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LETTER

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Bigger or better: The relative benefits of protected area network expansion and enforcement for the conservation of an exploited species

Caitlin D. Kuempel[1,2] | Vanessa M. Adams[1,2] | Hugh P. Possingham[1,2,3] | Michael Bode[4]

[1] Centre for Biodiversity and Conservation Science, School of Biological Sciences, University of Queensland, St. Lucia, QLD 4072, Australia

[2] ARC Centre of Excellence for Environmental Decisions, University of Queensland, St. Lucia, QLD 4072, Australia

[3] The Nature Conservancy, South Brisbane, Queensland 4101, Australia

[4] ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia

Correspondence
Caitlin Kuempel, Centre for Biodiversity and Conservation Science, School of Biological Sciences, The University of Queensland, Brisbane, QLD 4072, Australia.
E-mail: c.kuempel@uq.edu.au,
Tel:+61 7 3365 2491, Fax:+61 7 3365 1655

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Abstract

The global portfolio of protected areas is growing rapidly, despite widely recognized shortfalls in management effectiveness. Pressure to meet area-coverage and management effectiveness objectives makes it essential to determine how limited conservation funds should be allocated between expanding protected area networks and better enforcing existing reserves. We formally explore this question for the particular case of an exploited species in a partially protected system, using a general model linking protection, enforcement and legal/illegal resource extraction. We show that, on average, funds should be disproportionately invested in enforcement rather than expansion. Further, expansion alone, without additional enforcement, can actually reduce conservation outcomes. To help guide future decisions, we calculate the optimal allocation of resources between these two actions given any current level of enforcement and protected area coverage. In most cases, simultaneously investing in expansion and enforcement is the optimal decision. However, in places with low enforcement and high protection, protected area contraction, or strategically concentrating enforcement effort, produces the greatest benefits.

KEYWORDS

Aichi Target 11, compliance, management costs, management effectiveness, metapopulation modelling, natural resource management, poaching

1 | INTRODUCTION

International conservation agreements are driving the most rapid expansion of protected areas (PAs) in history. For example, Aichi Target 11 commits signatory countries to enclosing 17% of terrestrial and 10% of marine environments in “effectively and equitably managed” PAs by 2020 (Convention on Biological Diversity, 2010). Although many parts of the world now have substantial proportions of their land and sea territory under formal protection, over 50% of species have insufficient protection to meet current conservation targets (Butchart et al., 2015), and many PAs lack adequate management to effectively abate threats (Craigie et al., 2010; Geldmann, Joppa, & Burgess, 2014; Gill et al., 2017; Mora, 2006). While some initiatives are calling for even more of the Earth's surface to be dedicated to nature (e.g., “half-earth” (Wilson, 2016)), others suggest that shifting efforts towards implementation and enforcement of existing PAs would better serve conservation (Costelloe et al., 2015; Jenkins & Joppa, 2009). While there are alternative approaches to protect biodiversity and reduce threats (Buscher et al., 2017), strict PAs remain a cornerstone of modern biodiversity conservation.

Resource constraints make it difficult to improve both the effectiveness and coverage of PAs. The dramatic expansion of terrestrial and marine PAs over the past 25 years (by 92% and 513%, respectively (Butchart et al., 2015)), reflects a substantial investment in PA establishment. A corresponding investment in management capacity is not as apparent, with many existing PAs currently lacking the means to operate effectively due to shortfalls in resources and/or management planning (Gill et al., 2017; Leverington, Costa, Pavese, Lisle, & Hockings, 2010; Watson, Dudley, Segan, & Hockings, 2014).

Effective PA management is required to stop threats that undermine the values of parks. Such investment is particularly vital for extractive threats, including fishing (Bergseth, Russ, & Cinner, 2015; Mora, 2006), bushmeat hunting, and wildlife trade harvest (Hilborn et al., 2006). In these cases, a large part of effective management involves ensuring compliance with no-take regulations (Arias, 2015; Keane, Jones, Edwards-Jones, & Milner-Gulland, 2008). Illegal harvesting (i.e., poaching) is particularly problematic because poachers may become more attracted to PAs as they become more effectively enforced and protected populations increase (Arias & Sutton 2013; Hall, Milner-Gulland, & Courchamp, 2008). Additionally, as PAs expand, enforcement resources will be diluted across larger areas and longer perimeters, potentially decreasing the optimal number of reserves (Potts & Vincent, 2008). These dynamics create complex feedbacks between expansion, enforcement, and human behavior that are critical to understanding compliance and conserving biodiversity.

Ideally, maximizing expansion *and* enforcement would produce the best outcomes for conservation, but both actions are interdependent and demand the same resources. The optimal allocation decision is therefore not obvious. Here, we develop a general model that describes the coupled dynamics of protection and compliance in a partially protected habitat network, focusing on the case of a commercially valuable species. We apply this model to (1) evaluate the impact of PA expansion without additional enforcement funds; (2) determine how an increasing budget should be shared between enforcement and protection from a low protection/low enforcement state to a high protection/high enforcement state; and (3) guide the allocation of resources between these two actions given any current level of enforcement and protection.

2 | METHODS

Our model describes an exploited metapopulation of both commercial and conservation value, and the behavior of humans exploiting these organisms in a partially protected system (Figure 1). To focus on the trade-off between the extent of the PA network and the level of enforcement effort, the ecological and economic components of the model are straightforward and general. The model was parameterized to ensure that the harvested metapopulation was robust enough to persist without any protection, but where both the harvesters and population would respond to changes in protection and enforcement (see Table S1 for a complete table of model parameter values. Model code is publicly available at https://doi.org/10.5281/zenodo.1068314).

Population Model: We use a spatially implicit population model to describe a species with a two-phase life-history: a space-limited adult stage and a dispersive juvenile stage. This basic structure resembles many plant, insect, and mammal species, but is most similar to a fish species in a patchy coastal habitat (e.g., rocky or coral reefs). Space is represented by M habitat patches, which could represent sites or home ranges in a contiguous land- or seascape, or discrete patches in a metapopulation. The dynamics of individual patches are coupled by juvenile dispersal. The system is divided into R protected patches, where extractive activities are prohibited by a uniform level of enforcement (but are not necessarily absent), and $F = M - R$ unprotected patches, where there are no harvest restrictions. Patches are ecologically and economically identical (e.g., equal travel costs, productivity), but experience different levels of extractive effort due to the enforcement of harvest restrictions on protected patches. The model, therefore, describes two abundance levels: $\bar{N}_R$ on each protected patch and $\bar{N}_F$ on each exploited patch.

We model abundance on the reserved and harvested patches in discrete time with the equations:

$$\bar{N}_R(t+1) = \bar{N}_R(t)\left(1 - qE_R^z\right)(1-m) + I(t), \tag{1}$$

$$\bar{N}_F(t+1) = \bar{N}_F(t)\left(1 - qE_F^z\right)(1-m) + I(t). \tag{2}$$

The total abundance of the species across the system is therefore:

$$N_T(t) = R\bar{N}_R(t) + (M-R)\bar{N}_F(t). \tag{3}$$

Abundance declines through natural mortality, $0 \le m \le 1$, and human extractive effort on protected and unprotected patches: $0 \le E_R,\ E_F \le 1$. On each patch, populations increase by the immigration of new juveniles, $I(t)$. Harvests are described by a Cobb-Douglas production function, determined by the catchability, $0 \le q \le 1$, of the species, and a diminishing returns parameter, $0 < z < 1$, which reflects the effort-output elasticity or the fact that doubling effort does not double the yield.

Together, all patches produce J juveniles, proportional to the species' per-capita fecundity, f:

$$J(t) = f[RN_R(t) + (M-R)N_F(t)]. \tag{4}$$

Juveniles are highly dispersive, and are distributed at an even density across protected and unprotected patches. We explore how this assumption affects our results in Text S1.

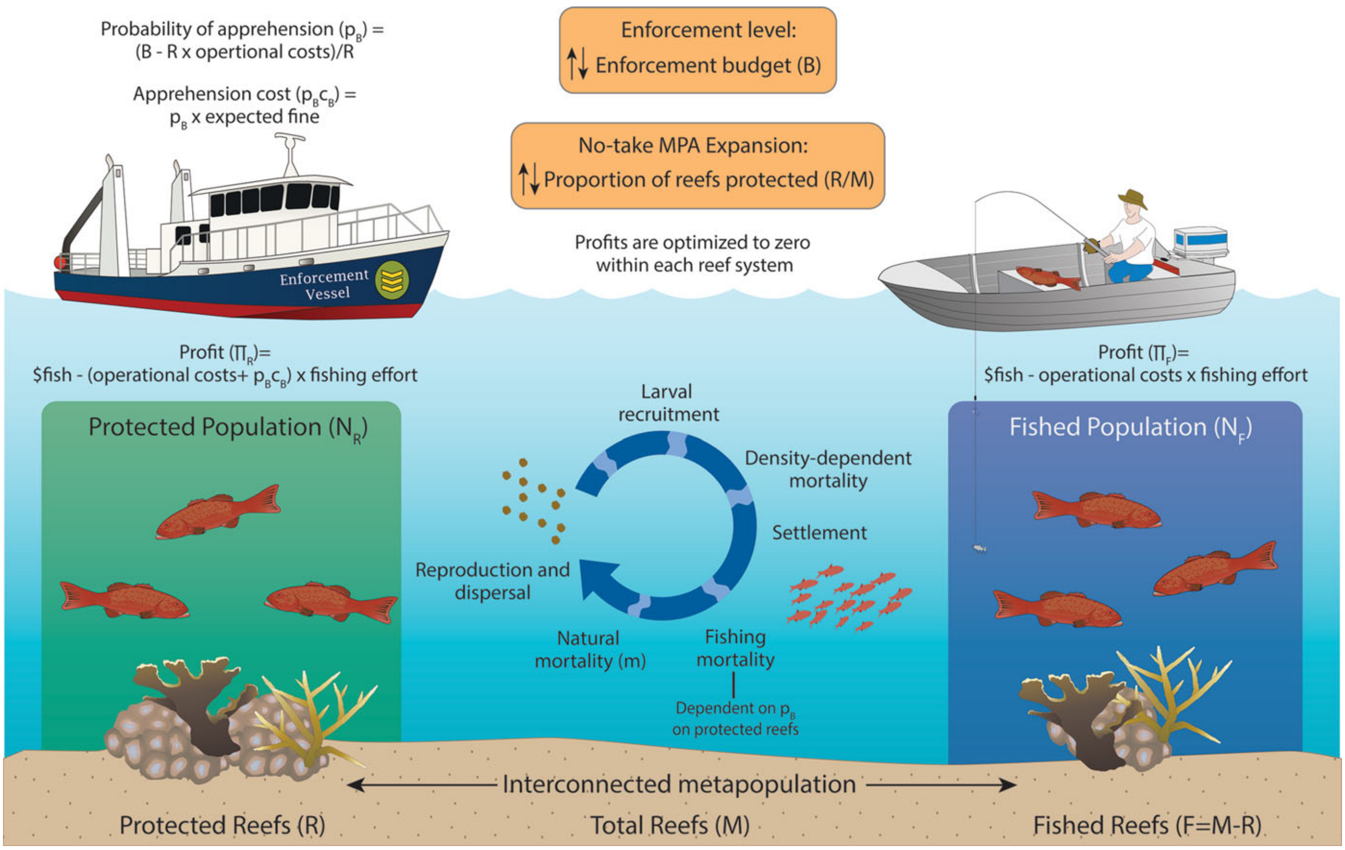

FIGURE 1 Schematic of model dynamics for an exploited, space-limited species in a marine context. The model depicts a partially-protected system (total patches = M). The population (N_R) on protected patches (green, R) and legally exploited population (N_F) on unprotected patches (blue, $F = M$ - R) are ecologically and economically identical. Extractive effort on protected patches is affected by the level of enforcement, which determines the probability of being apprehended, p_B, and the penalty incurred when apprehended, c_B. Profits on protected and unprotected patches (π_R and π_F, respectively) are equal to the difference between the market price (d) and the operational and the expected apprehension costs of harvesting those species. Enforcement level is varied by increasing or decreasing the budget for enforcement, B, which directly impacts the probability of being apprehended, p_B; expansion is simulated by increasing the proportion of patches that are protected ($\frac{R}{M}$), and which are therefore visited by enforcement officers. Symbols for diagrams courtesy of the Integration and Application Network (ian.umces.edu/symbols)

Upon arrival, juveniles experience density-dependent mortality before entering the adult population according to a Beverton-Holt relationship:

$$I(t) = \frac{\propto \frac{J(t)}{M}}{1 + \frac{\beta J(t)}{M}}. \tag{5}$$

We assume that $\alpha = 1$ and $\beta = 0.01$ for all examples below (but see sensitivity analyses in Text S2).

Economic model: We take an instrumental approach to compliance (Tyler, 1990), where resource users behave as rational, profit maximizers. From this perspective, protected patches carry higher expected extraction costs (as a result of penalties), but may also have a higher abundance of the target species. The amount of illegal harvesting occurring on protected patches reflects this expected cost.

Extractive effort on protected patches is thus affected by the level of enforcement, which determines the probability of being apprehended, $0 \leq p_B \leq 1$, and the penalty incurred when apprehended (e.g., fines, equipment confiscation, lost time), c_B. The expected cost of being apprehended while poaching is therefore $p_B c_B$. The apprehension probability of a harvester who spends a unit amount of time poaching is a function of the enforcement budget, B, minus overheads (e.g., travel costs, staff salaries) for each PA, c_T:

$$p_B = (B - Rc_T)/R. \tag{6}$$

We bound p_B between 0 and 1 (Figure S1). Note that because this probability is per unit time, increased poaching effort results in a higher expected apprehension cost (Bulte et al., 1999). Additionally, below a budget threshold that reflects enforcement overheads, ($B < c_T R$), $p_B = 0$, protected patches are essentially paper parks. Since very little is known about the relationship between the probability of apprehension and the amount of enforcement resources allocated we chose a linear relationship, but a logit functional form may also be appropriate. Profits on protected and unprotected patches (π_R and π_F, respectively) are equal to the difference between the unit market price of the resource, d, and the operational, c_E, and expected apprehension costs, $p_B c_B$, of harvesting:

$$\pi_R = dqN_R E_R^z - (c_E + p_B c_B)E_R \tag{7}$$

$$\pi_F = dqN_F E_F^z - c_E E_F. \tag{8}$$

Here, we assume harvester and enforcer operational costs are equal ($c_T = c_E$), but we vary them substantially within our sensitivity analysis (Text S2). Because access to the harvesting sector is unrestricted, the level of poaching effort on both protected and unprotected patches will increase until supernormal profits dissipate (i.e., until $\pi_F = \pi_R = 0$).

Prioritizing Expansion or Enforcement: Enforcement level is varied by increasing or decreasing the enforcement budget, B; expansion is simulated by increasing the proportion of protected patches.

We first test the impact of expansion without additional enforcement resources. We begin with only 5% of patches protected ($R/M = 0.05$), and an enforcement budget large enough to stop 95% of poaching (i.e., near perfect compliance: $E_P/E_F = 0.05$). We then simulate gradual PA expansion (up to 95% protection), but with no additional enforcement funds, to assess the impact of spreading a fixed enforcement budget over an expanding PA network.

Second, we consider the optimal pathway between a low-protection/low-enforcement state, and a high-protection/high-enforcement state. That is, how should an increasing budget be shared between enforcement and protection? We start with 5% protection ($R/M = 0.05$) and an enforcement budget low enough that harvesting effort on protected patches is 95% of harvesting effort on unprotected patches ($E_P/E_F = 0.95$). We then calculate the marginal benefit of directing an additional unit of funding toward increasing enforcement or increasing PA extent. The optimal decision will clearly depend on the relative costs of the two actions. Because we want to understand the intrinsic effectiveness of expansion and enforcement, not their relative costs, we standardize their costs. We calculate the improvement in N_T that results from increasing R/M from 5% to 10%. We then search for the amount of additional enforcement resources, δ_B, that creates the same improvement. Managers can therefore either increase protection by 5%, or add another δ_B to the enforcement budget.

Finally, based on the standardized units described above, we calculate the optimal state-dependent conservation decision for any current level of protection and enforcement. That is, for all management states (enforcement budget, B, and protection, R/M), we calculate whether managers should expand (by 5%), or enforce (by δ_B). We allow managers to reduce the area protected (i.e., reducing R/M by 5%), if doing so improves N_T. To assess the robustness of our findings, we tested the sensitivity of our results under two alternative model formulations (Text S1) and to parameter variation of ±50% (Text S2).

3 | RESULTS

With a fixed enforcement budget, our model predicts that expansion from a low-protection/high-enforcement state will initially deliver substantial increases in abundance. In other words, despite a dilution of enforcement resources, the benefits from increasing PA size outweigh the perverse effects of increased poaching. If expansion continues, total abundance is maximized at some mid-point of protection, beyond which the dilution causes conservation benefits to decline. Abundance eventually declines to the level of an unprotected system (Figure 2). At this point, enforcement offers no benefits because the entire budget is consumed by overheads. Figure 2 is generated from our particular parameterization, but the qualitative changes in performance–diminishing returns and an interior maxima beyond which expansion produces worse outcomes–are common to all parameterizations and two alternative model formulations (Figures S2–S5). In some systems a logit functional form for the probability of being caught, p_B,

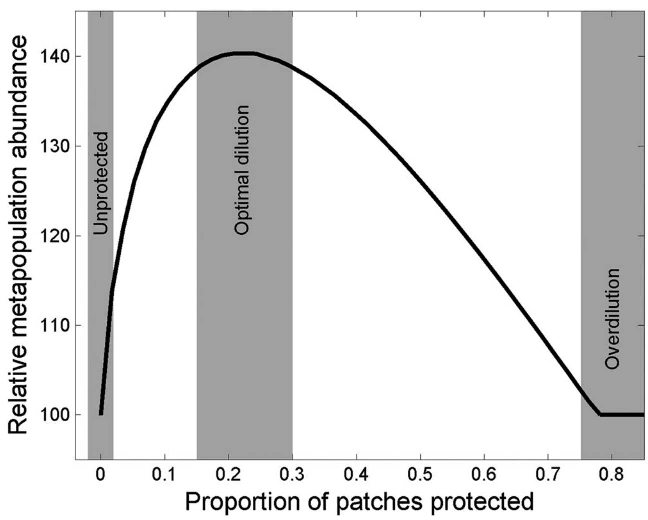

FIGURE 2 Impacts of protected area expansion on total species abundance under a fixed enforcement budget. Relative total abundance is standardized to an unprotected system. At the left-hand of the figure, the enforcement budget is high enough to stop 95% ($\frac{E_P}{E_F} = 0.05$) of illegal harvest in a system with 5% of patches protected ($\frac{R}{M} = 0.05$). Moving to the right along the curve, PA expansion initially increases total abundance, but delivers diminishing positive marginal returns. Once protection expands above 20%, these marginal returns become negative, as enforcement effort becomes too diluted. Beyond 75–80% protection, the budget is entirely consumed by travel time, and conservation outcomes are no better than an unprotected system. Replication code for this figure is publicly available at https://doi.org/10.5281/zenodo.1068314

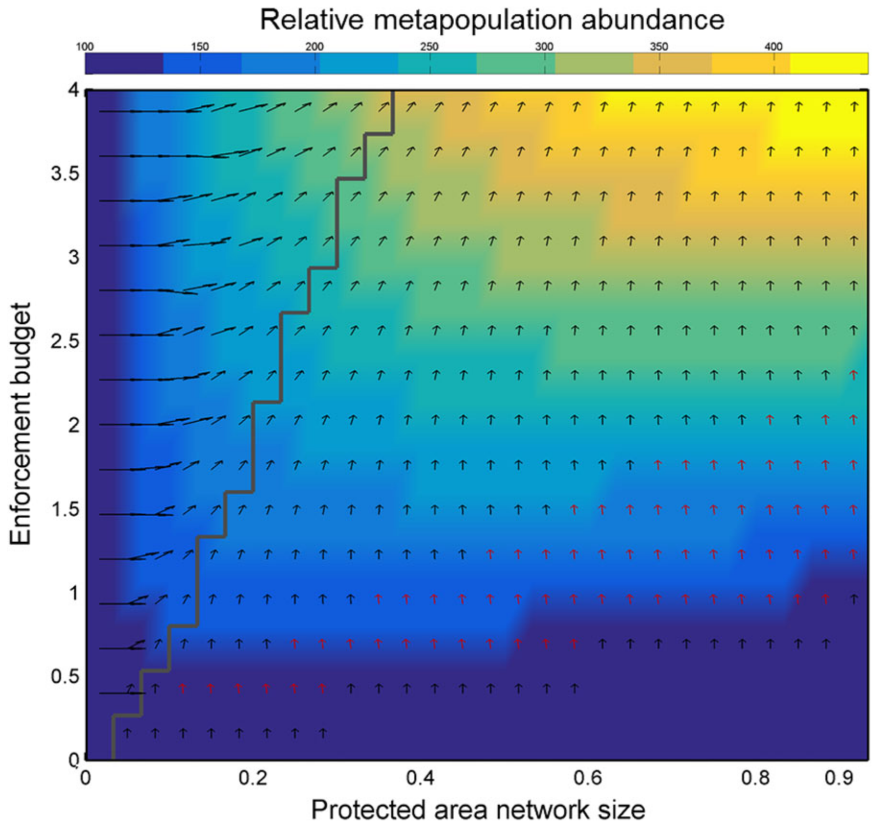

FIGURE 3 Total abundance (unprotected and protected patches) under varying levels of enforcement and protected area extent. Grey line indicates the optimal decision pathway from a low-enforcement/low-protection state to a high-enforcement/high-protection state. Arrows depict the state dependent decision between expansion and enforcement, for all levels of enforcement and PA network size. Red arrows indicate combinations of PA extent and enforcement budget where the optimal choice is actually to contract protected areas; black arrows indicate when expand, enforce or both produces the greatest conservation benefits

may be more appropriate, which would exhibit similar behavior but would likely shift the point where dilution occurs.

To maximize abundance, the optimal resource allocation from a low-protection/low-enforcement state prioritizes enforcement over expansion (grey line, Figure 3). Equal investment in expansion and enforcement initially produces optimal improvements, but enforcement quickly becomes the best use of additional resources, at a ratio of approximately 2:1. Importantly, this preference for enforcement holds broadly true across our sensitivity analysis. This recommends that, on average, decision-makers aiming to maximize the abundance of a given exploited species should always invest *at least* as much resources into enforcement as expansion (Text S2 and Figure S2).

Although enforcement is generally preferred over expansion, at low levels of protection the best option is to expand, since even low enforcement budgets can effectively exclude poachers across small areas. Moreover, small PAs are generally unable to produce larger populations, due to insufficient self-replenishment (Almany et al., 2009), making them less attractive to poachers. Interestingly, when PAs are relatively large but the enforcement budget is low, conservation outcomes are best achieved by contracting the PA network, coupled with either a constant or increased enforcement budget.

4 | DISCUSSION

The pressure to expand PAs to meet international targets (e.g., Aichi Target 11) may compromise enforcement efforts, particularly since area targets are clear and quantifiable while management effectiveness is difficult to measure. We explore scenarios where decision-makers aiming to maximize the abundance of an exploited species have two choices in how limited funds are spent: continue expanding PAs or increase enforcement in existing reserves.

Our results demonstrate that PA expansion without enhanced enforcement will always deliver diminishing marginal returns for the conservation of an exploited species, and may even deliver negative returns if it spreads the enforcement effort too thinly. Notably, many PA networks today have low levels of enforcement–that is, measured compliance is low–even in relatively well-managed conservation contexts. For example, the marine reserve network on Australia's Great Barrier Reef already covers >30% of reef area, but illegal harvesting has been estimated at 32.4% of comparable nearby unprotected reefs (Williamson, Ceccarelli, Evans, Hill, & Russ, 2014). Similarly, in the 1970–1980′s, 75% of Zambian elephant populations were lost in the Luangwa Valley because, despite substantial investments in anti-poaching patrols, enforcement effort was spread too thinly to stop poachers (Leader-Williams & Albon 1988; Leader-Williams, Albon, & Berry, 1990). In such cases, our results suggest that an expansion of the area under protection will deliver minimal or even negative conservation returns.

To avoid this, we found that the investment in enforcement should be at least equal to the investment in expansion, which may not be the case across many existing PAs. PA establishment without the means to ensure effective enforcement–"paper parks"–has been a major criticism of many conservation initiatives (Di Minin & Toivonen 2015; Dudley & Stolton 1999; Mora, 2006) and insufficient management resources have been cited across many PA networks (Gill et al., 2017; Leverington et al., 2010; Watson et al., 2014), which can limit enforcement efforts. Shortfalls in reporting on management actions and costs is likely contributing to these deficiencies. While expansion costs are often readily available or easy to estimate using proxies for area or opportunity cost (Armsworth, 2014; Naidoo et al., 2006), enforcement budgets are commonly too convoluted to approximate or include in systematic planning (Armsworth, 2014, Ban & Klein 2009; but see Davis et al. 2015). Improved transparency and accounting of management activities is urgently needed to prioritize actions and maximize biodiversity outcomes under constrained budgets.

In regions with extensive "paper parks" (i.e., high-protection/low-enforcement), our results show that PA *contraction* will deliver the greatest increase in exploited species abundance, particularly if resources are not available to increase enforcement effort. However, political difficulties in PA establishment often make downgrading, downsizing and degazettement (PADDD) illogical or unacceptable options. A politically feasible alternative would be to concentrate available enforcement resources into a subset of PAs, particularly those that would benefit the most from additional enforcement (e.g., those with high conservation value or high poaching levels). For example, consider the hypothetical PA system depicted in Figure 2: if 50% of habitat patches were protected, there would be an enforcement deficit and the PA network would provide little benefit. If additional enforcement funds were not available and PADDD was not a viable option, managers could strategically concentrate enforcement effort within 40% of protected patches to maximize conservation outcomes. This could be achieved through any mechanism that frees up money for increased enforcement in other areas such as triaging the most important or threatened reserves (as suggested by Fuller et al. (2010), Game, Bode, McDonald-Madden, Grantham, & Possingham, (2009), Leader-Williams & Albon (1988)) or through PA zoning schemes (e.g., strict no-take vs. multiple use or buffer/extraction zones). Albers (2010) showed that by strategically tailoring enforcement (or zoning) based on spatial patterns of de facto protection, where no patrolling is required, and de facto extraction, where patrolling does not deter illegal harvest, decision-makers can maximize the amount of pristine area protected.

It is important to note that the dichotomy between expansion and enforcement only exists within the paradigm of PAs. Many alternative approaches are available to reduce illegal extraction and/or conserve biodiversity that do not involve either enforcement or expansion. Our results therefore do not contribute to debates about whether spatial management is appropriate or socially equitable (Buscher et al., 2017; Duffy, St John, Büscher, & Brockington, 2016). Moreover, we focus on a single threat to a single commercially valuable species whereas modern PA design often considers multiple species, ecological processes or ecosystem services and tackles multiple threats (Watson et al., 2014). Our article ignores several important threats to biodiversity that can be associated with illegal harvests–the most obvious being habitat loss and degradation. While illegal extraction is a proximate cause of biodiversity loss, our results rely on the underlying assumption that habitat is maintained.

To provide a clear and interpretable contrast between enforcement and expansion, we chose a relatively simple formulation of a coupled ecological–economic system. Our extensive sensitivity analysis showed that our results are robust to changes in model parameterizations (see Text S1 and S2), but several caveats accompany our recommendations. First, our model is spatially homogeneous–all patches are of equal size, equal habitat quality, and have equal travel costs. Accounting for spatial heterogeneity would cause patches that are further away to be more costly to enforce and more costly, but perhaps more profitable, to illegally exploit. This would likely drive increased poaching, which we expect would increase the investment in enforcement over expansion. However, heterogeneity in both PA location and size can impact effectiveness (Geldmann et al., 2015) and implementation costs (i.e., acquisition and management (Ban, Adams, Pressey, & Hicks, 2011; Bruner, Gullison, & Balmford, 2004)) in complex ways, requiring further investigation. Second, we do not account for "willingness" to comply or issues of morality (e.g., a normative approach) that could affect poachers' behavior (Keane et al., 2008). Nevertheless, as long as additional enforcement and heavier penalties decrease illegal harvests, our conclusions will remain qualitatively robust. Finally, our model couples detection and apprehension rates and costs. Detection rates are likely to be higher than apprehension rates due to difficulties in proving culpability and costs of pursuing legal action. This would decreases the probability of incurring a penalty for illegal harvest, which would increase poaching and strengthen our results. Enforcement costs, however, may require discontinuous budget thresholds, such as the purchase of additional enforcement vehicles, to realize significant gains in protection probability which we did not account for in our model. These expenses are expected to significantly diminish in coming years with the implementation of vessel monitoring systems and new patrol technologies such as unmanned aerial vehicles (i.e., drones; Pimm et al., 2015).

The continued decline of biodiversity despite rapid PA growth calls into question the current focus on PA expansion. Our results reveal the close, interconnected, relationship between expansion, enforcement and PA network performance. They suggest that, despite difficulties in measuring and reporting enforcement, expansion must be associated with commensurate increases in enforcement resources. Our conclusions strongly underscore the importance of setting explicit, quantifiable goals for PA effectiveness and enforcement, in addition to extent.

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ORCID

Vanessa M. Adams http://orcid.org/0000-0002-3509-7901

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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