

LETTER

Balancing Ecosystem and Threatened Species Representation in Protected Areas and Implications for Nations Achieving Global Conservation Goals

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Introduction

Systematically planned protected areas (PAs) aim to ensure representative samples of ecosystems are protected and threatened species' habitats are retained (Barr *et al.* 2011; Watson *et al.* 2014; Butchart *et al.* 2015), yet global and national level analyses indicate that neither of these biodiversity conservation goals has yet been achieved (e.g., Rodrigues *et al.* 2004b; Dietz & Czech 2005; Venter *et al.* 2014). Gaps in PA coverage occur because of past biases in PA placement toward remote and unproductive areas with low land use conflicts, coupled with a more recent focus on achieving areal targets with-

Abstract

Balancing the representation of ecosystems and threatened species habitats is critical for optimizing protected area (PA) networks and achieving the Convention on Biological Diversity strategic goals. Here we provide a systematic approach for maximizing representativeness of ecosystems and threatened species within a constrained total PA network size, using Australia as a case study. We show that protection of 24.4% of Australia is needed to achieve 17% representation for each ecosystem and all threatened species habitat targets. When the size of the PA estate is constrained, trade-off curves between ecosystem and species targets are J-shaped, indicating potential "win-win" configurations. For example, optimally increasing the current PA network to 17% could protect 9% of each ecosystem and ensure that all threatened species achieve at least 78% of their targets. This method of integrating species and ecosystem targets in PA planning allows nations to maximize different PA goals under financial and geographical constraints.

out considering the underlying conservation objectives (Rodrigues *et al.* 2004a; Watson *et al.* 2011; Watson *et al.* 2016a). Future expansion of PAs can only fill these gaps if fine resolution data on species and ecosystem distributions are systematically included (Moilanen *et al.* 2009; Polak *et al.* 2015).

The Convention on Biological Diversity (CBD)'s strategic plan (CBD Secretariat 2010) provides systematic guidance for a global expansion of PAs. The 2010 CBD's Aichi Target 11 stipulates a quantitative goal to protect 17% of terrestrial and inland water area and 10% of marine and coastal ecosystems in areas of particular importance for biodiversity. These PAs should be ecologically

representative, effectively managed, and connected. The CBD advocates the use of ecosystems as the primary targets for the placement of PAs to achieve ecological representation (CBD Secretariat 2010; Woodley *et al.* 2012) and the phrase “areas of particular importance for biodiversity” has often been operationalized as protecting threatened species’ habitats (CBD Secretariat 2010; Watson *et al.* 2014; Butchart *et al.* 2015). In addition, Aichi Target 12, which refers specifically to preventing the extinction of threatened species, also refers to protecting habitat as one of the means to achieving this goal.

While the CBD plays an important role in bringing nations together to secure global biodiversity, its guidance is somewhat open to interpretation regarding the exact amounts of each ecosystem and threatened species range that should be protected. A common interpretation of the representation element of Target 11 is that 17% of each terrestrial ecosystem should be represented in PAs (Woodley *et al.* 2012; Venter *et al.* 2014). The guidelines for threatened species under Target 12 are even less specific (Butchart *et al.* 2015; Watson *et al.* 2016b). More quantitative guidance would assist countries in expanding their PAs in a way that provides maximum protection for threatened species as well as ecosystems.

As PA networks across the world continue to expand in response to the CBD targets, it is crucial that we understand the trade-offs between targets focused on ecosystem representation (Target 11) and those focused on threatened species habitat requirements (Target 12; Marques *et al.* 2014; Venter *et al.* 2014; Di Marco *et al.* 2015). Here, we address this challenge and provide a systematic approach for simultaneously maximizing representation of threatened species and ecosystems within fixed-size PA networks, using Australia as a case study. We start with a set of area-based targets for the country’s 85 major ecosystems and 1,320 listed threatened species, following Polak *et al.* (2015). We use trade-off curves and cost-effectiveness analysis to explore the possible representation of ecosystems and threatened species as PA coverage expands. For each of four PA network sizes (15%, 17%, 19%, and 21% of Australia’s total terrestrial area) we identify the optimal combination of ecosystem and species target sizes that can make the best use of limited conservation resources, offering key insights for PA expansion.

Methods

Biodiversity datasets and targets

We divided Australia into 85 bioregions, based on the Interim Biogeographic Regionalization of Australia (Figure 1, IBRA bioregions, version 6.1, Steffen *et al.*

2009), using a spatial resolution of approximately 10 km². Australia’s bioregions were derived by compiling geographic information on continental scale gradients and patterns in climate, substrate, landform, vegetation, and fauna, and each bioregion is considered a distinct ecologically and geographically defined area (Natural Resource Management Ministerial Council 2004). Bioregions are the unit used by Australia’s National Reserve System strategy (Commonwealth of Australia 2009) to represent ecosystems as referred to by the CBD, whereby the goal is to represent 17% of each bioregion to meet the CBD’s ecosystem representation goal (Commonwealth of Australia 2015). Other types of data may be used to best represent “ecosystems” in other national contexts. We refer hereafter to our selected units as “ecosystems” to allow for a more universal interpretation. Each ecosystem received an upper target representing 17% of its area, and a range of smaller target sizes was also explored.

We considered the distributions of 1,320 extant terrestrial species listed under the Environmental Protection and Biodiversity Conservation Act (EPBCA). We used maps of species’ distributions at a resolution of approximately 10 km², developed for extant threatened species available in the Species of National Environmental Significance (SNES) database (Commonwealth of Australia 2012). Species-specific targets for each of the 1,320 threatened species were set based on geographic range size and level of endangerment (Watson *et al.* 2011; Polak *et al.* 2015). These targets scale with geographic range size, requiring species with smaller ranges to be increasingly well protected (Rodrigues *et al.* 2004a). Critically endangered species and/or those with a geographic range size of < 1,000 km² were set a target of complete coverage (i.e., 100% of remaining distribution area). For species with large range sizes (> 10,000 km²), the target was set to cover 10% of current range. For species with geographic ranges of intermediate size (between 1,000 km² and 10,000 km²), the target was linearly interpolated between these two extremes (see Polak *et al.* 2015 for details).

For both ecosystems and species we masked out distributions that occurred in cleared areas devoid of native vegetation. Approximately 7% (0.5 million km²) of Australia is covered by “cleared areas” which are largely developed for urban or intensive agricultural land use (using a cleared land layer at 100 m² resolution in Arc GIS 10.2.2; ESRI 1996). These areas are not currently suitable for conservation through PAs and we were not able to consider the opportunity and financial costs and feasibility of improving their conservation value. For some species, the area of remaining available intact habitat was smaller than their representation target. In such cases, we reduced the target for these species to represent 100%

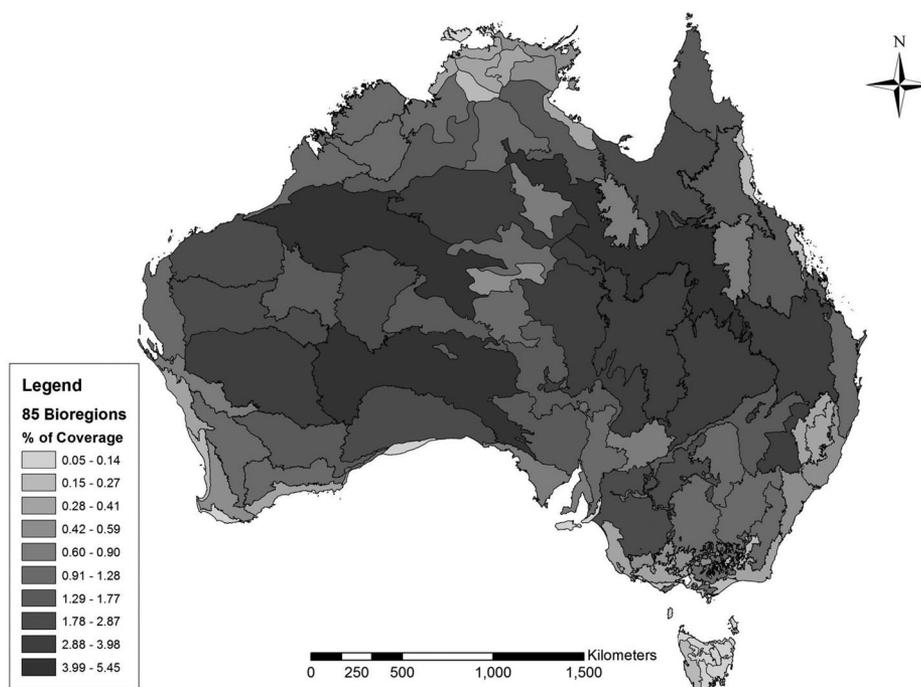


Figure 1 The spatial distribution and cover of Australia's 85 bioregions based on the Interim Biogeographic Regionalization of Australia (IBRA bioregions, version 6.1, Steffen *et al.* 2009).

of remaining available intact habitat. Thirteen of our 1,320 species had none of their distribution within areas that were considered intact and available for conservation. These were counted as gap species and their targets were set to zero. This left 1,307 species as our threatened species target set.

We created a planning unit layer of 10×10 km grid cells covering Australia, and intersected it with the Collaborative Australian Protected Area Database using PAs with IUCN categories I-IV. This resolution approximately matches the scale of the maps of threatened species (Watson *et al.* 2011) and ecosystems (Fuller *et al.* 2010). We intersected the planning unit layer with the PAs, species distribution and ecosystems layers, to determine the amount of each biodiversity feature in each planning unit and the amount already protected based on spatial overlap.

Trade-off and cost-effectiveness analyses

We used the systematic conservation planning software Marxan (Ball *et al.* 2009) to identify the efficiency frontier for the trade-off between representation targets for ecosystems and threatened species coverage when expanding Australia's PA network. Marxan is typically used to select multiple alternative sets of areas that meet pre-

specified biodiversity targets while minimizing overall cost (e.g., Carwardine *et al.* 2008; Smith *et al.* 2008; Klein *et al.* 2009). When investigating trade-offs between the two sets of targets, we locked in the current PA estate (Watson *et al.* 2011; Polak *et al.* 2015) and set the cost of each planning unit as the total area potentially suitable for conservation within the planning unit. We assumed that only nondeveloped areas would be suitable for inclusion in the PA estate and we used area as a surrogate for the costs of PA management (Ball *et al.* 2009).

To test the trade-off between the target of each ecosystem and threatened species that could be represented, we varied the size of target selected for each feature from 1 to 100% of the original target size, in 1% increments, for all features of the same type (ecosystem or threatened species). We evaluated all combinations of target percentages (e.g., 50% of the original target size for the ecosystem and 10% of the original targets size for the species), giving us 10,000 combinations of target size for the two kinds of features. These percentages of target size are only the minimum level of protection for each run, as Marxan will allow for more protection if it comes at no extra cost. Since there are ~1,300 biodiversity features, many with overlapping distributions, representation above a target level is common because some planning units containing an over-represented feature are critical for meeting targets for other features. Lastly, for ease of interpretation

of the results, we translated the percentage of target size for ecosystems to percentage of ecosystem area (i.e., 60% of the 17% target is 10.2% of the size of the ecosystem). We did this for ecosystems only as their target is uniform (17% of each ecosystem's area), while species targets are species-specific (see above).

For each of the target combination runs we identified 100 alternative PA networks and used the most efficient solution (i.e., the one that meets all targets at the lowest cost) in our analysis. We built trade-off curves between the protection of ecosystems and threatened species under four scenarios based on differing sizes of PA networks: 15%, 17%, 19%, and 21% of the land area of Australia. For each scenario we only recorded the unique combinations (out of 10,000) of target percentages that met the scenario's area constraints. Of those, we recorded how many of the targets for each set were met to 99.9% or above for each unique combination of target percentage. These results created a trade-off curve that provides the efficiency frontiers of the nondominated solutions: all points on the top edge of the curve cannot be outperformed by any other point. We also tested how much area of terrestrial Australia is needed to reach every target in full for both kinds of conservation features.

A J-shaped trade-off curve can indicate the existence of a "win-win" solution, where we can achieve relatively high percentages of both targets within the limitation of the set reserve area. To find the points that represent the most cost-efficient "win-win" solutions, we calculated the cost-efficiency of each point, which is the benefit (sum of the two percentages of targets met for species and ecosystems) divided by the area-based cost (i.e., the percentage of Australia's terrestrial area that was used to limit the analysis). Although each point on the efficiency frontier is optimal for the set of targets it meets, the most cost-efficient points provide the greatest feature coverage per unit area protected. The most cost-efficient points were compared within and between the scenarios. We plotted the benefit/cost value of each point along each efficiency frontier against the area constraint of each scenario to compare each area constraint in terms of overall value for investment.

Results

Expanding Australia's current PA network to meet 100% of all species and ecosystem targets requires 24.4% of the total land area, which is much higher than the minimum 17% recommended by the CBD and the area constraints we tested (15–21%). We identified clear trade-offs between target sizes for threatened species and ecosystems, for all four area-constrained scenarios. For each sce-

nario only a few hundred (out of the 10,000) runs met both the area constraints' restrictions and all their targets (Figure 2a–d).

All scenarios displayed J-shaped efficiency frontiers, indicating the potential for finding win-win combinations of target sizes for ecosystems and threatened species (Figure 3a). When the analysis was limited to 15% of Australia's land area, the most cost-efficient points corresponded to protecting between 7.14% and 7.8% of the area for each ecosystem and 54–58% of each species' area target. When following a common interpretation of Aichi Target 11's areal goal of protecting 17% of terrestrial area, the most cost-efficient points corresponded to ecosystem protection of at least 8.7–9.5% of the area for each ecosystem and threatened species protection of at least 75–80% of each species' target. A higher total PA network size of 19% of Australia improves representation of features to at least 81–82% of each species' area target and 12.5–12.8% of the area for each ecosystem. Finally, when the size constraint is at 21% of the land area of Australia, 88–90% of species targets could be met along with the coverage of 15–15.3% of the total extent of each ecosystem.

The cost-effectiveness of the optimal points along each efficiency frontier varied with the area constraint and the combination of target percentages represented (Figure 2b). The area constraint that gives the point with the highest cost-effectiveness ratio is 21% of Australia, at the point of representing ~15% of the ecosystems. While a PA of 24.4% could meet all targets, the targets met per unit PA were slightly lower.

Discussion

We provide a clear and systematic approach to show how to maximize both ecological representativeness and threatened species' coverage in a PA network within a constraint on the total size of the PA system within a country. This enables decision makers to operationalize the dual goal of adequately protecting important habitats for threatened species and achieving ecosystem representation in the global PA network, which is at the heart of the CBD strategic plan (CBD Secretariat 2010). Our approach provides trade-off curves for a wide range of optimal solutions (Polasky *et al.* 2005) allowing decision makers to choose between different configurations of target sizes within the constraints they set on the size of their PA network. For example, placing 17% of terrestrial Australia in PA can at best achieve 9% representation of all ecosystems and at the same time achieve at least 78% of each threatened species' habitat target. This is well short of what is needed to meet Australia's obligations under

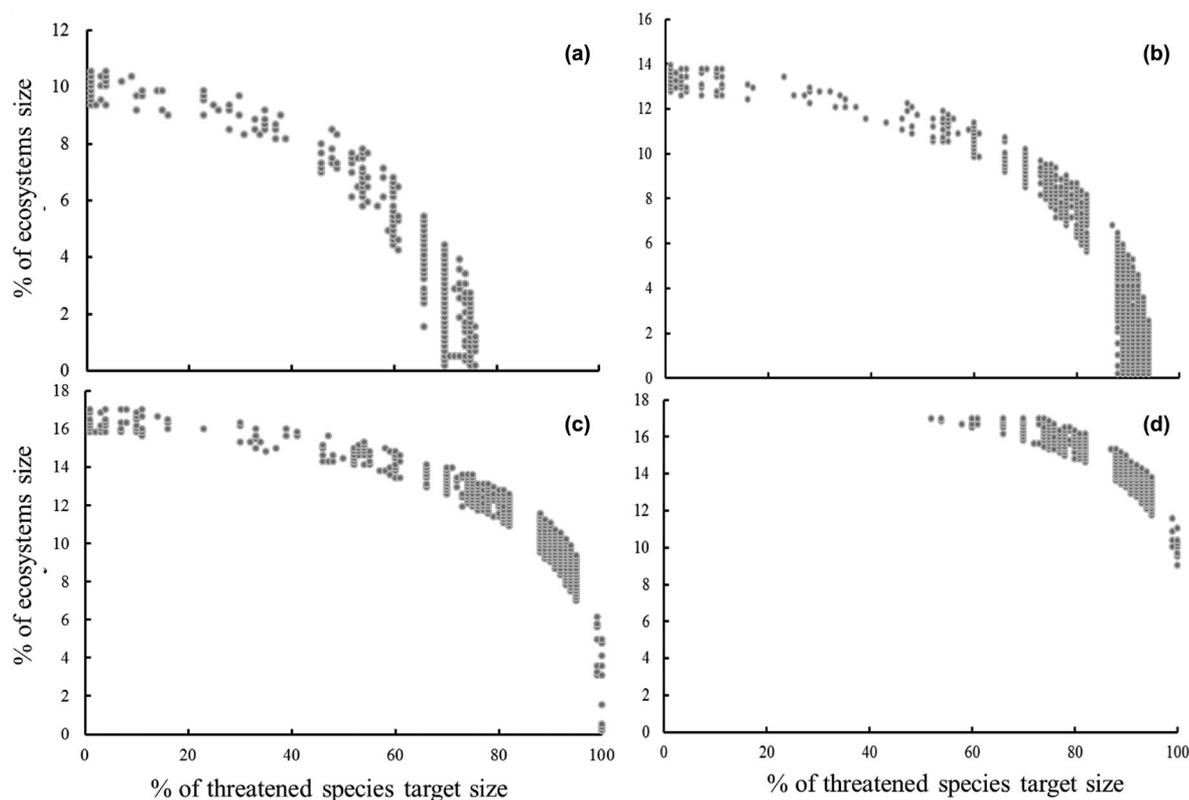


Figure 2 Trade-off curves between target size of species versus target size of ecosystems in a protected area network the size of: (a) 15%, (b) 17%, (c) 19%, and (d) 21% of Australia's land area. Gray points represent solutions that met the area constraints and met all their targets to a level of 99.9%.

the CBD, but maximizes the benefits of a size-limited total PA estate.

We found that among the multiple solutions along the efficiency frontier for each area-constrained scenario, there was a large range of cost-efficiency in terms of how many targets can be met in a limited area. Within each area-constrained scenario, the most cost-efficient points are the ones nearest the inflection point of the J-shaped frontiers, and cost-efficiency declines away from these win-win points (Polasky *et al.* 2005). When comparing between the different area-constraint scenarios (Figure 2b), we can see that the maximum cost-effectiveness increases slightly as more area is available for PA expansion, up to 21%, and then declines. This is likely because as more area becomes available there is more opportunity to select efficient areas that can protect multiple biodiversity features. Once the PA is above 21%, the more efficient and compact options for meeting targets will already be protected and gaining the remaining land required to meet the final parts of targets will require larger areas, resulting in less efficient PA networks.

Although the work we present here is based on information from one country, many of the same chal-

lenges faced by land management agencies in Australia occur in other countries (Waldron *et al.* 2013; Venter *et al.* 2014; Di Marco *et al.* 2015). This is because countries are challenged by the goals of meeting their current CBD and country-level PA targets (Waldron *et al.* 2013; Walsh *et al.* 2013). There is a clear need for systematic thinking around targets for species and ecosystem representation, and transparent analysis of the likely compromises between species-based and area-based objectives (Di Marco *et al.* 2015). The overall lesson from our study is that even when countries cannot reach full protection, it is still possible to make progress toward the targets logically and efficiently. Our approach can assist countries in deciding where and how to focus PA expansion efforts given a particular set of geographical and financial constraints.

Where possible, countries should employ spatial information on both ecosystems and threatened species to create their country-specific trade-off curves. If the two sets of targets (Targets 11 and 12) are relatively well aligned, the shape of the curve will exhibit a strong J-shape, making both targets easier to meet. However, if the two sets are relatively discordant, the curves will be closer to linear, and it will be more challenging and area-intensive to

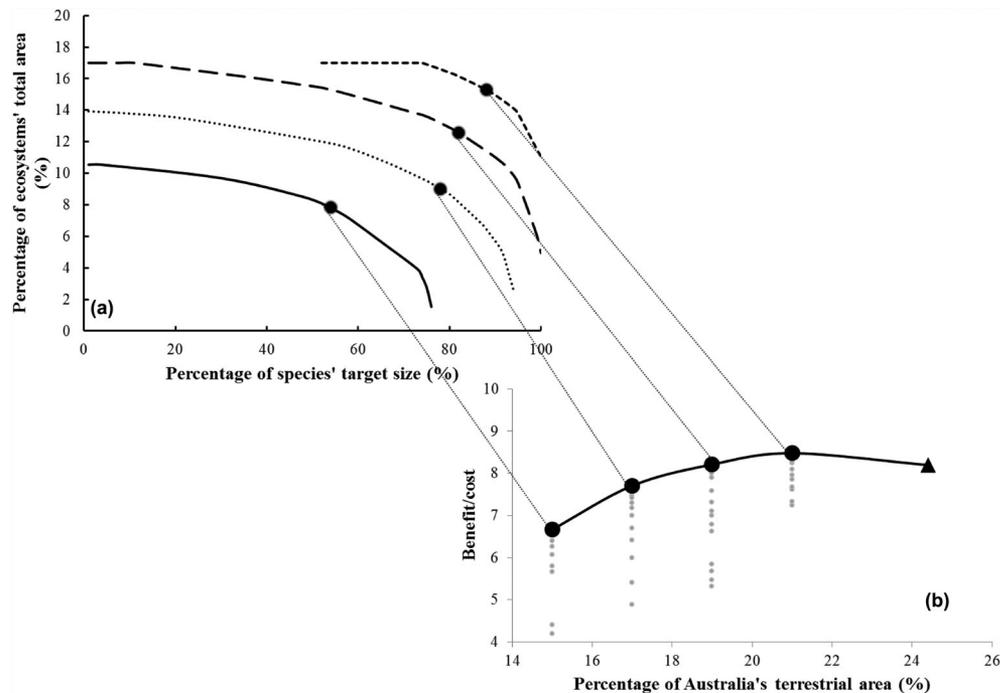


Figure 3 Efficiency frontiers and benefit/cost curves. (a) Efficiency frontiers of the nondominated solutions for the four trade-off curves (Figure 1), where x-axis is the percentage of threatened species' target size and y-axis is the percentage of ecosystems' size. Solid line represents 15% of Australia's land area; dotted line represents 17%; large dashed line represents 19%; and fine dashed line represents 21%. Black circles represent the configuration with the highest benefit/cost ratio for each frontier. (b) Benefit/cost curve of the five most cost-efficient percentage configurations for each of the area constraint curves from Figure 2a (the black circles): x-axis is the percentage of Australia's land area and y-axis is the combined target size percentages over the percentage of Australia's land area. Small light gray circles below each of these represent the benefit/cost values of the rest of the points along the efficiency frontier. Black triangle represents the point where both sets of targets are at 100% (24.4% of Australia's land area).

represent both sets of targets in a PA network. In many countries, distributions of threatened species reflect current and past land-use histories (Taylor *et al.* 2011). This may lead to spatial alignments between the two target types, where remaining threatened species' habitats overlap with the remnants of heavily impacted ecosystems. However, the financial and/or opportunity costs of PA networks in these cases may be relatively high due to the fact that heavily impacted ecosystems are often productive for other uses. In such cases it may be useful to investigate trade-off curves that consider costs as well as area.

Protecting threatened species typically requires a range of management actions, including PA establishment. Decisions on allocating resources among threatened species should consider how important PAs are for ensuring threatened species' persistence. For example, in New Zealand the highest priority action to conserve threatened species is predator control (Dowding & Murphy 2001; McGuinness & Carl 2001). Expanding PAs alone will not adequately protect threatened species unless resources for predator control are built into PA manage-

ment plans. As such, when planning PA expansion, New Zealand may prioritize the representation of ecosystems in PAs to meet Target 11 (i.e., points on the upper left of the efficiency frontier in Figure 3), while constructing separate threatened species management plans to meet the goals of Target 12.

We have addressed the trade-off between two of the fundamental goals of the CBD, the representation of ecosystems and threatened species through PA expansion. Further trade-offs also exist in the PA planning process. For example, a potential trade-off exists within Target 11 between representing ecosystems and "areas of importance for biodiversity and ecosystem services." Further, a synergy exists between protecting threatened species (Target 12) and reducing the rate of loss of natural habitat (Target 5), as identified by Di Marco *et al.* (2015). There is also a trade-off between protecting existing habitat and restoring some currently unsuitable habitat, especially for species with very limited suitable habitat remaining. Understanding and incorporating multiple trade-offs will improve the effectiveness of implementing the CBD targets. Our approach can be modified to

include additional criteria for making informed and optimal decisions when reality demands compromises among various biodiversity goals in PA estates.

Planning for PAs is a dynamic process. The CBD targets have adjusted with time—between 2004 and 2010, CBD targets for global PAs increased from 10% to 17%—and are likely to continue to change, along with countries' capacity to meet them (Noss *et al.* 2012). Changes in species' conservation status will occur and better data on species distributions and their responses to management are likely to become available in the future. For example, there is currently a taxonomic bias in threatened species listing, with many invertebrates missing (Walsh *et al.* 2013). The inclusion of more invertebrate species targets is likely to increase the area or resources required for their protection; however, further research is required to determine how well aligned the important areas for invertebrates with existing priority areas. Countries can use our approach to accommodate such changes, by re-evaluating the progress of PAs against new goals and information as they arise.

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