Modeling trade-offs across carbon sequestration, biodiversity conservation, and equity in the distribution of global REDD+ funds

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The program on Reducing Emissions from Deforestation and Forest Degradation (REDD+) is one of the major attempts to tackle climate change mitigation in developing countries. REDD+ seeks to provide result-based incentives to promote emission reductions and increase carbon sinks in forest land while promoting other cobenefits, such as the conservation of biodiversity. We model different scenarios of international REDD+ funds distribution toward potential recipient countries using 2 carbon emission reduction targets (20% and 50% compared to the baseline scenario, i.e., deforestation and forest degradation without REDD+) by 2030. The model combines the prioritization of environmental outcomes in terms of carbon sequestration and biodiversity conservation and social equity, accounting for the equitable distribution of international REDD+ funds. Results highlight the synergy between carbon sequestration and biodiversity conservation under alternative fund allocation criteria, especially for scenarios of low carbon emission reduction. Trade-offs increase when distributional equity is considered as an additional criterion, especially under higher equity requirements. The analysis helps to better understand the inherent trade-offs between enhancing distributional equity and meeting environmental targets under alternative REDD+ fund allocation options.

climate change | REDD+ | trade-offs | biodiversity | equity

Planning toward meeting environmental goals requires the integration of ecological and social aspects. However, social aspects related to conservation decisions have been particularly elusive (1–3). Among these aspects, social equity, one of the pillars of the Sustainable Development Goals (SDGs), stands as a key political criterion. However, efforts to effectively integrate equity considerations into environmental goals have been limited (4, 5). Only recently integrated modeling approaches have been able to show how addressing equity might affect biodiversity conservation goals (6) and climate mitigation targets (7). These are 2 of the most pressing global policy issues of our time (8) and can have feedback effects on economic inequality (9).

Deforestation and forest degradation currently account for up to 10% of the global greenhouse gas emissions (10). Avoiding deforestation and forest degradation is generally seen as a relatively low-cost abatement option (11) as well as critical element to reduce biodiversity loss (12). The international program about Reducing Emissions from Deforestation and Forest Degradation (REDD+) was created by the United Nations Framework Convention on Climate Change (UNFCCC) in 2007 at the 13th Conference of the Parties. The program has continuously evolved in order to promote environmental cobenefits, and it introduces social safeguards, reflected in the "plus," including the role of conservation and sustainable management of forests, and enhancement of forest carbon stocks.

All this has resulted in a complex financial landscape (13). Several initiatives focus on the readiness process to scale up REDD+, and so far, REDD+ has mainly focused on a so-called "phase I," consisting in developing a global strategy, supported by financial grants, that include creating guidelines, capacity development at country level, and strengthening forest-monitoring approaches (14). Currently, several developing countries have finished phase I and are starting phase II, which consists in the implementation of national policies or action plans. Only a few countries are in the position of receiving "phase III" results-based payments (RBPs) through bilateral and multilateral processes. The Green Climate Fund (GCF) has already raised over 10 billion US$ from 43 state governments (a call of 500 million US$ was recently opened in 2018), and, according to the 2015 Paris Agreement, the GCF "expects" to mobilize 100 billion US$ per year by 2020 (15).

Although the main focus of REDD+ is on carbon, there is increased interest in its associated cobenefits and trade-offs (16–20). Previous work on global REDD+ fund allocation estimated that including biodiversity as a criterion for the RBP allocation would significantly protect species richness without compromising "carbon efficiency" (21). However, the REDD+ program has also raised various concerns, especially regarding social aspects such as how REDD+ might affect social equity in its various dimensions (22–26). This question is particularly important because potential REDD+ country beneficiaries with a high proportion of their

Significance

Deforestation is a key driver of climate change. The program on Reducing Emissions from Deforestation and Forest Degradation (REDD+) is one of the major attempts to tackle climate change mitigation in developing countries. The program intends to provide result-based incentives to countries that reduce deforestation. We model various future scenarios of the distribution of REDD+ funds and assess how each scenario would contribute to reducing carbon emissions and to conserving biodiversity under different distributional equity rules. Results help to understand how the inclusion of distributional equity affects biodiversity and climate objectives under REDD+, and they provide insights about potential synergies and trade-offs between environmental and equity targets in broader policy arenas such as those related to the Sustainable Development Goals.

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rural population in poverty are also highly vulnerable to the impacts of climate change (27).

Social equity is a key political component in climate negotiations and climate governance planning. However, the incorporation of distributional equity in REDD+ fund allocation analysis to evaluate trade-offs and synergies with carbon efficiency at the global scale is lacking. This is also a knowledge gap regarding biodiversity conservation studies, as there are relatively few quantitative assessments on how the incorporation of social equity as an allocative criterion of global biodiversity conservation funds might affect global conservation outcomes (6). From the 3 main dimensions of social equity (recognition, procedural and distributional equity) (26), we focus here on distributional equity impacts of REDD+ allocation rules, to evaluate its potential trade-offs with carbon sequestration and biodiversity conservation (28).

Implementing environmentally effective, economically efficient and socially equitable (3E+) REDD+ faces multiple challenges (29). Here, we present a global model based on the reference point method (30) that allows the evaluation of different international REDD+ funds allocation scenarios considering carbon emission reduction from avoiding deforestation (scenario 1), biodiversity conservation (scenario 2), and the implementation of distributional equity rules (scenario 3). The model is run for the 3 scenarios with total budgets associated with carbon emission reduction of 20% and 50% compared to the baseline scenario, i.e., deforestation and forest degradation without REDD+. The model is based on multiobjective linear programming formulations developed at country level (*Materials and Methods* and *SI Appendix*). We evaluate how the incorporation of biodiversity conservation and distributional equity targets creates synergies and trade-offs that can impact on carbon emission reduction outcomes. We explored 2 alternative equity rules: a "max–min" rule that prioritizes the allocation of REDD+ funds to the poorest countries (scenario 3A), given the higher vulnerability of poor countries to the impacts of climate change (31, 32); and an "egalitarian" distributional equity rule based on distributing international REDD+ funds equally among all potential recipient countries (scenario 3B).

Results

Synergies between Forest-Based Carbon Emission Reduction and Biodiversity Conservation. The results of scenario 1, maximization of carbon sequestration (for a given REDD+ budget, obtaining the highest possible carbon sequestration globally), and scenario 2, maximization of biodiversity conservation (for a given REDD+ budget, achieving the highest possible number of species conserved globally), are shown in Fig. 1. Scenario 1 (blue line) and scenario 2 (red line) show a strong correlation, suggesting potential for synergetic outcomes in different international REDD+ fund allocation scenarios. The proximity among the curves suggests that the extra financial cost of optimizing biodiversity conservation is moderate. For small reductions in carbon emissions (i.e., carbon emissions reduced by less than 20%), biodiversity cobenefits can be achieved at relatively low economic costs. For a reduction of global forest carbon emissions larger than 20%, carbon and biodiversity are still correlated but the costs of obtaining biodiversity cobenefits are higher.

The estimated REDD+ budget required for a global reduction in carbon emissions of 20% and 50% with respect to a business as usual scenario (i.e., no REDD+), and the number of endemic species that would be lost in each of the REDD+ fund allocation scenarios is shown in Table 1. The model suggests that for a global reduction of carbon emissions of 20%, maximizing biodiversity conservation (i.e., conserving the highest possible number of species globally) would cost 86% more than if REDD+ only focused on abating forest carbon emissions, that is, without taking biodiversity conservation into account as a side objective. Optimizing the allocation of funds to also maximize biodiversity cobenefits while reducing by 20% emissions from deforestation and forest degradation would allow saving of 20% more birds, 17% more amphibians, and 29% more mammals compared to a "carbon-only" REDD scenario 1. For a 50% carbon emission reduction target, the cost of maximizing biodiversity conservation is more than 2 times the cost of not considering biodiversity as a side objective, but the number of species that would be saved would increase significantly (Table 1).

Trade-Offs across Carbon Emission Reduction, Biodiversity Conservation, and Social Equity. The effects of including equity considerations in the distribution of REDD+ funds are shown in Fig. 2 for the 2 fixed budgets that correspond to carbon emissions reduction of 20% and 50% as regards scenario 1. The baseline (black curve) indicates the relation between biodiversity conservation and carbon emission reduction without any consideration for distributional equity. Any point within the curve corresponds to an optimized solution for carbon and biodiversity. Considering equity to a small extent, that is, distributing a small share of the total budget across countries based on an equity rule ($E = 0.25$; implying 25% of the budget being distributed according to fulfilling an equity rule; green curve), would not lead to a major loss in carbon emission reduction or biodiversity conservation, as the green curve is relatively close to the black curve and has a similar shape. However, when the majority of funds are distributed following an equity rule instead of environmental criteria (i.e., $E = 0.75$; yellow curve), this would imply a higher trade-off

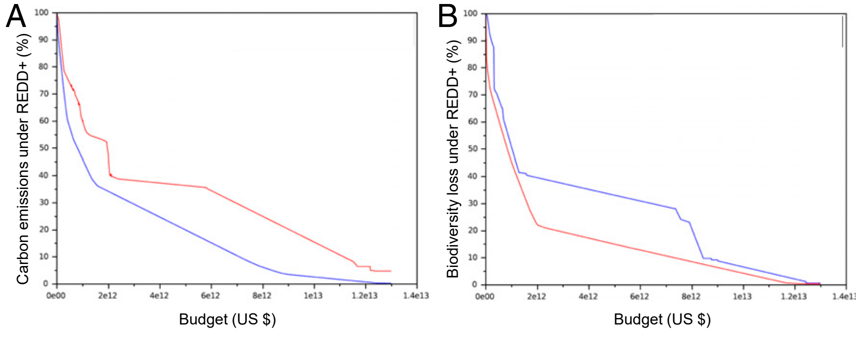

Fig. 1. Response of carbon emissions and biodiversity loss to different REDD+ budget levels. (*A*) Percentage of carbon emissions under REDD+ relative to the baseline (i.e., no REDD+) (*y* axis) for different global REDD+ budget levels (*x* axis). The red line stands above the blue line as for the same REDD+ budget the maximization of biodiversity conservation results in higher carbon emissions globally. (*B*) Percentage of biodiversity loss under REDD+ (*y* axis) relative to the baseline for different REDD+ budget levels (*x* axis). In both panels, the blue line represents optimized levels for carbon sequestration (scenario 1) and the red line represents optimized levels for biodiversity conservation (scenario 2).

Table 1. Model results in terms of carbon emissions and biodiversity loss per year across REDD+ budget optimization scenarios

REDD+	Scenarios	No. of bird species lost per year, % birds lost relative to the baseline	No. of amphibian species lost per year, % amphibians lost relative to the baseline	No. of mammal species lost per year, % mammals lost relative to the baseline	Billion tons of forest carbon emissions per year, % of total emission relative to the baseline	Total funds required, billion US$
Yes	Scenario 1 for a 20% carbon emissions reduction	7 (93.75)	17 (76.39)	7 (90.44)	2.17 (80.15)	220
Yes	Scenario 2 for a 20% carbon emissions reduction	5 (72.48)	12 (59.18)	5 (61.61)	2.16 (80.14)	410
Yes	Scenario 1 for a 50% carbon emissions reduction	5 (67.56)	9 (48.49)	4 (47.59)	1.36 (50.10)	970
Yes	Scenario 2 for a 50% carbon emissions reduction	3 (42.17)	4 (21.05)	2 (27.62)	1.38 (50.86)	2,000
No	Baseline (BAU)	8 (100)	22 (100)	8 (100)	2.71 (100)	0

Scenario 1 (maximization of carbon sequestration) and scenario 2 (maximization of biodiversity conservation) for global REDD+ budgets associated with 20% and 50% carbon emissions reductions. Biodiversity impacts are measured in terms of the number of lost species of birds, amphibians, and mammals. The bottom row represents the baseline scenario, in which the REDD+ program is not implemented. BAU, business as usual.

between carbon and biodiversity objectives, as reducing forest carbon emissions would imply larger biodiversity losses due to the steep concave shape of the curve. Both for a large budget (Fig. 2*A*) and low budget (Fig. 2*B*), maximizing equity ($E = 1$) results in significantly higher carbon emissions and biodiversity loss.

The relative loss of carbon efficiency and of biodiversity conservation when incorporating different levels of equity in the distribution of REDD+ funds among countries are shown in Fig. 3. In both cases (for a reduction target of 20% and 50% in forest carbon emissions), relatively small increases in distributional equity ($E = 0.25$) are associated with a relatively small increase in carbon emissions and biodiversity loss. In contrast, when funds are allocated considering solely equity criteria, large losses in carbon efficiency and species conservation emerge. For a REDD+ budget equivalent to 20% carbon emissions reduction, considering equity at the level $E = 1$ would lead to a scenario in which carbon emissions would only be reduced by 5% (instead of 20% if no equity rule was considered), and the percentage of species lost compared to a scenario without REDD+ would increase from 72 to 87%. For the larger REDD+ budget associated with a 50% forest carbon emission reduction, total prioritization of equity ($E = 1$) would imply that carbon emissions be reduced by 16% (instead of 50%), and the percentage of species lost compared to the baseline scenario would be 75% (instead of 53%).

Scenarios of Global REDD+ Funds Allocation across Countries for Carbon, Biodiversity, and Equity. The optimized distribution of international REDD+ funds given a low and high budget levels for the 3 scenarios: scenario 1 (maximization of carbon emission reduction), scenario 2 (maximization of biodiversity conservation), scenario 3A (application of a "max–min distribution rule" with countries receiving a share of total REDD+ funds based on their relative income poverty levels, with a fixed equity level at $E = 0.25$), and scenario 3B (the "egalitarian distribution rule" with a share of the

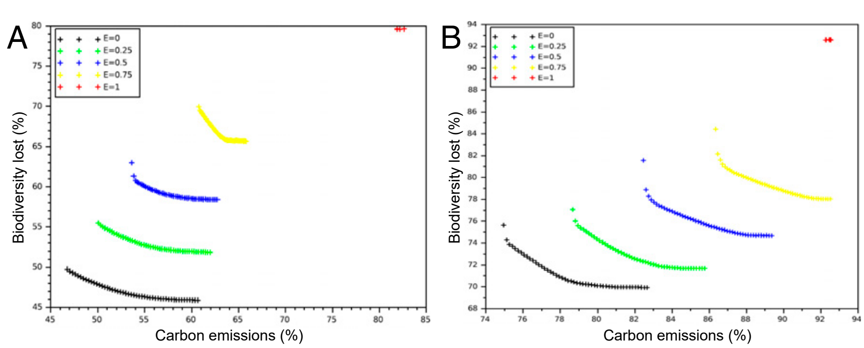

Fig. 2. Trade-offs between the reduction of carbon emissions and the conservation of biodiversity for different levels of equity in the global distribution of REDD+ funds. Equity not included ($E = 0$). Equity included via a percentage of the total funds allocated according to various equity levels: $E = 0.25$ (25% of funds distributed according to the max–min equity rule), $E = 0.50$ (50% of funds distributed according to the max–min equity rule), $E = 0.75$ (75%), and $E = 1$ (100%). (*A*) Fixed budget corresponding to a 50% carbon emission reduction compared to the baseline (i.e., no REDD+ program implemented); and (*B*) fixed budget corresponding to a 20% carbon emission reduction compared to the baseline. The figure shows how for increasing levels of equity in the distribution of REDD+ funds (from nonconsideration of equity $E = 0$, to having all funds distributed under an equity rule, $E = 1$), the trade-offs between reducing carbon emissions and biodiversity conservation tend to increase.

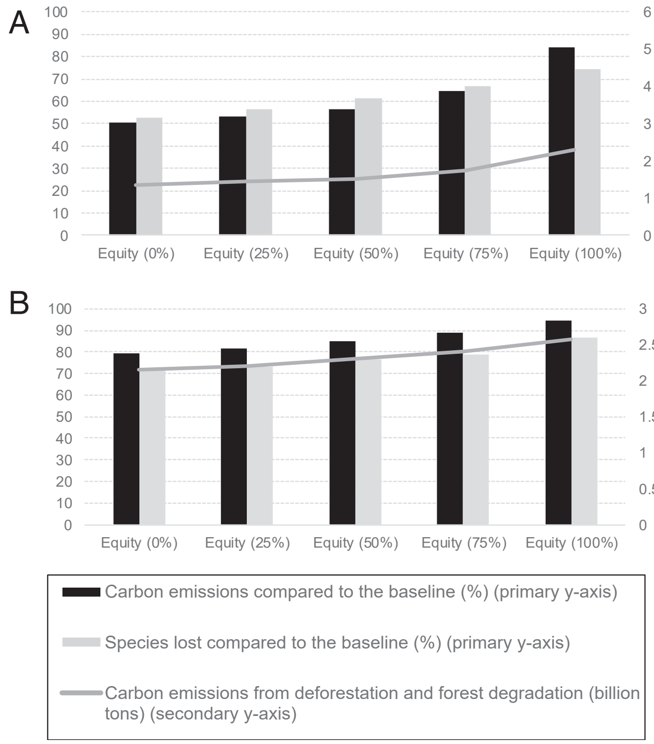

Fig. 3. Effects of considering different equity levels in the allocation of international REDD+ funds on forest carbon emissions and biodiversity loss per year compared to the baseline (i.e., no REDD+ program implemented). (*A*) Fixed budget corresponding to a 50% carbon emissions reduction compared to the baseline; and (*B*) fixed budget corresponding to a 20% carbon emissions reduction compared to the baseline.

total budget distributed equally among all potential receiving countries, with $E = 0.25$) is shown in Fig. 4. In the case of the lower REDD+ budget under scenario 1, the model selects first those countries with the highest ratio of deforestation and carbon density to forest conservation opportunity costs, resulting in the selection of several African countries such as Tanzania, Mozambique, Guinea, Namibia, Zimbabwe, as well as Argentina in South America (Fig. 4*A*). For the same emissions reduction target, under scenario 2, the model selects a few more countries, including Honduras, Madagascar, Seychelles, Colombia, and Mauritius, which are considered biodiversity hot spots (Fig. 4*B*). In the case of using the larger budget, the model covers up to 13 countries, both under scenario 1 (Fig. 4*C*) and scenario 2 (Fig. 4*D*). The main difference between both scenarios is that, when biodiversity is maximized (Fig. 4*D*), the model selects more countries from South and Latin America such as Colombia, Mexico, Ecuador, and Panama, which contain very high biodiversity levels. The incorporation of an equity criterion implies a larger number of recipient countries, 50 under the max–min approach (Fig. 4*E*) and 51 under the egalitarian approach (Fig. 4*F*). The main difference between these 2 allocative models is that, under the egalitarian distributive approach, the funds are more evenly distributed across countries, while under the max–min approach, poorer countries, such as Bangladesh, India, Madagascar, Nigeria, and Seychelles, receive a relatively larger share of the total REDD+ budget.

Discussion

The interactions between the SDGs, especially among climate action (SDG 13) and others such as life on land (SDG 15), and reducing social inequalities (SDG 10), is an issue of increasing debate (33), but quantifying trade-offs across these SDGs in a spatially explicit way has been elusive. Within conservation science prioritizing the allocation of global conservation efforts is a recurrent topic (34, 35). Here, we present the results of a model with performance guarantees associated with alternative fund allocation options, which includes ecological and social aspects simultaneously (carbon, biodiversity, and equity). Including equity (under 2 different distributional rules, i.e., max–min and egalitarian rules) results in the selection of a larger number of fund-recipient countries, which is aligned with the inclusive spirit of the UNFCCC. This also allows our model to select more countries to protect endemism and profiting from the high slope of the species-area relationship across different countries, even in cases in which the amount of allocated land under REDD+ program in some countries might be relatively small. Our results contribute to the debate about the extent of trade-offs between climate change mitigation, biodiversity conservation, and social equity under multilateral environmental efforts and policies (7). Considering different equity rules leads to rather different outcomes, confirming the need to transparently set political criteria underpinning equity and fairness in global REDD+ funds allocation. Such transparency should help deal with ethical dilemmas in allocation decisions of policy makers in the fields of biodiversity conservation and climate change (36).

Allocation of REDD+ funds for forest conservation demands making hard decisions, especially involving countries with high development priorities. Transparent analytical models, which can present synergies and trade-offs between ecological and societal objectives, are thus necessary to inform decisions over budget allocation options (37). Our model can be run quickly (~5 min for computation under average computer power), allowing participatory processes to jointly assess trade-offs with decision makers and other stakeholder groups with different interests and identify cost-effective and socially acceptable fund allocation options.

Our main results concur with previous studies that forest carbon emission reduction potential and biodiversity conservation are positively correlated (38), although this correlation does vary (39). We suggest that the correlation decreases as carbon emissions are abated beyond ~20% relative to the business-as-usual scenario while also confirming that the relationship between optimal carbon abatement and biodiversity conservation is nonlinear (40).

Most of the existing studies that link carbon and biodiversity objectives do not take into consideration social outcomes of potential interventions, including via REDD+. This has the potential to undermine conservation projects (28, 41), as could happen if equity is not explicitly considered in climate and biodiversity governance (42). The distribution of international REDD+ funds without proper account of distributional equity concerns held by potential recipient countries may result in politically unacceptable outcomes that may question the fairness of global institutions from an environmental justice perspective (43). This could be the case if no measures are adopted before large countries that can cope with the important readiness costs begin to receive REDD+ funds from international donors. Some big REDD+ countries such as Brazil are already well advanced in their progress toward starting to receive them.

The transparent consideration of equity in the distribution of conservation funds as well as assessing the outcomes in terms of carbon efficiency and biodiversity conservation is increasingly needed in conservation practice (36). The "frontier solutions" in which trade-offs are minimized (7) are also present in our study at relatively low levels of equity. However, it is also worth noting that while carbon inefficiencies in the short term may increase as distributional equity increases, the model is not capable of envisaging second-order effects of considering equity in the longer term, given that efficiency and equity are likely interdependent in the medium to the longer term via political processes (28).

Our model shows that the explicit incorporation of distributional equity in the way REDD+ funds are allocated could lead

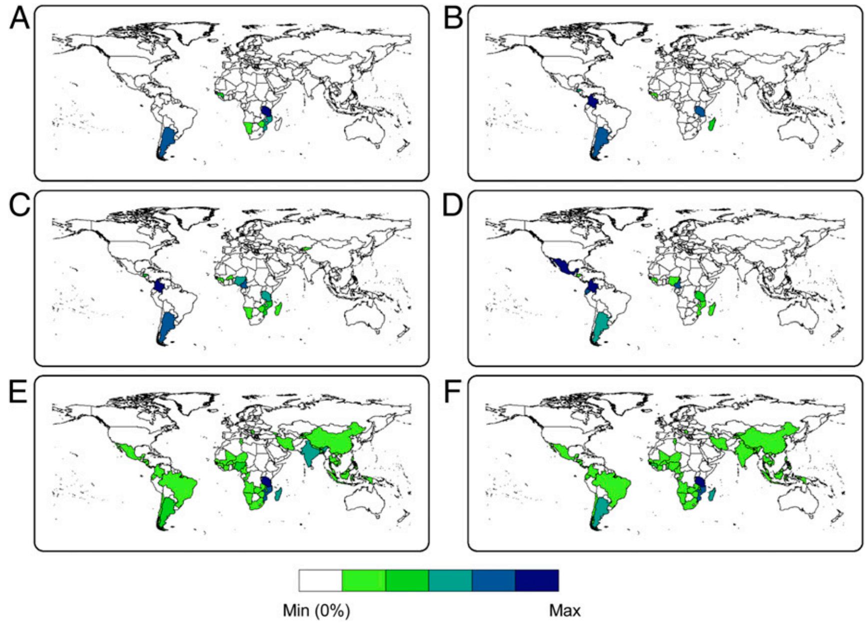

Fig. 4. Global distributions of REDD+ funds under different budget optimization scenarios: (*A*) scenario 1A, maximization of carbon emission reduction under a 20% emissions reduction-based budget; (*B*) scenario 2A, maximization of biodiversity conservation under a 20% emissions reduction budget; (*C*) scenario 1B, maximization of carbon emission reduction under a 50% emissions reduction budget; (*D*) scenario 2B, maximization of biodiversity conservation under a 50% emissions reduction budget; (*E*) scenario 3A, incorporation of equity (at level $E = 0.25$) under a max–min distributional rule under a 20% emissions reduction budget; and (*F*) scenario 3B, incorporation of equity (level $E = 0.25$) under the egalitarian distributional rule under a 20% emissions reduction budget.

to a larger number of recipient countries, thus, if adequately implemented, contributing in many poor countries to covering the readiness implementation gap (44). For species-based biodiversity conservation, previous studies have found that distributing funds across a larger number of species can provide better outcomes (45). However, the prior preparation by some countries before receiving any result-based payment is a key element in order to achieve equitable outcomes under REDD+ (46). Achieving successful REDD+ implementation requires a certain institutional environment within countries (47) and poverty challenges can undermine REDD+ outcomes (48). It is thus necessary to address the underlying causes of deforestation, which are often related to poverty and weak institutional context and governance (49). Incorporating equity in REDD+ fund negotiations might also imply bringing countries with potentially less developed institutions and larger inequalities within them into the REDD+ arena. Here, it is fundamental to respect REDD+ safeguards, such as the Rights of Indigenous Peoples. There is a fund-absorption capacity of countries to use REDD+ funds, which our model does not account for. In this regard, previous experiences have found that countries needed twice the time estimated to absorb the funds given different absorption capacities.

Various assumptions affect the results of the model and indicate the need for further research. First, we used the Global Forest Assessment data from the Food and Agriculture Organization of the United Nations (FAO) for forest cover and forested protected areas, although in this database each country provides data based on a different definition of forest and missing values are completed by extrapolation. We assumed economic opportunity costs of forest conservation at country level without considering spatial variations within countries. However, this should not affect significantly trade-offs at the global scale considering the large number of countries included in the study. Unfortunately, without spatially explicit data on opportunity costs, we were not able to indicate the exact location of forest protection in each country. Further studies using spatially explicit opportunity costs would probably allocate funds to a larger number of countries, as some parts of countries would have lower opportunity costs than the average we used for each country. Last, new research should also focus on assessing the extent to which more equitable approaches, despite resulting in carbon and biodiversity inefficiencies in the short term, could in the medium to longer term catalyze more effective, legitimate, and sustainable REDD+ processes within a larger number of countries and therefore be more successful toward meeting the SDGs.

Materials and Methods

Identifying the best possible allocation of funds considering carbon sequestration, biodiversity conservation, and equity requires doing optimal planning according to a precise model that includes areas dynamics (available land for deforestation and protected area), protected areas' implementation costs, and criteria (carbon, biodiversity, and equity) expressions formulations (functions of available land and protected areas). Having several criteria demands generating Pareto frontiers (the set of all existing Pareto efficient allocations) given different REDD+ budgets. Given this model, finding an optimal planning is a hard task because the number of all possible planning is infinite. To tackle this problem, we developed a multiobjective optimization model, based on a linear programming approach, that provides optimal solutions within less than 1% of errors (more details in *SI Appendix*). In our model, the opportunity costs per country determined the cost of implementing protected areas and equivalates the funds received by each country. Conversely to previous studies, we did not use a single-objective optimization heuristic to generate solutions, but a multiobjective exact optimization approach, so we did not need to reimplement the solutions afterward as the guarantee that our approach is optimal (within 1% of error) is provided by the modeling approach. The various datasets used to feed the optimization model are described in the following lines.

Deforestation. We used the latest dataset from the Global Forest Resource Assessment from the FAO for information on forest cover, above ground biomass and surface of forest protected for the years 1990, 2000, 2005, 2010, and 2015 per country. With this data, we estimated the deforestation rate in each country and we projected it using an exponential smoothing algorithm to obtain the deforestation rates for the period 2016 to 2030. To estimate carbon emissions, we used the carbon density of above-ground biomass per country from the FAO.

Biodiversity. To compute the main parameters of the biodiversity conservation criteria expression, we evaluated the number of species going extinct in various deforestation scenarios, as done in previous studies (21). We used the numbers of endemic forest dwelling species of birds, mammals, and amphibians in every country that were provided by the International Union for the Conservation of Nature (IUCN).

Opportunity Costs. Opportunity costs were used to estimate the cost of setting aside a certain amount of land as protected area (and therefore protected from deforestation). Since there are not any robust global estimates of spatially explicit opportunity costs, we used the agricultural opportunity cost as a proxy variable. To estimate the average agricultural opportunity costs in each country from 2001 to 2013, we used the countries' gross value of agricultural production (in 2017 US dollar values) and the agricultural areas in each country (in hectares) of the FAO. We then projected these values to estimate future opportunity costs using an exponential smoothing algorithm.

Poverty. We took the number of people living below 1.90 purchasing power parity dollars per day in each country as a proxy for poverty, which we used to assign funds to different countries under the max–min equity rule. We used the last value available in the World Bank Database since 2006 for each country. Then we estimated the percentage of poor population living in each selected country.

Eligible Countries. The countries eligible to receive REDD+ funds were the nonannex 1 countries of the UNFCCC. Since poverty, opportunity costs, forest protected areas, carbon density, and biodiversity data were not available for all of the eligible countries, we excluded further countries from the analysis, mostly small island countries. A total of 51 countries was included in the final dataset. None of the major emitter countries was excluded. The model description and operation are described in *SI Appendix*.

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