomes. Biol Conserv 191:716–727

Firn J, Martin TG, Chadès I, Walters B, Hayes J, Nicol S, Carwardine J (2015) Priority threat management of non-

native plants to maintain ecosystem integrity across heterogeneous landscapes. J Appl Ecol 52:1135–1144
Flint E, Rehkemper C (2002) Control and eradication of the introduced grass, Cenchrus echinatus, at Laysan Island, Central Pacific Ocean. In: Turning the tide: the eradication of invasive species. pp 110–115
Frazee S, Cowling R, Pressey R, Turpie J, Lindenberg N (2003) Estimating the costs of conserving a biodiversity hotspot: a case-study of the Cape Floristic Region, South Africa. Biol Conserv 112:275–290
Gardener MR, Atkinson R, Rentería JL (2010) Eradications and people: lessons from the plant eradication program in Galapagos. Restor Ecol 18:20–29
Glen AS et al (2013) Eradicating multiple invasive species on inhabited islands: the next big step in island restoration? Biol Invasions 15:2589–2603. https://doi.org/10.1007/s10530-013-0495-y
Helmstedt KJ, Shaw JD, Bode M, Terauds A, Springer K, Robinson SA, Possingham HP (2016) Prioritizing eradication actions on islands: it's not all or nothing. J Appl Ecol 53:733–741
Holmes N, Campbell K, Keitt B, Griffiths R, Beek J, Donlan C, Broome K (2015a) Reporting costs for invasive vertebrate eradications. Biol Invasions 17:2913–2925
Holmes ND, Griffiths R, Pott M, Alifano A, Will D, Wegmann AS, Russell JC (2015b) Factors associated with rodent eradication failure. Biol Conserv 185:8–16
Howald G, Donlan CJ, Faulkner KR, Ortega S, Gellerman H, Croll DA, Tershy BR (2010) Eradication of black rats Rattus rattus from Anacapa Island. Oryx 44:30–40. https://doi.org/10.1017/S003060530999024X
Jenness J (2006) DEM Surface Tools: Topographic Position Index (tpi_jen.avx) extension for ArcView 3. x, v. 1.3 a. Jenness Enterprises. http://www.jennessent.com/arcview/tpi.htm
Jones HP et al (2016) Invasive mammal eradication on islands results in substantial conservation gains. Proc Natl Acad Sci 113:4033–4038
Keitt B et al (2015) Best practice guidelines for rat eradication on tropical islands. Biol Conserv 185:17–26. https://doi.org/10.1016/j.biocon.2014.10.014
Kier G et al (2009) A global assessment of endemism and species richness across island and mainland regions. Proc Natl Acad Sci 106:9322–9327. https://doi.org/10.1073/pnas.0810306106
Knight AT, Cowling RM, Rouget M, Balmford A, Lombard AT, Campbell BM (2008) Knowing but not doing: selecting priority conservation areas and the research—implementation gap. Conserv Biol 22:610–617
Lohr C, Passeretto K, Lohr M, Keighery G (2015) Prioritising weed management activities in a data deficient environment: the Pilbara islands, Western Australia. Heliyon 1:e00044
Lohr C, Wenger A, Woodberry O, Pressey RL, Morris K (2017) Predicting island biosecurity risk from introduced fauna using Bayesian belief networks. Sci Total Environ 1173–1181
Marshall V, Lewis M, Ostendorf B (2012) Buffel grass (Cenchrus ciliaris) as an invader and threat to biodiversity in arid environments: a review. J Arid Environ 78:1–12
Martins T, Brooke ML, Hilton G, Farnsworth S, Gould J, Pain D (2006) Costing eradications of alien mammals from islands. Anim Conserv 9:439–444
McConnachie MM, Cowling RM, Van Wilgen BW, McConnachie DA (2012) Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. Biol Conserv 155:128–135
McLeod LJ, Saunders GR, Miners A (2011) Can shooting be an effective management tool for foxes? Preliminary insights from a management programme. Ecol Manag Restor 12:224–226
McMaster D, Adams V, Setterfield SA, McIntyre D, Douglas MM (2014) Para grass management and costing trial within Kakadu National Park. In: 19th Australasian Weeds Conference. Weed Society of Tasmania Inc., Hobart, Tasmania
Medina FM et al (2011) A global review of the impacts of invasive cats on island endangered vertebrates. Glob Chang Biol 17:3503–3510
Moro D (2001) Evaluation and cost-benefits of controlling house mice (Mus domesticus) on islands: an example from Thevenard Island, Western Australia. Biol Conserv 99:355–364. https://doi.org/10.1016/S0006-3207(00)00231-7
Murdoch W, Polasky S, Wilson KA, Possingham HP, Kareiva P, Shaw R (2007) Maximizing return on investment in conservation. Biol Conserv 139:375–388
Myers JH, Simberloff D, Kuris AM, Carey JR (2000) Eradication revisited: dealing with exotic species. Trends Ecol Evol 15:316–320
Naidoo R, Balmford A, Ferraro PJ, Polasky S, Ricketts TH, Rouget M (2006) Integrating economic costs into conservation planning. Trends Ecol Evol 21:681–687
Nogales M et al (2004) A review of feral cat eradication on islands. Conserv Biol 18:310–319
Oppel S, Beaven BM, Bolton M, Vickery J, Bodey TW (2011) Eradication of invasive mammals on islands inhabited by humans and domestic animals. Conserv Biol 25:232–240
Pressey RL, Mills M, Weeks R, Day JC (2013) The plan of the day: managing the dynamic transition from regional conservation designs to local conservation actions. Biol Conserv 166:155–169
Ratcliffe N et al (2010) The eradication of feral cats from Ascension Island and its subsequent recolonization by seabirds. Oryx 44:20–29
Rejmánek M, Pitcairn M (2002) When is eradication of exotic pest plants a realistic goal. In: Turning the tide: the eradication of invasive species. pp 249–253
Schirmer J, Field J (2002) The cost of revegetation. Department of Forestry, Australian National University, Canberra, p 116
Simberloff D (2009) We can eliminate invasions or live with them. Successful management projects. Biol Invasions 11:149–157
Simberloff D, Parker IM, Windle PN (2005) Introduced species policy, management, and future research needs. Front Ecol Environ 3:12–20
Sutton N, Armsworth P (2014) The grain of spatially referenced economic cost and biodiversity benefit data and the effectiveness of a cost targeting strategy. Conserv Biol 28:1451–1461

Tjelmeland AD, Fulbright TE, Lloyd-Reilley J (2008) Evaluation of herbicides for restoring native grasses in buffelgrass-dominated grasslands. Restor Ecol 16:263–269
Towns DR, Ballantine W (1993) Conservation and restoration of New Zealand island ecosystems. Trend Ecol Evol 8:452–457
van Wilgen BW, Fill JM, Baard J, Cheney C, Forsyth AT, Kraaij T (2016) Historical costs and projected future scenarios for the management of invasive alien plants in protected areas in the Cape Floristic Region. Biol Conserv 200:168–177. https://doi.org/10.1016/j.biocon.2016.06.008
Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of earth's ecosystems. Science 277:494–499
Wilkinson I, Priddel D (2011) Rodent eradication on Lord Howe Island: challenges posed by people, livestock, and threatened endemics Island Invasives: Eradication and Management'(Eds CR Veitch, MN Clout and DR Towns) pp 508–514
Wilson KA et al (2007) Conserving biodiversity efficiently: what to do where, and when. PLoS Biol 5:e223. https://doi.org/10.1371/journal.pbio.0050223