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Incorporating climate change adaptation into national conservation assessments

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Abstract

The Convention on Biological Diversity requires that member nations establish protected area networks that are representative of the country's biodiversity. The identification of priority sites to achieve outstanding representation targets is typically accomplished through formal conservation assessments. However, representation in conservation assessments or gap analyses has largely been interpreted based on a static view of biodiversity. In a rapidly changing climate, the speed of changes in biodiversity distribution and abundance is causing us to rethink the viability of this approach. Here we describe three explicit strategies for climate change adaptation as part of national conservation assessments: conserving the geophysical stage, identifying and protecting climate refugia, and promoting cross-environment connectivity. We demonstrate how these three approaches were integrated into a national terrestrial conservation assessment for Papua New Guinea, one of the most biodiverse countries on earth. Protected areas identified based on representing geophysical diversity were able to capture over 90% of the diversity in vegetation communities, suggesting they could help protect representative biodiversity regardless of changes in the distribution of species and communities. By including climate change refugia as part of the national conservation assessment, it was possible to substantially reduce the amount of environmental change expected to be experienced within protected areas, without increasing the overall cost of the protected area network. Explicitly considering environmental heterogeneity between adjacent areas resulted in protected area networks with over 40% more internal environmental connectivity. These three climate change adaptation strategies represent defensible ways to guide national conservation priority given the uncertainty that currently exists in our ability to predict climate changes and their impacts. Importantly, they are also consistent with data and expertise typically available during national conservation assessments, including in developing nations. This means that in the vast majority of countries, these strategies could be implemented immediately.

Keywords: biodiversity, connectivity, convention on biological diversity, gap analyses, geophysical classification, Marxan, Papua New Guinea, protected areas, refugia, systematic conservation planning

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Introduction

Globally, significant conservation effort is driven by national commitments under the Convention on Biological Diversity (CBD). The CBD requires that member nations set aside at least 10% of their territory in protected areas to slow the global loss of biodiversity. In 2010, this target was increased to 17% for all terrestrial and inland water areas (CBD, 2010a). The Program of Work on Protected Areas (PoWPA), adopted by the 7th CBD Conference of Parties in 2004, is a global action plan to address impediments to meeting the protected area targets established under the CBD. In 2005, the United Nations Development Program – Global Environment Facility identified a set of 13 priority PoWPA activities, and allocated substantial funding to assist the world's least developed states complete these activities. One of these 13 priority activities is to '*complete protected area system gap analyses at national and regional levels based on the requirements for representative systems of protected areas that adequately conserve terrestrial, marine and inland water biodiversity and ecosystems.*'

Protected area gap analyses were initially conceived as a quantitative approach to determining the elements of biodiversity underrepresented in existing protected areas (Jennings, 2000; Scott *et al*., 2001). Typically, however, gap analyses are conducted as part of a more comprehensive conservation assessment which includes

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not only reviewing target achievement in existing protected areas, but also identification of priority sites for expansion of the protected area network to achieve unmet representation targets (Jennings, 2000; Powell *et al.*, 2000; Pressey & Bottrill, 2008; Nel *et al.*, 2009). The most common and well established approach to national and regional conservation assessments is the process of systematic conservation planning (Margules & Pressey, 2000; Groves *et al.*, 2002; Cowling & Pressey, 2003; Pressey & Bottrill, 2008; Smith *et al.*, 2008; Klein *et al.*, 2009). The strength of systematic conservation planning lies in its ability to efficiently and transparently identify priority areas that are adequately representative of a region's biodiversity (Possingham *et al.*, 2006).

The distribution of biodiversity is a dynamic property (e.g., Pickett *et al.*, 2004). However, because the pace of this dynamism has generally been slow relative to the temporal scales of conservation management, representation in conservation assessments has typically been interpreted based on a static view of biodiversity (Pressey *et al.*, 2007). In a rapidly changing climate, the speed of changes in biodiversity distribution and abundance (Parmesan, 2006) is causing us to rethink the viability of this approach. Because many protected areas exist as islands in a highly modified landscape, there is a real risk that the ecosystems and species they were established to protect will not simply be able to move in response to changing climatic regimes (Peters & Darling, 1985). These sorts of uncontrollable threats were not anticipated when the CBD requirements for gap assessment were conceived. Although climate change is just one of many threats to biodiversity, and often not the most acute, it is an important consideration for national conservation assessments and CBD obligations, both because of the focus on a representation-based approach to conservation priority, and because the vision established under the PoWPA is intended to address long-term conservation goals. The importance of incorporating climate change adaptation strategies into national plans for protected areas was explicitly acknowledged in the decisions of the 10th CBD Conference of Parties in 2010 (CBD, 2010b). For those countries that have met, or are close to meeting, their original CBD protected area obligations, the recently increased target for the protection of terrestrial areas (CBD, 2010a) provides the opportunity to identify additional land areas most critical for climate change adaptation. Additionally, national and regional conservation assessments represent the scale at which it is probably most effective to respond to the challenge of climate change (Biringer, 2003; Game *et al.*, 2010). To a large degree, climate change adaptation in conservation is simply acknowledging the reality of a dynamic world and ensuring this is reflected in our planning.

The conservation literature contains a daunting number of recommendations for climate change adaptation (see, Heller & Zavaleta, 2009). Here we focus on three explicit strategies for climate change adaptation that are relevant for national conservation assessments. These strategies are described in detail in Game *et al.* (2010) but are summarized in Table 1. These three climate change adaptation strategies were chosen principally because they represent defensible ways to guide national conservation priority given the uncertainty that currently exists in our ability to predict climate changes and their impacts. This defensibility is derived from the fact that all three approaches will still lead to prioritizations that are likely to meet our long-term biodiversity conservation objectives regardless of whether climate change impacts play out as expected. In other words, these approaches are largely *indeterministic* (Millar *et al.*, 2007). In addition, all three approaches can be executed based on data that will be available to most national conservation assessments.

The island of New Guinea [of which Papua New Guinea (PNG) covers the eastern half] supports an estimated 5–9% of the world's terrestrial biodiversity in <1% of the land area (Mittermeier *et al.*, 1998; Myers *et al.*, 2000). It also contains the world's third largest contiguous area of tropical rainforest, and habitats ranging from alpine grasslands, to cloud forests, to lowland wet tropical forests, swamps and dry sclerophyll woodlands (Hammermaster & Saunders, 1995). PNG has more than 18 894 described plant species, 719 birds, 271 mammals, 227 reptiles, 266 amphibians, 341 freshwater fish (Vie *et al.*, 2009). Although knowledge of the status of biodiversity in PNG is poor, available data suggest that at least 738 species are currently threatened, vulnerable, endangered, or critically endangered (IUCN Red List) (Vie *et al.*, 2009). Given the rapid rates of forest conversion and degradation currently occurring in PNG (Shearman *et al.*, 2008), it is highly likely that many more species will also fall into these categories in the near future. Because approximately one in five PNG species are endemic, including the highest number of endemic mammals globally (Wikramanayake *et al.*, 2002), the loss of species in PNG constitutes a high likelihood of global extinction. By any measure, PNG is a globally important focus of biodiversity conservation.

PNG is a signatory to the CBD, and at the request of the PNG Department of Environment and Conservation (DEC), The Nature Conservancy (TNC) worked with DEC to complete a National Terrestrial Gap Analysis as part of PNG's commitments under the CBD. Here we demonstrate how the three climate change adaptation strategies described in Table 1 were

Table 1 Description of three climate change adaptation strategies for national conservation assessments. For more background on these strategies see Game *et al.* (2010)

Strategy #1 – conserving the geophysical stage	The relationship between species and physical settings (e.g., elevation and geology) can be extremely tight (Anderson & Ferree, 2010). As the climate changes, some species shift their locations and some communities reorganize into novel assemblages with no historical precedent. Evidence from many different climatic regimes suggests that contrasting geophysical settings maintain distinctive ecological communities in a variety of climates (Rosenzweig, 1995). Therefore, one strategy for conserving regional biodiversity in a dynamic climate is to conserve the full spectrum of geophysical settings (Beier & Brost, 2010). If geophysical diversity helps to maintain species diversity, then conserving representative examples of geophysical settings will hopefully protect biodiversity under both current and future climates (Beier & Brost, 2010)
Strategy #2 – protecting climatic refugia	The rapidity of climate driven changes in ecosystems can outpace the natural capacity for adaptation in many species (e.g., Breshears *et al.*, 2005), and therefore represents a very real cause of biodiversity loss. However, the probability, speed and extent of these changes are unlikely to be uniform across a region. Places where climatic changes are attenuated are likely to serve as important climatic refugia for species and habitats that become marginalized through ecological changes elsewhere (Saxon, 2008). Through identifying and protecting these refugia, we might improve the scope for natural adaptation, and buy the time to help improve the broader ecosystem's ability to cope with climate driven changes
Strategy #3 – environmental connectivity	Increasing landscape connectivity is the most commonly cited climate change adaptation strategy for biodiversity management (Heller & Zavaleta, 2009). For climate change, a particular challenge is determining the pattern and nature of connectivity needed to allow species or communities to track changing habitat conditions *through space and time*, when we cannot necessarily anticipate where new habitat is going to exist in the future, how long it will persist as climate continues to change, or even whether a species' connectivity pattern will remain similar in an altered climate. This adds a temporal component to connectivity that differs from how we conceive of connectivity under current conditions. One response to this uncertainty is to emphasize connectivity between different habitats (e.g., cooler and warmer, drier and moister), increasing the likelihood populations will remain connected to a suitable set of habitat conditions as the climate changes (Peters & Darling, 1985; Ashcroft *et al.*, 2009; Hodgson *et al.*, 2009). This cross environment connectivity will be most efficiently accomplished by prioritizing the protection of locations with high environmental heterogeneity

integrated into a national terrestrial conservation assessment for PNG. Additionally, we explore the implications of applying these strategies, on the characteristics of the potential protected area network identified as part of the assessment.

Methods

Conservation features

Vegetation. The Forest Information Management System (FIMs) maps the occurrence of 55 vegetation types across PNG (36 forest, 6 woodland, 3 savannah, 3 scrub, 11 grasslands, and 1 mangrove) at a scale of 1 : 100 000 based on the interpretation of SKAIPIKSA air photography taken in 1973–1975 (Hammermaster & Saunders, 1995). Because these vegetation types are being used as a surrogate for biodiversity across PNG, for the national conservation assessment they were subsequently stratified by a modified version of the World Wildlife Fund's terrestrial ecoregions (see Lipsett-Moore *et al.*, 2010). This gave the original extent of a total of 231 vegetation types.

Significant logging and land use change has occurred in PNG since 1975 (Shearman *et al.*, 2008). In order to calculate the current extent of each vegetation type, we used a version of the FIMs data updated in 1996 using Landsat TM imagery (McAlpine & Freyne, 2003). Based on the assumption that forest degraded through logging is less suitable for biodiversity conservation, we further discounted the current occurrence of forest vegetation types based on known logging history (see Lipsett-Moore *et al.*, 2010 for a detailed description of this process).

Land Systems. Land Systems represent a geophysical classification of environments across a region. Using the PNGRIS digital data set maintained by the PNG Forest Authority and similar Indonesian data (RePPProT, 1990), Sheppard & Saxon (2008) developed a uniform set of abiotic Land Systems for the entire New Guinea Archipelago. Sheppard and Saxon classify all areas above 600 m according to slope, geological substrate, and elevation using a 90 m digital elevation model (SRTM) (Farr *et al.*, 2007), while in the lowlands (<600 m) the classification is based on topography/landform and frequency of inundation (http://

www.esri.com/mapmuseum/mapbook_gallery/volume23/conservation5.html).

Fauna. To ensure that protected area solutions adequately captured PNG's unique fauna, the conservation assessment included the distribution of 147 restricted range endemic species (reptiles, amphibians, and mammals), from data held by the Bishop Museum (provided by Allen Allison, Bishop Museum).

Conservation targets

Consistent with PNG's commitments under the CBD, the target representation for vegetation types was set at 10% of their original extent. This target was adjusted upwards for rare vegetation types (rarity criteria are scaled based on ecoregion size, see *Lipsett-Moore et al.*, 2010), and endangered vegetation types (those whose distribution has contracted by over 90%). A 10% target was used uniformly for all Land System types. Because they frequently exist in only a single remaining location, the target for restricted range endemic species was set at 50% of their current known distribution.

Planning units

The occurrence of all conservation features was summarized with 5000 ha hexagonal planning units, clipped to the coastline. The 'cost' of including each planning unit in a protected area network solution was an equally weighted average of the total population within that PU (derived from the 2000 population census data) and its area. The rationale for including population as part of the cost surface is that protected area negotiations with more people are likely to be more difficult, protracted, and ultimately more costly (Rose Singadan, Department of Environment and Conservation, Government of Papua New Guinea, personal communication).

Analysis

Conserving the geophysical stage. Conserving the geophysical stage is based on the protection of representative examples of all Land Systems across PNG. First, as an initial test of the hypothesis that Land Systems are an effective surrogate for regional biodiversity, we assessed how well a national assessment run solely with Land Systems did at representing both vegetation and fauna features. We did this by running the conservation planning software MARXAN (Ball *et al.*, 2009) 100 times (10 million iterations per run) with targets set only for Land System representation. For each run we calculated the total number of vegetation and faunal features captured in the resulting protected area solution. As the ability of protected area network solutions to capture regional patterns of biodiversity might be dependent on how clumped or dispersed the protected areas are, we repeated this test across a range of values (0–1.2) for the Boundary Length Modifier (BLM), a parameter in MARXAN that controls the clumping of solutions (Game & Grantham, 2008).

Second, we explored the impact on the overall protected areas for PNG of including Land Systems as additional conservation features in the assessment. Including additional conservation features in a national assessment is likely to change the solutions in terms of the location of protected areas, the total size of the protected area network, and reduce the number of potential protected area solutions that meet all the necessary targets. As such, we need to know the extent of this change to assess whether it is worth the compromise. To do so we calculated both, whether the inclusion as explicit features led to dramatically better representation of Land Systems in the final solutions, and to what extent were these final protected area solutions larger or more costly. We approached this by running two parallel scenarios in MARXAN; one with targets only for vegetation and fauna, and one with targets for vegetation, fauna, and Land Systems. So that the solutions represented realistic outcomes and not just the capture of Land System targets in tiny additional blocks, we adjusted the two scenarios so that the boundary-to-area ratio of solutions remained constant across both scenarios. Again each scenario was run 100 times, but only the best solution from each scenario was compared.

Refugia. Climate change refugia were defined as areas with projected future environmental attributes similar to their current environmental attributes, including both invariant physical attributes and climate variables (Saxon *et al.*, 2005). Following the methodology described in Saxon *et al.* (2005), we defined current environmental attributes based on 14 topo-edaphic variables at each location. The seven physical attributes were: elevation, compound topographic index, potential solar radiation, profile available water capacity, soil bulk density, soil carbon density, and total soil nitrogen. The seven climate attributes were: potential evapo-transpiration, precipitation/potential evapo-transpiration, precipitation coldest quarter, precipitation warmest quarter, mean temperature coldest quarter, mean temperature warmest quarter, and average monthly temperature. The seven climate-dependent variables were defined using 4-km data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for the period 1961–1990 (Daly *et al.*, 2002), resampled to 5-km resolution. Projected values for the same climate variables in the year 2100 were identified under climate scenario A2 (Nakicenovic & Swart, 2000), using the HadCM3 general circulation model (GCM) (Gordon *et al.*, 2000). HadCM3 is a highly climate-responsive GCM and scenario A2 assumes limited climate mitigation action. Treating all 14 variables equally, these projections were used to predict the difference between current and future environmental conditions across PNG.

In order to preferentially identify protected areas in locations of likely climate change refugia, each planning unit was assigned a probability that corresponded to the projected extent of climate change. To assign probabilities, the projected difference between current and future environmental conditions was normalized to a scale from 0 to 1, with 1 being assigned to the pixel that was projected to experience the greatest change in climate, across the entire Island of Papua

(PNG and Indonesian Papua) (Fig. 1). Within each planning unit, probabilities were averaged across pixels, to give a mean probability of change per planning unit. A high probability meant that a planning unit is less likely to act as a climate change refuge, where as those planning units with a lower probability have a higher chance of being refugia.

The refugia probabilities were then used as inputs to a modified version of the conservation planning software MARXAN (Ball *et al.*, 2009). The use of probabilities of change within MARXAN is described by Game *et al.* (2008). Ultimately, the protected area solutions generated by this modified version of MARXAN are combinations of sites that offer the greatest possible chance of meeting our conservation targets into the future, given the largely uncontrollable impact of a changing climate.

To test how the inclusion of climate change refugia influenced the priorities identified by the national conservation assessment, we compared the average expected change in climate conditions per conservation feature across 10 MARXAN runs with and without the inclusion of climate data. To reduce the influence of rare conservation features and total portfolio area in this test, only vegetation and Land Systems were used as conservation features and the total cost of the solutions were equivalent with and without climate data.

Environmental connectivity. In order to identify protected areas with high levels of connectivity between different environments, we employed a novel conservation planning methodology. Using the mean value of a planning unit for each of the 14 environmental attributes described in the refugia data above, we calculated the Euclidean distance in environmental space between all adjacent planning units. We then assigned this distance as the boundary length between adjacent planning units. In MARXAN, a high boundary length between two planning units is used to ensure that if one of those planning units is selected in the solution, the second is also likely to be included. This input is typically used to ensure that solutions are a set of clumped areas with low boundary to area ratios, rather than a set of small dispersed areas (Game & Grantham, 2008). This procedure is based on the premise both, that it is ecologically preferable to have larger protected areas that are less subject to edge effects, and that it is typically more palatable for stakeholders and cheaper, to have a few larger protected areas rather than many small ones. Although it can be used to signify connectivity between nonadjacent planning units (Beger *et al.*, 2010), the boundary length is typically the geographic length of the shared boundary between adjacent planning units. The extent to which overall boundary length is reduced in a solution is controlled in MARXAN by a parameter called the Boundary Length Modifier (BLM) (Game & Grantham, 2008).

To explore the effect of using environmental distance in lieu of the uniform polygon boundary length to help improve cross environment connectivity, we compared protected area network solutions with environmental boundaries to those with traditional geographic boundaries. Because an expected outcome of using environmental distance is that sites selected in areas of high homogeneity will be highly dispersed, we explored using a combination of environmental distance (the

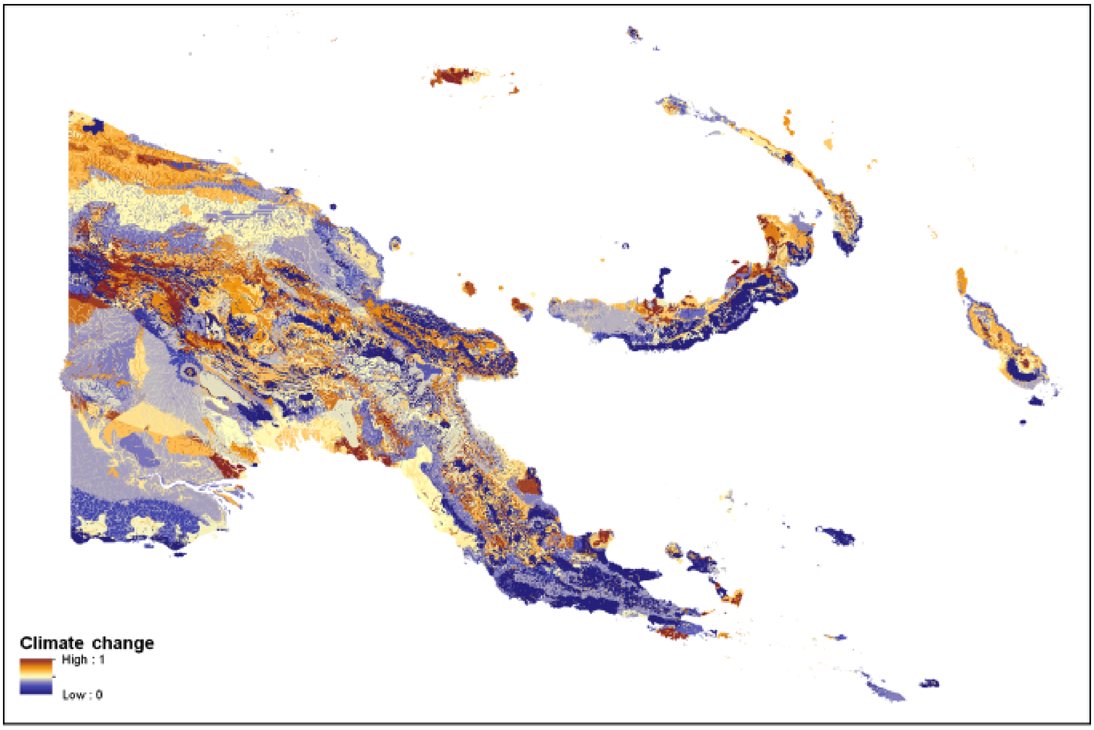

Fig. 1 Projected difference between current and future (2100) environmental conditions in Papua New Guinea, normalized to a scale from 0 (least projected change) to 1 (most projected change).

Euclidean distance in environmental space between adjacent planning units) and geographic distance (the actual physical length of the boundary shared by adjacent planning units) as the boundary length variable in MARXAN. Any change to the boundary file means that the influence of the BLM on the MARXAN objective function will also change. In order to maintain consistency across trials, we adjusted the BLM in each case so that the relative size of the boundary penalties added to the MARXAN objective function was constant.

Results

Conserving the geophysical stage

Protected area networks designed based solely on the distribution of Land Systems did remarkably well in representing the diversity of vegetation communities across PNG. On average more than 90% of the 231 vegetation types were represented in final solutions (Fig. 2). Representation of the 147 fauna species included in the analysis was somewhat lower, with an average of just over 50% of species being represented in final solutions (Fig. 2).

The effectiveness of Land Systems as a surrogate for the diversity of both vegetation and fauna, was influenced by how clumped the protected area solutions were. Where no clumping was applied (BLM = 0), solutions on average captured nearly 100% (0.98) of vegetation types across PNG. At all other levels of clumping, representation of vegetation types was roughly constant at 90%. The influence of clumping was more pronounced on the representation of fauna, with the no-clumping scenario representing nearly 80% of fauna but representation quickly dropping to slightly below 50% as the BLM was increased. Overall, Land System based protected area solutions that allowed maximum dispersion of potential protected areas, did substantially better at capturing vegetation and fauna diversity, but the extent of clumping beyond this had only marginal impact on surrogacy effectiveness.

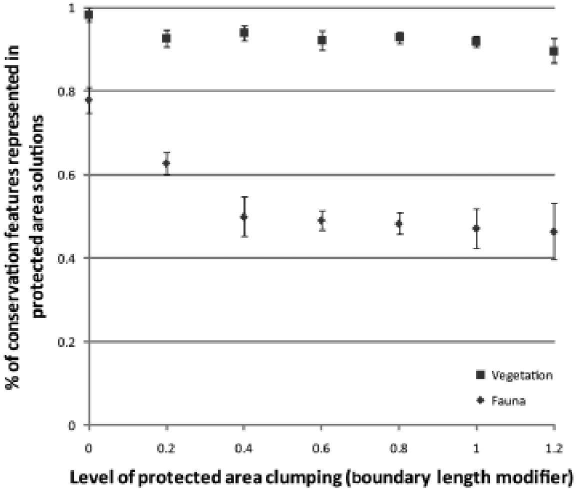

Fig. 2 The effectiveness of protected area networks based on Land Systems at representing diversity in vegetation communities and range restricted endemic fauna across Papua New Guinea (PNG). Representation is compared across different levels of protected area clumping, determined by the value of the Boundary Length Modifier (BLM). Values along the *x*-axis are the actual BLM values used. Error bars show standard deviation across solutions.

The inverse approach, protected area networks designed based solely on the distribution of vegetation and fauna, resulted in 20% of Land System types not captured at all, and a further 18% of Land System types only partially represented. This suggests that different and additional areas need to be protected in order fully represent the diversity of Land Systems. This result was also reflected in the fact that the inclusion of Land System targets in addition to vegetation and fauna resulted in protected area solutions that on average were around 10% more expensive and required just under 9% more land area. Using Land Systems as additional conservation features increases the comprehensiveness, extent and cost of the resulting protected area solutions (Table 2) as well as changing their distribution.

Refugia

By explicitly including climate change refugia as part of the national conservation assessment, it was possible to substantially reduce the amount of environmental change expected to be experienced within protected areas. Without increasing the cost of the overall protected area network, it was possible to select areas that still met the targets for all features but meant that on average (and assuming no movement) each conservation feature was 7 ± 0.4% more likely to be in an environment similar to their present one, in the year 2100 (Table 3). In order to achieve this however, proposed protected area solutions were slightly more fragmented when climate refugia were considered, leading to a higher total number of protected areas in the final solutions (Table 3).

Environmental connectivity

Treating the environmental distance between adjacent planning units as if it were the length of their shared boundary, increases the environmental heterogeneity within individual protected areas by roughly 70% (Fig. 3; 100% environmental solution). However, in regions of low environmental heterogeneity, emphasis

Table 2 Changes in total cost and area of protected area networks in PNG as a result of including Land System representation as an additional conservation requirement

	Vegetation and fauna	Vegetation, fauna and Land Systems	% difference
Mean total cost of Protected Area network (arbitrary units)	3827103.50	4248353.70	9.92
Mean total area of Protected Area network (# of Planning Units)	1582.42	1733.25	8.70

Table 3 Comparison of the projected extent of climate change experienced by conservation features in protected areas, and the average number of protected areas in the network, between scenarios where climate change refugia are considered in the design of protected areas and where they are not

	Without considering climate change in protected area design	With consideration of climate refugia in protected area design
Projected climate change per conservation feature (mean probability of change)	0.257 (± 0.005)	0.187 (± 0.004)
Average number of protected areas in final solution	141 (± 6.6)	163 (± 11.2)

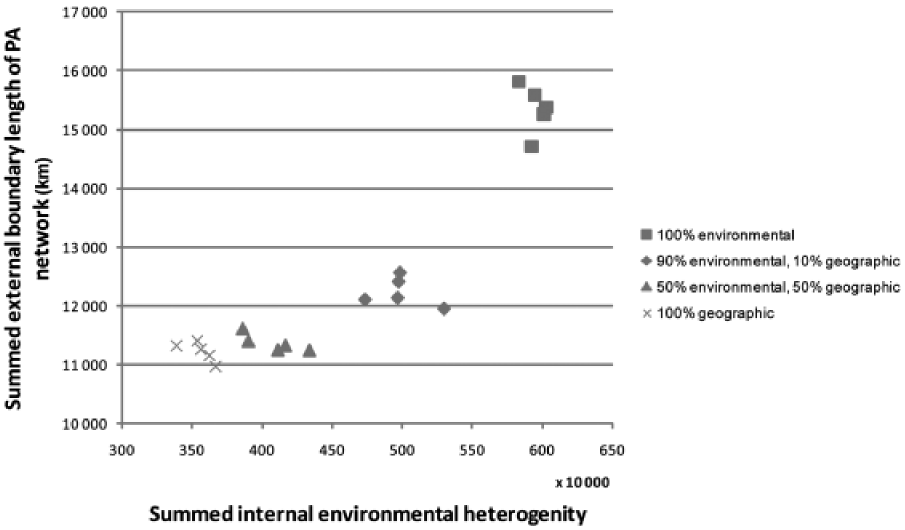

Fig. 3 Comparison of the amount of environmental heterogeneity captured internally within a protected area network (*x*-axis), and the total external boundary length of the network (*y*-axis). Four different boundary length formulations are shown: 100% environmental distance; 90% environmental distance and 10% geographic distance; 50% environmental distance and 50% geographic distance; and 100% geographic distance.

on environment diversity within individual protected areas leads to highly fragmented solutions as the algorithm rejects solutions that would require much larger areas to clump distant, dissimilar sites. The total boundary length of these fragmented protected area network solutions is nearly 40% greater than if geographic distance alone was used as the boundary between planning units (Fig. 3; 100% geographic solution). The total boundary length of a protected area network provides an indication of fragmentation.

Given the trade-off between the amount of environmental heterogeneity within protected areas and the level of protected area fragmentation across the network, an optimal solution for PNG involves modifying the boundary length values to include some component of both the geographic boundaries shared by planning units and the environmental distance between adjacent planning units. A combination of 90% environmental distance and 10% geographic distance lead to solutions that improved the internal environmental connectivity by over 40%, but did so with only a 9% increase in the overall network boundary length (Fig. 3, 90% environmental 10% geographic solution). Further reducing the environmental distance component of boundary length to 50%, lead to little change in overall fragmentation (+ 1%) but only improved cross environment connectivity by 15% (Fig. 3, 50% environmental 10% geographic solution).

Discussion

Successful adaptation of natural systems to climate change will depend on proactive conservation strategies: specific adjustments in our management of natural or human systems in anticipation of climate change (IPCC, 2007). Based on well-established ecological principles, this paper demonstrates three climate-adaptive strategies for national conservation assessments. All three are consistent with current gap assessment practices under the Program of Work on Protected Areas. They are also consistent with both the data typically available during national conservation assessments, and the expertise and capacity that most countries, including developing nations, have at their disposal. This means that in the vast majority of countries, these strategies could be implemented immediately. Climate change adaptation requires some additional data and concepts, but neither new tools nor necessarily more complicated analyses. As part of the PNG terrestrial conservation assessment, all three strategies were integrated with conventional practices using an unmodified version of freely available and widely used conservation planning software.

The ability to easily integrate these adaptation approaches into the established systematic conservation planning framework is important not only because it represents a consensus view of conservation (Sarkar, 2005), but also because it retains the emphasis on efficient use of national resources which is at the heart of systematic conservation planning. However, making recommendations for national resource use also comes with substantial responsibility; they represent a vision for long-term public investment in conservation to safeguard a country's natural heritage. For this reason, it is essential that we understand how adaptation recommendations like those proposed here, influence the outcomes of national conservation assessments.

The hypothesis that geophysical diversity as captured in Land Systems reflects ecological diversity appears to hold true in PNG, especially with regard to vegetation communities. Although the distribution of species included in the assessment exhibited slightly lower correlation with Land Systems, this is perhaps predictable because of their reduced or restricted ranges. However, the importance of including geophysical setting in national conservation assessments depends to some extent on whether their inclusion would change the outcome, in terms of national conservation priorities – would the priorities be any different if we ignored geophysical setting? In this case, including Land Systems (or another geophysical classification) as part of the PNG national conservation assessment substantially changed the outcome, illustrated by the fact that areas selected based on vegetation and fauna alone did a poor job of representing the diversity of Land Systems, and achieving representation of Land Systems required a 9% increase in total area protected.

Given the potential for Land Systems to represent current national biodiversity, we might be tempted to conclude that these are the only underlying features worth considering. Caution is, however, warranted, as even though Land Systems represent diversity well, they do not reveal anything about the condition of the ecological communities. To ensure that representation of geophysical setting is achieved in functional rather than highly degraded ecosystems, it is necessary to use geophysical data in combination with more direct ecological surrogates, such as vegetation type and condition.

Land Systems have the further advantage of being invariant under climate change and other drivers of biodiversity loss. Although we do not know how vegetation and fauna will respond to climate change, nor how land use and land condition will be altered under diverse economic and social changes. Consequently, geophysical settings are best treated as complementary data to the more direct ecological surrogates traditionally used to set biodiversity goals under the Convention on Biological Diversity.

Evaluating how national conservation goals should be interpreted in light of expected changes is an important part of adaptation. For example, consider the objective of conserving a set of areas that represent a region's biodiversity. If, under the influence of climate change, the species and habitats across that region change, will our set of protected areas be adequate to protect a representative sample of these new ecological communities, and will this still achieve our goals? The geophysical approach to representative biodiversity is predicated on a fundamental acknowledgement that biodiversity is dynamic and will change through time, and that conservation efforts should aim to conserve the national capacity to support the full suite of biodiversity.

Simply by considering the heterogeneity in projected climate across PNG, it was possible to substantially reduce the overall amount of climate change that habitats in protected areas are predicted to experience. The fact that this could be achieved without a commensurate increase in overall expected cost of the protected area network reflects the fact that there are a large number of possible solutions that would meet PNG's conservation targets – this will not always be true in countries with a higher degree of habitat conversion.

The identification and protection of climate refugia as an approach to adaptation, relies upon assumptions that are less easily tested than those that accompany the geophysical stage approach. For instance, it assumes that ecological changes will be least severe in those places where climate remains relatively constant. In addition to uncertainty over the validity of this assumption, a large amount of uncertainty is also introduced simply through the choice among scenarios and models used for climate projections. Importantly, however, unlike some proposed approaches to climate change adaptation in conservation planning, climate projections alone do not drive the selection of protected areas – targets for all conservation features are still being met based on current knowledge of biodiversity distribution. Consequently, these solutions are no worse than those that ignore climate change, and potentially much better. This is the essence of a 'no-regrets' strategy.

Although the protection of areas with high environmental heterogeneity is gaining currency as a climate change adaptation strategy (e.g., Ashcroft *et al*., 2009; Hodgson *et al*., 2009), it is not a new recommendation. As early as 1985, Peters and Darling suggested that 'locating reserves where topography and soil types are heterogeneous could increase the chance that a species' precise temperature or moisture requirements would be met.' To the best of our knowledge, however, the work described here is the first time this approach to climate change adaptation has been formulated as part of a systematic conservation plan. This represents a conservative, but also parsimonious approach to enhancing connectivity as an adaptation strategy in national conservation assessments.

There is a natural tendency in any Marxan based conservation assessment that applies a Boundary Length Modifier (BLM), to target areas of high heterogeneity as these are typically spatially efficient solutions (especially as planning unit size increases). However, as we show here, a great deal more environmental heterogeneity inside protected area boundaries can be achieved by explicitly incorporating this property into a systematic plan. On the other hand, relying on environmental heterogeneity alone to drive protected area clumping, had the predictable, and unacceptable, consequence of fragmenting proposed protected areas in regions of homogeneous habitat. This is the reverse of typical conservation assessment solutions in which there are usually larger, clumped protected areas in regions of relatively homogenous habitat because of large targets for these features, whereas features found in areas of high variability tend to be smaller in overall extent, and their targets therefore met in smaller protected areas.

Using a combination of environmental and geographic distance as a boundary between planning units appeared to generate elegant protected area solutions with internal heterogeneity increasing by over 40% and overall solution fragmentation increasing by $<10\%$. An alternate approach, not explored here, would be to set minimum clump sizes for each feature, either based on an understanding of its particular ecology, or as a function of its total occurrence extent.

All three climate change adaptation strategies described here can be employed simultaneously in a national conservation assessment. In the case of PNG, the resulting protected area solutions reflected all the characteristics described above. Using these strategies in combination does, however, make sensitivity testing and parameter setting in MARXAN more challenging. As such the influence of each strategy on protected area solutions is best explored on its own before using the strategies in combination. Another consequence of using all three strategies simultaneously is that there are likely to be fewer 'good' solutions available; although this is not necessarily a weakness as it can reduce ambiguity around which areas are priorities for conservation.

We have no reason to believe that one strategy is a more effective approach to climate change adaptation than the others, and employing all three strategies together provides a level of insurance against uncertain results. However, each strategy does have individual characteristics and assumptions that might be perceived as strengths or weaknesses depending on confidence in the underlying data and the ecological beliefs of those involved in the assessment. For example, conserving the geophysical stage is probably the simplest to incorporate and involves the smallest departure from current gap assessment practice. Protecting refugia is the only strategy of these three that makes explicit use of climate change projections, which could be viewed as either strength or weakness. Environmental connectivity is perhaps the most intuitive and easily communicated of the three strategies, and the one whose influence is most easily detected in potential protected area solutions. While we recommend that conservation planning teams explore the influence of each of these strategies independently, we would encourage them to additionally develop and evaluate protected area solutions that make use of all three strategies in combination.

We cannot accurately predict the future of biodiversity and ecosystems in a changing climate. It is important that national conservation assessments in particular, are conducted in ways that are as robust to uncertainty as possible. And yet, we must be thoughtful about likely changes in order to moderate the most adverse impacts. While we believe the strategies described here are all 'no-regrets' ways to improve the long-term likelihood of conserving a country's biodiversity, we cannot yet judge their effectiveness. As such, conservation investment at a national level must be dynamic enough to respond to unexpected changes. Successful adaptation will require not only a revised approach to identifying priority areas for conservation, but also changes to the management of protected areas and the larger policy context in which they are established. The authors would to thank Chris Zganjar for assistance with the climate change projections, and two anonymous reviewers for comments that improved the manuscript.

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