The cost of enforcing marine protected areas to achieve ecological targets

9 Nov 2017

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Keywords

Marine reserve, fisheries, poaching, conservation planning, coral reef.

Abstract

Protected areas are the primary management tool for conserving ecosystems, yet their intended outcomes may often be compromised by poaching. Poaching can be prevented through educating community members so they support protected areas and enforcement, but both activities can be costly. Consequently, many protected areas are ineffective 'paper parks' that contribute little towards conserving ecosystems. We develop a model of enforcement in a marine protected area and ask how much does it cost to enforce a marine protected area so that it has greater biomass of fished species than a paper park or has fish biomasses that meet ecological targets. Using a case-study from one of the most biodiverse reef systems globally, Raja Ampat in Indonesia, we find that slight improvements in the biomass of fished species beyond paper park status are relatively cheap, but achieving pristine fish biomass is far beyond the budget of most conservation agencies. We find that community engagement activities that reduce poaching rates can greatly reduce the cost of enforcement. Thus we provide dollar values that can be used to compare the value of community engagement with the cost enforcement. We conclude that the current policy of protected area enforcement is an ineffective way to manage protected areas. Budgets for park management should be optimised across spending on enforcement and alternative activities, like education to build community support. Optimized budgets will be much more likely to achieve ecological targets for recovering fish biomasses.

Introduction

Protected areas are a primary tool for conserving ecosystems. In marine ecosystems, protected areas are often used to protect species from the effects of fishery exploitation, which reduce the biomass and diversity of species (Edgar et al. 2014). Recent international commitments to meeting Convention on Biodiversity targets has seen rapid growth in marine protected areas globally, with coverage increasing more than four times since 2000 (Watson et al. 2014; Boonzaier & Pauly 2016). However, many of these new protected area may be 'paper parks' that are not enforced (Gill et al. 2017). Globally, the marine protected areas with the highest biomasses and diversity of large fish are those that are old, large, fully protected from fishing, isolated and well enforced (Edgar et al. 2014).

Ensuring that protected areas deliver their intended conservation outcomes requires sufficient ongoing funding for enforcement and for building community support (Gill et al. 2017). The expense of enforcing protected areas may be a major impediment to their long-term success (Ban et al. 2011). Poaching in protected areas can erode their benefits for conserving biodiversity (Bergseth et al. 2015; Rizzari et al. 2015). Poaching may occur when poachers perceive the probability of detection is low and/or if the park's objectives lack community support (Arias & Sutton 2013; Bergseth et al. 2017). Patrols of protected areas are critical to maintain compliance (Kelaher et al. 2015), but often patrols on their own cannot be comprehensive enough to maintain compliance. Community support is also critical, so that fishers avoid poaching and report offenders. Community support can be achieved through engagement activities, such as education and consultation with communities on management plans (Leisher et al. 2012). However, the connection between expenditure on enforcement and the benefits of protection are generally not considered during the design stage, where expectation around benefits typically involves an implicit assumption of perfect enforcement (but see Davis et al. 2015). Numerous studies have addressed the opportunity costs of marine protected areas for fishing (e.g. (Smith et al. 2010)). What has not been addressed is how much needs to be spent on enforcing compliance to meet particular targets for ecological relevant levels of fish biomass. Further, budgets for enforcement and community engagement are typically allocated ad-hoc, but budget allocations may be more effective if we could value community support in terms of avoided cost of patrols (Fox et al. 2017).

Here we develop an analytical framework for estimating the cost of enforcing protected areas so that fish biomass meets a conservation targets. We use the framework to quantitatively define a 'paper park' so we can calculate the cost of enforcement to achieve fish biomass that is significantly greater than that in an unenforced park. We also estimate the cost of achieving ecological relevant targets for fish biomass and compare this to the cost of achieving pristine fish biomasses. We apply the framework to model the Kofiau and Boo Islands Marine Protected Area in Raja Ampat Indonesia ((Ahmadia et al. 2015), Fig. S1). Raja Ampat is the global center of coral and fish diversity, but faces considerable pressure from fisheries. Efforts over the past ten years to establish protected areas have been successful and now management is transitioning to fiscal sustainability, thus quantifying budgetary needs for effective management is timely.

Results

Poachers often act like 'roving bandits' (Berkes et al. 2006), so we modeled biomass of fish in a park where the timing of poaching events is stochastic and a poaching event ends once fish biomass has been depleted to a certain level (Fig 1A). Given intermittent poaching, we can predict the probability of different biomass levels (Fig 1B).

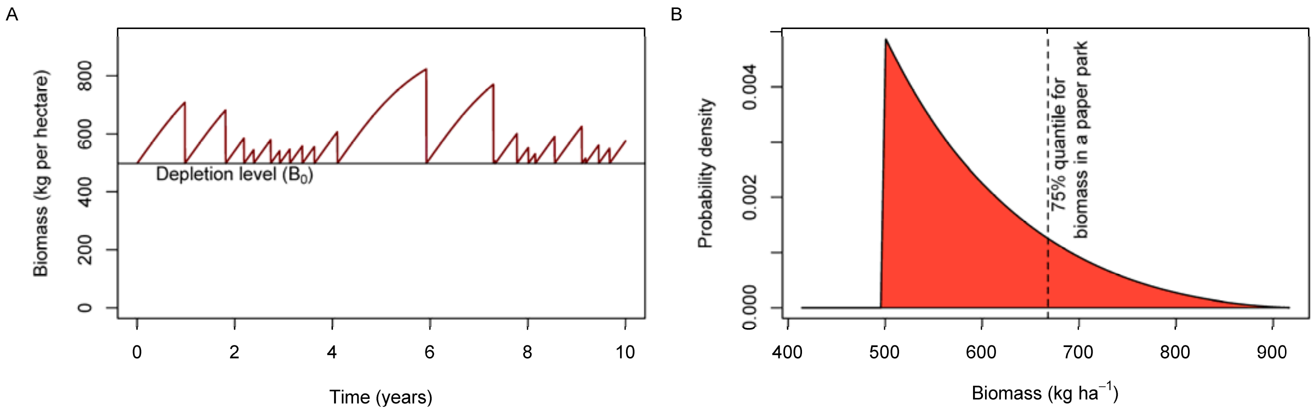

Figure 1 Example of fluctuations in fish biomass over time with discrete poaching events (A) and the probability density for biomass observed at random times (B). The 75% quantile for biomass in a paper park indicates the threshold that a park's mean fish biomass must be greater than to be classified as an effective park.

The definition of an effectively enforced park, a protected area that has a greater fish biomass than an unenforced protected area, depends on the poaching rate with no enforcement and the depletion level (Fig. 2). For Kofiau, we estimated pristine fish biomass at 926 kg ha-1 and an effective protected area occurs at a reef fish biomass of 500 kg ha-1. The limit for an effective protected area rapidly decreases as the rate of poaching increases towards an asymptote of the depeletion level (estimated at 497 kg ha-1) for Kofiau. Reef fish biomass has a slow recovery rate (MacNeil et al. 2015), so we expect it to be near the depletion level for even low rates of fishing. We found the limit for an effective protected area is close to the depletion level for fishing frequency of greater than once every 5 years (Fig. 2).

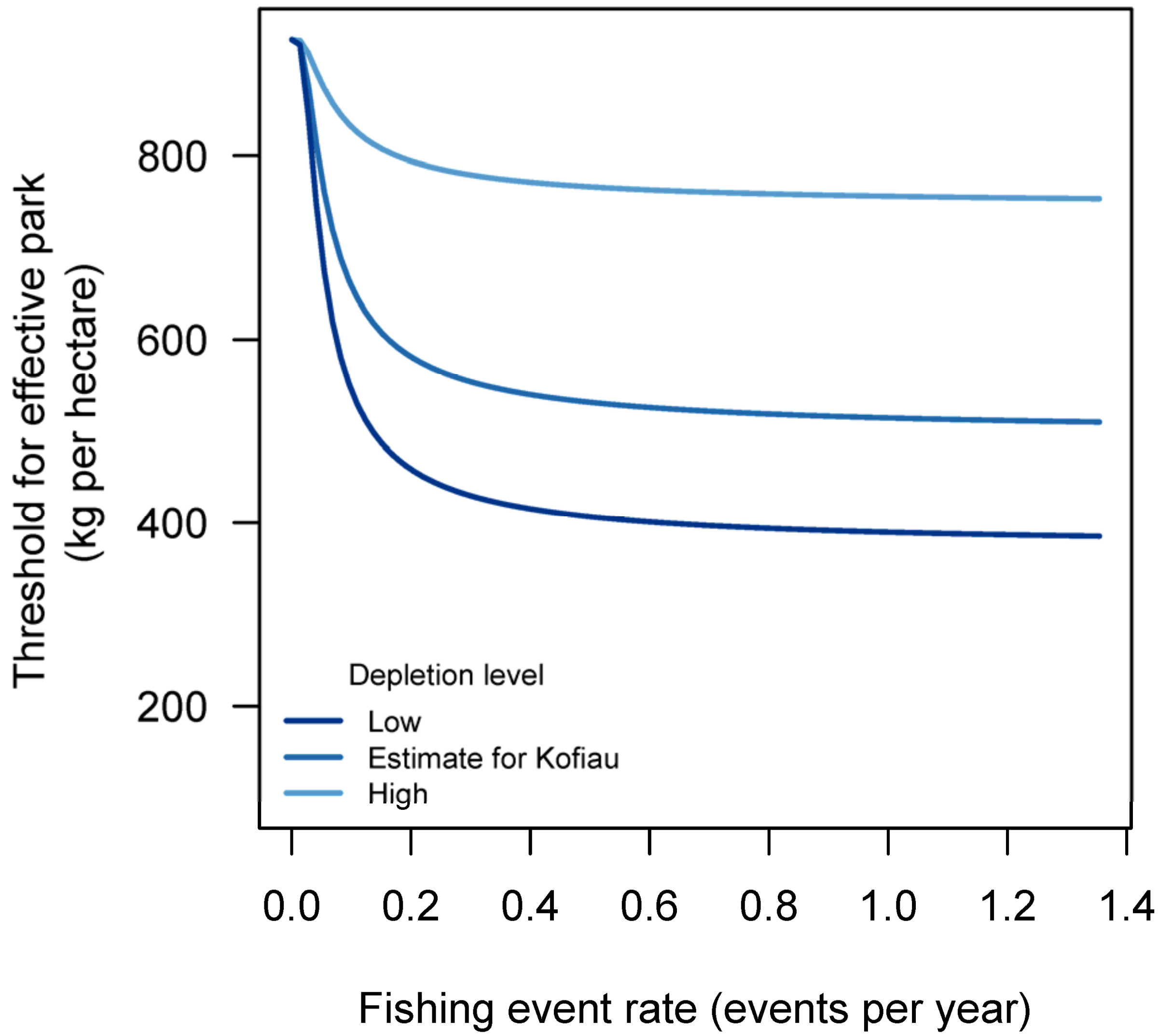

Figure 2 Thresholds for the size of effective parks based on the 75th quartile for biomass in a paper park, for different rates of fishing events and depletion levels (A); and the relationship between poaching rate and days patrolled for three scenarios of community support for a park (B).

If fish biomass is depleted to a lower density then the limiting biomass for a paper park is also lower (Fig. 2). Protected areas that have low poaching rates and little depletion prior to enforcement have a much greater limit for their fish biomass to be higher than a paper park. Protected areas in such places may therefore have high fish biomass, but are 'residual protected areas' in the sense that they have not improved fish biomass beyond the baseline.

For Kofiau, we estimated it would cost $USD16,000 per year in enforcement costs to achieve an effective protected area. The cost was greater to achieve greater levels of fish biomass, reaching $USD57,000 per year to achieve pristine fish biomass.

Communities that support protected areas may be less likely to engage in poaching and may contribute to enforcement through surveillance and deterrence of poaching conducted by non-local fishers. In communities that support protected areas we may expect that increasing the rate of patrols will cause more rapid declines in the rate of poaching than in communities that are unsupportive of protected areas. In communities that do not support protected areas the rate of poaching will be less sensitive to the rate of patrols. We estimated that to achieve an effective park in Kofiau the cost of community opposition was $USD 5000, whereas the value of having community support was $USD 5000.

While the ex-ante difference in enforcement costs is dependent on the specifics of the fishery, the relative value of community support depends only on the sensitivities of poaching to enforcement with and without community support (SI text, Fig S1). Thus, empirical estimation of how increasing enforcement rate affects poaching rates is critical when valuing community support, regardless of the fish population's life-history parameters or the targeted biomass.

Next we model four fish species types that cover a range of life-history parameters, have previously been identified to perform important ecological functions in coral reef ecosystems

(Brown & Mumby 2014) and include some groups that are currently used as indicators for the park's status (Glew et al. 2015). The reef fish types were: large groupers (family Serranidae) that predate on meso-predator fish and thus can suppress trophic cascades but are relatively slow growing; triggerfish (family Balistidae) that are important predators of bio-eroding sea urchins and have a moderate population growth rate; and parrotfish (family Scaridae) whose grazing can supress algal blooms and are relatively fast growing (Brown & Mumby 2014). We also include snappers (family Lutjanidae) because they are an important indicator species for the Kofiau reserve (Glew et al. 2015).

Of the three species types, the cost of enforcement was greatest to achieve biomass levels relative to unfished for slow growing grouper and lowest for the fast growing snapper (Fig 3). The cost of achieving incrementally larger biomass targets for slower growing species increased rapidly, because they can support very little fishing. For fast growing species, the incremental increase in cost for greater biomass targets approached a linear relationship.

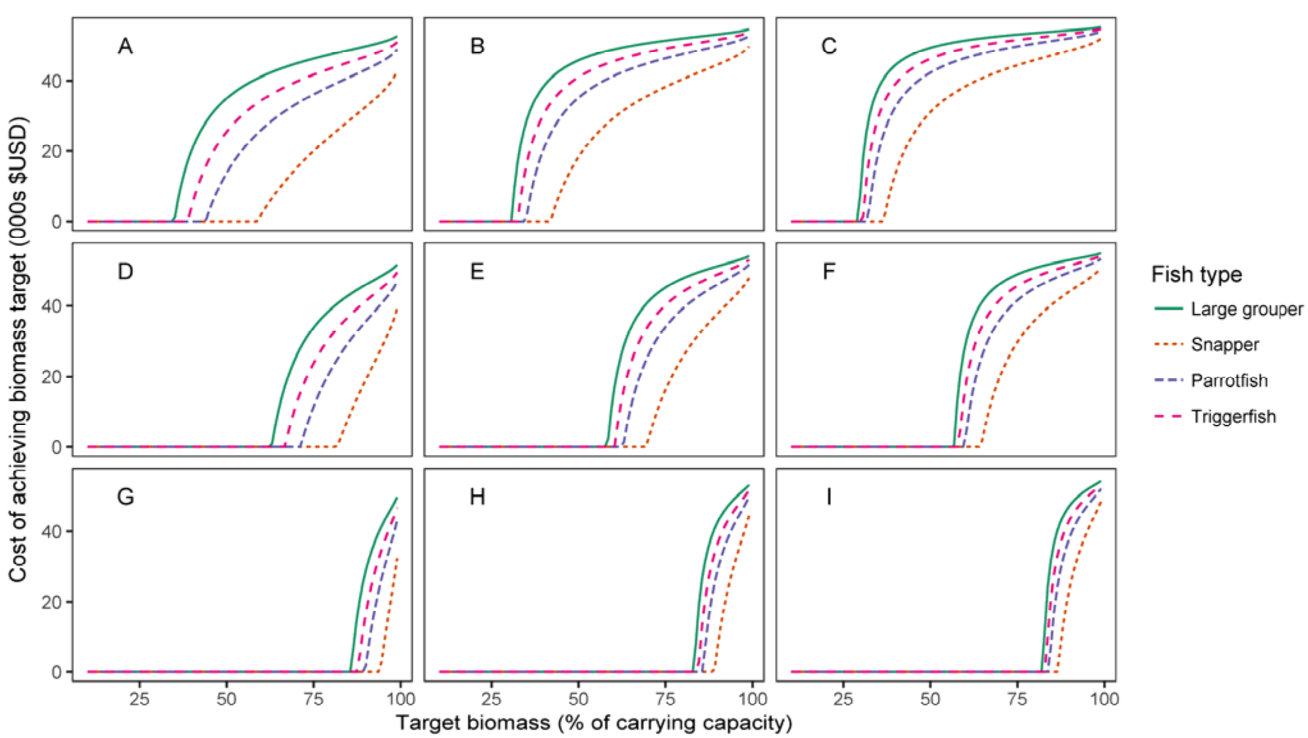

Figure 3 Cost of achieving biomass targets for each fish functional group for: little (A, B, C), moderate (D, E, F) and high (G, H, I) depletion; and for low (A, D, G), moderate (B, E, H) and high (C, F, I) intervals between poaching events. For each parameter the lower values are half the baseline, moderate values are equal to the baseline and high values are double the baseline, where the baseline are those values that were estimated for the primary analysis.

For all species, it cost less to achieve the same biomass level when the minimum depletion level was higher (Fig 3 - compare rows) or the average interval between poaching events was greater (Fig 3 - compare columns). For instance, achieving biomasses of 40% of their unfished levels cost $USD32,000 to $USD40,000 if the fish types were depleted to low levels and their was frequent poaching (Fig 3C), whereas no enforcement was necessary to achieve fish biomasses >90% of their unfished level if poaching was infrequent and there was little depletion of fish biomass (Fig 3G).

Discussion

The rapid expansion of protected areas requires quantitative definitions for assessing when a protected area is more effective than just its boundaries on a map. We suggested that a "paper park" be defined as a protected area where the average fish biomass does not exceed the bounds expected from a park with pre-protection levels of fishing, to a specified probability level. This formal definition of a paper park allowed us to consider the cost of enforcement. In doing so, we could estimate the annual variable cost of an effective park versus the cost of achieving functionally relevant or pristine fish biomass. Estimating the cost of enforcing protected areas can help inform appropriate allocation of management resources and increase the likelihood of protection achieving its intended benefits (Ban et al. 2011; Davis et al. 2015).

The definition of a paper-park established here could be used to identify "residual protected areas" (Devillers et al. 2015) that are placed in areas so remote to fishing that they have no ecological benefits. Residual protected areas will have a higher level of expected fish biomass with no enforcement. Thus, our criteria allows distinguishing politically motivated protected areas that do little to protect biodiversity when compared to the counterfactual situation of no protection In contrast, a protected area with a moderate level of poaching may be more effective than a residual protected area if enforcement is sufficient to enhance fish biomass over the unenforced counterfactual. In future, the design of new protected areas could combine our definition of a paper-park with expected ongoing funds for enforcement, so as to maximise the return on investment of placing protected areas in different locations.

For the case of Kofiau, Raja Ampat, we found that achieving fish biomass that was greater than a paper-park to a 75% probability level was approximately equal to the current annual budget for fuelling patrols (~$16,000). The limit for an effective protected areas occurred at a total reef fish biomass of 53% of its unfished level. However, targets for fish biomass that ensure they perform their functional roles can be considerably greater than 53% of unfished biomass (McClanahan et al. 2011; Brown & Mumby 2014; Karr et al. 2015). For instance, triggerfish may need to be at 80% of their unfished biomass to provide their functional role of predating on bioeroding invertebrates (Brown & Mumby 2014). We estimated that it may cost >$30,000 to achieve 80% triggerfish biomass if fishing pressure on this group is similar to the ecosystem aggregate estimate of fishing pressure. Achieving functional levels of biomass may therefore be much more costly than achieving an effective park.

Gaining community support for protected areas may enable functional levels of fish biomass to be achieved with fewer patrols and at a much lower cost. We estimated that community support for protected areas can result in significant cost savings for enforcement. In most cases effective protected areas will require both enforcement and community engagement (e.g. Watson et al. 2015; Bergseth et al. 2017). Compliance will likely be low if the perceived probablity of detection by enforcers is low, so some enforcement is necessary (Bergseth et al. 2017). Engagement activities can aid in increasing the perceived probability of detection (Bergseth et al. 2017). In this instance, assumed community support enhanced detection because local community members were more likely to report illegal fishing by non-local boats. Engagement activities that address the potential of protected areas to enhance ecosystems or fishing is also often necessary to change fishers beliefs about the benefits of protected areas for fishing opportunities (Leisher et al. 2012; Arias & Sutton 2013; Pieraccini et al. 2017). Our model could be used to value community support for park and thus apportion conservation budgets between engagement activities that enhance community support and enforcement. During the design of the Kofiau protected areas there was extensive consultation and engagement with local fishing communities, members of whom are employed to monitor and patrol protected areas (Fox et al. 2017). This model of engagement has resulted in much greater compliance from local people and may also help to deter roving bandits because local people who are invested in protecting the protected areas will aid in surveillance and enforcement of the protected areas when they are out fishing (Berkes 2010).

Further work is needed to quantify how poaching rates are affected by community engagement activities, so that management budgets can be balanced between these activities. A total of $USD1,020,223 was spent over 2004-2010 leading up to and during the creation of the protected areas around Kofiau and around the nearby island of Misool (Leisher et al. 2012). This engagement considerably increased community understanding and support for the protected areas between 2004 and 2010 (Leisher et al. 2012). This increase in community support may reduce poaching by roving bandits through local people reporting illegal fishing to enforcement officers (Alder 1996). If we conservatively assume that this engagement increased the sensitivity of poaching to enforcement by 50% then the engagement budget would be paid back in 20 years in terms of money saved on enforcement costs. The engagement budget would be paid back in only 5 years if the target was for pristine fish biomass, because of the much greater cost of achieving a pristine fish biomass. The key uncertainty in these estimates for the value of community engagement was the sensitivity of poaching rate to enforcement and how this changes when there is community supported for the procted area. Social surveys that quantify how reporting and poaching rates change across users whose participation in engagement programs varies are now needed to more accurately quantify the value of engagement activities.

The model assumed that poachers were roving bandits and that poaching occurred in discrete events that depleted fish biomass to a fixed level. A model of discrete fishing events is appropriate for this type of density-independent fishing pressure. In cases where the amounts poached are small, but continuous, such as recreational fishers that frequently violate park boundaries, then a continuous model of poaching may be more appropriate (e.g. McDonald et al. 2016). Modeling poaching as a discrete event allowed us to consider stochasticity in fish biomass in a tractable way and thus forms the basis of defining paper parks. Globally, roving bandits are an issue for many protected areas, so this model will be broadly applicable.

Our model can be used to help inform budgeting for management of protected areas, both to estimate how much is required to support a park and also how to allocate a budget between community engagement versus enforcement. Considering the cost of effective protected areas is important in the planning process, for instance, it estimates of the cost can be used to focus to development of new protected areas in places where they will be most effective. We also estimated the dollar value of community support for protected areas. Ultimately, both community support and enforcement are necessary to effectively protect the biodiversity of protected areas.

Materials and Methods

First we describe a model of fish biomass inside protected areas, when the fish population is subject to variable levels of poaching. Then we describe application of the model to the case-study in Raja Ampat.

Model of enforcement

We assumed fish growth was logistic growth with fixed parameters r (intrinsic growth rate) and K (maximal biomass), that poaching occurred at random intervals where the interval time d was described by an exponential distribution with rate u_z and finally that each poaching event depleted biomass to a fixed level B_0 (fig. 1B).

Taking the above assumptions, we can calculate the probability of observing fish biomass B^{Obs} at a random sampling time as:

$$pr(B^{Obs}) = u_z e^{-u_z t_z}$$

Where t_z is defined by the solution to the logistic growth function:

$$t_z = \frac{\ln(B^{Obs}K - B^{Obs}B_0) - \ln(KB_0 - B^{Obs}B_0)}{r}$$

We could thus define a paper park as any park where the expected biomass was smaller than a pre-specified probability quantile for biomass with no enforcement (Fig 2A), whereas we term 'effective parks' those with a biomass greater than this probability level. These definitions of effective and paper parks mean that parks with a high fish biomass can be defined as paper parks if the expected biomass before the creation of the park was also high. Such parks have also been termed 'residual protected areas' in the literature.

Enforcement increased the average time interval between poaching events, such that enforcement patrols decreased the rate of poaching in proportion to the number of days per year that were patrolled:

$$u_z = u_{base} - b u_{base} \frac{d}{365}$$

Where u_{base} was the poaching rate with no enforcment, d is the expected interval between enforcment events and b is a parameter controlling how sensitive poachers are to enforcement. If $b = 1$ then poachers reduce their rate of poaching in proportion the the amount of enforcement (Fig 2B). Community support for a park may manifest in a greater decline in the rate of poaching than the rate of increased enforcement. Thus, when $b > 1$ poaching rate is more sensitive to enforcement, representing communities that are supportive of a park. If $b < 1$ poachers are are unsupportive of the park. The value of community support was then calculated as the ex-ante difference between the cost of enforcement with and without community support. We conservativley assumed that community support would increase b by 50% based on surveys that indicated community engagement increased the awareness and support of protected area rules by at least 50% (Leisher et al. 2012). For comparison, we assumed a 25% reduction in b if the community were unsupportive of the protected area.

Estimating poaching rate and fish biomass in Raja Ampat protected areas

We apply the enforcement model to estimate cost of achieiving biomass targets for reef fish biomass in the Kofiau and Boo Island Marine Protected Area, Raja Ampat, Indonesia. Initially we derived parameters for the model to represent reef biomass across all diurnally active fish observed in diver surveys, because total reef fish biomass is a common management target (e.g. MacNeil et al. 2015). We then focus analysis on three different types of reef fish.

The estimate of the intrinsic growth rate of total fish biomass ($r = 0.054$) was taken from a global meta-analysis of recovery in reef fish biomass (MacNeil et al. 2015), though we test the effect of varying this parameter in analyses below. We then used data from the Kofiau marine protected area, Raja Ampat, Indonesia to estimate the parameters K, B_0, u_{base} and the daily cost of enforcement (Ahmadia et al. 2015). Enforcement costs were obtained from Kofiau's park managers and here we only consider the variable cost of fuel to run patrol boats, the budget for which is a main determinant of how often patrols are conducted.

We used resource use monitoring data to estimate a maximum baseline for the poaching rate. The resource use monitoring program conducted surveys around the island of Kofiau from 2005 to 2009 (36 surveys), before the protected areas were officially decreed. During surveys a patrol boat drove a predetermined route and approached all boats that were observed. Each boat was surveyed, including type of boat, type of fishing gear, activity (travelling, resting, actively fishing), catch if any and home port. It was assumed that since the implementation of the MPAs fishing rates inside the MPAs would be equal to or less than this baseline. We focus analysis of enforcement of poaching by non-local boats only (those from outside of the Papua region). Poaching by locals is likely negligible because they generally support the MPAs, for instance they are involved with monitoring parks (Fox et al. 2017), and local catch is small enough (average 3.2kg per boat per day) that the impacts of poaching by locals are negligable. Non-local boats are typically larger and will visit region for a limited period of time and take a large catch (often >

1000kg per boat per day). Many of these non-local boats may operate like roving bandits, moving across large spatial regions and sequentially depleting coral reefs as they move.

We estimated the carrying capacity of reef fish per hectare of reef in Kofiau by finding the equilibrium solution for the logistic growth equation and solving for K:

$$K = \frac{\hat{B}}{1 - \frac{F}{r}}$$

Where B_{obs} is the per hectare biomass observed on reefs and F is the instantaneous fishing mortality rate. This model assumed that observed biomass was stable over time. The observed biomass ($\hat{B}$) was estimated from diver surveys of reef fish biomass conducted at 39 sites around Kofiau's coral reefs. To account for spatial variation in fish biomass across reefs, we interpolated mean observed biomass values per hectare across all reefs with a generalised additive model using a thin plate regression spline specified as an interaction over the x and y coordinate space (maximum degrees of freedom = 34) (Wood 2003). We could then estimate the regional fish biomass and mean biomass per hectare.

We estimated the instantaneous fishing mortality rate prior to the protected area as:

$$F = 1 - exp(\frac{-(H_l + H_f)}{\hat{B}})$$

Where H_l and H_f were annual harvest (per hectare) for local and non-local boats. The harvest values were estimated by scaling up daily landings of reef fish from the resource use survey to an annual time unit. The resource use survey included surveys of tuna long-line and purse seiners, and these data were excluded from calculations so that harvest was only estimated over reef fishers.

The baseline fishing rate (interval between poaching events) had units of boats per day per hectare and was estimated as the median number of actively fishing non-local boats observed per resource use survey per unit reef area searched by the resource surveys (Fig S1). The depletion level after a single poaching event (B_0) was estimated for each park by solving for B_0 given the baseline fishing rate and the expected mean biomass that a fisher would encounter B_{obs}. We estimated B_{obs} as the expected biomass without fishing by locals. We could then calculate the depletion level as:

$$B_0 = \frac{KB_{obs}}{Ke^{rt} - B_{obs}(e^{rt} - 1)}$$

It was not possible to estimate all model parameters for the reef fish functional groups using local data sources, because the resource use monitoring survey did not resolve fish to the Family level. Therefore, we conduct sensitivity analyses to explore the effect of fishing rate and depeletion level on enforcement costs. For each fish type we derived its maximum population growth rate relative from literature values (SI text). Population biomass was modelled as a % of the carrying capacity, so that group biomasses were comparable across fish types. We then simulated enforcement efficacy for each fish type assuming across poaching rates and depeletion levels that varied from half to double their baseline values.

Acknowledgements

CJB was supported by a Discovery Early Career Researcher Award (DE160101207) from the Australian Research Council.

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