LETTER

Biodiversity co-benefits of reducing emissions from deforestation under alternative reference levels and levels of finance

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Keywords
Biodiversity conservation; climate change; extinction; mechanism design; reduced emissions from deforestation and forest degradation (REDD+); reference levels; UNFCCC negotiations.

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Abstract

The extent to which an international mechanism to reduce emissions from deforestation and degradation (REDD+) can also provide biodiversity co-benefits will depend on whether the mechanism results in the retention of forest in countries harboring substantial biodiversity. Countries' decisions whether or not to participate in REDD+ will be influenced by their national reference level of emissions from deforestation, below which their verified emissions can be credited as reductions. In this article, we explore the reduction in extinctions of forest species achieved under four alternative national reference level designs and three alternative levels of finance for REDD+. We use an 85-country partial equilibrium model and species-area relationships to estimate extinction rates for 2,472 nationally endemic forest-dependent amphibian, bird and mammal species if a REDD+ mechanism had been in place during 2005–2010. Our results indicate that elements of REDD+ that are most effective for climate change mitigation—greater finance combined with reference levels which reduce leakage by promoting broad participation across countries with both high and low historical deforestation rates—also offer the greatest benefits for biodiversity conservation.

Introduction

International climate negotiations are expected to produce a mechanism for the reduction of emissions from deforestation and forest degradation, plus the conservation, carbon stock enhancement and sustainable management of forests ("REDD+"; UNFCCC 2009a), to address the roughly one-sixth of greenhouse gas emissions caused by deforestation (IPCC 2007; van der Werf *et al.* 2009). The United Nations Framework Convention on Climate Change (UNFCCC) REDD+ mechanism is being designed primarily to deliver climate change mitigation benefits. However, there is increasing interest by parties to the convention (Parker *et al.* 2009), observers (ATBC/GTO 2009), scientists (Campbell 2009; Harvey *et al.* 2010), and other international conventions in the extent to which REDD+ could generate ancillary social[1] and ecological benefits (so-called "co-benefits").

Forests are a global storehouse of biodiversity, with tropical forests alone harboring at least two-thirds of all known terrestrial species (Raven 1988). By contrast, the agricultural and pastoral land uses to which forests are converted are comparatively poor in biodiversity (Sala *et al.* 2000). Habitat loss remains the greatest threat to terrestrial biodiversity (Sala *et al.* 2000), with deforestation leading to extinctions at the time of occurrence and into the future (Tilman *et al.* 2002). A successful REDD+ mechanism offers great potential to retain standing forests and the species that they harbor. But the

[1] Poverty alleviation and sustainable development co-benefits of REDD+ are beyond the scope of this analysis. For an introduction to this topic, see Peskett et al. (2008).

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extent to which REDD+ can be expected to conserve biodiversity will depend on whether the countries incentivized to retain forest habitat because of a REDD+ mechanism are those countries that harbor substantial biodiversity.

Forest countries' decisions whether or not to participate in REDD+ will be influenced by their national reference level—the level of emissions from deforestation below which a country's verified emissions could be credited as reductions. Since a country's carbon revenue is proportional to the difference between its emissions and its reference level, reference levels (RLs) differ in the compensation countries would receive for reducing emissions, and thus in the economic incentives countries would have to decrease—or increase—their rate of deforestation. Deforestation could decrease in countries where high reference levels enable the distribution of sufficient carbon payments to outcompete alternative land uses such as agriculture and timber. On the other hand, deforestation could increase in countries where low reference levels do not provide sufficient economic incentives to outcompete agriculture and timber revenues, which can be expected to increase as deforestation is reduced elsewhere. Parties to the UNFCCC have agreed that reference levels are to be "based on historical data, adjusted for national circumstances," (UNFCCC, 2009b) though this remains to be quantified explicitly.

Research to date on reference level design has compared alternative designs' effectiveness in reducing greenhouse gas emissions (Busch *et al.* 2009), cost-efficiency at producing emission reductions (Griscom *et al.* 2009; Busch *et al.* 2009); perceived applicability (Huettner 2009), distribution of revenue across country types (Angelsen *et al.* 2009; Griscom *et al.* 2009; Cattaneo *et al.* 2010) and equity (Cattaneo *et al.* 2010). Meanwhile, research on the biodiversity co-benefits of REDD+ has focused on the spatial congruence of biodiversity and carbon (Kapos *et al.* 2008; Strassburg *et al.* 2010), biodiversity and carbon income potential (Ebeling & Yasue 2008), the biodiversity implications of alternative rules and policies for reducing emissions from deforestation and sequestering carbon in forests (Caparros & Jacquemont, 2003; Nelson *et al.* 2008; Venter *et al.* 2009; Harvey *et al.* 2010), and management options to produce ecological and biodiversity co-benefits (Stickler *et al.* 2009). This article extends these previous works by estimating biodiversity co-benefits under a simulated REDD+ mechanism that accounts for leakage of deforestation emissions, and incentives for national participation based on national reference levels.

In this article, we compare the extent and distribution of biodiversity co-benefits under a REDD+ mechanism with alternative REDD+ reference levels and levels of finance. We use an 85-country partial equilibrium model (Busch *et al.* 2010) to model national deforestation rates had a REDD+ mechanism been in place from 2005 to 2010, taking into account countries' decisions of whether or not to participate in REDD+, and leakage of deforestation pressure from deforestation-reducing countries. We use species-area relationships to estimate the impact of national deforestation rates on national and aggregate species extinction rates across 2,472 forest species.

Methods

We extended the Open Source Impacts of REDD+ Incentives Spreadsheet model ("OSIRIS"; Busch *et al.* 2010) to simulate national participation, deforestation, and species extinction rates under REDD+ across 85 tropical or developing countries thought to be potentially eligible for REDD+. Though we refer to REDD+ throughout this article, we only examined mechanism incentives related to deforestation and forest carbon stock conservation. We did not examine incentives related to forest degradation, sustainable management of forests or carbon stock enhancement. We examined four proposed REDD+ reference level designs (Santilli *et al.* 2005; Mollicone *et al.* 2007; Cattaneo *et al.* 2008; Strassburg *et al.* 2009) that could be considered consistent with the UNFCCC agreement that national reference levels for REDD+ should be "based on historical data, adjusted for national circumstances" (Table 1). We examined three levels of annual finance for REDD+, consistent with either fund or market financing for REDD+. Under "full" financing for REDD+, all national emission reductions that were available at a carbon price of \$5/tCO_2e were purchased. The resulting total level of annual finance, \$28–31 billion, is comparable to other studies estimating the level of finance required to meet a target of reducing deforestation by 50% to range from \$15–33 billion annually (see Angelsen *et al.* 2009).[2] Under "partial" and "minimal" finance scenarios, all national emission reductions that were available at a carbon price of \$3/tCO_2e or \$1.50/tCO_2e were purchased, resulting in total levels of annual finance of \$14–15 billion or \$5–6 billion annually, respectively.

OSIRIS is a single-period partial equilibrium model for a single commodity—the composite output of agriculture, including a one-time timber harvest, produced on

[2] The model used in this study produces estimates near the low end of this range of estimates, with \$14–15 billion annually reducing deforestation by 50–54%, and \$28–31 billion annually reducing deforestation by 68–72%, depending on the reference level design. See the next paragraph and footnote 3 for more detail on the cost data and approach used in the model.

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Table 1 Description of REDD+ reference level designs and impacts of reference level designs under "full finance" for REDD+ on national participation, reduction in emissions from deforestation relative to business-as-usual, and cost per emission reduction. Adapted from Busch *et al.* (2009).*

Reference level design	Reference	Description and OSIRIS parameter assumptions	Number of countries reducing or maintaining GHG emissions ($n = 85$; "participation)	Change in total emissions from deforestation %/yr; "effectiveness")	Cost per ton of total emissions reductions (2008 US\$/tons CO_2/yr) ("efficiency")
"Without REDD"	FAO (2010)	Forest cover change, 2005–2010; Counterfactual business-as-usual scenario	–	–	–
"National historical"	Santilli *et al*. (2005)	Reference deforestation rates are historical average national rates for all countries	60	−73%	$7.73
"Higher than historical for countries with low deforestation rates"	Santilli *et al.* (2005); Mollicone *et al*. (2007)	Reference deforestation rates have a floor of 0.10% for low-deforestation countries; Reference deforestation rates are historical national rates for high-deforestation countries	76	−76%	$7.54
"Weighted average of national and global rates"	Strassburg *et al*. (2009)	Weighted reference deforestation rates of 0.20 ∗ historical global average rate+ 0.80 ∗ historical national rate for all countries	76	−76%	$7.28
"Flow withholding and stock payment"	Cattaneo *et al*. (2008)	Reference rates are historical national rates for all countries; 15% of flow payments are withheld to fund stock payments	79	−76%	$6.93

*The following parameter values were used in OSIRIS v3.3: carbon price = \$5/ton CO_2; permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD+ = 0.10; coefficient on slope of supply curve extensions = 0.10; Social preference for agricultural surplus parameter = 1.00; fraction of national average timber rent included = 1.00; management and transaction cost = 2001 US\$3.50/ha/yr; national start-up cost = \$0; institutional hurdles = none; reference period = 1990–2005; crediting period = 2005–2010.

one hectare of land cleared from the tropical forest frontier. Countries participated voluntarily in REDD+, choosing to "opt in" only if the national economic surplus from forest carbon exceeded the foregone national economic surplus from agriculture and one-time timber harvest. Otherwise countries chose to "opt out." Countries with higher national reference levels had a greater financial incentive to opt in to REDD+. After opting in to or out of REDD+, countries chose a rate of deforestation to maximize their aggregate national economic surplus from forests and agriculture.[3] Leakage of deforestation occurs endogenously in the model, as a reduction of deforestation in one country led to a higher price for frontier agriculture and increased pressure to deforest in other countries. The model was parameterized using spatially explicit global data on potential agricultural revenue

[3] While this opportunity cost framework offers a starting point for comparing impacts across reference level designs and countries, it oversimplifies reality in two respects. First, countries' decisions to participate in REDD are likely to be more complex than a simple comparison of earnings from agriculture and earnings from REDD. Poverty alleviation, traditional values, political economy, ecological services and biodiversity are likely to factor into countries' land use decisions. Second, some promising methods for reducing emissions from deforestation do not involve directly outcompeting opportunity cost at a site—notably, removal of perverse agricultural subsidies, moratoria on road construction, increased capacity to enforce forestry laws, and improved fire management (Busch *et al.* 2009).

(Fischer *et al.* 2000; Naidoo & Iwamura 2007; Strassburg *et al.* 2009), national average forest biomass (Ruesch & Gibbs 2008) and soil carbon (GSDTG 2000) within forests (Schmitt 2008), national-level tabular data on returns to one-time timber harvest (Sohngen & Tennity 2004), forest cover and forest cover change (FAO 2010),[4] and a global average management and transaction cost (James 2001). Reference levels were based on average deforestation rates during a 1990–2005 reference period and applied to a 2005–2010 implementation and crediting period. This analysis used many of the same set of illustrative parameter values as Busch *et al.* (2009). Internal parameters for reference level designs were set to maximize climate-effectiveness and cost-efficiency under default parameter values.[5]

Species-area relationships[6] were applied to national deforestation rates to estimate the extinction rate of nationally endemic forest-dependent amphibian (Schipper *et al.* 2008), bird (Birdlife International, 2010) and mammal (Stuart *et al.* 2004) species (hereafter referred to as "forest species")–the only three taxa for which national-level distribution data are comprehensive.[7] We restricted our analysis to nationally endemic forest-dependent species to provide a lower-bound estimate of extinctions due to forest loss within a country, since these are the only species that are certain to be directly threatened by forest loss within a country. Our analysis thus omitted species extinctions due to deforestation occurring in more than one country, or due to other processes such as climate change. In the absence of spatially explicit data, we assumed that the distributions within countries of forest loss and endemic species were neither positively nor negatively correlated. Extinction rates were bounded to account for uncertainty in the extent to which a country's current number of species has equilibrated to extinction debt resulting from past forest loss. The maximum extinction rate was consistent with the assumption that a country's current number of species had already fully equilibrated to the extinction debt from past forest loss, so that every forest species was subject to becoming an additional extinction due to future forest loss. The minimum extinction rate was consistent with the assumption that a country's currently observed number of species had not yet equilibrated to any of the extinction debt from past forest loss, so that only a smaller subset of forest species are subject to becoming an additional extinction due to future forest loss (see Appendix A for derivation).

The OSIRIS model was constructed to compare impacts across REDD+ policy options and across countries under a common set of data and assumptions, rather than to predict the magnitude of impacts of an international REDD+ mechanism with certainty. This lack of certainty arises because no prior implementation of a global REDD+ mechanism exists against which to calibrate parameters or validate model performance, global data were aggregated from sources of varying quality, and parameters to which the model is sensitive such as elasticity of demand for frontier agriculture have uncertain values. For this reason we tested the robustness of our findings to alternative parameter assumptions regarding leakage, preference for agricultural income relative to carbon income, national readiness, reference period and commitment period, species-area parameter z, and taxa included in the measure of endemism.

Results

A REDD+ mechanism substantially reduced the aggregate deforestation rate across all 85 countries relative to business-as-usual under all 12 scenarios—three levels of finance and four reference level designs. "Full" finance for REDD+ ($28–31 billion per year with no limit to the reductions in emissions purchased at $5/ton) reduced aggregate deforestation rate by 68–72% depending on reference level design, while "partial" finance ($14–15 billion per year with no limit to the reductions in emissions

[4] For an in depth critique of using FAO Forest Resource Assessment rates for REDD reference levels, see Olander *et al*. (2008).
[5] Default parameter conditions used in OSIRIS v3.3 (data, model and country-by-county outputs may be downloaded at http://www.conservation.org/osiris) were as follows, unless otherwise indicated: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US$3.50 ha−1 yr−1; fraction of national average timber rent included = 1.00; reference period = 1990–2000. Furthermore, the following design-specific parameters are assumed: reference level floor for countries with low deforestation rates = 0.001; weight on national historic rates = 0.80; flow withholding = 0.15.
[6] Species-area relationships are well-documented functions relating the number of species an area contains to its size. Species-area relationships have been applied to biodiversity patterns over a range of spatial scales (Rosenzweig 1995; Turner and Tjørve 2005), including to predict species loss due to forest loss at the national level (e.g. Cowlishaw 1999; Venter *et al.* 2009).
[7] Distributional datasets for reptiles and freshwater fish are not yet considered comprehensive (IUCN 2009).

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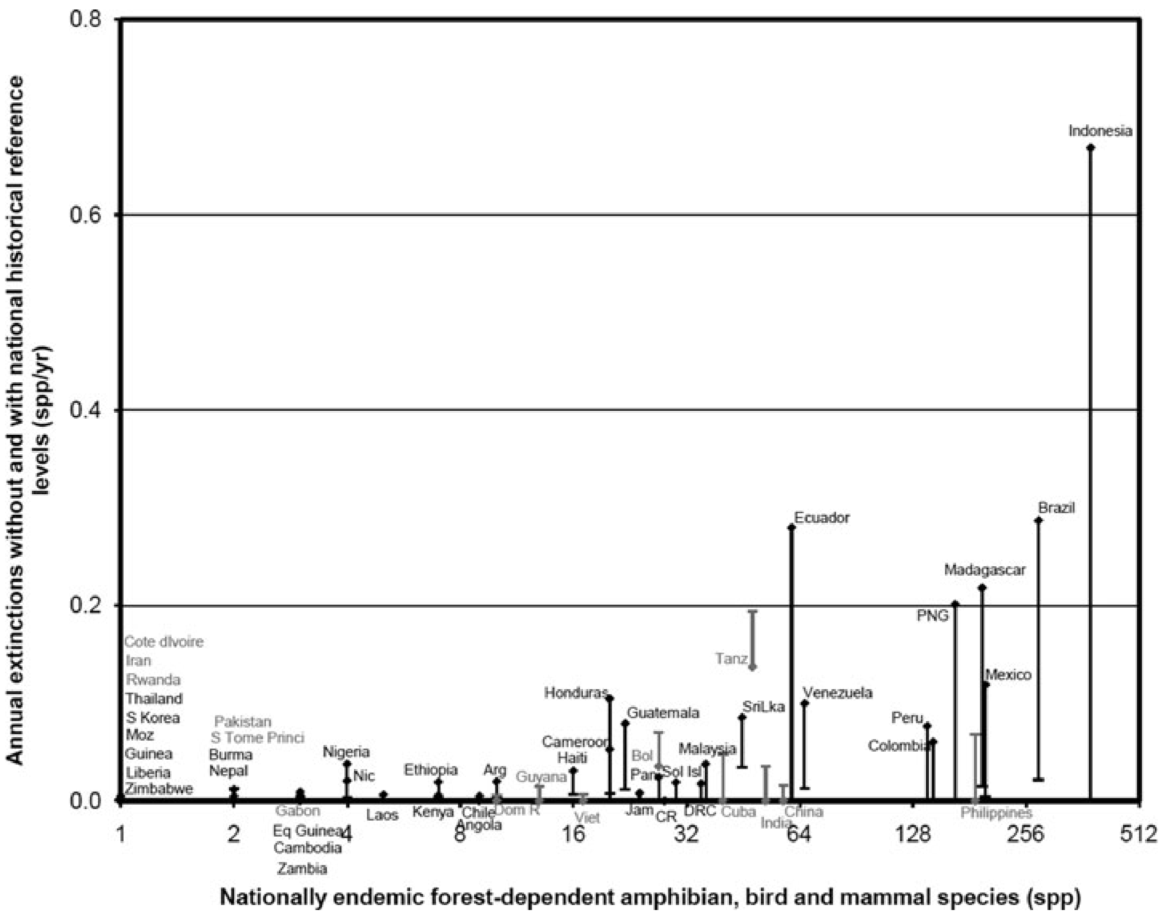

Figure 1 Country-by-country extinction rates without and with a fully financed REDD+ mechanism with national historical reference levels. Points represent countries' extinction rate without REDD+. Bars represent countries' maximum extinction rate with REDD+, consistent with an assumption that countries' current number of species have already fully equilibrated to past forest loss, so that every forest species is subject to becoming an additional extinction due to future forest loss. Countries with decreased extinction rates due to REDD+ are marked with black bars and labels; countries with increased extinction rates due to REDD+ are marked with gray bars and labels.

purchased at \$3/ton) and "minimal" finance (\$5–6 billion per year with no limit to the reductions in emissions purchased at \$1.50/ton) for REDD+ reduced aggregate deforestation rate by 50–54% and 27–29%, respectively. Reduction in deforestation exhibits diminishing returns to level of finance since increases to the carbon price are applied to all emission reductions and not only to the marginal emission reduction.

Reductions in deforestation occurred in most of the 85 countries under full finance (n = 60–79 depending on reference level design; Table 1). Among high-endemism countries (≥20 nationally endemic forest-dependent amphibian, bird and mammal species; n = 25),[8] which collectively harbor 94% of such species (Figure 1–2), participation in REDD+ was particularly high (n = 19–23 depending on reference level design). High-endemism countries participated in REDD+ more than other countries, due to high-endemism countries' generally higher carbon densities and lower potential agricultural revenues, leading in almost all cases to greater reductions in deforestation across high-endemism countries than across forest countries generally (Tables 2–5).

As a result, the extinction rate of the 2472 forest species was reduced by 78–82% below business as usual under

[8] Indonesia, Brazil, Mexico, Madagascar, Philippines, Papua New Guinea, Colombia, Peru, Venezuela, Ecuador, China, India, Tanzania, Sri Lanka, Cuba, Malaysia, Democratic Republic of the Congo, Solomon Islands, Costa Rica, Panama, Bolivia, Jamaica, Guatemala, Cameroon, Honduras.

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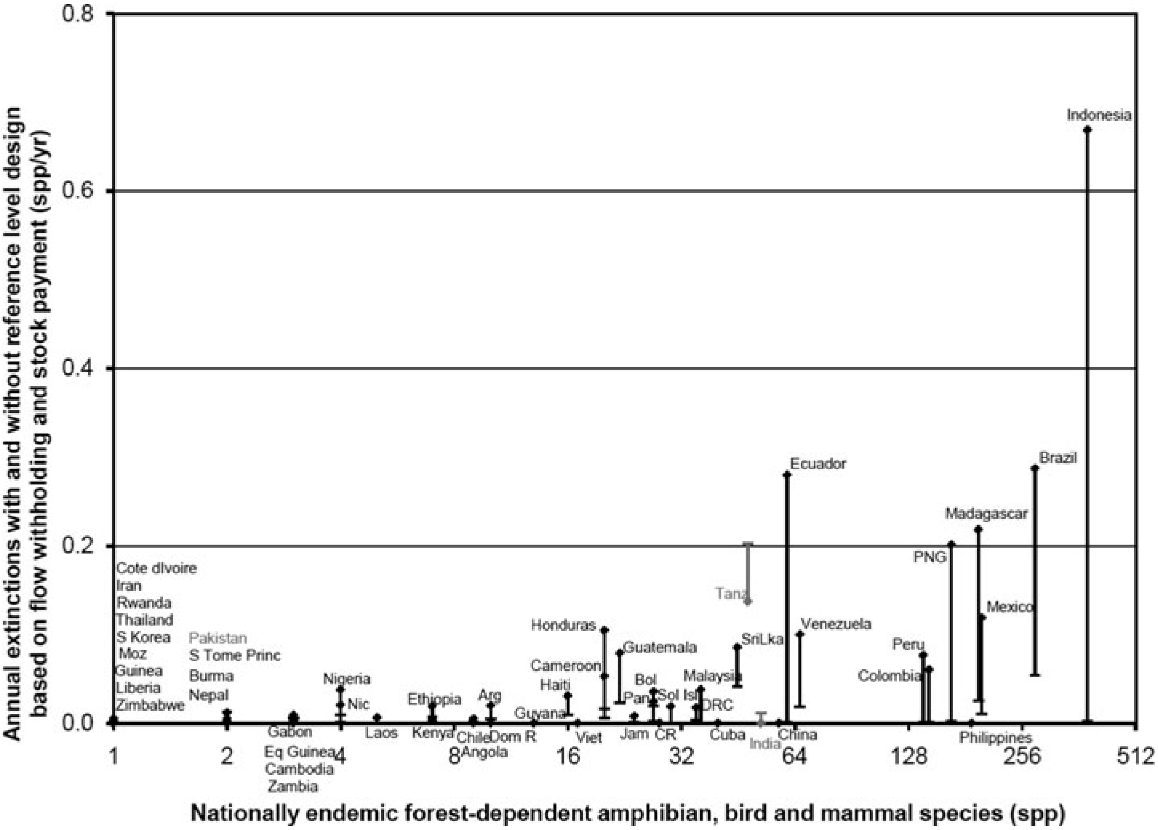

Figure 2 Country-by-country extinction rates without and with a fully financed REDD+ mechanism with "flow withholding and stock payment" reference levels). Dots represent countries' extinction rate without REDD+. Points represent countries' maximum extinction rate with REDD+, consistent with an assumption that countries' current number of species have already fully equilibrated to past forest loss, so that every forest species is subject to becoming an additional extinction due to future forest loss. Countries with decreased extinction rates due to REDD+ are marked with black bars and labels; countries with increased extinction rates due to REDD+ are marked with gray bars and labels.

full finance—from 2.37–2.79 species per year in the absence of a REDD+ mechanism to 0.42–0.62 species per year with REDD+ (Table 6). Partial and minimal finance reduced the extinction rate by 71–74% and 43–49%, respectively. Reductions in national extinction rates exceeded the corresponding reductions in the national deforestation rates due to the nature of the species-area relationship. As forest habitat is diminished, each unit of habitat loss poses successively greater threat of extinctions. So conversely, the first units of forest habitat loss avoided in each country provide the greatest value in preventing extinctions, with diminishing returns thereafter.

Though most countries in our analysis decreased their rates of deforestation and species extinction in response to incentives created by a fully financed REDD+ mechanism, some countries increased deforestation in response to increased agricultural and timber prices caused by reductions in deforestation elsewhere (n = 6–25 depending on reference level design; Table 1). This "international leakage" resulted in an increase in the extinction rate of forest species in these countries. REDD+ reference level designs varied in the extent to which they prevented leakage-induced extinctions. Under a fully financed REDD+ mechanism with historical reference levels, increases in deforestation occurred in 25 out of 85 countries (Tables 2–5), containing 19% of all endemic forest-dependent amphibian, bird and mammal species, reducing the global extinction rate of endemic forest-dependent species across all countries to 0.51–0.62 species per year (Table 6). In contrast, under full financing reference levels designed to control leakage broadened participation to include low-deforestation countries and reduced extinctions (Figure 3). For example, the fully-financed "flow withholding and stock payment" design, which spurred the broadest participation in REDD+,

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Table 2. Sensitivity to parameter values of estimated change due to REDD+ in deforestation rate, deforestation rate among high-endemism countries (≥20 nationally endemic forest-dependent amphibian, bird and mammal species), and extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species relative to business-as-usual, with national historical reference levels.

	National historical reference levels								
	$1.50			$3.00			$5.00		
	CD[a]	CDHE[b]	CE[c]	CD	CDHE	CE	CD	CDHE	CE
Price elasticity of demand for frontier agriculture									
0	0%	−9%	−25–27%	0%	−12%	−39–42%	0%	−9%	−50–51%
1	−19%	−29%	−41–43%	−36%	−44%	−61–62%	−51%	−57%	−72–73%
2[d]	−28%	−35%	−46–48%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
3	−33%	−42%	−51–53%	−57%	−60%	−74–75%	−75%	−77%	−82–83%
inf.	−41%	−48%	−60–61%	−71%	−71%	−82–83%	−91%	−90%	−92–93%
Preference for agricultural income relative to carbon income									
1[d]	−28%	−35%	−46–48%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
2	−19%	−29%	−37–39%	−34%	−48%	−68–69%	−50%	−63%	−77–78%
3	−7%	−11%	−31–32%	−24%	−39%	−43–45%	−36%	−58%	−71–72%
Readiness score (RFF 2009) as hurdle to national participation?									
no[d]	−28%	−35%	−46–48%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
Yes	−18%	−30%	−38–39%	−32%	−45%	−58–60%	−42%	−57%	−67–70%
Reference Period/Commitment Period									
1990–2005/2005–2010 (FAO 2010)[d]	−28%	−35%	−46–48%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
1990–2000/2000–2005 (FAO 2010)	−22%	−23%	−42–44%	−52%	−60%	−67–68%	−70%	−75%	−76–77%
1990–2000/2000–2005 (FAO 2005)	−25%	−30%	−66–66%	−54%	−66%	−82–82%	−68%	−81%	−89–90%
Species-area parameter *z*									
0.15	−28%	−35%	−46–47%	−52%	−56%	−71–71%	−68%	−66%	−78–78%
0.25[d]	−28%	−35%	−46–48%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
0.35	−28%	−35%	−46–49%	−52%	−56%	−71–72%	−68%	−66%	−78–79%
0.58	−28%	−35%	−46–50%	−52%	−56%	−71–73%	−68%	−66%	−78–79%
Taxa included in endemism measure									
−28%	−35%	−46–48%	−52%	−55%	−71–72%	−68%	−65%	−78–79%	
Amphibians	−28%	−41%	−42–44%	−52%	−57%	−67–68%	−68%	−66%	−75–75%
Birds	−28%	−44%	−57–59%	−52%	−63%	−77–78%	−68%	−73%	−81–83%
Mammals	−28%	−39%	−42–44%	−52%	−62%	−70–71%	−68%	−74%	−78–79%

[a]CD denotes change due to REDD+ in deforestation across 85 tropical forest countries relative to business-as-usual.

[b]CDHE denotes change due to REDD+ in deforestation across 25 high-endemism countries relative to business-as-usual.

[c]CE denotes change due to REDD+ in extinction rate of forest species across 85 tropical forest countries relative to business-as-usual.

[d]Default parameter value. Unless otherwise indicated, the following parameter values were used in OSIRIS v3.3: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US$3.50 ha^{-1} yr^{-1}; fraction of national average timber rent included = 1.00; reference period = 1990–2000. Furthermore, the following design-specific parameters are assumed: reference level floor for countries with low deforestation rates = 0.001; weight on national historic rates = 0.80; flow withholding = 0.15.

resulted in the least international leakage. Under this design deforestation increased in only six of 85 countries, containing just 4% of endemic forest species, reducing global extinction rate of endemic forest-dependent species across all countries to 0.42–0.50 species per year (Table 6). Thirteen of the countries that did not participate in REDD+ with national historical reference levels but did participate with flow withholding and stock payments harbored at least one endemic forest species.[9] The benefit of reference levels designed to control leakage was greater under greater levels of finance, which produced

[9] These countries were the Philippines, China, Cuba, Bolivia, Vietnam, Guyana, the Dominican Republic, Chile, Gabon, Sao Tome and Principe, Iran, Rwanda and Cote d'Ivoire.

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Table 3 Sensitivity to parameter values of estimated change due to REDD+ in deforestation rate, deforestation rate among high-endemism countries (≥20 nationally endemic forest-dependent amphibian, bird and mammal species), and extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species relative to business-as-usual, with reference level floors for low-deforestation countries.

	Reference level floor for low-deforestation countries								
	$1.50			$3.00			$5.00		
	CD[a]	CDHE[b]	CE[c]	CD	CDHE	CE	CD	CDHE	CE
Price elasticity of demand for frontier agriculture									
0	0%	−6%	−25–27%	0%	−12%	−40–43%	−1%	−14%	−55–55%
1	−20%	−28%	−42–44%	−38%	−43%	−63–64%	−51%	−53%	−74–74%
2[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
3	−34%	−42%	−51–53%	−59%	−61%	−75–76%	−80%	−80%	−87–87%
inf.	−41%	−48%	−60–61%	−71%	−71%	−82–83%	−91%	−90%	−92–93%
Preference for agricultural income relative to carbon income									
1[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
2	−19%	−29%	−38–39%	−36%	−49%	−69–69%	−51%	−63%	−79–79%
3	−7%	−11%	−31–32%	−25%	−38%	−44–45%	−37%	−58%	−69–70%
Readiness score (RFF, 2009) as hurdle to national participation?									
no[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
yes	−18%	−30%	−38–40%	−33%	−45%	−58–60%	−43%	−57%	−68–70%
Reference Period / Commitment Period									
1990–2005 / 2005–2010 (FAO 2010)[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
1990–2000 / 2000–2005 (FAO 2010)	−22%	−22%	−42–44%	−53%	−59%	−67–68%	−72%	−78%	−80–81%
1990–2000/2000–2005 (FAO 2005)	−26%	−29%	−65–65%	−55%	−65%	−81–82%	−71%	−83%	−90–90%
Species-area parameter *z*									
0.15	−29%	−35%	−47–48%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
0.25[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−66%	−81–81%
0.35	−29%	−35%	−47–49%	−54%	−57%	−72–74%	−72%	−66%	−81–81%
0.58	−29%	−35%	−47–51%	−54%	−57%	−72–74%	−72%	−66%	−81–81%
Taxa included in endemism measure									
All included[d]	−29%	−35%	−47–49%	−54%	−57%	−72–73%	−72%	−67%	−81–81%
Amphibians	−29%	−41%	−42–44%	−54%	−56%	−68–70%	−72%	−64%	−76–76%
Birds	−29%	−43%	−58–60%	−54%	−64%	−80–81%	−72%	−77%	−87–87%
Mammals	−29%	−38%	−42–45%	−54%	−63%	−71–72%	−72%	−77%	−81–81%

[a]CD denotes change due to REDD+ in deforestation across 85 tropical forest countries relative to business-as-usual.
[b]CDHE denotes change due to REDD+ in deforestation across 25 high-endemism countries relative to business-as-usual.
[c]CE denotes change due to REDD+ in extinction rate of forest species across 85 tropical forest countries relative to business-as-usual.
[d]Default parameter value. Unless otherwise indicated, the following parameter values were used in OSIRIS v3.3: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US\$3.50 ha^{-1} yr^{-1}; fraction of national average timber rent included = 1.00; reference period = 1990–2000. Furthermore, the following design-specific parameters are assumed: reference level floor for countries with low deforestation rates = 0.001; weight on national historic rates = 0.80; flow withholding = 0.15.

greater aggregate reduction in deforestation. Under minimal finance incentives for reducing deforestation were more important than incentives for controlling leakage (Figure 3).

The finding that participation in REDD+ and reductions in deforestation were greater among high-endemism countries than among other forest countries was robust to variations in parameter assumptions (Tables 2–5). The finding that reference levels designed to control leakage incentivized greater reductions in extinctions was greatest at lower price elasticity of demand for frontier agriculture (greater leakage), was reversed under minimal finance, but was robust to other variations in parameter assumptions.

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Table 4 Sensitivity to parameter values of estimated change due to REDD+ in deforestation rate, deforestation rate among high-endemism countries (≥20 nationally endemic forest-dependent amphibian, bird and mammal species), and extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species relative to business-as-usual, with reference levels based on a weight average of global and national rates.

	Weighted average of national and global rates								
	$1.50			$3.00			$5.00		
	CD[a]	CDHE[b]	CE[c]	CD	CDHE	CE	CD	CDHE	CE
Price elasticity of demand for frontier agriculture									
0	0%	−12%	−26–27%	0%	−19%	−45–48%	−1%	−20%	−62–63%
1	−21%	−31%	−38–40%	−38%	−50%	−68–69%	−50%	−62%	−77–78%
2[d]	−29%	−39%	−45–47%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
3	−32%	−42%	−50–52%	−57%	−62%	−75–76%	−81%	−79%	−86–86%
inf.	−40%	−49%	−61–62%	−70%	−71%	−82–83%	−91%	−90%	−92–93%
Preference for agricultural income relative to carbon income									
1[d]	−29%	−39%	−45–47%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
2	−18%	−30%	−37–38%	−38%	−58%	−62–64%	−54%	−71%	−79–80%
3	−7%	−11%	−31–32%	−20%	−33%	−43–45%	−41%	−64%	−65–67%
Readiness score (RFF, 2009) as hurdle to national participation?									
no[d]	−29%	−39%	−45–47%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
Yes	−18%	−30%	−38–39%	−32%	−44%	−50–53%	−43%	−58%	−68–70%
Reference Period / Commitment Period									
1990–2005/2005–2010 (FAO 2010)[d]	−29%	−39%	−45–47%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
1990–2000/2000–2005 (FAO 2010)	−21%	−23%	−39–41%	−51%	−63%	−65–67%	−73%	−78%	−74–75%
1990–2000/2000–2005 (FAO 2005)	−22%	−30%	−63–63%	−53%	−69%	−81–82%	−72%	−83%	−87–88%
Species-area parameter z									
0.15	−29%	−39%	−45–46%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
0.25[d]	−29%	−39%	−45–47%	−50%	−59%	−73–74%	−72%	−66%	−81–81%
0.35	−29%	−39%	−45–48%	−50%	−59%	−73–74%	−72%	−66%	−81–82%
0.58	−29%	−39%	−45–50%	−50%	−59%	−73–75%	−72%	−66%	−81–82%
Taxa included in endemism measure									
All included[d]	−29%	−39%	−45–47%	−50%	−60%	−73–74%	−72%	−67%	−81–81%
Amphibians	−29%	−42%	−38–41%	−50%	−59%	−70–71%	−72%	−64%	−77–77%
Birds	−29%	−45%	−59–60%	−50%	−67%	−82–82%	−72%	−77%	−87–88%
Mammals	−29%	−45%	−41–44%	−50%	−65%	−69–70%	−72%	−77%	−81–82%

[a]CD denotes change due to REDD+ in deforestation across 85 tropical forest countries relative to business-as-usual.
[b]CDHE denotes change due to REDD+ in deforestation across 25 high-endemism countries relative to business-as-usual.
[c]CE denotes change due to REDD+ in extinction rate of forest species across 85 tropical forest countries relative to business-as-usual.
[d]Default parameter value. Unless otherwise indicated, the following parameter values were used in OSIRIS v3.3: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US\$3.50 ha^{-1} yr^{-1}; fraction of national average timber rent included = 1.00; reference period = 1990–2000. Furthermore, the following design-specific parameters are assumed: reference level floor for countries with low deforestation rates = 0.001; weight on national historic rates = 0.80; flow withholding = 0.15.

Discussion

The reduction in deforestation incentivized by a REDD+ mechanism has the potential to greatly reduce the extinction rate of forest species. Greater levels of REDD+ finance would lead to greater reductions in deforestation, greater climate change mitigation and greater provision of biodiversity co-benefits. The level of finance generated by even a partially-financed REDD+ mechanism ($15–16 billion annually with no limit to the reductions in emissions purchased at $5/ton; Table 6) would dwarf current conservation spending on nature reserves worldwide (around $6 billion annually; James *et al.* 1999) or spending by international conservation organizations ($1.5

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Table 5 Sensitivity to parameter values of estimated change due to REDD+ in deforestation rate, deforestation rate among high-endemism countries (≥20 nationally endemic forest-dependent amphibian, bird and mammal species), and extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species relative to business-as-usual, with flow withholding and stock payment.

	Flow withholding and stock payment								
	$1.50			$3.00			$5.00		
	CD[a]	CDHE[b]	CE[c]	CD	CDHE	CE	CD	CDHE	CE
Price elasticity of demand for frontier agriculture									
0	0%	−4%	−22–23%	0%	−7%	−44–45%	−1%	−15%	−60–60%
1	−20%	−21%	−38–40%	−43%	−50%	−64–66%	−56%	−57%	−76–76%
2[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
3	−33%	−39%	−48–49%	−57%	−61%	−74–75%	−76%	−77%	−85–85%
inf.	−42%	−48%	−56–58%	−66%	−68%	−79–79%	−86%	−85%	−90–90%
Preference for agricultural income relative to carbon income									
1[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
2	−25%	−34%	−42–44%	−44%	−53%	−61–63%	−55%	−70%	−82–82%
3	−7%	−9%	−24–25%	−28%	−45%	−46–48%	−46%	−71%	−77–78%
Readiness score (RFF, 2009) as hurdle to national participation?									
no[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
yes	−20%	−29%	−41–42%	−33%	−42%	−51–53%	−45%	−61%	−77–78%
Reference Period / Commitment Period									
1990–2005/2005–2010 (FAO 2010)[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
1990–2000/2000–2005 (FAO 2010)	−26%	−29%	−37–38%	−53%	−56%	−66–67%	−72%	−73%	−79–79%
1990–2000/2000–2005 (FAO 2005)	−29%	−35%	−62–62%	−56%	−65%	−81–81%	−73%	−78%	−89–89%
Species-area parameter *z*									
0.15	−27%	−30%	−43–44%	−54%	−58%	−71–71%	−72%	−73%	−82–82%
0.25[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
0.35	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
0.58	−27%	−30%	−43–46%	−54%	−58%	−71–73%	−72%	−73%	−82–83%
Taxa included in endemism measure									
All included[d]	−27%	−30%	−43–45%	−54%	−58%	−71–72%	−72%	−73%	−82–82%
Amphibians	−27%	−32%	−37–38%	−54%	−59%	−68–69%	−72%	−73%	−81–82%
Birds	−27%	−32%	−55–56%	−54%	−60%	−78–79%	−72%	−74%	−87–87%
Mammals	−27%	−31%	−41–43%	−54%	−58%	−68–69%	−72%	−73%	−79–80%

[a]CD denotes change due to REDD+ in deforestation across 85 tropical forest countries relative to business-as-usual.
[b]CDHE denotes change due to REDD+ in deforestation across 25 high-endemism countries relative to business-as-usual.
[c]CE denotes change due to REDD+ in extinction rate of forest species across 85 tropical forest countries relative to business-as-usual.
[d]Default parameter value. Unless otherwise indicated, the following parameter values were used in OSIRIS v3.3: Permanence reduction scale = 1.00 (no withholding to ensure permanence); exponential demand for frontier agriculture with price elasticity = 2.00 (2% decrease in supply leads to 1% increase in price); fraction of soil carbon credited under REDD = 0.10; social preference for agricultural revenue relative to carbon revenue = 1.00; management and transaction cost = 2001 US$3.50 ha^{-1} yr^{-1}; fraction of national average timber rent included = 1.00; reference period = 1990–2000. Furthermore, the following design-specific parameters are assumed: reference level floor for countries with low deforestation rates = 0.001; weight on national historic rates = 0.80; flow withholding = 0.15.

billion annually; Halpern *et al.* 2006). This level of finance has the potential to dramatically reduce species extinction rates.

Encouragingly, high-endemism countries had greater-than-average participation in REDD+ and thus experienced greater-than-average reductions in deforestation rates. But for countries with low historical rates of deforestation, including some high-endemism countries, forest loss due to leakage was only reduced by REDD+ reference level designs that incentivize their participation. As finance for REDD+ increases, reference level designs that incentivize participation by a broader suite of countries can not only increase mitigation effectiveness and potentially increase mitigation cost-efficiency (Busch *et al.* 2009; Cattaneo *et al.* 2010) but can also result in fewer extinctions of forest species.

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Table 6 Impacts of REDD+ reference level designs and levels of finance on deforestation, emissions from deforestation and extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species.

	Reference level design	Total amount spent on REDD+ (2008 US$billion)	85-country deforestation rate (%/yr)	Change in emissions from deforestation relative to business-as-usual (%)	Extinction rate of nationally endemic forest-dependent amphibian, bird and mammal species (spp/yr; n = 2472 spp)
Business-as-usual (no REDD+ mechanism)	None	–	0.42%	–	2.37–2.79
Minimal finance for REDD+ mechanism (no limit to reductions purchased at $1.50/ton CO_2e)	"National historical"	$5.5	0.30%	−32%	1.23–1.50
	"Reference level floor for countries with low deforestation rates"	$5.7	0.30%	−33%	1.22–1.49
	"Weighted average of national and global rates"	$5.4	0.30%	−34%	1.25–1.55
	"Flow withholding and stock payment"	$4.8	0.30%	−30%	1.31–1.58
Partial finance for REDD+ mechanism (no limit to reductions purchased at $3/ton CO_2e)	"National historical"	$15.1	0.20%	−56%	0.67–0.82
	"Reference level floor for countries with low deforestation rates"	$15.2	0.19%	−58%	0.63–0.77
	"Weighted average of national and global rates"	$14.4	0.21%	−55%	0.62–0.76
	"Flow withholding and stock payment"	$14.1	0.19%	−58%	0.67–0.82
Full finance for REDD+ mechanism (no limit to reductions purchased at $5/ton CO_2e)	"National historical"	$30.4	0.13%	−73%	0.51–0.62
	"Reference level floor for countries with low deforestation rates"	$30.8	0.12%	−76%	0.45–0.54
	"Weighted average of national and global rates"	$29.9	0.12%	−76%	0.44–0.53
	"Flow withholding and stock payment"	$28.3	0.12%	−76%	0.42–0.50

[*] See Table 1 for parameter values.

The importance of forests for biodiversity conservation may vary greatly within a country. While changes in deforestation rates were modeled at the national level to capture the country participation decision created by national reference levels, within-country heterogeneity in forest loss and endemism, and decisions made within a country about which forests to conserve, will affect the co-benefit potential of REDD+. Furthermore, while our analysis was neutral as to the policy or management strategies used to prevent forest cover loss, different strategies could have differing implications for other activities such as over-hunting that impact biodiversity.

In addition to reduced deforestation and forest conservation, a REDD+ mechanism is likely to also incentivize reduced degradation, carbon stock enhancement, and sustainable management of forests (UNFCCC 2009a). Incentivizing these other activities could shift the suite of countries participating in REDD+, and could have more ambiguous impacts on biodiversity. For example, biodiversity concerns with a REDD+ mechanism have centered on possible afforestation and carbon stock enhancement provisions. Unless safeguards in the current UNFCCC draft text (UNFCCC, 2009a) are retained, loopholes in the definition of a forest could result in the conversion of degraded but biodiverse natural forests (Sasaki & Putz 2009) or biologically significant nonforest habitats (Putz & Redford 2009) to timber or biofuel plantations with limited value for biodiversity. Future research can attempt to quantify the impacts of these other provisions

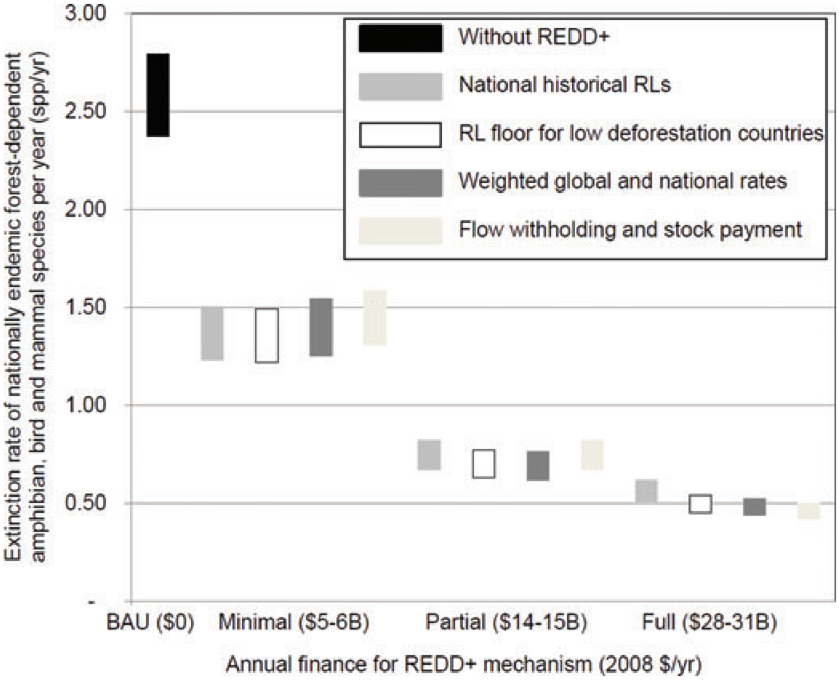

Figure 3 Annual extinctions of 2,472 nationally endemic forest-dependent amphibian, bird and mammal species across 85 tropical forest countries under alternative RLs and levels of finance for REDD+, 2005–2010. Business-as-usual extinction rates are based on reported national deforestation rates from 2005 to 2010 (FAO 2010). Extinction rates with REDD+ are based on modeled deforestation rates if REDD+ incentives had been in place from 2005 to 2010. The upper bound of the range of extinction rates assumes that countries' current number of species have already fully equilibrated to past forest loss, so that every forest species is subject to becoming an additional extinction due to future forest loss. The lower bound of the range of extinctions assumes that countries' current number of species has not equilibrated to any past forest loss, so that only a smaller subset of forest species are subject to becoming an additional extinction due to future forest loss.

of a REDD+ mechanism, as well as the indirect land-use impacts of REDD+ on biodiversity in nonforest biomes such as grasslands and wetlands.

There is naturally interest in further increasing the scale of biodiversity co-benefits produced by REDD+. To what extent should an international REDD+ mechanism be designed to promote co-benefits (Harvey *et al.* 2010)? It may be tempting to seek modifications to the UNFCCC text to explicitly direct REDD+ activities toward high-biodiversity forests. However, adding such a requirement to an already-complicated UNFCCC discussion on REDD+ risks delaying or undermining reaching a landmark agreement on REDD+. Furthermore, excessive proscription of biodiversity co-benefits risks making REDD+ participation so burdensome as to become a barrier to entry. Fortunately, our results suggest that the biodiversity co-benefits resulting from REDD+ provisions for reducing deforestation and for conservation could be substantial even in the absence of provisions to explicitly direct REDD+ activities toward high-biodiversity forests.

It remains uncertain that a REDD+ mechanism will emerge and achieve its potential to mitigate climate change and produce biodiversity co-benefits. Our results suggest that parties, observers and conventions that support biodiversity conservation should work to ensure that a REDD+ mechanism emerges that is both fully financed and designed to incentivize broad participation. Full finance in the case of a REDD+ fund mechanism can be promoted through greater annual fund size. Full finance in the case of a REDD+ market mechanism can be promoted through more ambitious developed-country emission reduction targets combined with greater flexibility to achieve these targets through REDD+. Broad participation can be promoted through reference level designs that incentivize both reducing high rates of deforestation emissions and maintaining low rates of deforestation emissions.

A REDD+ mechanism can be complemented with other measures to conserve biodiversity. Future research can quantify the extent to which extinctions can be further reduced through the development of supplemental finance mechanisms to subsidize REDD+ activities in high-biodiversity forests. These supplemental finance mechanisms could include biodiversity matching funds, REDD+ standards and labeling approaches, and bundled ecosystem service payments. It should also be recognized that REDD+ will not be a viable or available strategy for supporting forest biodiversity conservation in all countries. In some forest countries, deforestation can be expected to increase as prices rise for frontier agricultural commodities. In these countries especially, traditional strategies such as protected areas will remain critical for the conservation of biodiversity.

Conclusion

The REDD+ mechanism emerging from international negotiations is being designed with the primary goal of

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mitigating climate change. Thus it is encouraging for biodiversity conservation that elements of REDD+ which are best for effective mitigation—greater financing combined with reference levels which promote broad participation—also offer the greatest benefits to biodiversity. Our results suggest that parties, observers and conventions supportive of biodiversity conservation as well as climate change mitigation should work to ensure that such a fully financed, broadly participatory REDD+ mechanism is ultimately adopted.

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Appendix A: Derivation of extinction rate of forest species

Extinction rates of forest species were estimated from national deforestation rates using species-area relationships. Extinction rates were bounded to account for uncertainty in the extent to which a country's current number of species has equilibrated to extinction debt from past forest loss. The maximum extinction rate, $E_i^{\max}$, was consistent with the assumption that a country's current number of species had already fully equilibrated to the

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extinction debt from past forest loss. In this case every forest species was subject to becoming an additional extinction due to future forest loss. The minimum extinction rate, $E_i^{\min}$, was consistent with the assumption that a country's currently observed number of species had not yet equilibrated to any extinction debt from past forest loss. In this case some portion of forest species were already committed to deforestation, so only a smaller subset of forest species were subject to becoming an additional extinction due to future forest loss. Maximum and minimum extinction rates were derived as follows:

Maximum extinction rate

The maximum extinction rate was consistent with the assumption that the current number of species in every country has already fully equilibrated to the extinction debt from past forest loss. By the species area relationship, $S_0 = cF_0^z$, where S_o represents a country's current number of forest species, F_0 represents a country's current forest cover, c is a constant, and z, the slope parameter from the power form of the species-area relationship, $S = cA^z$, is specified to equal 0.25, a lower-bound value for species-area relationships for island archipelagoes or other habitat patches surrounded by unsuitable habitat (Rosenzweig 1995).[10] Similarly,

$$S_i = cF_i^z = c[F_0(1-d_i)]^z = cF_0^z(1-d_i)^z = S_0(1-d_i)^z, \quad (1)$$

where S_i represents the number of species after one year of REDD+ with reference level design i, F_i represents a country's current forest cover after one year of REDD+ with reference level design i, and d_i represents the deforestation rate (%/year) simulated under reference level design i. So, the maximum area-related species loss (species/year) under reference level design i is

$$E_i^{\max} = S_0 - S_i = S_0 - S_0(1-d_i)^z = S_0[1-(1-d_i)^z]. \quad (2)$$

Minimum extinction rate

The minimum extinction rate was consistent with the assumption that the current number of species in every country had not yet equilibrated to any of the extinction debt from past forest loss. That is, a country's current number of species was S_0, but its current number of species which were not already subject to pending extinction debt from past forest loss is only $S_d < S_0$. By the species area relationship, $S_0 = cF_{\max}^z$, and $S_d = cF_0^z = c(F * F_{\max})^z = S_0F^z$, where F_{max} represents a country's original forest area. F represents a country's current forest area as a proportion of its original forest area, $F = F_0/F_{\max}$. Current forest area was obtained from FAO (2010); original forest area was estimated from the World Wildlife Fund's map of terrestrial ecoregions (Olson & Dinerstein 2001).[11] Similarly,

$$S_i = cF_i^z = c[F_0(1-d_i)]^z = cF_0^z(1-d_i)^z = S_d(1-d_i)^z. \quad (3)$$

So, the minimum area-related species loss under reference level design i (species/year) is:

$$E_i^{\min} = S_d - S_i = S_d - S_d(1-d_i)^z = S_d[1-(1-d_i)^z] = S_0F^z[1-(1-d_i)^z]. \quad (4)$$

[10] Rosenzweig (1995) finds that z is generally between 0.25 and 0.35 in such cases, but can be as high as 0.58, and can be as low as 0.15 within mainland provinces. We find in a sensitivity analysis that estimated reduction in extinction rate due to REDD+ is not sensitive to alternative values of z (Table 2).

[11] For limitations of using ecoregion maps to derive original forest cover, see Schmitt *et al.* (2009).

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