LETTER

Promise and problems for estimating management costs of marine protected areas

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Abstract

Management costs are rarely taken into account in marine protected area (MPA) design. We estimate the management costs of two different protection scenarios within a large proposed MPA, the Coral Sea in Australia. We use three methods to estimate costs: an existing model of global MPA management costs; a new statistical model based on Australian MPA management costs; and expert estimates that extrapolate from the adjacent Great Barrier Reef Marine Park. Both the new statistical model and expert estimates were relevant to both protection scenarios and indicate that a single large no-take reserve is less expensive to manage than a multiple-use MPA of the same area with a 30% no-take component. Expenses associated with compliance drive the difference in management cost between scenarios. Estimating management costs of MPA scenarios adds an important, though still challenging, financial perspective to MPA design.

Introduction

Completion of a network of marine protected areas (MPAs), including no-take areas, remains a global goal (CBD 2006; Wood *et al.* 2008) and the costs of such a network are increasingly being considered (Balmford *et al.* 2004; Ban & Klein 2009). Opportunity costs are used to guide prioritization of MPA networks (Klein *et al.* 2008; Ban & Klein 2009), but management costs are rarely taken into account (Ban & Klein 2009). Management costs cannot easily be mapped as an input to MPA design because they depend on the results of design, particularly on the location, configuration, socio-economic context, and zoning of MPAs. However, management costs are among several important criteria for evaluating different protection scenarios (California Department of Fish and Game 2008).

Consideration of management costs and their drivers is important for several reasons. First, predicting management costs allows planners to budget for effective, long-term management so that MPAs fulfill their promise (Bruner *et al.* 2001; Balmford *et al.* 2004). Second, knowledge of cost drivers allows planners to locate and configure MPAs in ways that minimize long-term management costs. Third, because current management budgets are rarely sufficient, estimating the shortfalls between current and required management funding can raise awareness about costs, and help to secure adequate resources upon implementation of MPAs.

In addition to ongoing coastal MPA planning initiatives (e.g., Coral Triangle, Marine Life Protection Act process in California, marine bioregion planning in Australia), there have been several recent announcements of large MPAs with potentially sizeable or complete no-take components (e.g., Coral Sea Conservation Zone in Australia, Australian Government 2009, Chagos Island marine reserve in the Indian Ocean (http://news.bbc.co.uk/2/hi/8599125.stm; Monuments declared by former U.S. President Bush, US Department of State 2009). These add urgency to answering questions such as: What approaches can be used to estimate management costs? How do management costs differ between small versus large no-take areas, and multiple-use versus no-take zones?

Several different kinds of costs are entailed in managing marine and terrestrial protected areas: staff expenses, regular operational costs, and recurrent capital costs (Balmford *et al.* 2004; Bruner *et al.* 2004), together referred to as recurrent annual expenditures. Staff expenses include salaries, overhead costs, and training. Regular operational costs are associated with field or day-to-day management such as fuel, maintenance of buildings and equipment, and education and outreach. This includes compliance-related costs such as chartering of vessels and aircraft as well as office investigations and legal fees for prosecution. Regular capital expenses include purchase of vehicles, vessels, and their replacement. Not included in recurrent annual expenditures are one-time capital outlays, such as office accommodation, or expenses associated with consultations such as buy backs of fishing licenses. Cost can also be divided into fixed and variable costs (Perloff 2009). Fixed costs stay independent of the management activity (e.g., rent), or may be stepped when they remain constant up to a threshold, then increase. Ideally, estimates would address fixed and variable costs separately but this is often impossible. Management data are typically highly aggregated and only reflect broad categories (e.g., staff, operational costs) or total costs (Balmford *et al.* 2004; Gravestock *et al.* 2008).

The limited literature on management costs suggests that annual MPA management costs are linear on log scales: lower per-unit-area costs for larger MPAs (Balmford *et al.* 2004; Gravestock *et al.* 2008). Economies of scale mean that larger MPAs achieve considerable management cost savings (Balmford *et al.* 2004). For example, a minimum level of staffing and infrastructure might be required for any MPA, but the same minimum personnel may be sufficient to manage a large area (i.e., fixed cost below a threshold), perhaps with some additional expenses (e.g., fuel; a variable cost).

Past models that include management costs have several limitations. Global or continental assessments (James *et al.* 1999a; James *et al.* 1999b; James *et al.* 2001; Balmford *et al.* 2004; Bruner *et al.* 2004; Moore *et al.* 2004) have used highly aggregated data or extrapolated widely from sparse samples of reserves. The resulting models are difficult to apply within regions to individual MPAs that might differ in important characteristics. A second limitation is that, like most global analyses, studies applicable to individual reserves within regions (Wilkie *et al.* 2001; Frazee *et al.* 2003; Blom 2004) are limited by little or no breakdown of costs by activity (e.g., control of invasive species, maintenance of visitor facilities, surveillance). This is important because the relative cost of activities likely varies between regions and between individual reserves. Including such detail would therefore produce more accurate estimates of management costs. A third limitation is that models rely on existing budgets, which are generally considered insufficient for effective management (Balmford *et al.* 2004; Bruner *et al.* 2004). Modeling these data is therefore likely to estimate costs that are unrealistically low. Finally, MPAs on which current models are based are small compared to some recent MPA announcements and proposals, requiring questionable extrapolations. Overall, the scope for improved data and statistical models is considerable, as is the potential for expert advice as an alternative or complement to formal modeling.

We contribute to current debate around no-take zoning in the Coral Sea, Australia, by estimating potential management costs for this large marine region. Positions among organizations and interest groups in Australia range from advocating a complete no-take area across the Coral Sea to arguing that no additional management is needed. The Australian portion of the Coral Sea was recently declared a Conservation Zone for interim protection during assessment for possible inclusion in one or more Commonwealth marine reserves (Australian Government 2009). The Coral Sea Conservation Zone covers approximately 972,000 km^2 of Australian waters and seabed, extending from the eastern boundary of the Great Barrier Reef Marine Park to the limit of Australia's Exclusive Economic Zone (Figure 1). We use three approaches to estimate management costs of potential Coral Sea MPA(s) for two scenarios, considering recurrent annual expenditures. We do not consider other costs related to MPA establishment, such as acquisition, transaction, and opportunity costs (Ban & Klein 2009; Naidoo *et al.* 2006), or the potential financial benefits of protection. Our study contributes to the sparse literature on estimating MPA management costs by addressing the problem of extrapolating estimates well beyond the area range of established MPAs and by comparing statistical modeling with expert estimates based on individual management activities.

Methods

We applied three approaches for estimating management costs of the proposed Coral Sea MPA: (1) a global statistical model (Balmford *et al.* 2004), in which the cost of management is predicted by MPA area, distance from inhabited land, and purchasing power parity; (2) new statistical modeling using data on management costs of

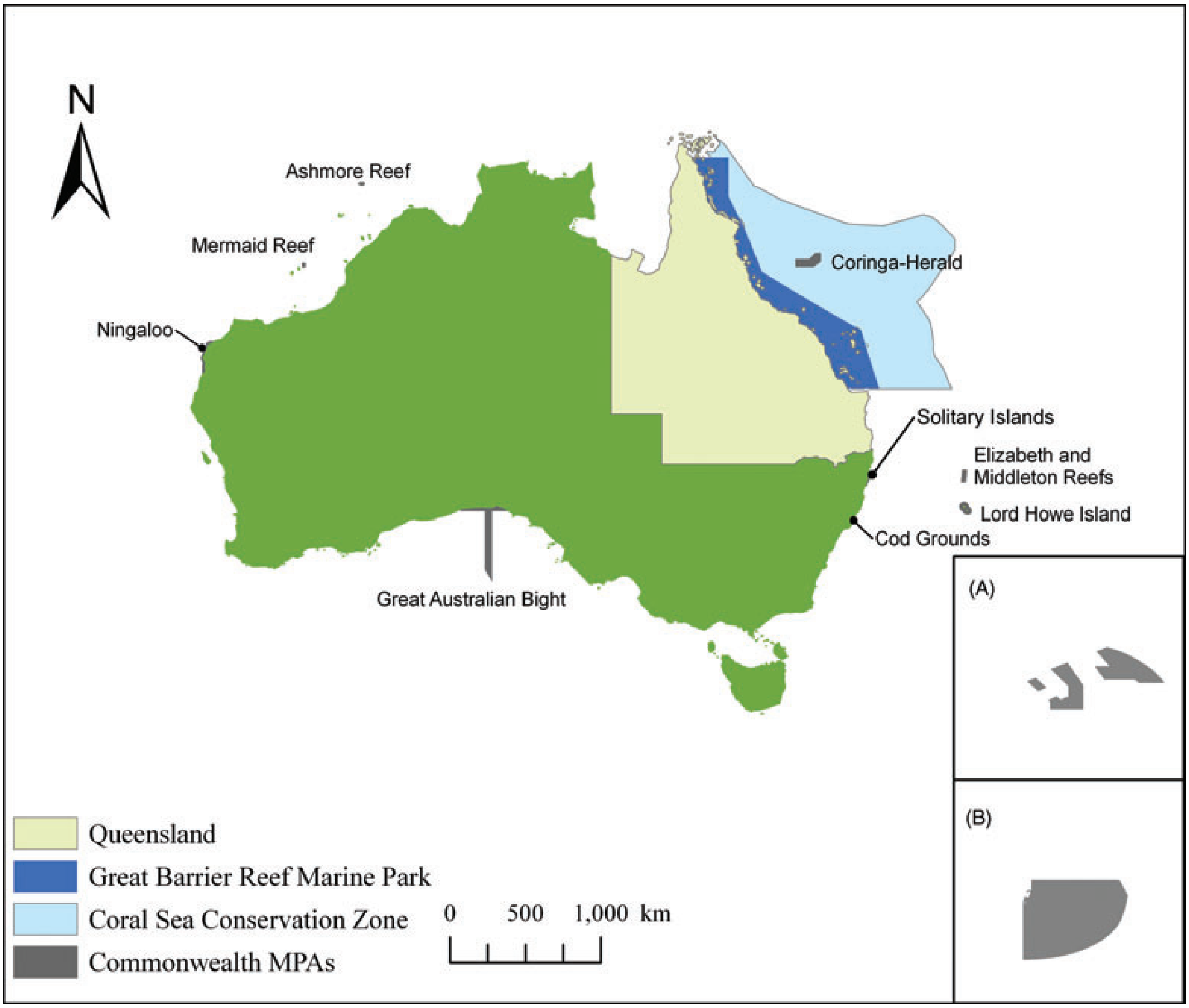

Figure 1 Overview map of Australian Commonwealth MPAs considered for our statistical model. The Coral Sea Conservation Zone extends from the Great Barrier Reef Marine Park boundary to the Australian economic exclusive zone boundary. Insets (at same scale) are (A) Heard Island and McDonald Island Marine Reserve, which lies approximately 1,500 km north of Antarctica and over 4,000 km southwest of Australia's mainland and (B) Macquarie Island Commonwealth Marine Reserve, which lies approximately 1,500 km southeast of Australia's mainland.

Australian Commonwealth Government MPAs; and (3) expert-based assessment. Our two scenarios for the Coral Sea Conservation Zone were (1) 100% no-take coverage, and (2) 30% no-take coverage with the remaining 70% managed for multiple use. The 100% no-take scenario is being advocated by several environmental organizations and scientists (Zethoven 2008). The 30% no-take scenario approximates the no-take portion of the adjacent Great Barrier Reef Marine Park and follows scientific recommendations for MPAs generally (e.g., Roberts & Hawkins 2000; Gell & Roberts 2003). For all three approaches to estimating management costs, we projected costs over 20 years with a discount rate of 3% (reflecting current interest rates in Australia, www.rba.gov.au).

To apply the global model (Balmford *et al.* 2004), we sourced data on purchasing power parity from the CIA World Factbook (CIA 2009) and estimated area and distance to land for the Coral Sea and, for validation, the Great Barrier Reef Marine Park. This model does not distinguish between no-take and other zones. It predicts management costs in year 2000 U.S. dollars, which we converted to 2009 U.S. dollars using the average inflation, and then to Australian dollars. We compared the model results to the management budget for the Great Barrier Reef Marine Park.

We developed a new statistical approach using explanatory variables related to MPA management costs in Australia to extrapolate to our two scenarios for the Coral Sea. Extrapolation was necessary because no-take areas for both Coral Sea scenarios were much larger than any other Australian MPA. We used available data for the most recent available year, 2008–2009, on management budgets, years since establishment and last gazettal, percent designated as recreational zones, number of zones, and percent area without no-take restrictions for Commonwealth Marine Parks (Director of National Parks 2009) (Tables S1 and S2).

For our new statistical model, we hypothesized that management costs would be related to the size of the MPA as well as zoning arrangements. We summarized potential predictors associated with size and zoning and reduced them to seven that were not strongly correlated. We plotted the predictors against the log of management cost to explore the relationships (Figure 2).

We applied a model-averaging approach (Burnham & Anderson 2002) by developing a subset of feasible models with the seven potential predictors. We tested that our data met the Gauss–Markov assumptions for multiple regression. Previous work (Balmford *et al.* 2004) showed that size of MPAs was an important predictor of management cost, so we included MPA size in all models. We hypothesized that the relationship between cost and area would be either linear (Balmford *et al.* (2004) or polynomial because costs are unlikely to continue diminishing linearly (otherwise very large MPAs would cost nothing to manage). We then created 63 generalized linear models in R (R Development Core Team 2005), and compared them using Akaike's Information Criterion corrected for small sample sizes (AIC, Table 1). For each of our predictor variables, we computed the model-averaged parameter estimate.

We then used the multimodel averages to estimate management costs (in Australian dollars) for the two Coral Sea scenarios. While these two scenarios reflect current political interest, we also explored the full range of first-year costs based on percentage no-take between 10% and 50%. We tested the sensitivity of our model to budget variations by using the previous year's data (2007–2008) to repeat the methods; we also tested sensitivity to one outlier data point, the Great Barrier Reef Marine Park (see supplementary methods).

Finally, we used an expert-based approach to estimate potential management costs for the two Coral Sea MPA scenarios. We interviewed key managers from the Great Barrier Reef Marine Park Authority, the Queensland Parks and Wildlife Service, and the Australian Fisheries Management Agency to obtain their estimates of management costs for the Coral Sea (Australian dollars). We used a semistructured approach for interviews, following line items of management costs listed in Tables 2 and 3 to obtain expert cost estimates. Experts were familiar with the kinds of management issues in the Coral Sea and able to extrapolate or adjust their estimates based on differences related to factors such as remoteness and coverage of surveillance. Experts interviewed were particularly familiar with management of the Great Barrier Reef Marine Park, the closest actively managed park to the Coral Sea Conservation Zone. We interviewed experts individually and in small groups to identify management outputs (i.e., enforcement, monitoring, outreach), management activities needed to achieve these outputs, and costs thereof. Where activities or line items were given without associated costs, we estimated these costs from Great Barrier Reef Marine Park budgets and financial reports. Several assumptions about management arrangements and compliance scenarios had to be made (see Supporting Information).

Results

For the Great Barrier Reef Marine Park, the global model (Balmford *et al.* 2004) estimated an annual management cost of $12 million, whereas the current (2008–2009) budget is $45 million per year. For the Coral Sea, the global model estimated annual management cost at $3 million, and the 20-year management cost with a 3% discount rate at $46.8 million. These figures were about $5 million to $21 million lower annually than those estimated by the other two methods (Table 4). Because this model was derived from MPAs with various management measures (no-take and multiple-use), it does not include number of zones or distinguish between no-take areas and other zones. We were therefore unable to use it to compare our two scenarios.

Our new statistical method (Figure 3A, Table 1) identified several consistently good predictors of management cost per hectare: *logha,* the log of total MPA area in hectares; $logha^2$, the square of the previous term (allowing a polynomial relationship); and *num*, the number of zones in the MPA. There was a weak negative relationship with *yrsgaz*, the number of years since the MPA was last gazetted. The remaining predictors were inconsistent. Given the importance of the polynomial term, we accepted the hypothesis that the functional relationship between cost per hectare and area was polynomial.

Using the modeled-average predictions, we estimated the management cost for a 100% no-take area for the Coral Sea at about $12.5 million per year and about

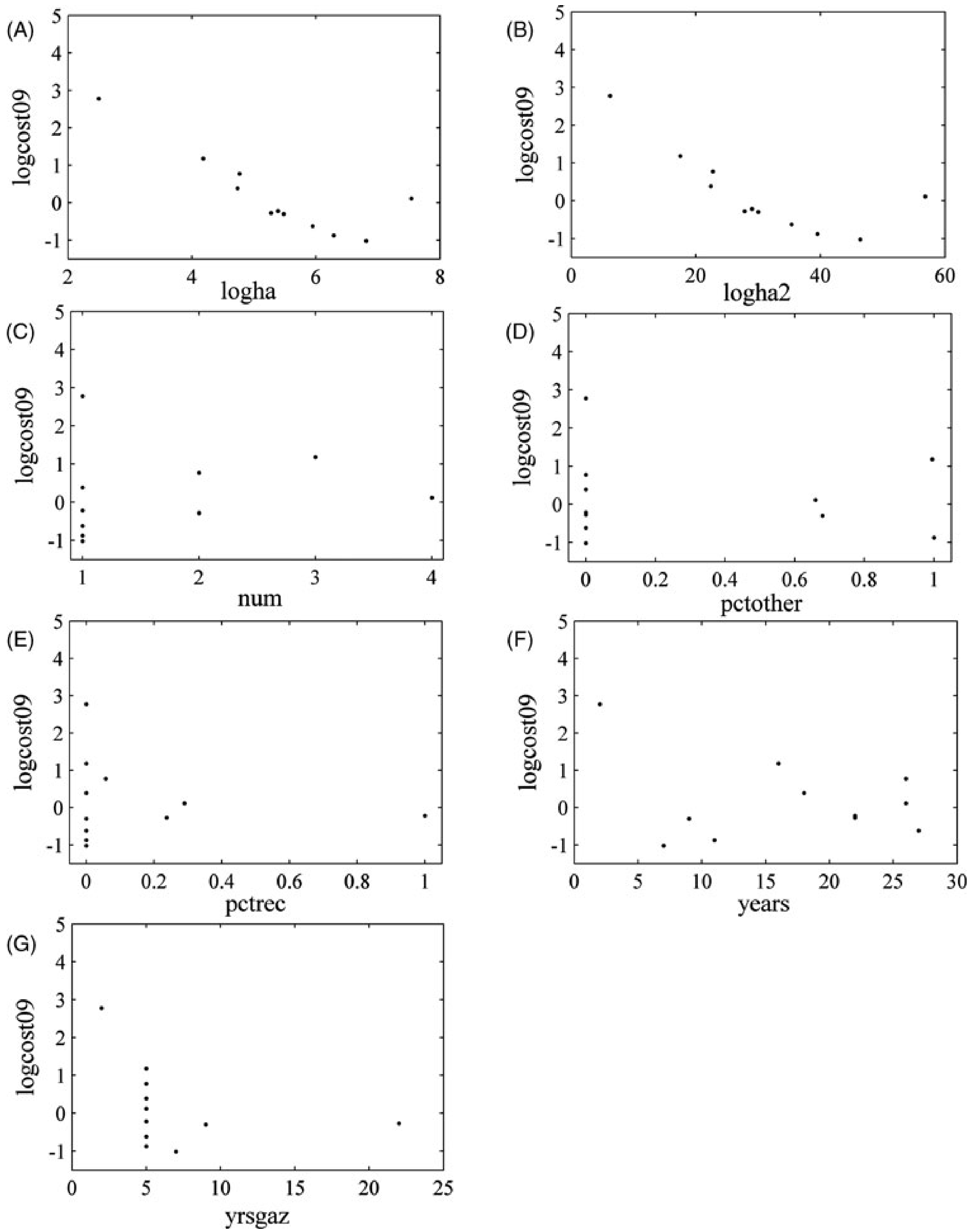

Figure 2 Relationships between the log of management cost per hectare *(logcost09)* (y-axes) and predictor variables (x-axes): (A) log of area (*logha*); (B) square of logha (*logha^2*); (C) number of zones (*num*); (D) percentage of MPA in zones other than IUCN categories I or II (*pctother*); (E) percentage of MPA in recreation zones (*pctrec*); (F) number of years since MPA establishment (*years*); and (G) number of years since last gazettal (*yrsgaz*).

Table 1. Summary of generalized linear model comparisons using Akaike's information criterion corrected for small sample sizes (AIC_c), sorted by AIC_c. *logha* is the log of total MPA area in hectares; $logha^2$ is the square of the previous term (allowing a polynomial relationship); *num* is the number of zones contained in the MPA; *years* is the number of years since establishment; *yrsgaz* is the number of years since the MPA was last gazetted; *pctother* is the percentage of area covered in zones where some extractive use is allowed; and *pctrec* is the percentage of area classified in recreation area zones. (A) lists the five candidate models (out of 63) with the lowest AIC_c; (B) lists the five candidate models with the highest AIC_c; and (C) gives the multimodel inference for parameters. The full list of models is shown in the Supporting Information

	K	AIC_c	Delta_AIC_c	AIC_cWt	Cum.Wt	LL
(A) Top five candidate models (with lowest AIC_c)						
logcost09∼logha+logha²+*num*	5	16.62	0.00	0.77	0.77	2.69
logcost09∼logha+logha²+*num*+yrsgaz	6	21.08	4.46	0.08	0.86	5.96
logcost09∼logha+logha²	4	22.22	5.60	0.05	0.90	−3.78
logcost09∼logha+logha²+*num*+years	6	22.70	6.08	0.04	0.94	5.15
logcost09∼logha+logha²+years	5	23.04	6.43	0.03	0.97	−0.52
(B) Bottom five candidate models (with highest AIC_c)						
logcost09∼logha+logha²+*num*+ yrsgaz+pctrec+years	8	68.30	51.68	0.00	1.00	9.85
logcost09∼logha+logha²+*num*+ pctother+pctrec+years	8	77.66	61.04	0.00	1.00	5.17
logcost09∼logha+logha²+yrsgaz+ pctother+pctrec+years	8	84.11	67.49	0.00	1.00	1.95
logcost09∼logha+*num*+yrsgaz+ pctother+pctrec+years	8	85.52	68.90	0.00	1.00	1.24
logcost09∼logha+logha²+*num*+ yrsgaz+pctother+pctrec+years	9	173.70	157.09	0.00	1.00	12.15

	Model-averaged estimate	Unconditional SE	95% unconditional CI Lower	95% unconditional CI Upper
(C) Multimodel inference for parameters				
Logha	−0.74	0.12	−0.98	−0.51
Logha²	0.16	0.04	0.09	0.24
Num	0.32	0.08	0.16	0.48
Pctother	−0.09	0.33	−0.73	0.55
pctrec	0.1	0.36	−0.61	0.81
years	0.02	0.01	0	0.05
yrsgaz	−0.03	0.01	−0.06	0

$192.3 million over 20 years. For the 30% no-take scenario, the estimated management cost was about $24.5 million per year and, over 20 years, about $375.9 million (Table 4).

In sensitivity tests, the 100% no-take scenario remained cheaper than the 30% no-take scenario. Specifically, when using management budgets from 2007 to 2008 instead of 2008–2009 (Figure 3B), model predictors remained similar but the relative magnitude of estimated management costs varied (the 100% scenario was 1.3 times less expensive than the 30% scenario with 2007–2008 data, vs. 2.0 times less expensive using 2008–2009 data). Sensitivity testing of a potential data outlier (the largest MPA datum, Great Barrier Reef Marine Park) showed that the polynomial fit with area of MPA still applied, but the magnitude of estimates varied (see Supporting Information).

The expert-based approach estimated the annual management cost of the 100% no-take scenario at almost $8 million and that of the 30% scenario at about $13.5 million (Table 4; see Tables 2 and 3 for detail), assuming synergies with management of the adjacent Great Barrier Reef Marine Park. Estimated 20-year costs were $122.6 million for the 100% no-take scenario and $206.9 million for the 30% no-take scenario. The difference in management costs between the scenarios was primarily due to

Table 2. Expert-based approach to estimating potential management costs for the Coral Sea: full-time equivalent (FTE) staff positions and associate costs[a]

Activity[b]	Estimated staff for 100% no-take	Estimated cost for 100% no-take	Estimated staff for 30% no-take	Estimated cost for 30% no-take
General administration and management	Management: 1FTE Administration: 2FTEs		Management: 1FTE Administration: 3FTEs	
Long-term protection and conservation	Compliance: 4FTEs Natural resource management (NRM) experts (e.g., biologists to implement monitoring activities): 4FTEs		Compliance: 8FTEs NRM experts: 6–8 FTEs	
Ecologically sustainable use	Permits: 2FTEs Management planning: 2FTEs Incidence response: 1FTE		Permits: 2FTEs Planning: 2FTEs Incidence response: 1FTE	
Understanding and enjoyment	1 FTE		1 FTE	
Operating expenses (computers, training, field equipment, etc)		$20,000 per FTE		$20,000 per FTE
Facility leasing (offices)		$10,000 per FTE		$10,000 per FTE
Total staff and on-costs[c]	17 FTEs	~ $2.2 million	24–26 FTEs[d]	~ $3.1 million

[a]Cost estimates are the additional, marginal costs to the existing field management regime for the GBR, not a new, stand-alone management regime.
[b]Based on categories used by the Great Barrier Reef Marine Park Authority and Queensland Parks and Wildlife Service.
[c]FTE costs are based on an average of Great Barrier Reef Marine Park staff costs at $80,000 per FTE per year. On-costs are estimated at 25% (e.g., superannuation, leave entitlements). The total estimate of staff costs is thus $100,000 per FTE per year.
[d]Estimate based on lower bound of 24 FTEs.

increased compliance and enforcement costs for the 30% scenario.

Discussion

Ours is the first study of MPA management costs to compare estimates of different protection scenarios for a large proposed MPA. The seminal studies in estimating MPA management costs were the global MPA model (Balmford *et al.* 2004) and subsequent related analyses (Richardson *et al.* 2006; Gravestock *et al.* 2008). To our knowledge, this work has not informed management costs of alternative MPA scenarios. Using a statistical model and expert-based methods, our estimates of management costs for the Coral Sea indicated that a single large no-take reserve is less expensive to manage than a multiple-use MPA of equivalent area with a 30% no-take component. The main factor in this difference was the number of zones, although this was a surrogate for compliance costs, according to experts: infringement is more likely in a complicated zoning design so enforcement is more expensive. Estimating management costs of different MPA scenarios is challenging but adds an important financial perspective to MPA design.

The simplest approach to estimating management costs for MPAs would be to apply an existing model. However, we did not obtain realistic results for the Coral Sea from the global model of Balmford *et al.* (2004). This model does not differentiate between no-take and multiple-use MPAs. Also, the assumption of a linear reduction in management cost with increasing MPA area is unrealistic for very large proposed MPAs such as the Coral Sea because per-unit-area costs are predicted to be close to zero. Using data from Australian MPAs, we found a strong relationship between the log of per-unit-area cost and log of MPA area, but the best fit was polynomial, not linear. A polynomial relationship means that the initial economies of scale hold until a threshold is reached, whereupon costs increase again (Figure S4). As the size of MPAs increase, variable costs (e.g., fuel) also increase but at a slower rate than the increase in area, leading to cost efficiencies related to size. Although we could not differentiate between variable and fixed costs, we hypothesize that fixed costs increase in a stepped fashion while variable costs have a polynomial functional form. In combination, these result in a polynomial relationship between MPA area and per-unit-area management costs. Establishment of management budgets for recent very large MPAs might soon shed light on these relationships.

Estimates derived from our statistical model were higher than the expert estimate, but the ratio of costs between the 30% and 100% no-take scenarios was similar. With both methods, management of a multiple-use area with 30% protection was between 1.3 and 2 times

Table 3. Expert-based approach to estimating potential management costs for the Coral Sea[a]: purchase, contracting or leasing of equipment and services to enable management actions (non-staff costs; rough estimates not based on a risk assessment[b])

Outputs	Activity	Estimated requirement for 100% no-take	Estimated cost for 100% no-take	Estimated requirement for 30% no-take	Estimated cost for 30% no-take
Protected marine ecosystems (e.g., intact trophic structures in no-take zones)	Compliance monitoring[c] (fishing, tourism)				
	Aerial surveillance; frequency of flights should be determined by risk profile (e.g., timing and effort of fishing in regions adjacent to no-take areas)	One aircraft dedicated to Coral Sea about half of the time	$2 million	One aircraft dedicated to Coral Sea	$4 million
	Scheduled multi-agency on-water surface patrol. Cost estimate consists of vessel time and associated contract personnel for safe vessel operation. (compliance staff costs are estimated separately in Table 2)	Three times per year, for 2- to 3-week trips (estimate based on 20 days per trip)	$1.2 million	Six times per year, for 2- to 3-week trips (estimate based on 20 days per trip)	$2.4 million
	Unscheduled on-water compliance monitoring: on-call vessel to ensure incident response capacity. The on-call incident response rate assumes that last-minute chartering of vessels would require additional resources at three times the regular rate.	$60k/day, 14 days	$840,000	$60k/day, 28 days	$1.68 million
	Vessel Monitoring System (VMS) and Automated Identification System (AIS) operating costs (purchase or leasing and operation of receivers and related equipment and transmission services)		$25,000	Increased need to request data from VMS systems	$50,000
	Compliance investigations support (legal fees, international travel for investigations)		$100,000	Double the number of investigations	$200,000
Protected island ecosystems (high levels of natural integrity, minimal pests)	Research and monitoring of islands: invasive species management, surveys of seabirds and turtles	Two visits per year, one in summer, one in winter, 3 weeks on-site per visit, 12 people plus vessel crew (vessel and crew $20,000 per day)	$920,000	Additional on-site monitoring required for surrounding marine areas to determine effectiveness of more complex zoning. Three visits per year, 3 weeks on-site per visit, 12 people plus vessel crew	$1,380,000

Continued

Table 3. Continued.

Outputs	Activity	Estimated requirement for 100% no-take	Estimated cost for 100% no-take	Estimated requirement for 30% no-take	Estimated cost for 30% no-take
Protected vulnerable species and habitats	Research funds (e.g., for collaboration with universities)		$500,000		$500,000
Sustainable tourism and recreation facilities	Outreach, including development and distribution of educational materials and maps, signage, website		$50,000	Zoning makes compliance more challenging, and hence users need to be provided with sufficient maps, signage, etc.	$100,000
Total purchase, contracting or leasing of equipment and services to facilitate management actions			$ 5.6 million		$10.3 million
Total staff and on-costs (from Table 2*)*			$2.2 million		$3.1 million
Total			$ 7.8 million		$13.4 million

[a]Cost estimates are the additional, marginal costs to the existing field management regime for the GBR, not a new, stand alone management regime
[b]A risk assessment involves an assessment of times and locations of increased risk of noncompliance. For example, migratory pelagic species subject to illegal harvest may be prevalent during specific times of the year in part of the region. Increased compliance resources should be assigned to such a region during those times. Such a risk assessment was beyond the scope of this research, and hence is not considered in these estimates.
[c]Compliance scenario: We assumed that legislation would enable effective compliance and enforcement. For example, permits would be required for tourism operators, vessel monitoring systems would be mandatory for all tourism and fishing vessels that operate in the region, and minimum speeds would be imposed on commercial fishing vessels for travel through no-take areas to preclude fishing. A relatively new system, the Automatic Identification System (AIS) might soon be mandatory, and would further facilitate compliance and enforcement through improved tracking of vessels.

more expensive than the same area with 100% protection (but see Supporting Information for sensitivity tests). The expert estimate may be lower because it assumed efficiencies associated with an extension of the management arrangements for the Great Barrier Reef Marine Park. Therefore, expert cost estimates were the additional, marginal costs to the existing field management regime for the Marine Park, not a new, stand-alone management regime. For example, the work force estimated was much smaller than if a separate management

Table 4. Summary of model results for management costs of the Coral Sea (2008–2009)

Model and scenario where applicable	Estimated cost per year (Australian dollars)	Estimated cost over 20 years with 3% discount rate (Australian dollars)
1. Application of Balmford *et al.* model[a]	3,056,000	46,835,000
2A. Statistical model using Australian MPA data, 100% no-take scenario	12,550,000	192,324,000
2B. Statistical model using Australian MPA data, 30% no-take scenario	24,528,000	375,866,000
3A. Expert-based estimate, 100% no-take scenario	7,800,000	122,590,000
3B. Expert-based estimate, 30% no-take scenario	13,400,000	206,871,000

[a]The global model, derived from MPAs with various management arrangements including no-take and multiple-use, does not differentiate between no-take and multiple-use MPAs and hence could not be applied to the two scenarios.

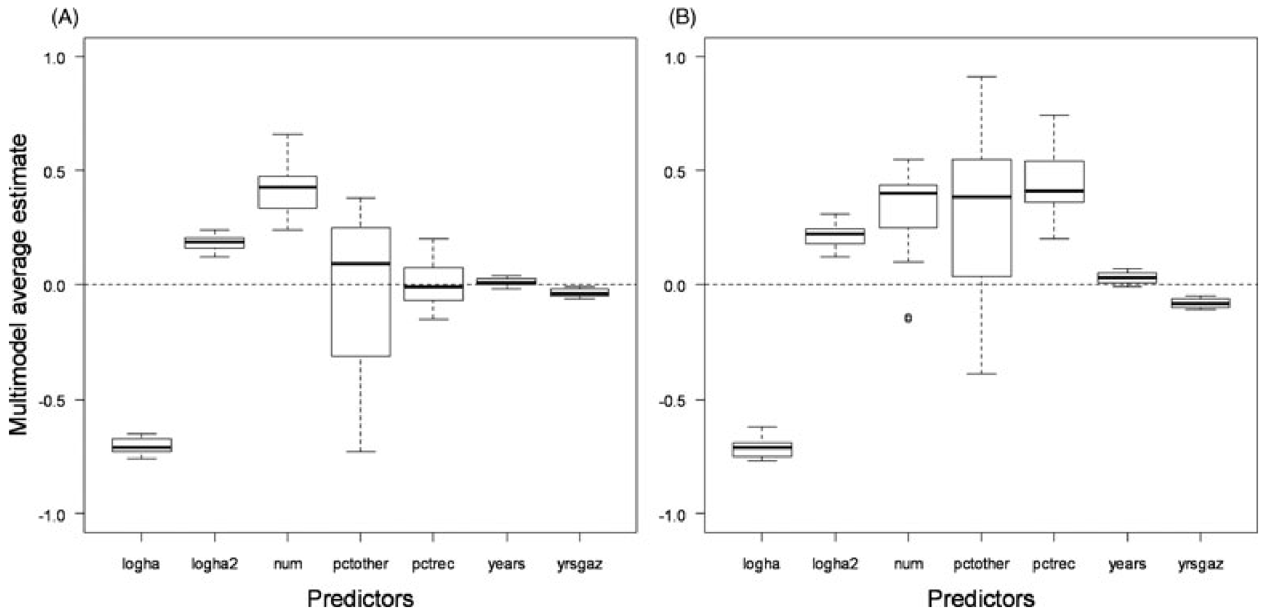

Figure 3 Box plots of multimodel predictor estimates. Medians are shown by heavy horizontal lines. Ends of boxes are 95% confidence intervals. Dashed vertical lines with light horizontal lines at ends indicate maximum and minimum values. (A) budget data for 2008–2009; (B) budget data for 2007–2008.

Table 5. Estimation of management costs of new MPAs from data on existing MPAs: ideal and actual data for statistical models

Type of data	Ideal	Actual: Balmford *et al.* and our statistical model based on Australian MPA data
Spatial resolution of cost data	Individual MPAs, with costs distinguished for internal zonings	Individual MPAs, no data for costs of zones
Management resolution of cost data	Individual MPAs, divided into fixed and variable costs, with costs of individual management activities	Individual MPAs, data only recorded as total costs not fixed and variable costs, and no data for management activities
Estimates of required costs	Current costs distinguished from enhanced costs (costs required to perform management activities to one or more explicit, agreed standards). This allows estimates of funding shortfalls for existing MPAs and supports more realistic estimates for new MPAs	Current costs only
Sample of existing MPAs	Covering the full ranges of predictor variables (so that prediction involves interpolation within these ranges)	Balmford *et al.* (2004) used data on MPAs that ranged from $<0.1\text{km}^2$ to $>300{,}000\ \text{km}^2$. Our data were from Australian MPAs that ranged from 3km^2 to $344{,}000\ \text{km}^2$. Modeling costs of the $972{,}000\ \text{km}^2$ Coral Sea Conservation Zone therefore extrapolated considerably.
Identification of predictors of costs	Data recorded for all plausible predictors likely to be associated with costs	Only some predictors
Spatial resolution of data on predictors of cost	Individual MPAs, with predictors recorded separately for internal zonings	Individual MPAs, no data for zones
Management resolution of data on predictors of cost	Individual MPAs, with predictors recorded separately for individual management activities	Individual MPAs, no data for management activities

authority were established specifically for the Coral Sea. In contrast, by using data from existing MPA budgets, the statistical modeling carried the implicit assumption that the Coral Sea would be managed separately.

Our statistical approach had several limitations (and see Table 5). First, it was based on only 11 data points, constraining its statistical power. Second, these 11 MPAs are much smaller than the proposed Coral Sea MPA; the largest is the Great Barrier Reef Marine Park with 344,520 km^2 compared to 972,000 km^2 for the Coral Sea, necessitating extrapolation. Third, data for several potentially important explanatory variables were lacking (e.g., visitor numbers [Gravestock *et al.* 2008], presence of islands, costs associated with managing different zones, distinguished variable, and fixed costs). Fourth, our cost data reflect current budgets rather than assessed management needs. Previous studies and experts advising on this study indicate that current budgets are likely insufficient (Balmford *et al.* 2004). Budgets from nonmanagement agencies may also contribute funding not accounted for in management budgets. For example, in 2002 the Great Barrier Reef Marine Park Authority estimated that actual management costs were about twice the budget (GBRMPA 2002). The absolute figures from our model should therefore be interpreted with caution.

The expert-based approach also relied on many assumptions (see supplementary materials). Ideally, cost estimates should be based on a full risk assessment, for example analyzing times and locations of increased risk of infringement, and allocating resources accordingly. This was beyond the scope of our research. Experts attempted to be comprehensive in their estimates, but they might have missed some costs. The estimates were, however, an improvement over other approaches such as the global cost model (Balmford *et al.* 2004) because they considered the costs of individual activities as well as the context of the region, using management of the adjacent Great Barrier Reef Marine Park as a guide.

Statistical and expert-based methods are complementary and their combined application might be valuable in subsequent studies. Statistical modeling, especially with a rich sample of data, can identify the relative importance of predictors and interactions between them (Barry & Elith 2006). But statistical models always benefit from expert scrutiny (Wintle *et al.* 2005), and independent expert estimates, as derived in our study, can lend credibility to modeled estimates.

Our statistical model and expert estimates converge on two important conclusions. First, both methods indicate that management costs for the proposed Coral Sea MPA are substantial (see Table 4). Although not current practice (Ban & Klein 2009), there is a clear need to include estimates of management costs when designing and proposing MPAs. As shown here, these estimates are difficult to obtain, but additional work will make them more sophisticated and accurate. Second, our statistical and expert-based methods both indicate that a large no-take area is less expensive to manage than the same area managed as multiple use with a smaller no-take component. While this result was relatively robust to sensitivity tests (see supplementary materials), studies are needed in other parts of Australia and in other countries for corroboration. We suggest two rules of thumb that can be tested: (1) management of large no-take areas is more cost efficient than multiple-use areas of the same area; and (2) per-unit-area management costs initially decrease with increasing MPA size, but this relationship cannot be extrapolated to very large MPAs; instead, after some threshold size, management cost per unit area increases again, resulting in a polynomial relationship.

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Supporting Information

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

Supporting materials

Table S1: Commonwealth marine parks and Great Barrier Reef Marine Park details and operating costs.

Table S2: Predictors of MPA management costs used in our modeling approach.

Table S3: Full listing of candidate models.

Supporting methods and results

Relationship between log of cost and explanatory variables

Range of no-take and multiple-use options

Sensitivity testing: Effect of Great Barrier Reef Marine Park data point (2008–2009)

Schematic of hypothetical economies of scale for MPA enforcement

Expert-based management cost estimates for the Coral Sea: assumptions

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