Potential Biodiversity Benefits from International Programs to Reduce Carbon Emissions from Deforestation

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Abstract Deforestation is the second largest anthropogenic source of carbon dioxide emissions and options for its reduction are integral to climate policy. In addition to providing potentially low cost and near-term options for reducing global carbon emissions, reducing deforestation also could support biodiversity conservation. However, current understanding of the potential benefits to biodiversity from forest carbon offset programs is limited. We compile spatial data on global forest carbon, biodiversity, deforestation rates, and the opportunity cost of land to examine biodiversity conservation benefits from an international program to reduce carbon emissions from deforestation. Our results indicate limited geographic overlap between the least-cost areas for retaining forest carbon and protecting biodiversity. Therefore, carbon-focused policies will likely generate substantially lower benefits to biodiversity than a more biodiversity-focused policy could achieve. These results highlight the need to systematically consider co-benefits, such as biodiversity in the design and implementation of forest conservation programs to support international climate policy.

Keywords Forests · Carbon · Biodiversity · Conservation · REDD · Priorities

INTRODUCTION

Climate change and the loss of biodiversity are among the most pressing global environmental problems today. Many nations have expressed great concern about these issues at international gatherings in Kyoto, Rio de Janeiro, Copenhagen, Cancun, Nagoya, and more. Two separate international conventions, the United Nations Framework Convention for Climate Change (UNFCCC) and the

Convention for Biological Diversity (CBD), both signed at the Earth Summit in Rio de Janeiro in 1992, address climate change and biodiversity. The achievements and political challenges faced by the UNFCCC are perhaps more widely known, although the CBD is as or even more ambitious in its goals. However, despite seeking to stop biodiversity loss by 2010, it is now widely acknowledged that the CBD has been unable to substantially slow the rate of biodiversity loss (Convention on Biological Diversity 2010).

Deforestation is one specific area where climate change and biodiversity loss overlap. In the context of climate change, deforestation is among the chief contributors to global greenhouse gas (GHG) emissions and is a particularly pressing problem in the developing world (IPCC 2007; Gibbs et al. 2007; Angelsen 2008). In the context of biodiversity conservation, habitat change in general is one of the main drivers of biodiversity loss, and the conversion of forests to agricultural uses is among the most detrimental kinds of land use change in its effects on biodiversity (Pereira et al. 2010).

Programs for Reducing Emissions from Deforestation and Degradation (REDD) have received substantial attention in research and policy discussions regarding climate change. Many climate policy makers and analysts view REDD programs with optimism because they appear to have the potential to provide low-cost options to mitigate global GHG emissions by engaging developing countries in some form of international climate policy architecture (Angelsen 2008; Kindermann et al. 2008a, b). Rather than adopting high-cost mitigation actions domestically, developed countries could meet their emission reduction commitments by financing developing countries to achieve similar but less costly emission reductions through reduced deforestation. REDD programs also have the potential to

provide considerable emission reductions in the near future, which may be essential to meet near-term emission reduction targets with allowance prices that are perceived to be politically acceptable. Moreover, several countries, such as Brazil and Indonesia, which currently have high rates of GHG emissions from deforestation, are developing national action plans to reduce emissions and REDD is expected to serve as an important instrument in implementing those plans (Government of Brazil 2008; Republic of Indonesia 2009).

In efforts to preserve biodiversity, one key challenge is the design and implementation of effective policies to prevent the loss of natural habitats, which continues at a rapid pace especially in developing countries. The conversion of natural areas to agricultural, residential, and commercial uses reduces the habitat available to support species and populations. As natural habitats continue to disappear, the ranges of many species shrink and become fragmented. Both phenomena tend to reduce species richness and abundance and eventually drive species to extinction when the remaining habitats are unable to support minimum viable populations. Given the focus of REDD initiatives on preventing the loss and degradation of forest habitat, proponents and analysts of biodiversity conservation therefore recognize REDD programs as potentially powerful means of also reducing the rate of species loss (Niekisch et al. 2009; Harvey et al. 2010; Venter et al. 2009).

While it stands to reason that most realistic versions of REDD programs will provide some biodiversity co-benefits, it is still unclear to what extent, and at what cost, REDD programs may help to address the broader challenges of global biodiversity conservation. The magnitude of benefits to biodiversity from REDD programs will vary depending on their geographic distribution, and it may be possible to design REDD programs to achieve substantially greater biodiversity benefits with relatively small sacrifices in emissions reductions.

Although recent research suggests that biodiversity will benefit from REDD programs, the body of literature so far provides an incomplete assessment of the drivers and scale of these potential biodiversity co-benefits (Venter et al. 2009; Busch et al. 2011). The lack of information on the systematic associations between biodiversity and carbon benefits of REDD programs limits the ability to fully evaluate and optimize the design of REDD programs and to strike the best balance between GHG emission reduction and biodiversity protection. Furthermore, while tradeoffs between GHG reductions and biodiversity protections will be unavoidable in the design of REDD programs, improving our understanding of the spatial relationships between carbon and species will help to anticipate and manage these tradeoffs.

Our goal in this article is to highlight and discuss the potential of REDD programs to generate benefits to biodiversity. We compile a variety of global statistics, maps, and alternative forest conservation program configurations to systematically evaluate different options for REDD. We focus mostly on non-Annex I countries (i.e., all countries excluding OECD countries and economies in transition), which mainly include developing countries without committed GHG reduction targets and are the proposed locales of international REDD programs.

Our results indicate that the congruence of high-value target areas for REDD programs and biodiversity conservation may be surprisingly small. For example, we find that regions with the potential to supply avoided carbon dioxide emissions from deforestation at the lowest cost per ton may not have the highest biodiversity. While the most attractive options for REDD programs occur where the opportunity cost per ton of avoided carbon dioxide emissions (accounting for the carbon content of the forest and the threat of deforestation) is lowest, we find that the correlation between species richness in major taxonomic groups and the opportunity cost per ton of avoided emissions is close to zero. We further examine and illustrate the divergence of carbon and biodiversity goals by identifying regions that would be targeted by policies focused on either carbon or biodiversity. The differences in the targeted areas are fairly stark, and they demonstrate that while carbon-focused policies would concentrate in the Amazon region, Central Africa, and Indonesia and the surrounding areas of Southeast Asia, a species-focused policy would distribute conservation efforts more widely and invest in regions less rich in carbon yet richer in species.

GREENHOUSE GAS EMISSIONS, DEFORESTATION, AND REDD

According to the most recent estimates, average annual emissions of carbon dioxide from deforestation and forest degradation are roughly 1.2 Gt of carbon, or about 4.4 Gt of carbon dioxide. This represents around 12% of total anthropogenic carbon emissions (van der Werf et al. 2009). To help put these figures in context, the estimated current annual emissions from deforestation are over 4½ times the annual emissions from all sources in Germany and roughly equal to the emissions from all sources in the entire European Union in 2009 (UNFCCC 2011a, b).

In some areas, including several tropical countries, deforestation is the main source of carbon emissions. For example, Brazil and Indonesia are globally among the largest emitters of GHGs almost entirely due to their emissions from deforestation (Parker and Blodgett 2010). Furthermore, deforestation has the potential to be even

more detrimental to climate change if concerted efforts to reduce forest losses are not undertaken or turn out to be less effective than anticipated. The carbon pool currently stored in the world's forests and possibly subject to release due to deforestation is massive: more carbon is estimated to be stored in standing forest biomass and forest soils combined than currently resides in the atmosphere (IPCC 2007; Pan et al. 2011). Much of these current and potential emissions are not covered by existing reduction targets or management frameworks.

Despite the general optimism regarding the potential of REDD programs to help mitigate GHG emissions, it also is widely acknowledged that many challenges remain in incorporating REDD programs into the international climate policy portfolio. Ensuring that REDD programs generate real emission reductions represents perhaps the most difficult barrier. The development of robust methods to monitor and verify forest carbon emissions and their reductions therefore are of central importance to the practical implementation of REDD (Angelsen 2008; Palmer and Engel 2009; Gorte and Ramseur 2010; Macauley and Sedjo 2011). In addition, an often-voiced concern regarding the European Union Emissions Trading Scheme (EU ETS), the world's largest mechanism for limiting carbon emissions and trading emission allowances, is that with potentially large volumes of REDD offsets available, the current emission allowance market may experience a significant price reduction (Commission of the European Communities 2008). However, to address these concerns, regulators could limit the volume of offsets available to maintain a suitable overall price level and incentives to invest in mitigation within the regulated sectors and countries. In the US, for example, a number of recent, albeit unsuccessful, proposals for comprehensive climate policies have incorporated land management-based domestic and international offsets in the policy portfolio while also limiting their maximum annual volume.

While these and other practical implementation difficulties stand in the way of REDD programs, they nevertheless provide an important option to combat climate change (Angelsen

2008). REDD is now included in the UNFCCC negotiation framework, and its crucial role and the need to provide positive incentives for preventing deforestation is emphasized (UNFCCC 2008). Furthermore, countries, such as Australia, France, Japan, Norway, UK, and the US have voiced commitments to move REDD programs forward, pledging considerable funding toward their implementation in the near term. But while moving in this direction, it also is essential to understand the broader ecological context for REDD. This is particularly important as biodiversity may become one of the greatest casualties of a changing climate, and tropical forests are among the areas of greatest biodiversity. Therefore, a thorough understanding of the relationships between climate change, deforestation, biodiversity, and possible programs to reduce deforestation is needed.

GLOBAL BIODIVERSITY, ITS CURRENT PROTECTIONS, AND THREATS

Ecologists have developed biogeographic classifications of the world's ecosystems to describe their distributions. The most recent and comprehensive of these assessments, by Olson et al. (2001), describes the terrestrial surface of the earth as a set of 867 distinct ecoregions, which we use as our main units of analysis. Separate assessments have been conducted for the marine ecoregions (Spalding et al. 2007), but we focus here solely on terrestrial systems. As the purpose of this study is to evaluate potential conservation actions in non-Annex I countries, we concentrate mostly on evaluating the 542 ecoregions with 50% or more of their total land area in the non-Annex I region.

We estimated the total area of forests in each ecoregion using the Global Land Survey (GLS) land cover data (USGS and NASA 2009). Accordingly, we estimate that the worldwide total area of forests is about 4×10^9 million hectares (Table 1). This is close to other available estimates; for example, the most recent Forest Resource Assessment (FRA) by FAO estimated that the global forest cover is about 3.95×10^9 million hectares (FRA 2005).

Table 1 Forest area, current protected areas, endemic species, and percentage of mammals, birds, and amphibians listed as endangered or critically endangered by the IUCN, on average by ecoregion

	Global	Non-Annex I countries	Non-Annex I countries experiencing forest loss
Total land area (10^9 millions of hectares)	14.73	9.60	5.77
Forests (10^9 millions of hectares)	4.01	2.15	1.82
Current protected areas, % of total area	10.4	6.4	7.3
Endemic species	24 163	22 154	19 388
Mammals, % endangered	7.6	9.1	8.8
Birds, % endangered	13.6	13.3	12.2
Amphibians, % endangered	15.3	20.3	20.6

According to the GLS data, $\sim 65\%$ (9.6×10^9 million hectares) of the global land area is located in non-Annex I countries. This area includes about 2.2×10^9 million hectares of forests, which represent 54% of global forests. Within these areas, we use data from the FRA to estimate the change in the forest area within each ecoregion between 1990 and 2005. Ecoregions often cross country borders, so we used ArcGIS to calculate the total area of different countries within each ecoregion, and then calculated the ecoregion-specific deforestation rate as an area-weighted average of country-level deforestation rates. These data indicate that roughly 85% of non-Annex I areas (1.8×10^9 million hectares) are currently experiencing a net loss of forest area, and are therefore considered here to be subject to deforestation. Overall, about 45% of the global forests occur in non-Annex I regions currently subject to a net loss of forest area. The average rate of forest loss among non-Annex I ecoregions, which are currently experiencing a net loss of forest area, is about 0.6%/year. This estimate is a forest area-weighted average of the annual deforestation rate between 1990 and 2005, by ecoregion.

Considerable areas of land are already under some protective measures. Using spatial data from the World Database on Protected Areas (WDPA), which is a joint initiative between the International Conservation Union (IUCN) and World Conservation Monitoring Centre of the United Nations Environmental Programme (UNEP-WCMC) (IUCN and UNEP-WCMC 2010), we estimate that about 10% of the world's total land area is under some type of protection (as indicated by IUCN conservation categories I–VI). The percentage of land area under protection is somewhat lower in the developing world: some 6.4% of the land area is protected in non-Annex I ecoregions, and about 7.3% of the land area is protected in non-Annex I ecoregions currently experiencing forest loss (Table 1).

Endemic species are those that are found in a particular region and nowhere else in the world. At the ecoregion level, roughly 24 000 endemic mammals, birds, amphibians, and reptiles have been identified by previous assessments (Olson et al. 2001). Endemic species are highly concentrated in non-Annex I regions, which host nearly 92% of them. About 80% of the world's endemic species in these taxonomic groups occur in non-Annex I countries currently experiencing forest loss. This highlights both the threats to biodiversity from deforestation and the potential of policies aimed at reducing carbon emissions from deforestation to also address biodiversity preservation goals.

IUCN has assessed the conservation status of almost all known mammals and a majority of avian and amphibian species (IUCN 2010). IUCN data are the most comprehensive resource detailing the global conservation status of

plants and animals (e.g., Rodrigues et al. 2006). These data are used routinely in conservation assessments (see, for example, Schipper et al. 2008). Using IUCN's assessments of species conservation status along with digitized maps of the range of each species, we compiled data on the number of mammals, birds, and amphibian species known to exist in each ecoregion, as well as the share of species considered to be under serious threat of extinction—i.e., “critically endangered” or “endangered”—by the IUCN.

Worldwide, ~ 7.6 , 14, and 15% of mammals, birds, and amphibians, respectively, have been designated as either critically endangered or endangered (Table 1). The portion of species under similar threat of endangerment is roughly the same worldwide, in the non-Annex I region, and in the non-Annex I region current subject to deforestation. Amphibians are a minor exception: about 15% are critically endangered or endangered worldwide, but the comparable figure for the non-Annex I region is over 20%. However, it is important to bear in mind that species richness in general is greater in the non-Annex I region so it holds a greater absolute number of endangered species.

Global climate change caused by the anthropogenic release of greenhouse gases may itself drive substantial biodiversity loss (e.g., Thomas et al. 2004). Although species have some capacity to adapt to new environmental conditions, climate change may occur at a rate that exceeds the abilities of many species to evolve or migrate to more hospitable areas. Alteration of temperature and precipitation regimes could potentially have numerous impacts on biodiversity, including shifts in migration and breeding patterns; expansions or contractions of natural species ranges; ocean acidification, which could place major stress on shell-forming marine organisms; increases in disease transmission and pest infestations; and more extreme fluctuations in habitat conditions. The adaptive capacity of many species may be overwhelmed by these new pressures, especially when combined with habitat loss and fragmentation from land use changes and other stresses that will create barriers to movements. Several recent studies that have attempted to quantify the risks to global biodiversity from climate change indicate that a considerable fraction of animal and plant species may be “committed to extinction” within 50 or 100 years under business-as-usual emissions scenarios (Thomas et al. 2004; Pounds et al. 2006; McInnes et al. 2009; Pereira et al. 2010; Hoffmann et al. 2010).

GLOBAL DISTRIBUTIONS OF FOREST CARBON, BIODIVERSITY, AND THE OPPORTUNITY COSTS OF FOREST PROTECTIONS

We compiled a high-resolution global dataset containing measures of forest carbon density, mammal species

richness, endemic species richness, and the opportunity costs of forest protections by ecoregion. We used a 5-min resolution (about 9 km by 9 km grid cells) in constructing the global dataset. Excluding the oceans, ~1.8 million grid cells are required for a global dataset. Our measure of forest carbon density denotes the mass of above-ground carbon in the forest biomass (metric tons per hectare), as estimated by researchers at International Institute for Applied Systems Analysis (Kindermann et al. 2008a). To calculate our indicator of biodiversity benefits, we used global GIS maps of species ranges from the IUCN to determine the number of endemic mammal, bird, amphibian, and reptile species in each ecoregion. The IUCN habitat range data comprise nearly 95% of all known mammal species, so the coverage of those data is especially suitable for a global assessment such as this. Information on endemic species by ecoregion was obtained from Olson et al. (2001). We use the annual flow of potential agricultural revenues as an indicator of the opportunity cost of conservation, estimated using data from Naidoo and Iwamura (2007). While these data do not consider timber revenue, which in some areas may constitute an important driver of deforestation, agriculture generally is the leading alternative use of forest lands (e.g., Sohngen 2009). Global maps of these four variables are presented in Fig. 1a–d.

The maps in Fig. 1 suggest some key observations. First, the forest areas richest in above-ground biomass are located in South America (especially the Amazon region, Central Africa) and South East Asia (especially Indonesia, Malaysia, and Papua New Guinea). However, it is important to note that above-ground carbon comprises only a portion of the total forest carbon. A considerable portion of forest carbon is often found below ground in plant roots and soils, as commonly observed in some boreal and temperate regions and tropical mangrove forests (e.g., Keith et al. 2009; Donato et al. 2011). Nevertheless, above-ground carbon represents a considerable portion of forest carbon sequestered in tropical forests, which are the main targets of suggested REDD programs. We focus on deforestation alone because no consistent measures of forest degradation are available at the global scale. Therefore, even though we refer to “REDD programs” throughout, we have a quantitative measure of the first “D” but not the second.

The geographic distribution of mammal species richness (Fig. 1b) and, especially, endemic species richness (Fig. 1c), is markedly different from the amount of carbon per hectare. Forest carbon is relatively high in the Amazon region, Central Africa, and Indonesia, Malaysia, and Papua New Guinea, while species richness is highest in northeast Columbia, Ecuador, Eastern Africa, coastal regions in Southeast Asia, and in mountain ranges around Mongolia and Tibet. Endemic species show similar patterns but are

even more divergent from forest carbon, with several endemic species hotspots, such as the southern portion of the South American continent situated in areas relatively low in forest carbon. These geographic patterns suggest that targeting areas richest in forest carbon would guide conservation efforts away from the regions richest in species, especially endemic species.

To provide incentives sufficient to forego deforestation, REDD and other forest conservation programs must compensate landowners an amount at least as high as the value of the economic opportunities foregone due to conservation. Agricultural production is one of the prime drivers of deforestation in non-Annex I countries, so potential agricultural revenue is the best single indicator of the opportunity cost of forest conservation in these regions.¹ The map in Fig. 1d shows that several parts of the different areas especially rich in forest carbon—Amazonas, Central Africa, Indonesia, Malaysia, and Papua New Guinea—do not have particularly high potential agricultural revenue. This suggests that significant opportunities to avoid emissions from deforestation may fortuitously occur in areas that are currently relatively inexpensive to protect. However, the volume of avoided emissions from forest protections depends not only on the carbon content of the forests, but also on their risks of deforestation. Therefore, we next examine the geographic patterns of current rates of deforestation.

DEFORESTATION RATES AND ESTIMATED COST PER TON OF AVOIDED FOREST CARBON EMISSIONS

Figure 2 shows the geographic distribution of deforestation rates in non-Annex I regions where forest losses occurred during that time period. Deforestation rates in each ecoregion were estimated using data from the FAO FRA (2005) using information on the change in forested area by country between 1990 and 2005. The figure shows that the highest rates of deforestation occur in parts of Indonesia, Papua New Guinea, and several other parts of Southeast Asia. Several regions in South America—in particular the Amazonas, parts of Bolivia, and Nicaragua—have relatively high rates of deforestation, as does much of northern and southern Africa. Central Africa, which is particularly

¹ In theory, the minimum annual payment that a landowner would be willing to accept to forego agricultural production on their land (i.e., the rental rate of the land) would be equal to the net revenues, or profits, that they could earn by farming the land, and the cost to purchase the land outright (i.e., the market price of the land) would be the discounted present value of the full future stream of potential net agricultural revenues.

Fig. 1 Global maps of above-ground carbon, mammal species richness, endemic species richness, and potential agricultural revenue. **a** Tons of carbon ha⁻¹, on average per ecoregion. **b** Total number of mammal species per ecoregion. **c** Total number of endemic mammal, bird, amphibian, and reptile species per ecoregion. **d** Potential agricultural revenue, USD ha⁻¹, on average per ecoregion

Fig. 2 Deforestation rate in non-Annex region with forest loss in 1990–2005, by region (darker colors indicate greater deforestation rates)

rich in forest carbon, stands out with relatively low rates of deforestation.

Next, we use data on the estimated mass of forest carbon, opportunity costs of conservation, and deforestation rates to project the relative cost of avoided emissions by ecoregion, which we index by i . As explained above, we use potential agricultural revenue per hectare, ar_i (\$ ha⁻¹ year⁻¹), as an indicator of the opportunity cost of protecting forests. Avoided emissions are calculated as the product of forest carbon per hectare, fc_i (tons C ha⁻¹), and the annual rate of deforestation, df_i (year⁻¹). Next, we estimate the total annualized cost of protecting the remaining forests in ecoregion i as $ar_i \times F_i$ (\$ year⁻¹), where F_i (ha) denotes the total forest area of the ecoregion. Assuming that the rate of deforestation is uncorrelated with forest carbon content within each ecoregion, the projected total annual emissions from the ecoregion i are $F_i \times fc_i \times df_i$ (tons C year⁻¹). The estimated cost per ton of avoided carbon emissions is then simply $ar_i / (fc_i \times df_i)$ (\$ tons C⁻¹), which is mapped in Fig. 3.

We anticipate that the prime targets for REDD programs will be those regions with the lowest cost of avoided carbon emissions. In Fig. 3, these areas are shown in darker color, and their distribution evidently is highly correlated with the distribution of forest carbon (Fig. 1a), though perhaps somewhat more evenly distributed. Overall, the patterns in Fig. 3 indicate that the Amazonas, much of the broader Central African region, and parts of Southeast Asia will be the most attractive to REDD programs that would focus on generating net revenue from carbon credits, or,

more generally, programs that aim to reduce emissions from deforestation cost effectively.

CORRELATIONS BETWEEN LOW COST AVOIDED EMISSIONS AND BIODIVERSITY

Table 2 shows pair-wise correlations between some of the key variables that will influence the attractiveness of a region for REDD programs and biodiversity conservation. Specifically, we examine above-ground forest carbon content (tons C ha⁻¹), the emissions from deforestation in the region (i.e., the product of forest carbon content and the rate of deforestation) (tons C ha⁻¹ year⁻¹), and the opportunity cost per ton of avoided carbon emissions (\$ tons C⁻¹). We use the richness (total count) of all endemic, mammals, birds, and amphibian species as our measure of biodiversity.

The correlation coefficients in Table 2 confirm that carbon emissions tend to be high in areas relatively rich in above-ground biomass, which can be expected as the above-ground biomass is a key determinant of the potential emissions. However, the correlations between the opportunity cost per avoided emissions and both carbon content and projected emissions are practically zero, which suggests that the least expensive forest areas are not those richest in above-ground biomass. Under such conditions, a naïve targeting approach that prioritizes regions for REDD programs based solely on their above-ground carbon content or projected emissions would not maximize avoided

Fig. 3 Estimated cost per ton of avoided emissions from deforestation, by ecoregion (*darker colors indicate lower cost per ton*)

emissions for a given program budget. Rather, considering above-ground carbon in combination with the risk of deforestation and the cost of forest protections it is necessary for identifying regions where preservation maximizes avoided carbon emissions for a given budget (or minimizes the cost of achieving specific carbon targets).

Interestingly, both the above-ground carbon content and projected emissions per hectare are positively and statistically significantly correlated with all four indicators of biodiversity. Mammal and amphibian species richness are strongly positively correlated with carbon content and potential emissions. This indicates that species richness tends to be high in areas both rich in carbon and subject to high deforestation. However, there is practically no correlation between the opportunity cost per ton of emissions avoided—the main measure that we would expect to influence REDD investments—and the species richness measures. The estimated correlation coefficients between the cost per ton of emissions and all four measures of species richness are never statistically significantly different from zero.

In practical terms, the results in Table 2 suggest that targeting REDD programs solely based on the rate of forest carbon emissions, without any regard for the costs of conservation, may deliver relatively high biodiversity co-benefits. However, this approach is unlikely in practice and would be ill-advised as it would be very cost ineffective; the opportunity cost of land will likely be of central importance in REDD targeting. The data reviewed above suggest that if REDD programs are targeted to deliver carbon emission reductions at the least possible cost then these programs may not deliver particularly high

biodiversity co-benefits. That is, REDD programs that focus exclusively on carbon benefits may be no more effective at producing biodiversity benefits than a program that randomly selected forest parcels for protection. Insofar as more protected habitat is generally better for biodiversity, such a program would deliver some biodiversity benefits, but likely far short of what a systematic targeting scheme would deliver. In the next section, we examine in more detail the prioritization of areas at risk of deforestation in non-Annex I regions for both carbon and biodiversity benefits.

GEOGRAPHIC TARGETING OF CARBON AND SPECIES CONSERVATION PROGRAMS

As an illustration we examine two hypothetical conservation programs. The first program (carbon program) is intended to mimic a REDD-type policy focused on maximizing forest carbon emission reductions under a budget constraint. The second program (species program) is focused on biodiversity conservation and aims to maximize the number of endemic species protected under a budget constraint. The geographic scope of both programs comprises the entire non-Annex 1 region examined here. Our focus in assessing these programs is on examining their priority target areas and their potential geographical differences. The approach is similar to methods in the literature on evaluating global conservation priorities (e.g., Brooks et al. 2006).

Specifically, the carbon program selects ecoregions for protection in increasing order of the cost per ton of carbon

Table 2 Pair-wise correlations between above-ground forest carbon content (tons C ha⁻¹), projected emissions from deforestation (tons C ha⁻¹ year⁻¹), opportunity cost per ton of avoided carbonemissions (\$ tons C⁻¹), richness (total count) of all endemic, mammals, birds, and amphibian species, by ecoregion

	Carbon content	Projected emissions	Cost per tons C	All endemics	Mammals	Birds	Amphibians
Carbon content	1						
Projected emissions	0.5661**	1					
Cost per tons C	-0.0134	-0.0091	1				
All endemics	0.1005**	0.0759*	-0.0090	1			
Mammals	0.5919**	0.3021**	-0.0058	0.0007	1		
Birds	0.0821*	0.2110**	0.0027	0.0531	0.2339**	1	
Amphibians	0.6444**	0.2956**	-0.0099	0.0332	0.7630**	0.1162**	1

**, * Significance at 5 and 10% level, respectively

emissions avoided, calculated as described above and shown in Fig. 3. Similarly, the species program selects ecoregions for protection in increasing order of the cost per endemic species protected, $ar_i/df_i \times es_i$ (\$ species⁻¹), where es_i is the number of endemic species in region i , calculated using data from Olson et al. (2001).²

We examined how these two programs with alternative goals, a carbon program and a species program, would allocate a fixed conservation budget. For the available budget, we considered one-fifth of the estimated foregone agricultural net revenue from the total elimination of all deforestation in all non-Annex I countries. Specifying the program budget at one-fifth of the agricultural revenue loss associated with removing all deforestation is ad hoc, but is intended to illustrate the potential scope of the large scale international policy proposals in the context of REDD, such as the proposals presented (but ultimately rejected) in the US congress in 2008–2009. Conservation programs this large would likely induce non-negligible changes in land prices, but we ignore such effects here. These simplifying assumptions notwithstanding, this illustration still should serve to indicate the potential concordance between carbon-focused and species-focused forest protection programs. Figure 4 maps the ecoregions protected under each program.

The differences in the geographic distribution of conservation efforts between these hypothetical programs shown in Fig. 4 are distinct. While the carbon-focused program concentrates in the Amazonas, Central Africa,

Indonesia (mainly Borneo), and Papua New Guinea, the species-focused program distributes forest protection investments considerably more broadly, reaching out to a large number of ecoregions distributed across the world. These visible differences further strengthen the impression that an exclusively carbon-focused REDD program may deliver relatively modest biodiversity co-benefits.

The species program targets areas differently from the carbon program, and thereby delivers more biodiversity benefits. But as a consequence, the species program also would generate less avoided carbon emissions. In the above example, the reduction in the carbon emissions from the species program is about 44% of that from the carbon program. On the other hand, the species program protects nearly six times the number of endemic species as does the carbon program.

The programs considered above represent the polar cases of focusing solely on either carbon or species, but these results nevertheless raise the question of whether modest adjustments to exclusively carbon-focused REDD programs might deliver significant biodiversity benefits at an acceptable cost in terms of forgone carbon reductions. This question, and policy designs that might be used to modify REDD programs accordingly, should be high priorities for further research.

DISCUSSION

This assessment of the potential biodiversity benefits of REDD programs has been conducted with the aim of compiling the best available and high-resolution spatial data at the global scale of the central determinants of cost-effective forest carbon and biodiversity conservation programs. Using spatially explicit data on forest carbon, deforestation rates, biodiversity, and the opportunity cost of land, we were able to examine the geographic distributions of forest carbon, biodiversity, and opportunities for their cost-effective preservation.

² To illustrate the calculations, consider an ecoregion with 10,000 ha of forests and a deforestation rate of 0.6%/year. In this case, we expect 60 ha to be deforested in this ecoregion in the coming year. If the aboveground carbon content of these forests is 57 tons C/ha (the average in our data), 3,420 tons of carbon will be released into the atmosphere as a result of deforestation in this region. If the average annualized cost of forest protections in this ecoregion is \$11/ha (the average potential annual agricultural revenue in our data), the cost of avoiding these emission amounts to \$110,000. Therefore, the unit cost of avoiding these emissions is about \$32 per ton C, or \$8.8 per ton CO₂.

Fig. 4 Geographic targeting alternative forest conservation programs (ecoregions selected for conservation). **a** Program to generate REDD credits at the least cost per ton carbon. **b** Program to support species richness at the least cost per species

Incorporating forest conservation into international climate policy is considered essential, because deforestation is among the chief anthropogenic sources of carbon dioxide emissions. Although REDD programs are widely viewed as promising instruments to also help achieve global biodiversity conservation goals, it is unclear how effective REDD programs will be in producing biodiversity co-benefits. The geographic distributions of the least-cost forest carbon and species richness are not strongly correlated, so our findings suggest that while REDD programs undoubtedly will deliver some biodiversity benefits, they are unlikely to reach their full potential unless they are thoughtfully modified so that the areas at high risk of deforestation and also high in both carbon content and species richness receive highest priority.

Our findings stress the need to systematically consider co-benefits, such as biodiversity in the design and

implementation of forest conservation programs intended to support international climate policy. In the absence of systematic considerations for biodiversity, much of the potential for REDD programs to deliver substantial biodiversity co-benefits may remain unrealized.

REDD programs could be specifically targeted and designed using both carbon and biodiversity goals. With joint targeting, the same GHG emission reductions and biodiversity preservation objectives may be achieved at a lower total cost than by separate uncoordinated programs aimed at carbon and biodiversity. Alternatively, joint targeting may help achieve greater overall benefits at the same economic costs than uncoordinated targeting.

Global assessments are particularly useful for developing assessment preliminary view of the potential for REDD programs to promote biodiversity conservation, but such large scale assessments unavoidably miss potentially

Fig. 5 Deforestation is one specific area where climate change and biodiversity loss overlap. Photo by Stefan Nyholm (Stock.xchng)

important local variations. Moreover, the problems of biodiversity conservation and avoiding deforestation are highly complex, and an assessment such as ours necessarily has to overlook many important details. Therefore, the needs for further research are substantial. For example, in addition to global assessments, regional, country-level, and even more local evaluations clearly are needed so that a more complete appraisal of opportunities to preserve both forest carbon and biodiversity can be formulated. More local assessments may also enable examinations of biodiversity conservation potential using less aggregate measures of biodiversity than those used here, such as specific species groups or individual species of special concern. Incorporating direct assessments of the effects of deforestation on biodiversity, such as the estimated impacts of habitat loss due to deforestation on local species richness, also could help examine the potential of combining carbon and biodiversity goals in forest conservation (Fig. 5).

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