LETTER

Global priorities for conservation of threatened species, carbon storage, and freshwater services: scope for synergy?

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Abstract

The potential of global biodiversity conservation efforts to also deliver critical benefits, such as carbon storage and freshwater services, is still unclear. Using spatially explicit data on 3,500 range-restricted threatened species, carbon storage, and freshwater provision to people, we conducted tradeoff analyses, explicitly addressing both biodiversity and ecosystem services in selection of priority areas, to explore the potential for aligning these objectives. These analyses revealed a promising scope for aligning objectives, in particular for biodiversity and freshwater, which is not evident from previous studies that merely analyzed overlap of biodiversity and ecosystem services derived for each objective independently. However, this alignment is not complete. By revealing important synergies and tradeoffs among services, these analyzes suggest particular regions and service combinations for which spatial planning and appropriate conservation mechanisms (e.g., payments for ecosystem services) can be used to realize synergies and mitigate tradeoffs.

Introduction

Despite global conservation efforts and the Convention on Biological Diversity 2010 target to reduce the rate of biodiversity loss, the rate of biodiversity loss does not appear to be slowing (Butchart *et al.* 2010). Thus, efforts to protect important habitats for biodiversity are still critical to prevent species extinctions (Sala *et al.* 2000). Concurrently, there is a critical need to ensure provision of ecosystem services to people such as freshwater services, carbon storage to mitigate climate change, services that support food production, and others (Daily 1997). Given that deforestation and degradation accounts for up to ca. 15% of the yearly global CO_2 emissions (van der Werf *et al.* 2009), conserving carbon storage in natural habitats is seen as a critical ecosystem service of global importance (Turner *et al.* 2009). Curbing deforestation is suggested to be a highly cost-effective way of reducing CO_2 emissions (McKinsey & Company 2009) and consequently an international financial mechanism to reduce emissions from deforestation and forest degradation, plus the conservation, carbon stock enhancement, and sustainable management of forests (REDD+) has been established in the "Cancun Agreements" under the United Nations Framework Convention on Climate Change (UNFCCC 2010). No less important is freshwater services generated by natural ecosystems (Brauman *et al.* 2007); provision of freshwater, for example, is essential to meet household water and sanitation needs as well as the needs of agriculture and industry. More than 1.4 billion people currently lack reliable access to clean drinking water (WWAP 2009).

Conservation and development efforts could both benefit substantially if safeguarding habitats in the areas considered as priorities for biodiversity would also ensure considerable provision of ecosystem services.

While global conservation efforts to halt the loss of biodiversity will inevitably provide a range of ecosystem services (Daily 1997) including freshwater provision and carbon storage, we need to better understand the scope for alignment between conservation priorities for biodiversity and areas most important for delivering critical ecosystem services. Some important insights on the concordance between conservation of biodiversity and provision of ecosystem services have been revealed from relatively few recent studies, on either a national/regional scale (Chan *et al.* 2006; Anderson *et al.* 2009; Egoh *et al.* 2009;) or globally (Turner *et al.* 2007; Naidoo *et al.* 2008). However, these studies optimized for one objective independently and subsequently assessed how other objectives were covered by spatially overlapping the results; they did not optimize across two objectives and thereby, explicitly address both biodiversity and ecosystem services in selection of priority areas (but see Egoh *et al.* 2010 for approximation). With analyses that optimize for multiple objectives, it is possible to explore, for example, how a specific increase of carbon storage in a global network of priority areas would influence the fulfillment of biodiversity conservation targets.

Here, we perform a global analysis to better understand the scope for reconciling global priorities for species conservation with priorities for two critical ecosystem services: carbon storage and freshwater provision to people. Specifically, we first analyze how global priorities for biodiversity capture these two ecosystem services and vice versa. Second, we apply multicriteria analysis (MCA) to more fully explore the scope for identifying priority areas that in aggregate retain a high representation of biodiversity, while simultaneously ensuring a high provision of ecosystem services. Finally, given that funding in a REDD+ mechanism could be well beyond existing conservation funding with substantial consequent potential to influence global forest conservation (Miles & Kapos 2008), we conducted an analysis to explore the scope for synergy between priority areas for cost-effective solutions to avoid CO_2 emissions and biodiversity conservation in developing countries in particular.

Methods

Data

We conducted all analyses on a grid of equal area (2,591 km^2) hexagonal cells (Sahr *et al.* 2003). These cells avoid inaccuracies due to large, unequal units (e.g., countries, drainage basins) and are ideal for hydrological flow calculations because each is equidistant from its neighbors. As our biodiversity measure, we used data on the global distribution of the 3,500 most range-restricted threatened species (IUCN 2009), comprising 1,919 amphibians (Stuart *et al.* 2008), 740 mammals (Schipper *et al.* 2008), 799 birds (BirdLife International 2008), and 42 turtles (Iverson *et al.* 2009). This approach recognizes the importance of irreplaceability and vulnerability in conservation priority setting (Margules & Pressey 2000). The vulnerability criterion focuses efforts on those conservation elements having higher likelihood of being lost in the short term, while the irreplaceability criterion directly prioritizes the places that harbor species with few other spatial options for their conservation. As our freshwater measure, we estimated provision of water to downstream populations based on spatially explicit maps of runoff from the global hydrological water model WaterGAP, hydrological drainage directions, and human population density (see full methods in Supporting Information). For carbon storage, we used a global map of biomass carbon stored in above- and belowground living vegetation (Ruesch & Gibbs 2008). (See Figures S1A–C for global maps of species, carbon, and freshwater.) For our "REDD+ analysis," we estimated CO_2 emissions avoided in developing countries (those targeted for a REDD+ mechanism; Busch *et al.* 2009) by considering carbon storage (Ruesch & Gibbs 2008) restricted to forest (EC-JRC 2006) and deforestation rates. Potential annual CO_2 emissions avoided from deforestation were calculated for each cell as follows: forest carbon density in cell (t C/ha) $\times$ forest area in cell (ha) $\times$ estimated deforestation rate for country (%/year) $\times$ 3.66 CO_2 equivalents (t CO_2/t C). We used national deforestation rates (FAO 2005) for hexagon grids with deforestation rates above global mean, and the global mean rate of 0.22%/year for the remaining hexagons, to reflect that a REDD+ mechanism will likely provide an incentive to historically low-deforestation countries (da Fonseca *et al.* 2007). As our measure of opportunity costs in developing countries, we used a global map of economic rents from agricultural lands (Naidoo & Iwamura 2007).

Selection of priority areas

MCAs can be used to reveal tradeoffs and synergies between two or more objectives. MCAs operate based on pairwise comparisons where weights are assigned to each objective establishing their importance relative to the other objective (Moffett *et al.* 2006). The weights represent how much better it would be to improve the representation of one objective (e.g., species representation) versus improving the representation of another objective (e.g., carbon storage) in the total conservation network. We performed the following network priority analyses (see Figure S2 for objectives and related variables used for the analyses):

(1) Single objective (global): Select priority areas for each objective independently, maximizing representation of range-restricted threatened species, total carbon storage, or total water provision to downstream populations within 10% of global land area excluding Antarctica (the maximum coverage set problem; Church *et al.* 1996). For water provision, in addition to the above "global optimization," we also optimized within continents ("continental optimization") as a scenario, in which freshwater delivery was optimized within all continents separately (due to regional beneficiaries). We compared the representation of the three objectives in these optimal cases with random selection of areas totaling 10% of global land area ($n = 1{,}000$ sets of random areas).

(2) Multiple objectives (global): Select priority areas for each of the three pairwise combinations of objectives (biodiversity, carbon storage, freshwater). Pairwise comparisons were done using weights between 0 and 100% for each objective (e.g., 90% and 10%, 80% and 20%, 70% and 30%, and so on), indicating a range from weighting biased strongly toward the first objective to weighting biased toward the second objective. In this way, the performance of the two objectives was explored across a range of weights between the two extremes. For each pairwise combination, the solution becomes the selection of areas that maximize an objective function representing weighted sum off these two objectives within 10% of land area. For each weighting of objectives, a score was assigned to each of the over 56,000 iterations and the solution with the highest score was selected for each weighting (see Moffet *et al.* 2006 for details).

(3) Multiple objectives (developing countries): Select cost-effective priority areas optimizing the weighted sum of avoidance of CO_2 emissions from deforestation and representation of range-restricted threatened species. The weightings and selection of best solution followed the procedure described above. Because economic cost is used as a constraint (rather than area as in analysis 1 and 2), the opportunity cost for the analyses was fixed at the cost of the best set of priority areas to avoid CO_2 emissions with 10% of area.

For each species, we assigned an individual representation target as the percentage of range (i.e., fraction of hexagon cells) that must be included in the network of priority areas in order for the species to be considered covered. We assigned narrowly restricted species (<1,000 km^2) a representation target of 100% and widespread species (≥250,000 km^2) a target of 10%, and interpolated linearly in arithmetic space between these two extremes following Rodrigues *et al.* 2004.

The selection of priority areas was conducted with the ConsNet software (Ciarleglio *et al.* 2009). See Supporting Information for more details on general methods and MCA.

Results

The priority areas, defined as top 10% of area, selected solely for biodiversity, carbon storage, and freshwater, respectively, differed geographically (Figure 1). The overlapping area of all three objectives constituted 0.8% of global area, while overlap for biodiversity and carbon constituted 1.7%. Overlap was somewhat higher for biodiversity and freshwater (5.7% for continental optimization and 2.9% for global optimization). Priority areas for threatened endemics were found in areas characterized by tropical forest and rapid deforestation (e.g., the tropical Andes, Atlantic Coastal forest, the Afromontane systems, and Southeast Asia) and also include many islands; biomass carbon storage is most concentrated in tropical rainforest (e.g., the Amazon basin, Congo basin, and intact forest tracts in Southeast Asia); and freshwater provision to people was found in regions with high rainfall and many people downstream (Figure 1). As a consequence, the highest priority areas based on single objectives represented one another poorly (Table 1).

Unlike single-objective optimizations, analyses that considered both objectives were able to select priority areas that capitalized on win-win conditions. For example, while areas selected for biodiversity alone stored only 31% as much carbon as those selected for carbon alone, a multicriteria optimization including both biodiversity and carbon storage (e.g., weighted at 70% for carbon and 30% for species, respectively) increased carbon storage considerably (e.g., 66% of maximum) with limited loss of species representation (e.g., 90% of maximum retained; Figure 2A). Beyond this point, an additional increase in carbon storage would result in more substantial decreases in species representation. For example, one set of priority areas captured 74% of maximum for biodiversity and 87% of maximum carbon storage; the geographic distribution of these areas (Figure 3A) resembles that optimized for biodiversity alone (compare with Figure 1), but with more areas in carbon-rich tropical rainforest and fewer on small islands. This effect was even more pronounced when MCAs addressed biodiversity and freshwater (Figure 2B). For example, the network based on a weighting of 30% for biodiversity and 70% for freshwater retained high fulfillment of biodiversity conservation targets (88% of maximum), while freshwater services increased from 41% to 85% of maximum from

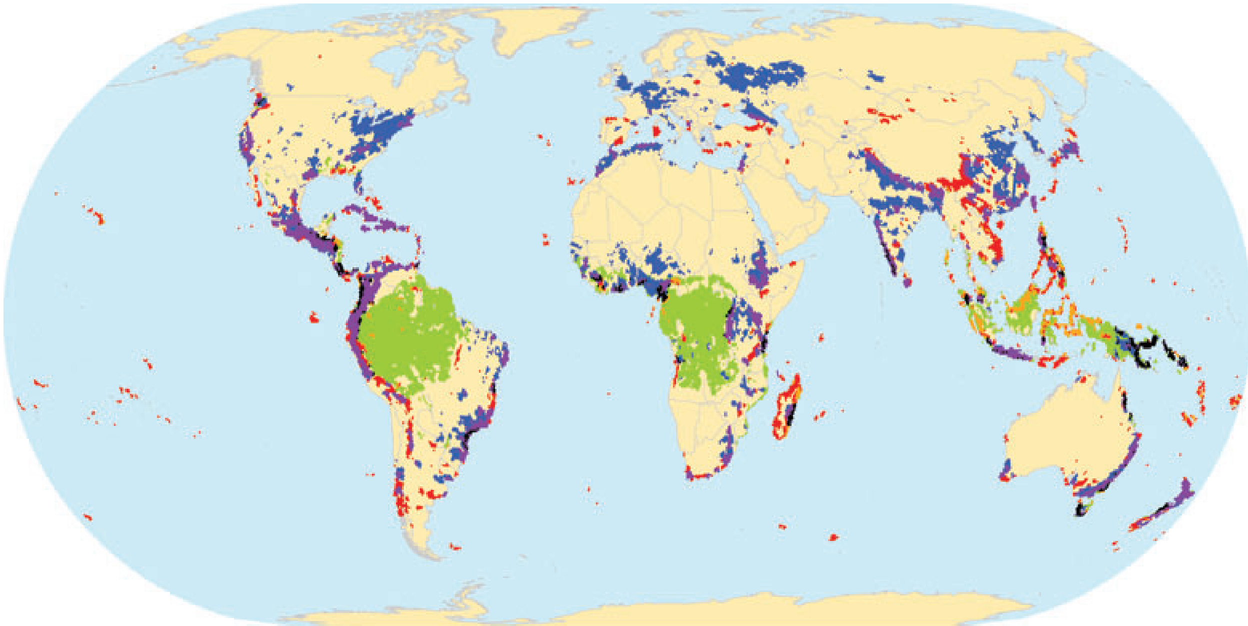

Figure 1 Area networks (10% of global area) selected independently to maximize representation of range-restricted threatened species (red), carbon storage (green), and freshwater provision to downstream people ("continental optimization"; blue). The map shows overlaps between priority areas for range-restricted threatened species and carbon storage (orange, 1.7% of global area), range-restricted threatened species and freshwater provision (purple, 5.7% of global area) and all three priority areas (black, 0.8% of global area).

the biodiversity-only case. This network included many areas important for biodiversity, with a particular emphasis on mountain systems additionally important for freshwater services to people, including the Himalayas, Andes, and Mesoamerican mountain ranges (Figure 3B). Finally, priority areas for either freshwater or carbon storage represented each other very poorly (Table 1), and the MCA revealed that an increase in one ecosystem service resulted in a more substantial decrease of the other (Figure 2C) than was the case for either service optimized with biodiversity.

Figure 2D shows the scope for priority areas selected for cost-effective avoidance of CO_2 emissions in developing countries to also benefit biodiversity conservation. Priority areas solely selected to optimize avoidance of CO_2 emissions represented biodiversity very poorly (only

Table 1 The effectiveness of the best network of priority areas selected independently to maximize representation of range-restricted threatened species, carbon storage, and freshwater provision to downstream people (optimized on both a global and continental scale). The effectiveness is given as the percentage of the maximum possible value within 10% of global area, that is, the network size. The effectiveness for priority areas for the combined priorities via multicriteria analysis (weight: 33%, 33%, 33%) and for random area selection is shown for comparison. The species representation is measured as the number of species that have their representation target achieved

	Effectiveness of priority areas in terms of representation of each of the three priorities (% of maximum possible)		
Priority areas	Species representation	Carbon storage	Water provision to people
Range-restricted threatened species	100	31	41
Carbon storage	5	100	10
Water provision (global optimization)	20	22	100
Water provision (continental optimization)	29	30	79
Random selection	48	20	14
Multicriteria for all three priorities	88	30	84

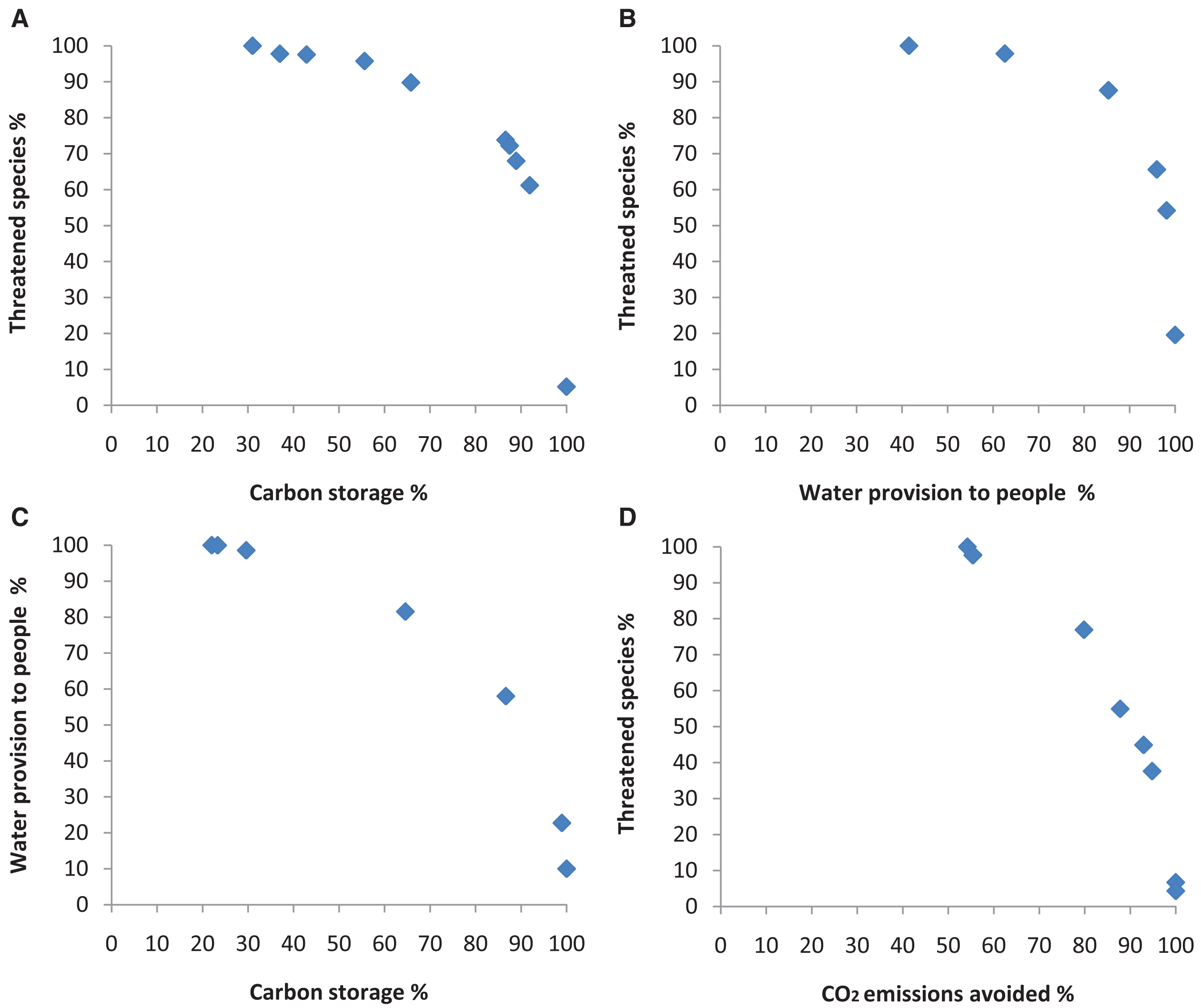

Figure 2 The effectiveness of a global set of area networks for each pairwise combination of objectives based on multi-criteria analysis: (A) range-restricted threatened species and carbon storage, (B) range-restricted threatened species and freshwater provision to people (global optimization), (C) freshwater provision to people (global optimization) and carbon storage, and (D) cost-effective avoidance of CO_2 emissions and range-restricted threatened species. Each area network has different weights between the two objectives in the multicriteria analysis spanning a range between 0% and 100% for each objective (e.g., 90% and 10%, 80% and 20%, 70% and 30% etc.). The effectiveness is measured in percentage of maximum possible effectiveness within 10% of area for (A), (B), and (C). For (D) area networks were selected solely within developing countries and benefits were optimized within a given sum of opportunity costs rather than 10% of area.

4% of maximum) as the priority areas differed markedly (Figure S3); only 13% of the priority areas overlapped. However, when biodiversity is included as an objective, multicriteria priority areas increased species representation substantially with only modest decrease in avoided CO_2 emissions. For example, a network with 25% biodiversity weighting and 75% CO_2 weighting retained 93% of maximum CO_2 avoidance while increasing species representation from 4% (the CO_2-only optimization) to 45% of maximum (Figure 3C). As expected, this area network includes many forest areas from the optimal area network for avoiding CO_2 emissions but also includes many other forest areas important for increasing the biodiversity target (compare Figures 3C and 1).

Discussion

Applying multiobjective analysis reveals greater scope for synergy between objectives than indicated by priority

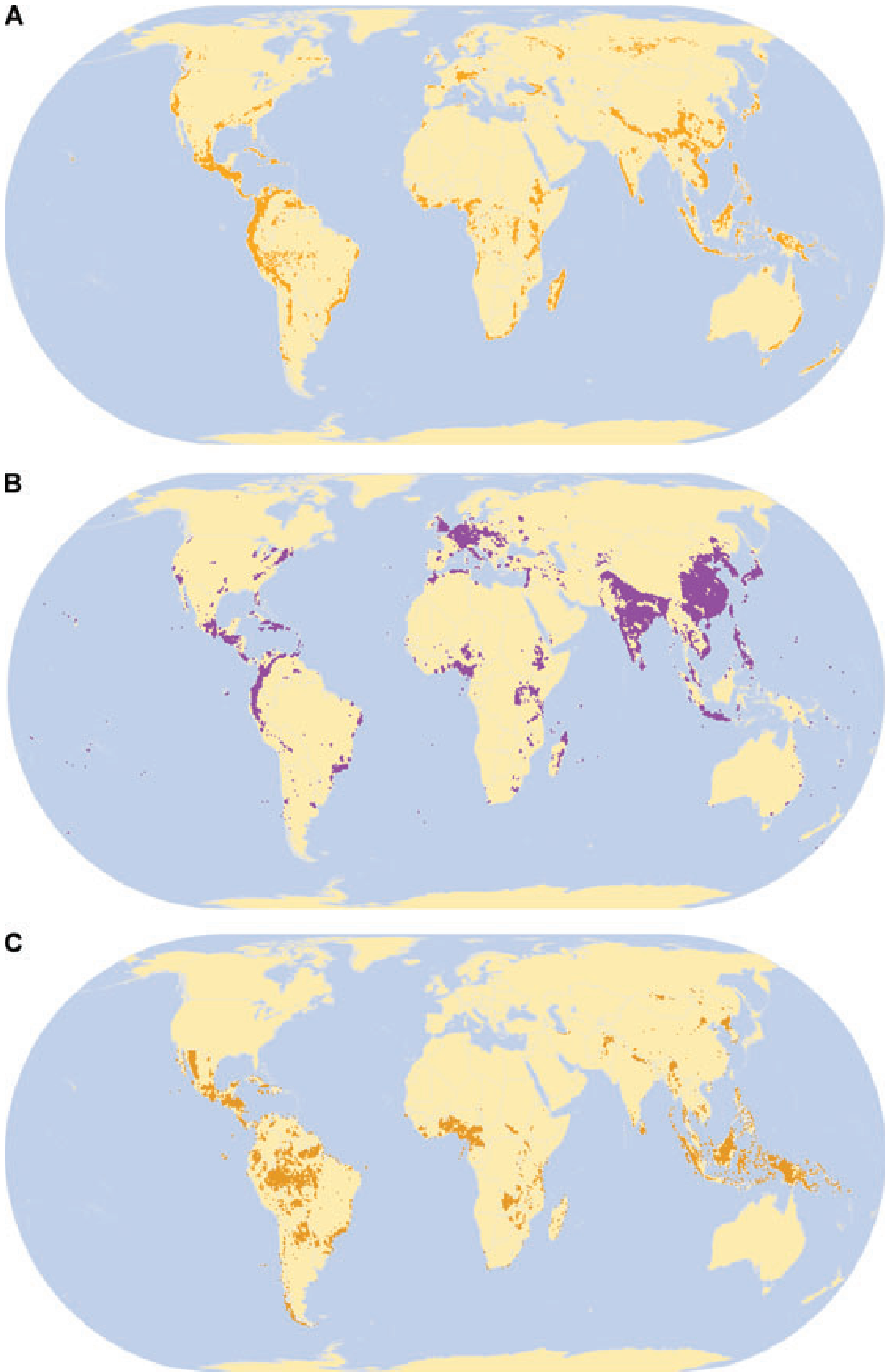

Figure 3 Examples of multicriteria area networks that achieve some level of alignment between objectives: (A) carbon storage (87% of maximum) and range-restricted threatened species (74% of maximum), (B) freshwater provision to downstream people (global optimization) (85% of maximum) and range-restricted threatened species (88% of maximum), and (C) cost-effective avoidance of CO_2 emissions (93% of maximum) and range-restricted threatened species (45% of maximum). For analysis, (C) area networks were selected solely within developing countries and benefits were optimized within a given sum of opportunity costs.

layers derived independently for the objectives of biodiversity conservation and provision of ecosystem services. Our findings suggest that efforts to conserve biodiversity and ecosystem services will be inefficient unless objectives for both are explicitly considered. Indeed, we found limited overlap between global priority areas identified solely for conservation of biodiversity, carbon storage, and to some extent freshwater with a consequent poor performance in representing one another. Priority areas for biodiversity showed little overlap with priority areas for carbon storage (13.5%) and stored limited carbon, which is in accordance with findings for ecoregions on a global scale (Naidoo *et al.* 2008) and for 10 km grid cells in Britain (Anderson *et al.* 2009). Similarly, priority areas for biodiversity also performed poorly in ensuring freshwater provision to downstream populations, which is also in accordance with findings for global ecoregions (Naidoo *et al.* 2008) and for 500 ha planning units in California (Chan *et al.* 2006). These previous findings suggest a limited scope for aligning priorities for conservation of biodiversity with delivery of these two important ecosystem services for human well-being. However, as our results indicate, reaching the biodiversity conservation target often allows for flexibility in area choices (Pressey *et al.* 1994), and different configurations of priority areas with a slightly lower representation of species might increase the representation of ecosystem services markedly, and in so doing increase the opportunities for conservation dramatically due to increased breadth of financing opportunities (such as payments for ecosystem services and a REDD+ mechanism) or increased support for conservation.

Our tradeoff analyses showed that priority areas could be selected that considerably increase carbon storage while retaining a high representation of biodiversity. These priority areas included regions such as parts of the Andes, Mexico, and Himalayas as well as areas in temperate regions (Figure 3A) beyond the areas included in both priority areas for both biodiversity and carbon (e.g., Central America, Western African forests, Eastern Madagascar, Western Ghats, Eastern Borneo, and parts of Papua New Guinea; see orange overlap in Figure 1). However, if weighting for carbon storage is increased beyond a certain level, further additional areas will be selected in the Amazon basin, Congo basin, and other areas which offer lower marginal improvements to threatened species conservation targets (as many species targets in these regions have already been met). Meanwhile, many areas important for fulfilling species conservation targets will not be included, resulting in marked loss of species representation. Conservation of biodiversity exhibited a higher scope for synergy with freshwater services to downstream populations, with little tradeoff exhibited between them (Figure 2B). Here, priority areas included more montane areas in addition to overlapping areas of priority for biodiversity and freshwater provision (Figure 1), which considerably increased the overall water provision while retaining a high representation of biodiversity. These findings reflect the value of mountain ecosystems for freshwater provision, the increase of habitat transformation due to human use (Sanderson *et al.* 2002), and the high levels of species endemism in mountainous areas (Myers *et al.* 2000) that results in an increase of threatened species (Figure 3B). Some areas are easily recognized as being important for all three priorities, including Central America, Brazil's Atlantic coastal forests, West African forests, Africa's Eastern Arc Mountains, Western Ghats, parts of Indonesia, and Papua New Guinea (Figure 1, and similarities between Figures 3A and 3B), which are areas also recognized by existing conservation priority schemes for biodiversity (Brooks *et al.* 2006).

Given the tremendous international interest in securing carbon storage in natural habitats, we investigated the scope for cost-efficient selection of priority areas to avoid CO_2 emissions from deforestation in developing countries to benefit biodiversity conservation. Our analysis revealed that while priority areas with a sole focus on cost-effective avoidance of CO_2 emissions performed poorly in achieving biodiversity conservation targets, there is a promising scope, if biodiversity is explicitly taken into account, for benefitting biodiversity conservation without much loss in avoided CO_2 emissions. This result is consistent with other research (Venter *et al.* 2009) finding modest biodiversity benefits (by predicting avoided species extinctions via the species-area relationship) for cost-effective allocation of REDD+ funding to countries. It is encouraging that our analysis on grid cells based on explicit species distributions and species-specific targets revealed similar results despite differences in methodology, and thereby suggests scope for REDD+ to provide substantial biodiversity conservation co-benefits if species are taken explicitly into account. Nonetheless, there is still much uncertainty on the specific design of REDD+ mechanisms at both international and within-country scales. Despite this uncertainty, it is increasingly clear that the biodiversity co-benefits of REDD+ can be substantial but may only be realized with explicit consideration of biodiversity. Some key design issues with importance for biodiversity benefits include the set of activities that are creditable, definitions such as what constitutes natural forests and whether plantations are included, reference levels, how leakage is addressed, and REDD+ financing (Harvey *et al.* 2010). Further research should explore the extent to which these REDD+ factors can address biodiversity conservation.

The scope for aligning priorities for biodiversity conservation with carbon storage and freshwater provision is promising, with the potential to increase provision of ecosystem services while still retaining high biodiversity conservation targets. However, there are limitations to the win-win conditions between biodiversity conservation and provision of ecosystem services when identifying priority areas. This synergy will partly depend on alternative options to meet biodiversity targets, which will vary with factors such as biodiversity targets used and region of focus (i.e., regions with high land cover change and less intact natural habitat will likely face more severe tradeoffs). The inevitable limitations of this global analysis should be noted, and caution should be taken in using global results to guide conservation priorities at regional and local scales. Our choice of measures, assumptions, cell size, and data metrics likely affect the results, in particular the identification of specific priority regions and subsequent win-win areas. For example, inclusion of soil carbon, use of spatially explicit global deforestation rates, other measures of freshwater service, and biodiversity might have identified other win-win regions, and further research to explore other measures on scales spanning global to local would further illuminate our understanding of win-win areas. For example, it remains to be seen whether win-win regions found at this global spatial scale translates to finer spatial scales (Larsen & Rahbek 2003; Anderson *et al.* 2009) and even suboptimal areas at broader spatial scales can contain important win-win situations at finer scales (Naidoo *et al.* 2008; Strassburg *et al.* 2009). Given the widespread degradation of natural habitats and increased threats to both species and ecosystem services, the scope for synergy can be expected to decrease over time, emphasizing the importance of timely action to arrest biodiversity loss. Spatially explicit analyses accounting for multiple criteria are a critical step toward identifying the tradeoffs between biodiversity conservation and ecosystem services across a range of spatial scales, ecosystem services, and regional contexts so that synergies can be realized via appropriately designed finance mechanisms.

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Supporting Information

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

1. Supplementary Methods
2. Supplementary References
3. Supplementary Figures S1A–C, S2, S3.

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