

# The economic value of tropical forests in meeting global climate stabilization goals

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## Long Form Research Paper

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### Non-technical summary

Conserving tropical forests has many benefits, from protecting biodiversity, sustaining indigenous and local communities, and safeguarding climate. To achieve the ambitious climate goals of the Paris Agreement, forest protection is essential. Yet deforestation continues to diminish the world's forests. Halting this trend is the objective of the international framework for Reducing Emissions from Deforestation and forest Degradation (REDD+). While previous studies have demonstrated the contribution of tropical forests to mitigate climate change, here we show that tropical forest protection can 'flatten the curve' of the costs of transition to climate stability, estimating tens of trillions of dollars in policy cost savings.

### Technical summary

The pledges made by parties under the Paris Agreement are insufficient to limit global warming to well below 2 °C relative to pre-industrial levels. We use a global climate-economic model to quantify the economic benefits from rapidly deploying programs for reducing emissions from deforestation and forest degradation and increased reforestation (REDD+) given current delays in the implementation of climate policies around the world. REDD+ has been shown to have substantial greenhouse gas emissions mitigation potential in the fight against climate change and can thus play a critical role in closing the emissions gap, thereby enabling the achievement of more ambitious climate targets. Under our principal scenario, we estimate that REDD+ can contribute up to US\$36 trillion in net policy cost savings by mitigating the adjustment costs of reaching a greenhouse gas emissions trajectory consistent with ambitious global climate stabilization goals. Investment in REDD+ has a high benefit-cost ratio; one dollar invested in REDD+ yields about US\$5.4 in net policy cost savings. Realizing the full estimated potential for REDD+ reduces the risk-adjusted carbon price in 2030 by US\$45/tCO<sub>2</sub>.

### Social media summary

Protecting tropical forests is crucial to achieve ambitious climate stabilization goals while saving trillions of dollars in economic value.

## 1. Introduction

The Paris Agreement established an ambitious environmental target to limit the rise of global temperature to 'well below' 2 °C above pre-industrial levels (UNFCCC, 2015). Despite this, greenhouse gas emissions continue to rise, rather than stabilizing and declining as required to keep the temperature increase to well below 2 °C (Rogelj et al., 2018) and a climate ambition gap remains (UN Environment, 2018). The greenhouse gas emission reduction pledges that countries have made to date to achieve the Paris goal – the Nationally Determined Contributions (NDCs) – are critical to reduce the risk of even more extreme temperature increases. However, even if they are fully implemented, they are insufficient to limit temperature increases to 2 °C or below (Rogelj et al., 2018).

There is a consensus that reducing deforestation and degradation and promoting reforestation in the tropics (REDD+) has substantial mitigation potential in the fight against climate change (Griscom et al., 2017; Houghton et al., 2015; IPCC, 2014). Tropical forests offer one of the largest opportunities to cost-effectively address near-term emissions (Lubowski & Rose, 2013). While climate policy uncertainties generally hamper mitigation investments, reducing deforestation could be more rapidly deployed than other mitigation strategies, which could help hedge risks of rising future climate policy costs (Golub et al., 2017, 2018). Forest protection strategies rely on existing technologies, entail relatively low costs, and are generally publicly acceptable given a range of non-carbon co-benefits such as the protection of biodiversity,

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**Table 1.** Total emissions from tropical forests under business-as-usual (BAU) and maximum mitigation scenarios over 2020–2100 (Gt CO<sub>2</sub>)

	Emissions (Gt CO <sub>2</sub> )	Cumulative (net) emissions from adding each respective option (Gt CO <sub>2</sub> )
BAU deforestation	366	366
BAU reforestation	–142	224
Reduced emissions from deforestation at \$100/tCO <sub>2</sub>	–250	–26
Removals from reforestation in 2020–2100 at \$100/tCO <sub>2</sub>	–72	–98

Note: Mitigation and removals denoted by a negative sign. Cumulative net emissions are calculated by progressively adding in each component, as one moves down the rows of the table.

improvements in local climatic conditions, and regulation of water supplies (de Coninck et al., 2018). The idea of using forest-based strategies as a low-cost, near-term strategy to address climate change has been around for a long time (Smith et al., 2014), with a typical focus on how forest strategies can help to buy time to develop lower-cost technologies to reduce fossil fuel emissions (e.g. Szolgayová et al., 2014). In general, forest-based mitigation has fundamental importance and without tapping its potential at large scale, the ambitious Paris targets might already be out of reach.

Our study uses a traditional global climate-economic model to highlight the enormous economic value of tropical forest mitigation in the context of global climate policies. We argue that the rapid deployment of reduced emissions from deforestation and forest degradation and proactive reforestation in tropical countries provides cost-effective mitigation that can enable countries to enhance the ambition of their NDCs. Furthermore, given the growing emissions gap, scaling up of REDD+ appears essential to remain on track to limit the temperature increase to below 2 °C, as shown in this study.

For our analysis, we modify the 2016 version of the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 2013) to include REDD+ supply. We then estimate costs and price trajectories for different emissions budgets, ranging from 970 to 1600 gigatons (Gt) of CO<sub>2</sub> cumulative emissions up until 2100, under different assumptions about tropical forest protection and reforestation. We assume that without interventions to protect tropical forests, emissions from tropical deforestation net of removals from reforestation total 155 Gt CO<sub>2</sub> between 2020 and 2050. Our results show that the realization of the REDD+ potential generates previously unquantified cost savings in the tens of trillions of US dollars. These net policy cost savings reach US\$31–36 trillion in our preferred policy case, with risk-adjusted savings even larger by about half a trillion dollars. In this case, tropical forestry absorbs 98 Gt CO<sub>2</sub>, instead of emitting 224 Gt CO<sub>2</sub> until 2100 with corresponding savings of up to 22% of climate policy cost.

The remainder of the paper is organized as follows: Section 2 presents the modeling framework, and Section 3 describes the policy scenarios and results. Section 4 provides a concluding discussion.

## 2. Modeling the economic value of REDD+

We use an Integrated Assessment Model (IAM) to assess the economic value of REDD+ across a variety of policy scenarios as well as ranges of possible model parameters. We modify this IAM to represent endogenous tropical forest conservation and reforestation supply. Section 2.1 first describes the marginal abatement cost curves (MACCs) that we incorporate. These include cost estimates for global fossil fuel abatement, avoided deforestation, and

reforestation. All three are increasing functions of the carbon price. The IAM then minimizes the discounted abatement costs over the period 2020–2100 while meeting a pre-defined emissions budget. Section 2.2 provides further discussion of the model and calibration of parameters for uncertainty analysis.

### 2.1. Assessing REDD+ potentials

A number of studies (e.g. Houghton et al., 2015) demonstrate that protection and restoration of tropical forests can buy vital time to navigate the decarbonization of the global economy. Houghton and Nassikas (2018) estimate that, under an aggressive scenario for conserving and restoring tropical forests, fossil fuel emissions would need to fall to zero by 2045–50, rather than by 2035 in the case with business-as-usual (BAU) forest emissions.

While these studies quantify the mitigation potential from reducing tropical deforestation and increasing reforestation in the tropics, here, we quantify the economic value of exploiting this potential. By using an IAM, we derive implications for the mitigation portfolio and its cost. We consider three types of scenarios: a reference scenario without any REDD+ abatement, a climate policy scenario with REDD+ efforts limited to emissions reductions from tropical forest conservation, and several policy scenarios with REDD+ that also allow for carbon removal from the atmosphere (also known as carbon dioxide removal or negative emissions) via tropical reforestation.

Drawing on updated analyses of tropical forest emissions (Houghton & Nassikas, 2018), Table 1 presents our assumptions for the BAU emissions from tropical deforestation and reforestation (i.e. BAU sinks from temperate and boreal forests have not been included) during 2020–2100 that are part of the reference case. Table 1 also shows the maximum mitigation potentials we consider under policy scenarios for reducing forest emissions and increasing forest sequestration in tropical regions.

We consider three potential global climate policy targets and corresponding emissions budgets for the period 2018–2100, corresponding to 1.8 °C, 2 °C, and 3 °C estimated temperature increases. The emission budgets were calibrated based on the IPCC's Fifth Assessment Report (AR5) and the UN Environment's Emissions Gap Report (IPCC, 2014; UN Environment, 2018).

Using recent estimates of the global costs of reduced emissions from deforestation and carbon sequestration from reforestation in tropical countries based on Busch et al. (2019), we obtain BAU emissions and the corresponding potential abatement supply for the period 2030–2050 (see Supplementary Table S1). We employ MACCs from REDD+ for the years 2025, 2035, and 2045 from Busch et al. (2019) that represent median estimates of annual abatement supply at given carbon prices over the corresponding decades. The estimates are derived econometrically with a consistent methodology and indicate higher costs of reduced

**Table 2.** Calibration of parameters for Monte-Carlo simulations

Variable	Mean	Standard deviation	Shape of distribution
Asymptotic global population (mill.)	11,500	110	Normal
Initial growth rate of Total Factor Productivity (TFP)	0.076	0.0057	Lognormal
Price of back-stop technology (US\$/tCO <sub>2</sub> )	550	110	Lognormal
Initial rate of decarbonization	0.1	0.0064	Lognormal
Climate sensitivity	3.1	1.6	Lognormal
CO <sub>2</sub> price in 2020 (US\$/tCO <sub>2</sub> )*	10	6	Lognormal
CO <sub>2</sub> price in 2025 (US\$/tCO <sub>2</sub> )*	25	15	Lognormal

\*Endogenous afterwards.

deforestation and expanded reforestation relative to previous studies (Busch et al., 2019). Thus, our estimated REDD+ potential is conservative.

We also are conservative in our estimates of supply in that we only consider mitigation potentials up until US\$100/tCO<sub>2</sub> from both reduced deforestation and reforestation. This is in line with past literature where the marginal abatement costs of REDD+ typically show a ‘hockey stick’ shape, with prices of US \$100/tCO<sub>2</sub> on the asymptotic part of the curve (e.g. Kindermann et al., 2008). Since the IAM (see Section 2.2) covers the period 2020–2100, we include an additional estimate of emissions and removals that take place after 2050. Our numerical analysis provides a conservative estimate of the potential for reduced deforestation and increased reforestation (see Supplementary Materials). For the potential to reduce deforestation, we extrapolate trends from the global land-use modeling cluster of the International Institute of Applied Systems Analysis (IIASA), as described in Gusti et al. (2015). For reforestation, we assume no additional reforestation after 2050 and include only the carbon removal on already reforested land.

To evaluate the impact of exploiting these different potentials, we consider one reference scenario (without any forest mitigation) and two mitigation scenarios summarized in Table 2.

### 2.1.1. Reference scenario

The reference scenario includes BAU levels of both deforestation and reforestation. The net emissions under the reference scenario are 224 Gt of CO<sub>2</sub> over the modeling period (2020–2100).

### 2.1.2. Reduced deforestation only

The next scenario – ‘Deforestation only’ – includes only REDD+ related mitigation from reduced deforestation. This leads to 26 Gt of avoided CO<sub>2</sub> assuming a carbon price of up to US\$100/t CO<sub>2</sub>.

### 2.1.3. Reduced deforestation and reforestation

The third scenario – ‘Reduced deforestation and Reforestation’ – includes the *additional* supply from reforestation up to US\$100/t CO<sub>2</sub>. The minimum net emissions under this scenario are –98 Gt CO<sub>2</sub>.

## 2.2. Quantifying REDD+ gains

For the numerical analysis of the economic implications, we adopt a traditional IAM, namely the 2016 version of the DICE model (Nordhaus, 2013). This integrates economics and climate science, with a simplified representation of the carbon cycle. We also conduct an uncertainty analysis using an envelope of estimates from

DICE. GDP is modeled as a response surface function and emissions are modeled as a function of GDP and abatement efforts. We consider a cost-effective solution rather than optimizing for emissions based on the costs and benefits of mitigation. Thus, a total emission budget is pre-determined in each scenario, and we solve for the least cost solution to meet the emissions target. The shadow prices for CO<sub>2</sub> resulting from constraining the emissions can thus be interpreted as a measure of policy cost to society without explicitly valuing avoided damages.

Many processes and sectors in the DICE model are simplified, but this also makes it more transparent than other IAMs. As a result, it has often been used to generate climate stabilization pathways and provide first quantifications of particular aspects, thus informing the discussions around climate policy (e.g. Nordhaus, 2017). An advantage is that it delivers tractable results, which can be further explored with more complex methods of analysis, e.g. for the impact of climate risk on financial assets (e.g. Dietz et al., 2016). Our analysis demonstrates the importance of including REDD+ in climate policy modeling. However, one implication of our analysis is that approaches with more spatial detail, land-use change, and other land-based mitigation options will be needed to derive more precise policy recommendations in the future. The outcomes of our study should therefore be understood as exploratory, as IAMs like DICE have been criticized for their level of abstraction and assumptions circumventing uncertainties, and may create an unwarranted ‘perception of knowledge and precision’ (Pindyck, 2013). Nevertheless, we believe that the analysis is useful for initial estimates of the economic value of REDD+.

Explicit consideration of catastrophic climate outcomes, which have been identified as the most important omission in standard IAMs (Pindyck, 2013; Stern, 2013), may even enhance the REDD+ value we determine here. Recent efforts to address some of these deficiencies identified in previous DICE analyses have focused on updating (i) the economic damage functions, (ii) the underlying climate science, (iii) social discount rates, (iv) assumptions on non-CO<sub>2</sub> greenhouse gas emissions and feasibility of carbon removals, and (v) constraints on the feasible speed of decarbonization (Hänsel et al., 2020). These improvements reconcile DICE results with the Paris targets, but do not consider the role of forest mitigation potential, as addressed in this paper.

In addition to these structural issues with the DICE model, there is a wide range of fundamental uncertainty around critical parameters such as the cost of abatement technologies, timing of climate policy implementation, and productivity of the global economy. To address these uncertainties, we run Monte-Carlo simulations using the extended DICE 2016 version described above. Following Dietz et al. (2016) and Gillingham et al. (2018),

we focus on the parameters summarized in [Table 2](#) for our uncertainty analysis. For the policy delay scenarios, we add assumptions about initial carbon prices in 2020 and 2025.

The mean values of the parameters in [Table 2](#) equal the values of the corresponding parameters in the DICE-2016 model, which are approximately the same as those used in the studies mentioned above. Standard deviations were calculated using the same coefficients of variability as tested in [Gillingham et al. \(2018\)](#). The major difference in our study is the application of lognormal distributions instead of normal distributions used in previous studies of Total Factor Productivity (TFP), the cost of the back-stop technology and the initial rate of decarbonization. A lognormal distribution better characterizes the nature of the underlying uncertain process. In particular, the cost of the back-stop technology should behave in the same way as the price of goods and services, and uncertain prices are usually represented with a lognormal distribution.

We also introduce uncertainty around exogenous initial carbon prices in 2020 and 2025. The carbon price in 2020 is assumed to be positively correlated with climate sensitivity – under the assumption that climate policies will be more stringent if climate impacts are more severe – and the price in 2025 is assumed to be correlated with the carbon price in 2020. The carbon price in 2020 is exogenous in all policy scenarios and endogenous thereafter. The carbon price in 2025 is exogenous only in the case of policy delay up until 2030, as described in the next section.

For the uncertainty analysis, we constrain the optimization to respect the corresponding carbon budgets specified in [Table 3](#) and add REDD+ to the original settings of the model. A simplified optimization routine (minimizing cost to meet the target) is embedded into the Monte-Carlo simulations. For each draw of a set of realizations of the underlying uncertain parameters, the optimization algorithm calculates the abatement, the corresponding CO<sub>2</sub> price, and the present value of total abatement costs.

### 3. Scenario analysis of REDD+ economic benefits

#### 3.1. Policy scenarios

We evaluated a set of stylized policy scenarios representing varying ambitions of global action on climate change. These scenarios mirror three different levels of the globally admissible carbon budgets reflecting both policy and scientific uncertainties. The other dimension is the timing of climate policy implementation to achieve a given budget; we vary the speed of increase in ambition to study the impact of delay. Our nine stylized policy scenarios are presented in [Table 3](#).

The stylized policy scenarios described in [Table 3](#) differ with respect to their expected feasibility. As barriers to the implementation of an aggressive emissions target, we consider both the total cost of climate policy and the spike in the cost (illustrated by the carbon price as a proxy) accompanying the announcement and implementation of tighter emission targets.

Based on anticipated political feasibility, we selected four core policy scenarios highlighted in [Table 3](#) in bold:

1. 2 °C-consistent carbon budget with some climate action undertaken during 2020s and 2030s, but major policy adjustment delayed until 2030 (2C, PD2030);
2. 1.8 °C-consistent carbon budget, with some climate action undertaken during 2020s and 2030s, but major policy adjustment delayed until 2030 (1.8C, PD2030);

3. 2 °C-consistent carbon budget, with some climate action undertaken during 2020s and 2030s, with major policy adjustment in 2030 that is insufficient to meet the target, such that sequential tightening of the budget is needed until 2050 (2C, MPD);
4. 3 °C-consistent carbon budget with some climate action undertaken during 2020s and 2030s, but major policy adjustment delayed until 2030 (3C, PD2030).

We also include the scenario shown in [Table 3](#) in italics of a 2 °C-consistent carbon budget with immediate implementation in 2025. This provides a ‘counterfactual’ policy scenario against which to demonstrate the cost of delay.

Based on these core global climate policy scenarios, [Figures 1–4](#) depict three different carbon price trajectories for situations (a) without REDD+ (abatement of fossil fuel emissions only, labelled ‘reference’), (b) reduced deforestation, and (c) reduced deforestation and reforestation. This decomposition of the abatement supply helps to better understand the role and value of the individual components.

[Figure 1](#) summarizes the carbon prices for the counterfactual scenario assuming no further delay beyond 2025 of switching to the 2 °C trajectory. Reducing deforestation mitigates a spike in the carbon price such that instead of jumping from about US \$10/tCO<sub>2</sub> in 2020 to \$121/tCO<sub>2</sub> in 2025, the price stays below US\$100/tCO<sub>2</sub> (US\$97/tCO<sub>2</sub>).<sup>1</sup> The incremental contribution of reforestation is comparatively minor due to a relatively inelastic supply of land for reforestation. Therefore, a focus on reduced deforestation is an important priority for emerging global climate policy.

Given the current political climate, an immediate ‘full steam ahead’ implementation of the global climate policy even by 2025 looks unlikely. To test the impact of this, we consider a delay until 2030 with the same 2 °C-consistent (1,170 Gt emission) budget as the most likely scenario. [Figure 2](#) shows that without reducing tropical deforestation, the CO<sub>2</sub> price will jump from about US\$25/tCO<sub>2</sub> up to \$160/tCO<sub>2</sub> within 5 years (2025–2030). The price level in 2030 will be kept below US\$130/tCO<sub>2</sub> (see [Figure 2](#)) by incorporating reductions in tropical deforestation, buffering at least part of the price shock and potentially enhancing the political feasibility.

An even more dramatic tightening of the emissions target to limit temperatures below 2 °C will be exceedingly challenging without reducing deforestation and forest restoration. The carbon price would have to quadruple over the 5-year period between 2025 and 2030 to over \$200/tCO<sub>2</sub> to converge to a 1.8 °C-consistent (970 Gt emissions) budget (see [Figure 3](#)).

Given the uncertainty in the response of the climatic system to greenhouse gas accumulation, a 1.8 °C target may even require a further tightening of the carbon budget in the future, which would further increase the policy cost. The results imply that large-scale efforts to reduce deforestation and reforestation are likely to dramatically enhance the chance of reaching this more ambitious emissions reduction target.

REDD+ provides some relief concerning the upward pressure on prices in the scenarios examined. However, this may not be enough to contain prices to socially acceptable levels in the face of both policy delays and tightening of the

<sup>1</sup>Note that prices are above US\$100/tCO<sub>2</sub> the full abatement potential is realized by our assumption of a marginal abatement cost curve vertical as of US\$100/tCO<sub>2</sub>.

**Table 3.** Stylized global climate policy scenarios

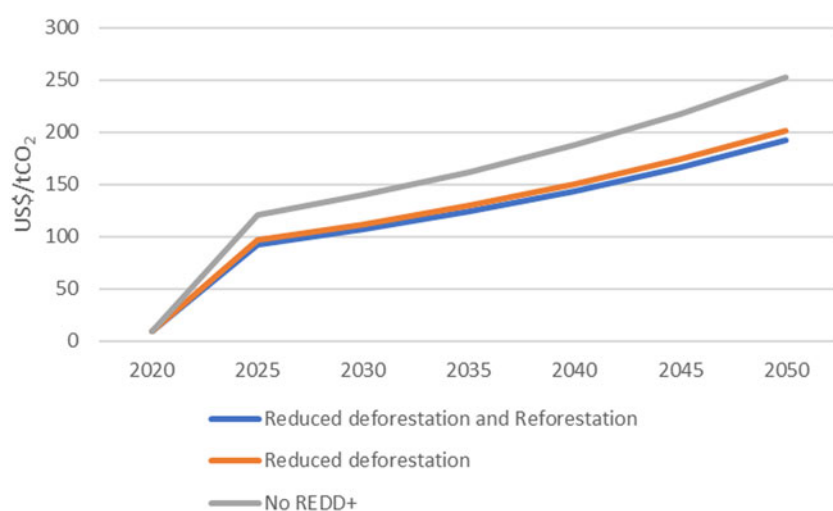
	2 °C-consistent carbon budget of 1170 Gt CO <sub>2</sub> for 2018–2100	1.8 °C-consistent carbon budget of 970 Gt CO <sub>2</sub> for 2018–2100	3 °C-consistent carbon budget of 1600 Gt CO <sub>2</sub> for 2018–2100
Global policy implemented in 2025*	<i>Low political feasibility. 'Counterfactual' scenario to estimate the cost of delay (2C, PD2025)</i>	Politically not feasible, unless there is significant REDD+ supply	Ruled out as unrealistic
Some climate action undertaken during 2020s, but major policy adjustment delayed until 2030 <sup>†</sup>	<b>Main scenario: introduction of new target in 2030 (2C, PD2030)</b>	<b>Feasible with REDD+ supply (1.8C, PD2030)</b>	<b>Compromise scenario given resistance of carbon-dependent industries (3C, PD2030)</b>
Major policy adjustment in 2030 insufficient to meet target, sequential tightening of the budget until 2050 (Multiple Policy Delays Scenario) <sup>‡</sup>	<b>Partial policy shock in 2030, continued adjustment of targets in future years (2C, MPD)</b>	Low political feasibility due to significant increase of economic burden post-2050	Low environmental feasibility, politically feasible for relatively low equilibrium climate sensitivity

Note: Core policy scenarios highlighted in bold and counterfactual scenario in italics.

\*Optimization starts in 2025. The carbon price in 2020–2024 is exogenous.

<sup>†</sup>Optimization starts in 2030. The carbon price in 2020–2029 is exogenous.

<sup>‡</sup>For modeling multiple delay scenarios, we apply the methodology from Golub et al. (2020). They show that, responding to climate policy uncertainty, buyers in the global carbon market will heavily discount future carbon prices. Over time, as confidence in climate policy increases, each jump in the carbon price represents an increase in confidence in the policy target. For modeling purposes, we adopt the annual average price increase of about 8%.



**Fig. 1.** CO<sub>2</sub> price for 2 °C-consistent (1170 Gt emissions) budget with policy implemented by 2025 (2C, PD2025 scenario) with and without REDD+.

emissions budget consistent with even 2 °C. The Multiple Policy Delays Scenario (MPD) in Table 3 indicates there could be a relatively modest initial tightening of the target, followed by further, sequential adjustments as described in Golub et al. (2017). We consider an MPD that produces the price path presented in Figure 4.

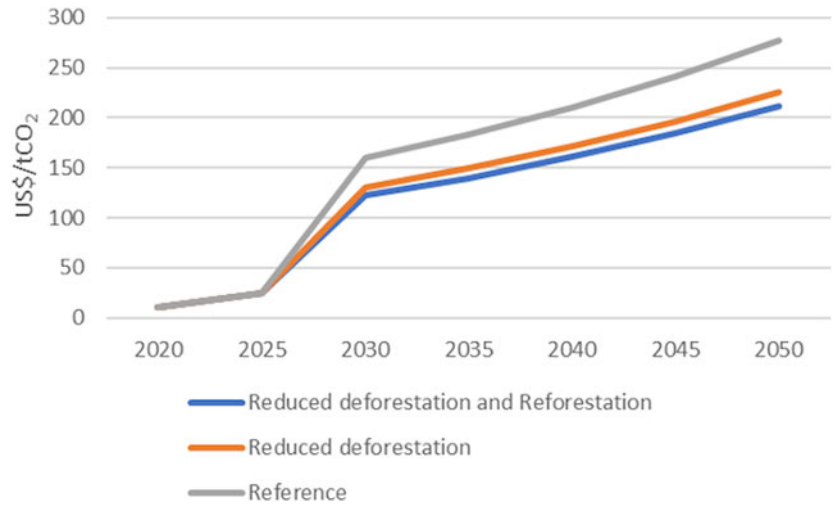
In this scenario, policymakers postpone climate policy adjustments reducing the magnitude of an initial price shock but requiring greater subsequent increases of carbon prices of 8% per year (see Figure 4). In the 2C MPD Scenario, reduced deforestation helps to cut the price increase by about 70% which is especially important by 2050 when the price gap between the reference scenario and the reduced deforestation and reforestation scenarios has built up. Instead of reaching US\$460/tCO<sub>2</sub>, the price stays below US\$270/tCO<sub>2</sub> when tropical forest mitigation options are fully included.

Figure 5 compares the price paths for different policy scenarios assuming the realization of the full modeled potential for reduced deforestation and reforestation. Switching to the optimal policy in

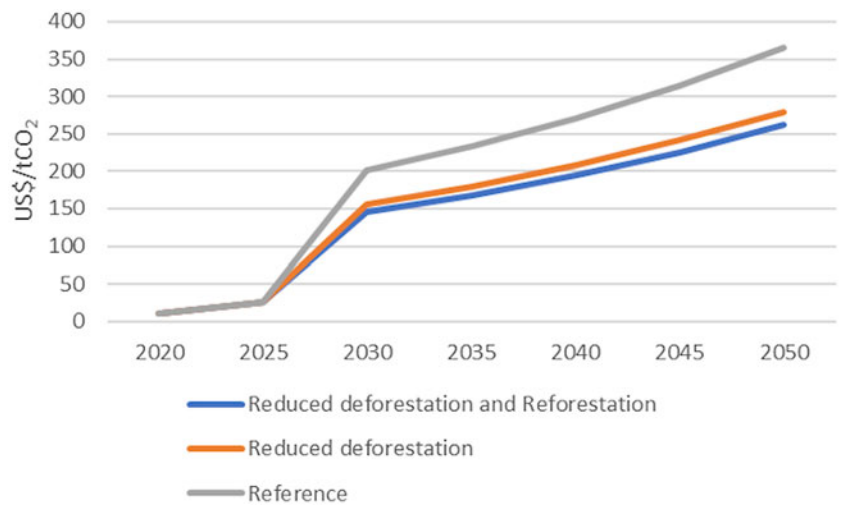
2025 yields the lowest carbon price by 2050 among scenarios with a 2 °C policy target, but such an abrupt switch to full-scale implementation of stringent global climate policy may still entail an unacceptable transition cost.

Reduced deforestation and tropical reforestation slightly mitigate an initial price jump, but not enough to completely avoid a large price increase. The relatively more 'relaxed' policy target of 3 °C unsurprisingly generates a slightly lower price path.

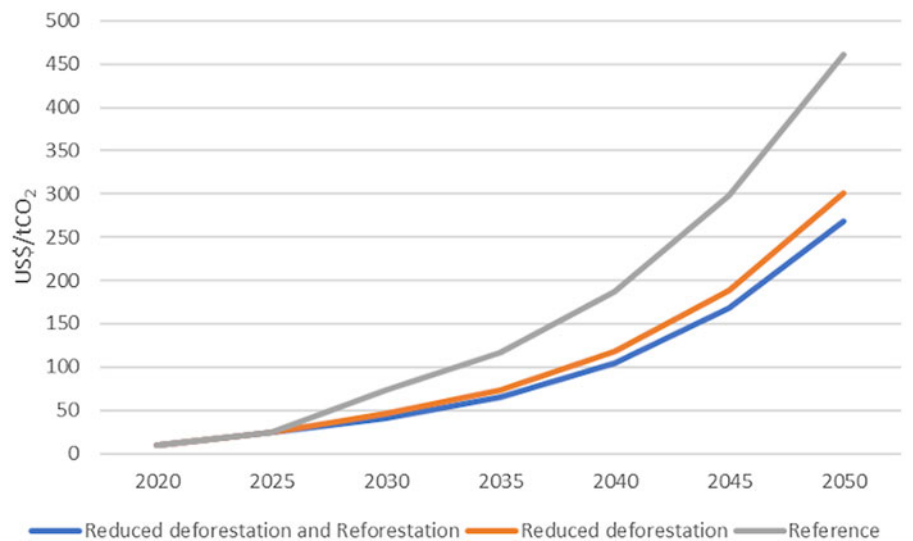
Based on these results, aggressive policies to reduce tropical deforestation, as well as restoring tropical forests, constitute a critical strategy to mitigate price shocks without compromising the global emission budget. Switching from the 2 °C-consistent carbon budget until 2100 to the 3 °C-consistent budget reduces the carbon price by about 43% in a scenario with policy delay till 2030. In comparison, achieving the full potential of reduced emissions from tropical deforestation and reforestation can dampen the price increase in 2030 by more than 30%, while holding cumulative emissions within the 2 °C budget, thereby providing about 70% of the carbon price containment.



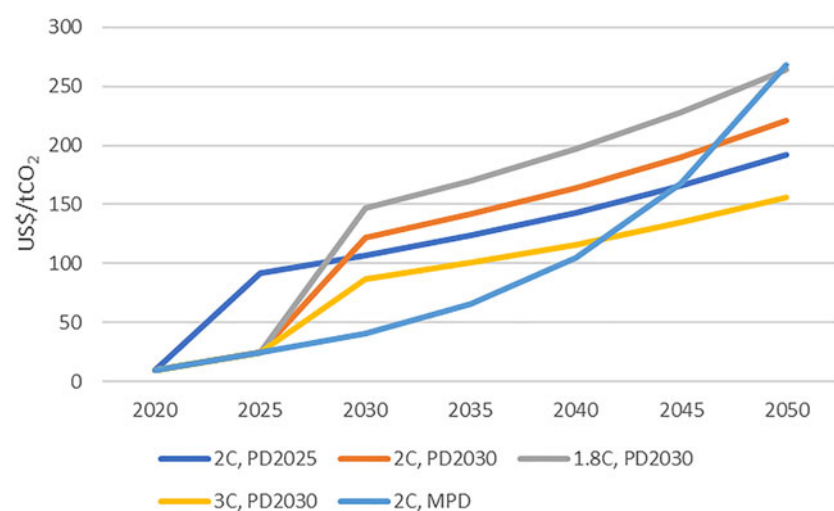
**Fig. 2.** CO<sub>2</sub> price for 2 °C-consistent (1170 Gt emissions) budget with policy delay until 2030 (2C, PD2030 scenario) with and without REDD+.



**Fig. 3.** CO<sub>2</sub> price for 1.8 °C-consistent (970 Gt emissions) budget with policy delay until 2030 (1.8C, PD2030 scenario) with and without REDD+.



**Fig. 4.** CO<sub>2</sub> price for 2 °C (1170 Gt emissions) budget with multiple policy delays before and beyond 2030 (2C, MPD scenario) with and without REDD+.



**Fig. 5.** CO<sub>2</sub> price for different policy scenarios, with full reduced deforestation and reforestation potentials.

**Table 4.** Net cost savings for different scenarios (US\$ trillion, mean values) including tropical forest mitigation potential

	2 °C emissions budget with delay until 2030 (2C, PD2030)	1.8 °C emissions budget with delay until 2030 (1.8C, PD2030)	3 °C emissions budget with delay until 2030 (3C, PD2030)	2 °C emissions budget under Multiple Delays Scenario (2C, MPD)
Reduced deforestation, relative to reference case without REDD+	27.03 (17.8%)	33.36 (18.4%)	15.77 (15.8%)	25.38 (15.3%)
Reduced deforestation plus reforestation, relative to reference case without REDD+	31.95 (21.1%)	39.79 (21.9%)	17.82 (17.9%)	30.20 (18.2%)
Reforestation, incremental effect, relative to reduced deforestation alone	4.92 (18.2%)	6.43 (19.3%)	2.05 (13%)	4.82 (19%)

Notes: The table summarizes the discounted value (at 3%) of net abatement cost savings of including REDD+ in trillion US\$ for the period 2030–2070. Savings are net of the costs of the forest mitigation activities.

### 3.2. Policy cost of reaching 2 °C (1170 Gt emissions budget) until 2100

Carbon prices indicate the marginal cost of abatement and provide a proxy for policy costs. We also compare total abatement costs of different mitigation policies, including – when relevant – the costs of reducing emissions from tropical deforestation and reforestation, as an expected present value of the total cost of climate policy for different scenarios at a discount rate of 3%.

The average benefit of reduced deforestation and reforestation (in terms of the discounted value of cost savings relative to the case without tropical forest mitigation) is in a range of US\$6–40 trillion for the period 2030–2070 across the scenarios (see Table 4). This represents the largest savings across scenarios, especially in the case of policy delay. To put these savings into perspective, they could reach about 0.6% of global output for the same period.

Depending on the policy scenario, the savings in abatement cost are between 15% and 22% of the total discounted abatement cost relative to the scenario case without tropical forest mitigation potential. Reduced tropical deforestation delivers about 81–87% of the savings, with reforestation accounting for the remaining 13–19%.

Under the 2 °C scenario with a delay until 2030 (2C, PD2030), the estimated present value of abatement costs from tropical forest

mitigation total US\$6.2 trillion, with US\$2.7 trillion and US\$3.5 trillion from reducing deforestation and restoring forests, respectively. The overall gross savings in terms of global abatement cost attributed to REDD+ is US\$33.5 trillion (mean value). One dollar invested in REDD+ yields about \$5.4 in savings on abatement of fossil fuels emissions. Reforestation yields incremental savings of US\$9.6 trillion with a corresponding return of about US\$2.7 per one dollar invested in reforestation.

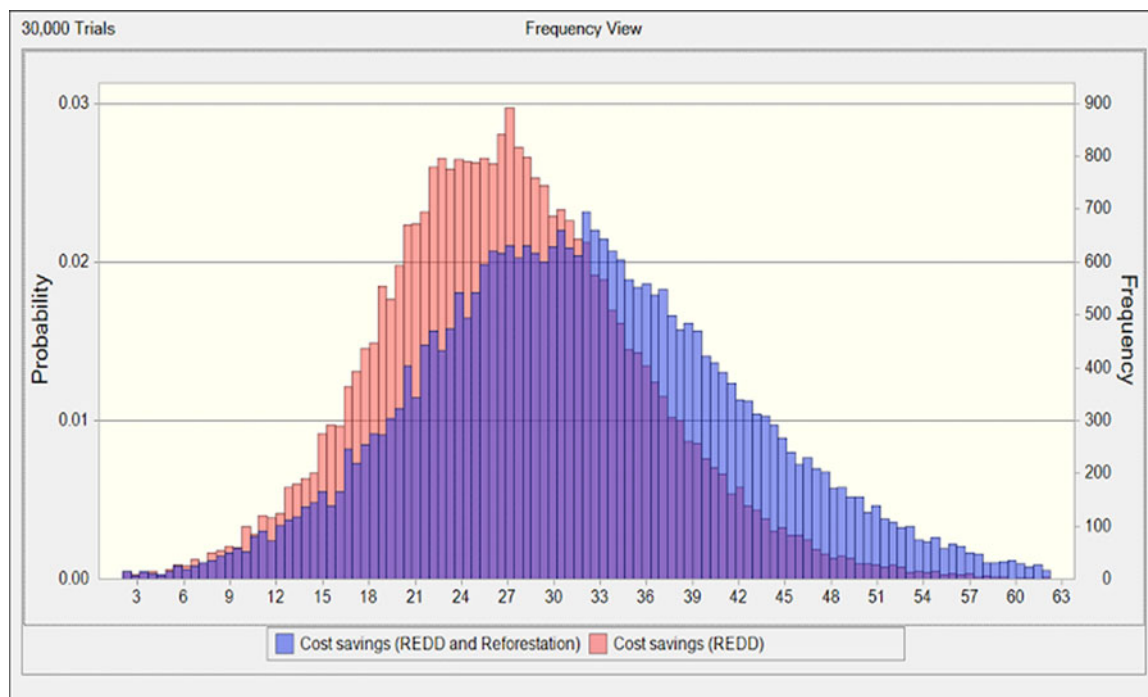
### 3.3. Uncertainty analysis

From a financial perspective, delaying abatement implies a short position on abatement relative to anticipated climate policy scenarios. Closing this short position will require additional abatement efforts. Given the uncertainties of abatement costs, the potential downside of holding on to an uncovered short position on abatement could be excessively risky (Golub et al., 2020). A typical finance instrument to cover short positions is known as an American call option, i.e. the right, but not the obligation to exercise the option to buy. Applied to abatement, such a call option would provide the possibility of tapping into the REDD+ supply to bridge any shortfall in emissions reductions when stringent climate policy suddenly drives up the CO<sub>2</sub> price (Golub et al., 2018).

**Table 5.** Risk-adjusted abatement cost (US\$ trillion) and carbon price (US\$/tCO<sub>2</sub>) under 2 °C (1170 Gt emissions) budget with policy delay until 2030

Statistics	Cost 2030–2070	Net cost savings	Net cost savings	Price in 2030	Price in 2030	Price in 2030
	Reference	With reduced deforestation	With reduced deforestation + reforestation	Reference	With reduced deforestation	With reduced deforestation + reforestation
5th percentile	62.0	–14.7	–16.0	\$109	\$82	\$75
Mean	151.7	–27.0	–31.9	\$164	\$130	\$122
95th percentile	250.9	–41.1	–49.6	\$230	\$185	\$175
Standard deviation	58.0	–9.05	–11.1	\$38	\$33	\$31
Risk-adjusted values	275	–30.6	–36.4	\$179	\$143	\$134

Note: Cost savings (net of abatement costs of REDD+ activities) are denoted as negative numbers. Risk-adjusted values are calculated as the sum of the mean value and the value of the at-the-money option that reflects the willingness to pay for hedging further price increases based on estimated distributions.



**Fig. 6.** Probability densities of net climate policy cost savings under 2 °C (1170 Gt emissions) budget and delay until 2030, with reduced deforestation in red and reduced deforestation plus reforestation in blue.

We use option valuation in order to estimate risk-adjusted costs. The risk-adjusted abatement cost equals the expected value of abatement cost, plus the value of the at-the-money option on abatement. In particular, valuing the call option and adding the expected value of abatement allows us to assess risk-adjusted costs by adding the two together (Anda et al., 2009). For the option value calculation, we apply the Bachelier option pricing formula: the value of the at-the-money option is approximately equal to 0.4 times the standard deviation of abatement costs. The same methodology was applied in Cooke and Golub (2020). Table 5 summarizes the results for our principal scenario of a 2 °C (1170 Gt emissions) budget and delay until 2030.

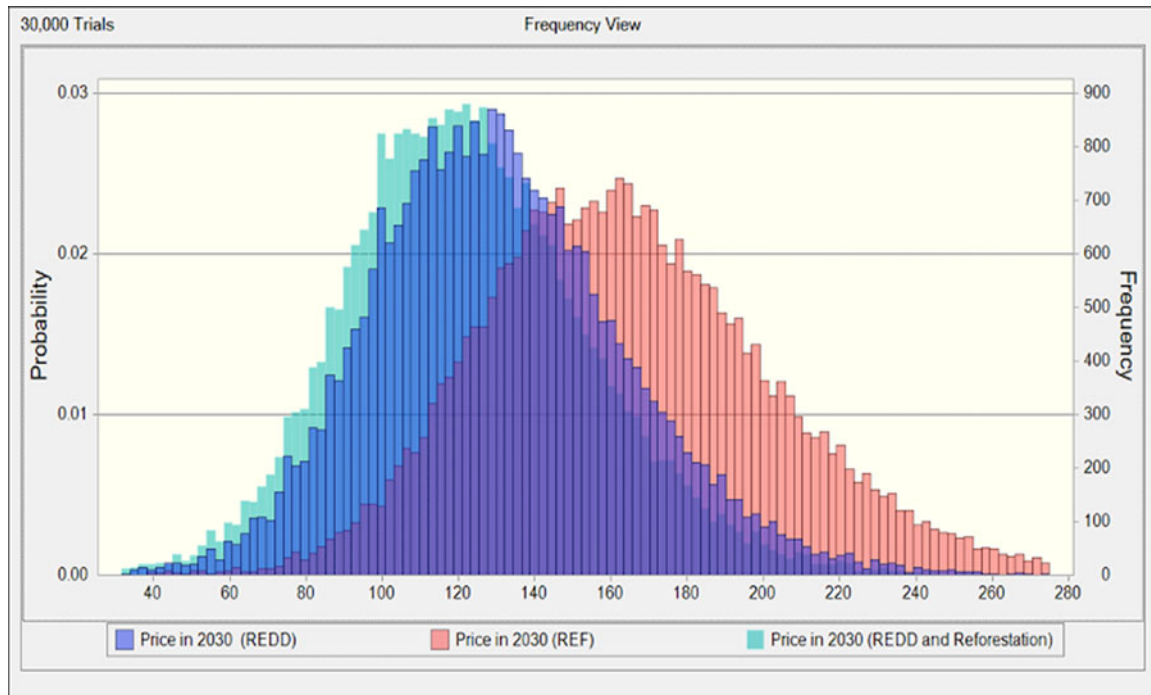
For a given emissions target, REDD+ reduces both the expected carbon price ('mean' in Table 5) as well as the

magnitude of price uncertainty (5th versus 95th percentile and standard deviation in Table 5). The policy cost savings through REDD+ reported in Table 5 are calculated on a net basis, i.e. the cost of avoided deforestation is subtracted from the savings in fossil fuel emissions abatement cost.

Not only may REDD+ thus slash abatement cost or help to achieve lower emissions targets at the same cost, REDD+ could also play an essential role controlling fat tail risks helping to avoid the excessively high cost of climate policy. Figure 6 depicts probability density functions for different REDD+ scenarios: REDD+ does not eliminate the tail risk of excessively high policy costs, but it can significantly reduce that risk.

Risk-adjusted values are calculated as the sum of the mean value and the value of the at-the-money option that reflects the





**Fig. 7.** Probability densities of carbon prices in 2030 under 2°C (1170 Gt CO<sub>2</sub>) budget and with policy delay until 2030, for selected scenarios (reference case shown in red, reduced deforestation in blue, and reduced deforestation plus reforestation in green)

estimated willingness to pay for hedging further price increases based on our estimated distributions. Risk-adjusted savings and carbon prices indicate average and marginal benefits of reduced deforestation and reforestation given the uncertainty of major economic variables as listed in Table 2. As shown in the last row of Table 5, we estimate the risk-adjusted savings from reduced tropical deforestation and reforestation at US\$30.6 and US\$36.4 trillion. The risk-adjusted carbon price falls from US \$179/tCO<sub>2</sub> in the reference to \$143/tCO<sub>2</sub> and \$134/tCO<sub>2</sub> when reduced deforestation and reduced deforestation and restoration potentials are included, implying estimated marginal benefits of US\$36/tCO<sub>2</sub> and US\$45/tCO<sub>2</sub>, respectively, in terms of reducing risk-adjusted carbon prices in 2030. Without reduced deforestation, the cost of climate policy at the 95th percentile equals US \$251 trillion, while with the maximum available mitigation potential from tropical forests (reduced deforestation plus reforestation), the 95th percentile of total abatement cost is about US \$200 trillion (see Table 5). Thus, REDD+, including principally reduced deforestation as well as a smaller potential from reforestation in the tropics, not only generates multi-trillion-dollar savings on climate policy cost without giving up the strength of the emission target, but also helps to contain the potential distribution of carbon prices in the period 2026–2030 (see Figures 6 and 7).

For future analysis, it will be important to determine the most crucial exogenous parameters and focus on representing them in a more detailed way. The cost of the backstop technology accounts for about 26% of the combined uncertainty of climate policy costs in the scenario with a delay until 2030 (with a positive correlation of about 0.5) and for about 65% of the combined uncertainty of potential savings provided by reduced deforestation and reforestation (with a correlation of about 0.77). The initial rate of decarbonization of the global economy exhibits a negative correlation with both the cost of climate policy (−0.8) and savings (−0.55).

This parameter accounts for about 63% of the combined uncertainty of climate policy costs and for about 32% of the combined uncertainty of potential savings. However, uncertainty concerning available carbon budgets may change the balance. In this study, we address this uncertainty in the form of ‘what-if’ scenarios. For future analysis, the carbon budget could be modeled as a probability distribution. Also, we did not model uncertainty related to the supply of reduced deforestation and reforestation. Adding these uncertainties would be an important next step to expand the analysis presented here.

#### 4. Discussion

In this analysis, we explore how the mitigation potential of tropical forests (REDD+) can help control the cost of climate policies so as to limit the rise in temperatures to no more than 2°C. We use a revised version of a traditional IAM, DICE, to assess the savings from including the relatively cost-effective mitigation potentials from REDD+. Note that previous versions of DICE have not assessed the REDD+ value due to the exogeneity of land-use emissions in the model. Other IAMs have endogenized land by introducing a flexible land supply curve, but they have focused more on assessing the opportunity costs of REDD+, which differ substantially across regions (close to US\$0 in Africa up to US\$60 in South-East Asia (Overmars et al., 2014)). As the representation of the land sector in IAMs is increasingly being improved – either by advancing the built-in land-use modules or by connecting to large-scale partial equilibrium models of land-use change (see e.g. Fricko et al., 2017) – one can expect both reduced deforestation and reforestation potentials to be assessed more widely and in more detail in the future.

Our current modeling effort presents scenarios and uncertainty analysis that indicates the significant value of REDD+ in terms of mitigating and hedging climate policy cost savings at global level.

Reduced deforestation and reforestation can save up to 22% of the cost of global climate policy, generating US\$30.6–36.4 trillion in risk-adjusted cost savings in 2030 under our principal scenario. This corresponds to US\$36–45/tCO<sub>2</sub> in terms of marginal reductions in the risk-adjusted carbon price in 2030. These benefits are dramatic given that current pay-for-performance systems for large-scale REDD+ programs are still in the range of just US\$5–10/tCO<sub>2</sub>.<sup>ii</sup> Our analysis helps underline the role that REDD+ plays in a wider mitigation portfolio in times when deforestation rates are still high and economic crises may divert attention from climate change mitigation. Our study also contributes to understanding how uncertainty translates to policy cost and shows how REDD+ can help to contain costs as well as reduce the risk of higher costs in the face of uncertainty over carbon prices, climate sensitivity and many other parameters. Finally, the results indicate that the political feasibility of more ambitious climate targets will critically hinge on the availability of REDD+, notably the protection of existing tropical forests.

Reforestation helps to further enable emissions targets consistent with maintaining total emissions until 2100 below 1200 Gt CO<sub>2</sub> so as to limit temperature increases to 2 °C or below. However, without exploiting the full REDD+ potential, this tightening of ambition quickly leads to escalating prices. Looking at temperature targets well below 2 °C, and possibly 1.5 °C, REDD+ is vitally important.

Importantly, this study abstracts from concerns of REDD+ implementation (see Lubowski and Rose, 2013). In the context of reaching ambitious climate targets, one frequent concern of allowing forest credits onto existing permit trading markets, or using them as offsets, is that relying on a large source of lower cost mitigation potential could crowd out more expensive investments. These investments are urgently needed to achieve the transition to carbon-neutrality by mid-century. While the problem does not apply to the macro-level analysis performed in this study, deployment of this option will need to introduce the necessary standards and the institutional design to avoid such outcomes (e.g. Koch et al., 2017). Enhancing climate policy ambition through the introduction of tropical forest mitigation will be key, and relying on REDD+ call options, which will be exercised in the medium to long-term at a reasonably high strike price can be a helpful instrument in this context (Golub et al., 2018).

Equally important are the current institutional barriers to the rapid implementation of REDD+ in many tropical countries, especially where environmental governance is weak and the necessary infrastructure to implement changes does not yet exist. However, previous meta-analyses find that not all aspects of improved governance are equally supportive of forest conservation (Wehkamp et al., 2018). Wehkamp et al. (2018) suggest that more nuanced analyses of specific aspects of environmental governance are necessary to guide evidence-based policy-making, which is beyond the scope of our analysis.

**Supplementary material.** The supplementary material for this article can be found at <https://doi.org/10.1017/sus.2020.34>

<sup>ii</sup>In September 2019, The Central African Forest Initiative (CAFI) in partnership with the government of Norway agreed to provide a guaranteed floor price for certified emissions reductions from REDD+ for 2016–2025, at \$5 and \$10 per ton of CO<sub>2</sub>, up to a maximum of \$75 and \$150 million, respectively, depending on the verification standard achieved (Government of the Gabonese Republic and the Central African Forest Initiative (Gabon and CAFI), 2019).

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**Conflict of interest.** None.

**Publishing ethics.** The manuscript is our own original work and does not duplicate any other previously published work. The manuscript has been submitted only to the journal *Global Sustainability* and it is not under consideration, accepted for publication, or in press elsewhere. All listed authors know of and agree to the manuscript being submitted to the journal. The manuscript contains nothing that is abusive, defamatory, fraudulent, illegal, libelous, or obscene.

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