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Estimating the potential of international carbon markets to increase global climate ambition

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ABSTRACT

By helping achieve emissions targets more inexpensively than expected, emissions trading systems can lower political resistance to more ambitious targets, enabling deeper and faster cuts in emissions over time. Using a dynamic global partial-equilibrium carbon market model, we quantify cost savings under scenarios for emissions trading within and across countries, as well as the corresponding potential to escalate reductions if those cost savings were translated into greater mitigation. We find global use of carbon markets could allow the world to nearly double climate ambition relative to current Paris pledges (NDCs) over 2020–2035, without increasing total costs compared to a base case without international markets. Significant potential to enhance ambition remain under scenarios where market participation is limited using a "heat map" analysis of countries' market readiness, as well as with policy uncertainty that delays climate investments. We also find that since protecting tropical forests offers so much low-cost mitigation potential, linking reduced deforestation to an international carbon market drives a majority of the potential ambition gains across the modeled scenarios. International markets, including for deforestation, play a potentially even more critical role as global ambition increases, with roughly double the volume and ten-fold the value of international transactions if countries' Paris pledges scale up to limit warming to 2°C. Under this scenario, global use of carbon markets lowers costs by two thirds, enabling one third more reductions for the same cost as without international markets, a gain sufficient to keep options open for limiting warming to 1.5°C. High-integrity approaches for international market cooperation—as envisioned under Article 6 of the Paris Agreement and with the inclusion of tropical forests as a priority—thus merit significant policy attention as means of closing the global emissions gap.
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1. Introduction

It is widely understood that expanding the scope of carbon markets both nationally and internationally can lower the costs of achieving global emissions targets, by enabling businesses and individuals to tap the lowest cost sources of emissions reduction available (e.g. Nordhaus & Joseph, 1999; Böhringer, 2000; Böhringer et al., 2021; Fujimori et al., 2016; Hof et al., 2017; Ranson & Stavins, 2015; Doda & Taschini, 2017; Liu et al., 2019; Parry et al., 2018; Aldy et al., 2016; Mani et al., 2018). What is less commonly emphasized—but potentially more important for the future of the planet over the longer term—is how cost savings from emissions trading could be reinvested into further abatement activities, generating deeper cuts in greenhouse gas emissions than could be achieved in the absence of trading. In this manner, by lowering total abatement costs and creating economic opportunities for firms and governments to benefit from climate policies, carbon markets offer the potential to boost climate ambition in both mandatory and voluntary contexts. Understanding this potential role of international climate cooperation through markets is critical as both countries and companies develop strategies for implementing their Paris commitments, net zero pledges and other climate goals.

Although climate goals are typically established on the basis of emissions targets, rather than expenditure targets *per se*, implementation costs are a key consideration for industry and other stakeholders with political influence. Moreover, climate policies are established iteratively over time. Carbon markets thus have the potential to lower the political resistance to increasing climate

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ambition during future periods by spurring innovation, creating a strong incentive for economic adjustment and transition planning, and helping to achieve initial targets more easily and at lower cost than expected (Keohane & Oppenheimer, 2016). This conjecture is consistent with practical experience, particularly notable within Emissions Trading Systems (ETS), also known as "cap-and-trade" programs. Under every major Emissions Trading System (ETS) to date, emissions have fallen faster and at lower cost than expected (Haites, 2018). While multiple factors have contributed to this phenomenon, periods of low prices and large "surpluses" (banks) of allowances have been followed by decisions to adopt more ambitious long-term targets. This dynamic has been observed within the European Union Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative (RGGI) and California's cap-and-trade program. This effect is more pronounced with ETS programs than with carbon tax systems, the other predominant approach to carbon pricing. While some tax systems have ratcheting provisions, most are established at low price and rarely readjusted to enhance ambition (Haites, 2018). This paper thus focuses on the potential of international carbon market cooperation under different scenarios to enable increases in climate ambition at the global level.

The need for new mechanisms to stimulate a global increase in mitigation ambition is relevant as, in the absence of such mechanisms, unilateral national action, currently codified through emissions reduction pledges under the Paris Agreement, known as Nationally Determined Contributions (NDCs), is insufficient to achieve climate goals (UNEP, 2021). While a number of studies have analyzed countries' current NDCs under the Paris Agreement, known as their Nationally Determined Contributions (NDCs) and found that, if successfully implemented, they would significantly reduce global emissions below a 2030 baseline, a significant ambition gap between current pledges and a pathway consistent with 2°C temperature rise remains (Akimoto et al., 2017; Fawcett et al., 2015; Kaya et al., 2016; Keramidas et al., 2018; Liu et al., 2019; Ou et al., 2021; Rogelj et al., 2016; Vandyck et al., 2016) (2015). While the most recent round of NDC pledge updates have significantly improved the near-term foundation for stabilizing temperatures below 2°C (Ou et al., 2021), it will still be necessary to ensure successful implementation and continued increases in ambition over time. The Intergovernmental Panel on Climate Change (IPCC, 2018) highlights enormous benefits from limiting global temperature rise to 1.5°C versus 2.°C. International markets have been proposed as a mechanism to close the global ambition gap by leveling the marginal cost of abatement across trading regions, increasing the overall efficiency of global mitigation (Aldy et al., 2016).

International emissions transfers to achieve Paris goals have been slow to emerge in practice given a lack of clarity around the rules governing such exchanges. At the end of 2021, COP26 in Glasgow saw the completion of the essential Article 6 rulemaking guidance, laying the groundwork for bi-lateral and multilateral exchanges of "Internationally Transferred Mitigation Outcomes" (ITMOs) between parties to the Paris Agreement (UNFCCC, 2021). Early demonstrations and ongoing refinements of the rules and accounting principles governing such international exchanges stand to increase clarity and accelerate such market-based collaboration.

Thus, we have structured our analysis to explore the potential contribution of international emissions trading to help increase ambition above levels currently expected if NDCs are achieved. For the purposes of this paper, rather than examining the welfare effects of alternative uses of such costs savings, we explicitly consider the question of how far such cost savings, if reinvested into greater climate ambition, could go in helping to close the "emissions gap" required to stabilize global temperatures below 2°C (UNEP, 2021).

We apply a dynamic partial equilibrium carbon market model to analyze the potential global cost savings under a set of scenarios for the development of global and regional linked carbon markets over 2020–2035. Total cost reductions are evaluated relative to a base case of current policies and measures under which the EU countries, Norway and the United Kingdom as a whole and other nations individually achieve their current NDCs in a close to cost-effective manner, similar to what would be achieved under a comprehensive domestic emissions trading system. We then examine the potential to "reinvest" the corresponding savings into raising global mitigation ambition, while breaking even on overall costs. We also explore international trading under a scenario in which countries' NDCs increase proportionately to match a pathway consistent with limiting temperatures to 2°C rise.

Other studies have estimated the potential cost savings from international carbon market linkages under the Paris Agreement (Böhringer et al., 2021; Edmonds et al., 2021; Fujimori et al., 2016; Hof et al., 2017; Rose et al., 2018; World Bank, Ecofys & Vivid Economics, 2016; Thube et al., 2022). Our analysis also builds upon a prior study which examined the potential for reinvesting gains from trade to achieve increased climate ambition focusing only on a bilateral market scenario between Brazil and the United States (Piris-Cabezas & Lubowski, 2009 cited in Nepstad et al., 2009). Our dynamic modeling framework brings advantages for analyzing carbon markets. Nevertheless, the central contribution of this study lies in the application of this framework, drawing from marginal abatement cost estimates from other models, to consider the potential role of carbon markets in enhancing climate ambition across a range of different scenarios for potential market evolution.

Our study differs in several respects from past studies. First, our study evaluates the total potential cost savings from international trading of mitigation outcomes across a range of market participation scenarios, and what the maximum increase in global ambition could be achieved through the reinvestment of such cost savings into greater ambition. While we use an idealized global market scenario as a benchmark, we consider feasibility constraints by evaluating carbon market scenarios with limited geographic and sectoral scope and with imperfect foresight on the part of market actors. As the basis for our market expansion scenarios, we conduct a "heat map" analysis to identify which countries are most prepared and inclined to implement carbon markets in the near term. As part of our intertemporal optimization, we also examine the impact of limited market certainty over future carbon market developments, which serves to delay mitigation and hamper cost-effectiveness. By considering these real-world constraints, we compare the idealized market case with potentially more realistic carbon market scenarios based on limited geographic coverage and ongoing policy uncertainty.

Second, we examine the cumulative period from 2020 to 2035. This expands upon the studies by Edmonds et al. (2021) and Thube et al. (2022) which estimated the additional reductions that could be secured with the cost savings from linkage for only one year (2030), rather than cumulatively over time.

Third, our partial equilibrium model offers greater sectoral and greenhouse gas coverage, including the potential of energy (including transport), industry, and reduced deforestation in our scenarios, evaluated across six major greenhouse gases (carbon dioxide, methane, nitrous oxide, SF6, HFC and PFC). We thus expand the scope of analysis beyond just fossil carbon emissions and energy, which have been the focus of most other analyses, with the notable exceptions of Edmonds et al. (2021) and Fujimori et al. (2016). Other studies, such as Hof et al. (2017), have included land use emissions in baseline reference scenarios, as well as NDC emissions targets, but do not explicitly model the cost savings from reducing emissions from the land sector. Previous studies have also considered the role of protecting tropical forests as part of climate stabilization pathways (e.g. Fuss et al., 2021; see Lubowski & Rose, 2013 for a review). Our analysis is the first to explore the major role of avoiding tropical deforestation (i.e. Reducing Emissions from Tropical Deforestation and forest Degradation; REDD+) to contribute to cost savings and enhanced ambition via international market linkages under the Paris Agreement.

Finally, we consider not only greater "where" flexibility, by adding additional sectors and gases, but additional "when" flexibility as well, a feature that is not considered by other studies which focus on cost-savings in individual years. Thus, our analysis is the first to evaluate the benefits of linking markets under the Paris Agreement using a dynamic model, taking into account the temporal flexibility to carry forward ("bank") emissions permits or emissions reduction credits during the 2020–2035 period to minimize costs according to expectations of future climate targets. Such flexibility is a key attribute of the cost-effectiveness of emissions trading systems (PMR and ICAP, 2016; Schmalensee & Stavins, 2017). While banking is yet to be universally agreed upon as an acceptable arrangement for meeting current NDCs, we believe it merits analysis given the critical role banking could play in facilitating the ratcheting down of emissions targets over time.

Assuming well-designed policies with accurate accounting rules and clear policy signals, we find the global use of carbon markets could allow the world to nearly double climate ambition, measured in terms of cumulative global mitigation over 2020–2035, in comparison to a pathway based on current Paris Agreement pledges (NDCs). Significant ambition gains remain under scenarios with less than half of global emissions linked via markets as well as with policy uncertainty that leads to delayed mitigation relative to the least-cost scenarios. Because reduced deforestation is such a large estimated source of low-cost mitigation, linking reduced deforestation to carbon markets accounts for most of the potential ambition gains. We also find significant potential of international markets, including tropical deforestation, to increase climate ambition—and even larger volumes and value of international transactions—under more ambitious policy scenarios consistent with 2°C.

Section 2 below describes our methods, covering the modeling framework, associated assumptions, data, and scenario construction. Section 3 presents our results. Section 4 provides discussion and we then conclude with a discussion of policy implications.

2. Methods

2.1. Model description

We develop and apply a partial equilibrium model of potential future carbon markets to examine emissions trends and abatement opportunities from 2020 through 2035 across the 27 EU countries plus the United Kingdom and 34 other countries/regions, encompassing the energy (including transportation) and industry sectors, as well as reduced tropical deforestation. The model framework, as used in Golub, Lubowski and Piris-Cabezas (2017, 2020) and first described in Piris-Cabezas and Keohane (2008) and Piris-Cabezas (2010), balances demand and supply for emissions abatement across multiple sources and sectors in a dynamic framework. The market demand for emissions reductions derives from the greenhouse gas (GHG) emissions (considering carbon dioxide, methane, nitrous oxide, SF6, HFC and PFC from industry and energy sources) under an assumed trajectory for annual emissions that establishes a hard limit or "cap" denoted as $\bar{E}_{c,t}$ on the aggregate emissions across all the sectors of each country c and year (time) t. The international aviation sector is treated as an independent "country" in this framework as international bunker fuels have their own emissions and climate commitments that are separate from national accounts under the United Nations Framework Convention on Climate Change (UNFCCC).

We evaluate scenarios for these emissions trajectories consistent with limiting emissions to the levels required for meeting each nation's currently announced NDC (first NDC), as well as additional scenarios for raising the ambition of these NDCs. The modeled trajectories determine each country's yearly and cumulative need for abatement under its current or enhanced NDC relative to a counterfactual "business-as-usual" (BAU) trajectory from 2020 through 2035. Abatement for each sector s in country c and year t is denoted as $A_{s,c,t} = \widehat{E}_{s,c,t} - E_{s,c,t}$ equal to the difference between actual and business-as-usual emissions denoted as $E_{s,c,t}$ and $\widehat{E}_{s,c,t}$, respectively. Countries' NDCs are expressed in diverse ways and do not necessarily involve a cumulative emissions budget. Nevertheless, for the purposes of our study, the aggregate annual abatement requirement to meet each country's NDC can be expressed as $\bar{A}_{c,t} = \sum_s \widehat{E}_{s,c,t} - \bar{E}_{c,t}$, where $\sum_{s=1}^{S} \widehat{E}_{s,c,t}$ is the sum of annual BAU emissions across all sectors $s = 1 \ldots S$ in each country. $\bar{E}_{c,t}$ is an aggregate annual, country-level emissions limit consistent with achieving the goals of each NDC, corresponding to the aggregate abatement requirement of $\bar{A}_{c,t}$.

In the case of international markets, demand and supply become aggregated across the participating countries and sectors, according to the scenario for market participation. The total market demand for abatement in each year—exclusive of the demand for banking abatement for use in future years, as discussed below—is the aggregation of the abatement requirements across all the countries, as well as from the international aviation sector based on commitments to reduce emissions under the International Civil Aviation Organization (ICAO). In turn, the supply of abatement is an aggregation of the estimated marginal abatement costs (MACs) for each year from the different sectors and countries included in a particular market scenario. Total and marginal abatement costs are denoted as $C(A_{s,c,t})$ and $C\prime(A_{s,c,t})$, respectively, for each sector, country, and year.

All countries plus the international aviation sector are assumed to meet their international mitigation commitments. Furthermore, we consider an idealized framework for climate policy implementation, such that all emissions reductions are accurately quantified and accounted for at the global level. In particular, only real and excess emissions reductions over and beyond what is needed to achieve each country's domestic emissions target can be exported. This is consistent with an international market scenario in which there is fully transparent accounting, with appropriate "corresponding adjustments" to ensure that emissions reductions traded internationally only count towards one international commitment, either of a country or of ICAO (Schneider et al., 2019). We also assume that market actors have the ability of market to "bank" emissions units and save them for use in later periods when caps may be tighter and corresponding mitigation costs higher. This type of temporal or "when" flexibility is typically allowed in carbon markets as a means to improve cost effectiveness (PMR and ICAP, 2016). The potential for market actors to "borrow" emissions units, delaying current mitigation in return for an obligation to make it up in the future, is often not allowed or heavily restricted in practice and is not considered in our analysis. Key assumptions for the international market scenarios are summarized in Table 1.

Based on these assumptions, the model solves for the cost-minimizing, inter-temporal equilibrium under alternative hypothetical markets for emissions units in which emissions targets can (or cannot) collectively be achieved across countries and

Table 1
Key assumptions for international trading.

- Mitigation potentials include energy (including transport) and industry sectors, as well as reduced tropical deforestation, and the six major greenhouse gases (carbon dioxide, methane, nitrous oxide, SF6, HFC and PFC) from these sectors.
- Nations achieve their domestic emissions reductions targets based on an annual trajectory that establishes an absolute limit on emissions for each sector; similarly, international aviation meets its international mitigation commitments under ICAO.
- Trading occurs based on a least-cost approach across participating nations and sectors based on marginal abatement cost curves.
- Full accounting transparency is in place for all trades of emissions reductions such that all traded units represent real mitigation and there is no double counting of reductions towards more than one international commitment.
- Banking (carry forward) of emissions units (based on emissions below the annualized target trajectory of NDCs) is permitted and occurs to the point where banked units appreciate at the rate of interest (plus a risk premium in the case of policy uncertainty).

sectors (and time periods), as described further below. For every market scenario, the model solves for the optimal amounts of abatement $A_{s,c,t}$ across each sector, country and year, as well as the associated shadow price, denoted as P_t, to solve following problem:Minimize $\sum_{s,c,t}\left(\frac{1}{(1+r)^t}\right)C(A_{s,c,t})$,subject to $\sum_{s,c,t}A_t \geq \sum_{c,t}\bar{A}_t$, where r is the real interest rate.

The constraint indicates that the total supply of abatement must equal the abatement demanded to achieve the collective emissions limits across the participating sectors, countries and time period.[1] In a market context, this means that the market must clear, such that, for every time period, the quantity of emissions reductions demanded at the current price, including banked tons, equals the quantity supplied at that price where the market price equals the marginal cost of abatement.

The first order conditions to the cost-minimization problem requires the marginal cost of abatement be equal to the shadow value of the constraint in present value terms across all sectors, countries and years, thus setting the market price of abatement across all sources of abatement as well as over time. Considering two periods t and t+1, this means that $P_t = \left(\frac{1}{(1+r)^t}\right)C'(A_{s,c,t})$= $\left(\frac{1}{(1+r)^{t+1}}\right)C'(A_{s,c,t+1}) = \left(\frac{1}{(1+r)^t}\right)P_{t+1}$. Thus, the present value of the emissions unit price must be equal in every period (i.e., the price rises at the market rate of interest). This condition accounts for the opportunity cost of capital invested in mitigation and carried over (banked) for use in future years to ensure that the present value of the marginal costs of abatement are equalized over time to the point of no intertemporal arbitrage possibility.

The real interest rate r is an important parameter that must be selected exogenously. A rate of 5% was assumed as the starting point for this analysis, but additional analyses were conducted to examine the sensitivity to this assumption and capture the role of uncertainty over future policies that establishes a risk premium for investments into banking (Golub, Lubowski, & Piris-Cabezas, 2020). An interest rate of 5% is the average historical US federal funds rate (1955–2022; Board of Governors of the Federal Reserve System, 2022), and is consistent with the basic appreciation rate of emissions allowances established under the California/Québec (Western Climate Initiative) carbon market, which establishes a minimum price floor at auction rising annually at 5% plus inflation. Finally, the model is solved using a mid-term 2035 time-horizon considering $\sum_{s,c,t}A_{s,c,t} = \sum_{s,c,t}\bar{A}_{s,c,t}$ in the aggregate for the period 2020–2035 to capture the impact that future compliance periods might have on demand for banking, based on a degree of imperfect, yet still non-zero market, foresight through 2030 and beyond.

Our analysis is grounded in the emissions projections and estimated marginal abatement cost curves from the Prospective Outlook on Long-term Energy Systems (POLES) model, a global energy-economic partial equilibrium simulation model with complete modeling from upstream production to final user demand and emissions. Estimates of emissions scenarios and marginal abatement costs from POLES were obtained from Enerdata, which updates and commercializes these estimates to carbon market actors and policy analysis. We chose to use the estimates from POLES as they are publicly available and provide consistently estimated and regularly updated information on marginal abatement cost curves across countries, sectors and gases. It is also a recognized tool from a policy perspective as it serves as the foundation for the European Commissions' major regional and global climate policy analyses.

POLES provides a set of cost estimates developed with a consistent methodology across a broad set of countries, sectors and gases. POLES was developed by Enerdata in collaboration with the European Commission's Joint Research Centre Seville and University of Grenoble and is used by the European Commission for climate policy analyses, including as the basis for its Global Energy and Climate Outlook (e.g., Keramidas et al., 2021). POLES follows a year-by-year recursive modelling, with endogenous international energy prices and lagged adjustments of supply and demand by world region, and examines the energy, transport and industry sectors, including CO_2 as well as non-CO_2 gases (Vandyck et al., 2016; Keramidas et al., 2018; Keramidas et al., 2021). The POLES model also accounts for endogenous developments in energy technologies, with impacts of public and private investment in research and development as well as learning by doing.

Enerdata further developed marginal abatement cost curves for three different scenarios built upon the POLES model: "Enerbrown," "Enerblue" and "Energreen" scenarios, which reflect estimated business-as-usual, current NDC pledges, and a 2°C-consistent emissions, respectively. The "Enerblue" scenario reflects the POLES modelers' interpretation of the myriad of climate and energy policies consistent with the NDC pledges (pre-2020 policies) as described in Vandyck et al. (2016). Each one reflects a different level of induced technological change.

We supplemented the data from POLES with country-level estimates of projected business-as-usual (BAU) emissions from tropical deforestation and the marginal costs of reducing these emissions, based on the global land-use modeling cluster of the International Institute of Applied Systems Analysis (IIASA), as described in Gusti et al. (2015). Emissions from the global agricultural sector are included within estimated global BAU emissions based on projections from the Food and Agriculture Organization (FAO) of the United Nations, but mitigation potential from agriculture was not included in this analysis. While there are various mitigation opportunities from the forest and land sector, this study focuses on reduced tropical deforestation given the availability of estimates and the importance of tropical forest conservation as the largest natural climate solution available in the near

[1] As discussed further below, our market scenarios consider "banking" but not "borrowing" of emissions units over time such that abatement requirements in future years can be met with abatement from past years but not vice versa. This means that the condition $\sum_{s,c,t}A_t \geq \sum_{s,c,t}\bar{A}_t$ must hold not just on aggregate but cumulatively at every year t from year 0 through final year T.

term, accounting for about half the estimated cost-effective potential through 2030 (Griscom et al., 2017). Reduced tropical deforestation is also the focus of international climate policy efforts, as per the framework for REDD+ affirmed under the Paris Agreement and the Glasgow Leaders' Declaration on Forests and Land Use, committing to halt and reverse global forest loss by 2030, signed by over 100 countries in November 2021.

2.2. Scenario description

We explore the impact of using international markets to meet emissions reduction goals by comparing overall compliance costs under a range of market scenarios relative to a base case where all the nations in a particular market scenario meet their current emissions targets through 2035 through domestic action alone. For each international market scenario, we further calculate a "cost-break-even" case, which indicates the amount of additional emissions reductions that are economically feasible without increasing total global costs relative to the base case without the use of international trading to take advantage of cost differentials among either countries or sectors.

As a base case for costs, we first estimate total global costs for meeting countries' Paris Agreement pledges given their existing use of markets and estimates of current sectoral plans and policies. We then quantify the cost savings under different scenarios for market coverage and integration, where market actors can lower their costs of meeting emissions limits by taking advantage of cost differentials across sectors, countries, and over time, both within and across countries.

We consider a set of idealized global market coverage scenarios where market actors have perfect information and estimate the potential cost savings and associated potential to increase climate ambition relative to the base case. We also compare those global market estimates to cases of more limited market participation across countries. All global and partial market scenarios are assessed with and without the inclusion of emission reductions from tropical forests (known as REDD+). We also consider the robustness under a case where market actors have incomplete market information that limits banking. Furthermore, to evaluate the potential role of international markets if climate ambition were to further increase, we analyze alternative global market scenarios using enhanced domestic emissions targets consistent with a global emissions pathway sufficient to limit temperature increases to 2°C. Our principal scenarios are summarized in Table 2 and corresponding assumptions are detailed further below.

2.2.1. BAU and current and 2°C NDC scenarios

The starting point of our analysis is a projection of BAU emissions and an estimate of current mitigation ambition under both each nation's current NDC pledges and enhanced ambition consistent with 2°C. Demand from the implementation of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) under ICAO was incorporated based on estimates from an interactive tool developed by the Environmental Defense Fund (EDF) that estimates overall coverage and demand from CORSIA, according to the levels of participation and offsetting obligations based on pre-2020 estimates.[2]

For the energy (including transportation), industry, and waste sectors, we consider annual emissions through 2035 from the "Enerbrown," "Enerblue" and "Energreen" scenarios from Enerdata, which reflect estimated business-as-usual, current NDC pledges, and a 2°C-consistent emissions, respectively. Global emissions are divided across 52 distinct countries/regions, including all countries of the EU-27 plus the United Kingdom. For the forestry and land-use sector, we follow the estimated BAU projections for each country developed by IIASA. We complement this with our own estimates of the cost-effective contribution of the sector to each country's NDC calibrated according to the country and global estimates provided by Forsell et al. (2016). For the 2°C scenario, we make the simplifying assumption that the mitigation ambition of the forest and land sector of each country is scaled up in the same proportion as that of the rest of the economy.

Table 2
Principal scenarios.

International Markets	Base-Case Ambition	REDD+*
No	Current NDCs	No
Global	Current NDCs	No
Global	Current NDCs	Yes
Partial: Heat Map	Current NDCs	Heat Map countries and Global
Partial: Americas	Current NDCs	Americas scenario countries and Global
Partial: Asia-Pacific	Current NDCs	Asia-Pacific scenario countries and Global
No	Enhanced 2°C NDCs	No
Global	Enhanced 2°C NDCs	No
Global	Enhanced 2°C NDCs	Yes

* Scenarios without REDD+ still include the role of tropical forests for meeting NDCs domestically but without the potential to trade additional reductions internationally.

The black line in Fig. 1 below shows global BAU emissions across all sectors, while the blue line shows emissions if countries achieve the current level of mitigation ambition under the NDCs across all sectors, and the green line showing the 2°C pathway. We estimate that, under the NDC case, currently pledged efforts entail a cumulative global reduction of 77 $GtCO_2e$ relative to BAU from 2020 through 2035, with over a quarter (27%) of these reductions estimated to come from efforts pledged from the land sector. This scenario stabilizes global emissions around current levels, beginning to bend down the trajectory of global emissions in 2024 and reducing emissions to just under 2017 levels by 2035.

While beginning to steer absolute emissions downward, the current NDC trajectory achieves less than a quarter of the reductions needed for our estimated pathway shown in green, consistent with keeping global temperatures from rising more than 2°C. The required reductions under the ambition levels of the NDC and 2°C scenarios are 77 and 246 $GtCO_2e$, respectively.

2.2.2. Base case without international markets

We consider two scenarios for achieving NDC targets with domestic policies alone.

2.2.2.1. Domestic policy base case. To establish a point of comparison for our trading scenarios, we estimate the costs of meeting our two global emissions target scenarios, NDC and 2°C, under a "base case" scenario of sector-specific country policies. This case is limited to existing use of markets (e.g., the EU ETS) and a projected mix of sector-by-sector polices and measures, based on current policy proposals for each country and assumptions of conversion over time across. This includes annual projections of energy efficiency requirements, renewable energy mandates, and transport-, industry-, and land-use-specific regulations varying across each country.

2.2.2.2. Domestic markets scenario. We then consider the case where each country can meet the cumulative reductions required by their NDCs at least-cost domestically via a carbon market or

[2] The tool is available at: https://www.edf.org/climate/icaos-market-based-measure.

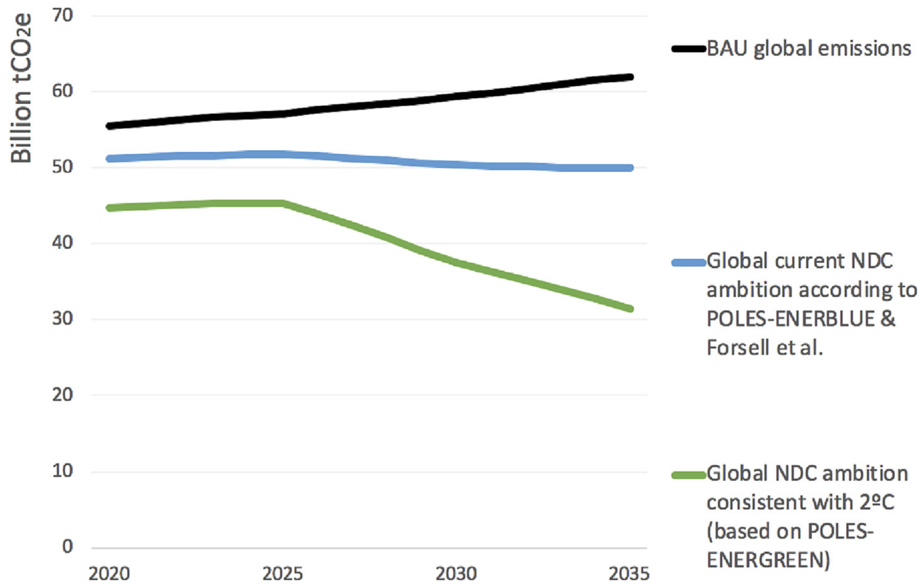

Fig. 1. Global emissions under business-as-usual (BAU), Paris Agreement pledges, and ambition consistent with a 2°C limit based on POLES emissions reduction trajectories.

other carbon pricing approach that achieves their target at least cost. Our model ensures marginal abatement costs are equalized across sectors and that market actors can optimally select the timing of their emissions reductions to achieve cumulative reductions at least-cost, assuming a discount rate of 5% to account for the cost of capital.

2.2.3. Full global markets

We next consider scenarios where all countries can cooperate through market trading to achieve their domestic targets at least cost. We analyze costs under a fully global market where trade is possible across all countries, and where it is also possible to cost-effectively select the timing of mitigation through banking.

2.2.3.1. With and without REDD+. Until recently, with the approval of REDD+ standards under CORSIA at the end of 2020, efforts to address emissions from tropical forests had been left out of compliance carbon markets. To isolate the potential importance of market-based approaches to protecting and restoring tropical forests, we consider a case where market actors can use emissions reductions from land use for their own emission target, but can only trade emissions internationally across the energy, transport, and industry sectors. We then examine the added benefit of allowing further trading of reductions from REDD+. We analyze these global scenarios for both the current NDC trajectory and the enhanced NDCs consistent with limiting warming to 2°C.

2.2.3.2. Limited anticipation. We also test the robustness of cost saving estimates under the full global market scenario using a sensitivity analysis that relaxes the assumption that market actors can bank emissions reductions based on perfect foresight regarding future climate policy requirements. We consider a case where market actors are uncertain about future mitigation requirements and therefore delay emissions reductions relative to the least-cost scenario. Regulatory and policy uncertainty will tend to induce market actors to adopt a wait-and-see attitude to mitigation investments, which will depress market demand (Golub, Lubowski, & Piris-Cabezas, 2020). We model this case by introducing a risk premium added to the 5% interest rate used in the perfect foresight scenarios. This risk premium gradually declines over time but lowers the benefit of banking emissions reductions for use in future periods compared to the case with full market certainty. Following the scenario of Golub, Lubowski, and Piris-Cabezas (2017), we assume the risk premium falls at five-year intervals, to reflect greater information that increases certainty over future policy. We assume a risk-adjusted interest rate, starting at 20% in 2020, falling to 15% in 2025 and 10% in 2030. The model is solved iteratively over 2020–2035, 2025–2035 and 2030–2035, carrying over the amount of emissions reductions banked from the previous runs.

2.2.4. International markets with partial country participation

To examine the robustness of results to alternative assumptions regarding the extent of international market cooperation, we consider a range of scenarios that constrain the assumption of a comprehensive global market and perfect foresight over time. For simplicity, we focus these scenarios on the case of current NDC targets.

We consider three cases for partial international market development, in which only subsets of countries participate in international trading. All countries continue to be engaged in meeting their NDCs, but partial market development only enables certain countries to take advantage of the cost savings from international trading. All these scenarios also include implementation of CORSIA under ICAO based on current levels of participation. Given the pivotal role of REDD+ for each partial market scenario, we also model scenarios where the limited global markets are open to additional REDD+ volumes above and beyond what tropical countries use to meet their own NDCs. In the Americas case, described below, we consider all of the additional REDD+ supply from Brazil, Mexico, Colombia, Peru as well as 50% of the potential supplies from rest of the world (Asia and Africa). In turn, in the Asia-Pacific case, described below, we consider the full additional REDD+ from Indonesia, Thailand and Malaysia and 50% of the potential supplies from rest of the world (Latin America and Africa).

Our limited participation scenarios are informed by our "heat map" analysis that applies a political economy perspective to indicate which countries are most likely to both demand and supply market-based climate policies. Notably, the heat map analysis ranks countries based on their readiness and importance in terms of emissions (both directly and via links to other important countries), rather than in terms of their ability to maximize gains from trade in a market system. Details on the heat map analysis are provided in the Appendix. All scenarios consider the EU, United States, and China, which rank highest on the heat map and then add additional groupings of countries to explore alternate scenarios for how carbon markets might evolve globally or along regional lines. Our three scenarios are described below and represented in the three world maps in Fig. 2a–c. (These maps do not show the additional country suppliers of REDD+ mitigation that are considered in the scenarios where the partial markets described below are opened up to reductions from tropical forests from other parts of the world.).

2.2.4.1. Global 'Heat Map' scenario. This scenario involves a global market based on the economy-wide coverage of the EU and the United Kingdom, United States, and China and the next 25 highest-ranking countries from our heat map analysis (see Appendix). This results in an estimated 79% coverage of current global emissions. This percentage declines slightly over time as the emissions from some of the countries not included in the heat map are growing relative fast, including in terms of emissions from deforestation.

2.2.4.2. Asia-Pacific scenario. This scenario envisions the regional evolution of a carbon market in Asia, as could emerge around China, South Korea, and Japan (e.g. Ewing, 2016), drawing in the highest-ranking countries from the heat map analysis in the Asia-Pacific region, as well as linking with Kazakhstan, given its existing ETS, but not yet including South Asia. This scenario includes economy-wide coverage of China, Thailand, Vietnam, Indonesia, Malaysia, South Korea, Japan, Singapore, Philippines, Kazakhstan, Australia, and New Zealand. This regional market development is assumed to catalyze coverage of all sectors in China. The scenario also includes participation from the EU, Norway and the United Kingdom as well as the U.S., but with their coverage limited to the power and industrial sectors (as per the current coverage of the EU ETS). This scenario results in estimated coverage of 42% of current emissions.

2.2.4.3. Americas scenario. This scenario explores the potential impact of the countries and subnational jurisdictions within the Western Climate Initiative and the Pacific Alliance leading to a greater coverage throughout the Americas. Such carbon market cooperation was envisioned by the Declaration on Carbon Pricing in the Americas (CPA) signed in 2017 by the governments of Canada, Chile, Colombia, Costa Rica, and Mexico, plus two US states and five Canadian provinces. This scenario envisions such a market that brings in all the highest-ranking countries from the heat map analysis across the Americas, including both the United States and Brazil. This scenario includes 100% coverage of the U.S., Canada, Mexico, Colombia, Peru, Chile, Argentina, and Brazil. The scenario also includes participation from the EU, Norway, the United Kingdom as well as China, but as above, with their coverage limited to the power and industrial sectors, as per the current coverage of the EU ETS. This scenario results in an estimated coverage of about 36% of current global emissions.

3. Results

Across all scenarios, we find significant cost savings associated with international market cooperation, with global trading including REDD+ resulting in the largest potential cost savings. These costs savings occur because there is a large spread in ambition across countries, resulting in lack of cost-effectiveness globally. Table 3 shows the wide range of modeled carbon prices under the base NDC case. In the scenarios based on current NDCs, reinvesting such cost savings into further emissions reductions yields potential increases in global ambition ranging from 18 to 70 $GtCO_2e$ of cumulative additional mitigation over 2020–2035, producing a 24% to 91% increase in ambition.[3] In the scenarios with enhanced NDCs consistent with 2°C, the potential further gains in ambition total 28–83 $GtCO_2e$ cumulatively, producing 11–34% greater ambition, depending on the inclusion of tropical forest mitigation.

Next, Section 3.1 presents results for the potential of international trading to increase ambition relative to current NDC pledges. Section 3.2 considers the potential role of international trading to further increase ambition in the case of enhanced NDCs consistent with 2°C. Section 3.3 summarizes estimated carbon prices across all the scenarios.

3.1. Potential to increase ambition relative to current NDC case

3.1.1. Domestic policy base case

Cumulative reductions under the base case where all countries act independently to achieve their current NDCs amount to 7 $GtCO_2e$ from 2020 to 2035. Achieving these reductions without any emissions trading—considering mitigation potentials across energy, transport, industry, waste, and tropical forests—has estimated global abatement costs totaling US $520 billion in present discounted terms, based on a 5% interest rate, or about 0.67% of global gross domestic product (GDP) in 2017.

3.1.2. Domestics markets scenario

Our estimates of the total cost savings from implementing purely domestic carbon markets in all nations yield a 4% reduction in total abatement costs relative to the domestic policy base case, which assumes a mix of sectoral policies. These cost savings are limited given that mitigation ambition is relatively low and the base case scenario already includes contributions across all sectors, including a large contribution from the forest sector and cost-effective achievement of NDCs within, if not across, each of the modeled sectors. Given these assumptions, the base case is therefore already akin to the result achieved under the use of carbon pricing. If we were to develop a model with greater granularity for non-market policies within each country and sector, the cost savings from implementing domestic markets would likely be substantially larger.

3.1.3. Full global markets

Global trading in emissions lowers total costs of meeting current NDCs relative to the domestic policy base case (by an estimated 62%—from over half a trillion to $197 billion current dollar terms—in the case of a global market that covers emissions from energy, transport, and industry sectors, but where reductions in tropical forest emissions (REDD+) are applied to meeting domestic targets only. This scenario for reducing the costs of achieving current NDCs results in average yearly international trade volumes of 1.1 $GtCO_2e$/year, averaged over 2020–2035, with average yearly financial flows of $19.7 billion per year.

If the large mitigation potential from reducing tropical forest emissions is included in the global market, costs of attaining the NDC trajectory fall an additional 43% relative to the prior case, from $197 to $111 billion, such that overall cost savings are 79% relative to the NDC base case. Average international trade volumes more than double from 1.1 to 2.6 $GtCO_2e$/year over 2020–2035 in the cases without and with REDD+ included in the international market, respectively. However, the value of yearly average financial flows from these trades decreases relative to the case without

[3] The lower bound corresponds to a scenario with partial coverage and without REDD+ (Asia-Pacific scenario). The upper bound corresponds to the scenario with global coverage with REDD+.

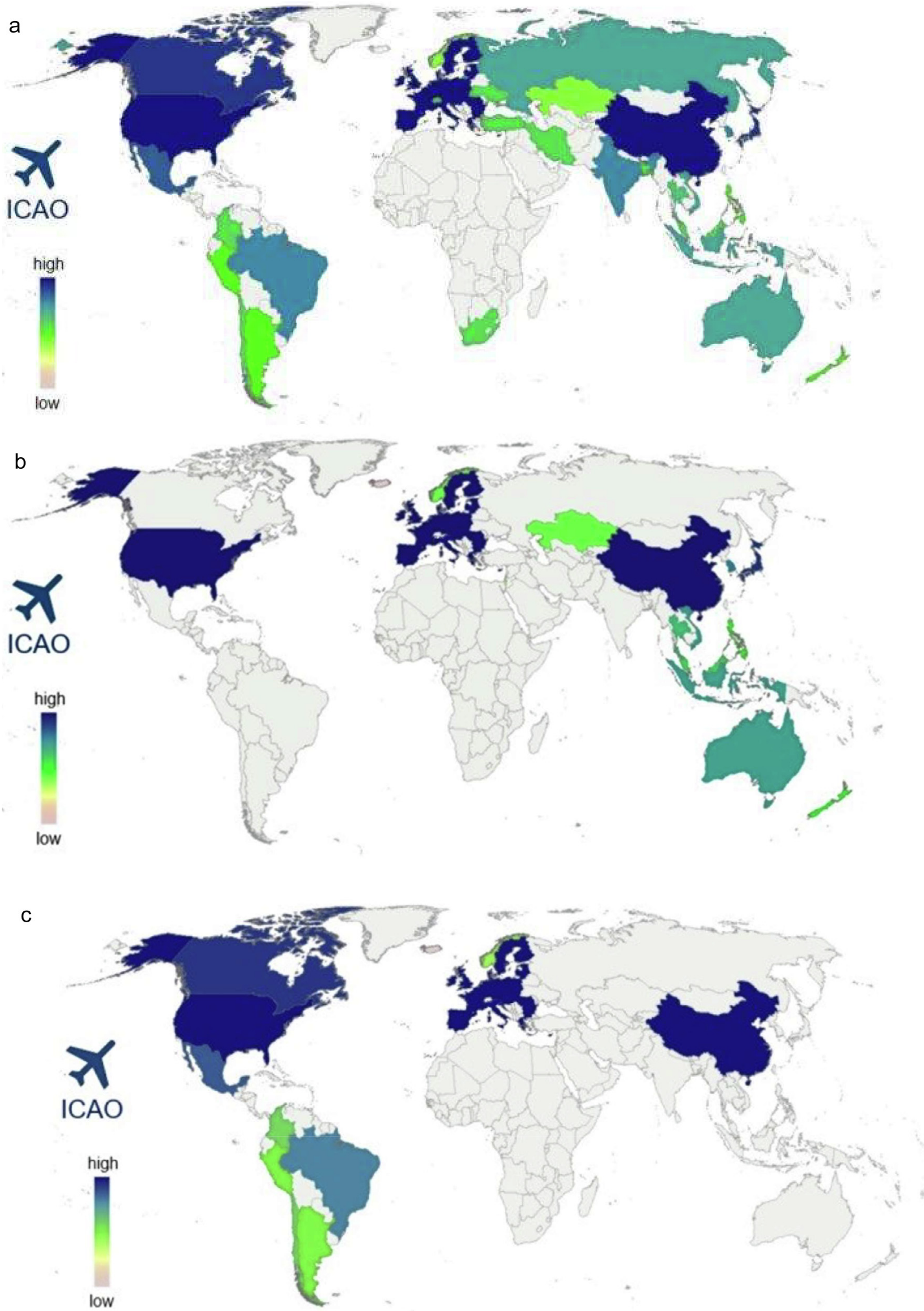

Fig. 2. a: global 'heat map' market scenario. b: Asia-pacific market scenario. c: Americas market scenario. Note: scenarios are based on top-ranked countries from 'Heat map' analysis discussed in Appendix A, with colors based on the Carbon Markets Societal Readiness and Strategic Priority score for each country from lowest (pink) to highest (dark blue). All scenarios include the international aviation market under CORSIA. Coverage of EU, Norway) and United Kingdom is limited to the power and industrial sectors in the Asia-Pacific and Americas scenarios. Coverage of the US and China is limited to the power and industrial sectors in the Asia-Pacific and Americas scenarios, respectively. Unless otherwise noted, coverage is economy wide.

Table 3
Spread in ambition across countries, as shown by estimated carbon price in 2020, 2025, 2030 and 2035 assuming domestic trading across energy and industry. ($/t$CO_2$e).

Country/Regional Grouping	2020	2025	2030	2035
EU27+ (EEA) & United Kingdom	$36.0	$46.0	$58.7	$74.9
United States of America	$45.4	$57.9	$73.9	$94.4
China	$6.3	$8.0	$10.2	$13.0
Australia	$14.6	$18.6	$23.8	$30.4
South Korea	$41.0	$52.3	$66.8	$85.2
South Africa	$6.6	$8.5	$10.8	$13.8
Canada	$46.7	$59.7	$76.1	$97.2
Mexico	$4.8	$6.1	$7.8	$10.0
Japan	$16.8	$21.4	$27.3	$34.9
Chile	$0.6	$0.8	$1.1	$1.3
New Zealand	$13.1	$16.8	$21.4	$27.3
Turkey	$1.6	$2.0	$2.6	$3.3
Thailand	$1.0	$1.3	$1.6	$2.1
Indonesia	$0.0	$0.0	$0.0	$0.0
Brazil	$0.9	$1.1	$1.5	$1.9
Argentina	$0.9	$1.2	$1.5	$1.9
Morocco & Tunisia	$1.1	$1.4	$1.8	$2.2
Viet-Nam	$1.8	$2.2	$2.9	$3.7
Malaysia	$0.5	$0.6	$0.8	$1.0
Philippines	$0.0	$0.0	$0.0	$0.0
India	$3.4	$4.3	$5.5	$7.1
Russia	$1.3	$1.6	$2.1	$2.6
Ukraine	$1.5	$1.9	$2.4	$3.1
Egypt	$1.5	$1.9	$2.4	$3.1
Rest of Europe	$0.0	$0.0	$0.0	$0.0
Gulf countries	$1.7	$2.2	$2.8	$3.6
Middle East Med.	$0.4	$0.6	$0.7	$0.9
Algeria & Libya	$1.0	$1.2	$1.6	$2.0
Rest of South and East Asia	$1.2	$1.5	$2.0	$2.5
Rest of South America	$0.7	$0.9	$1.1	$1.4
Rest of CIS	$1.3	$1.6	$2.0	$2.6
Rest of Central America & the Caribbean	$0.3	$0.4	$0.5	$0.7

REDD+, from $19.7 to $15.6 billion per year due to a roughly 50% reduction in the average carbon price across the period, as shown in Table 4 and discussed in Section 3.3.

Translating the prospective costs savings global markets into the potential for greater climate ambition, while still "breaking even" on total global costs relative to the base case, yields the total global mitigation levels shown in Fig. 3. A global market without and with REDD+, respectively, offers the opportunity to raise total cumulative reductions over 2020–2035 from 77 to 109 and 147 GtCO_2e, without any added costs compared to the base case—an increase of 91%. This means the costs savings from trading could cover the costs of increased ambition by 42% if trading is limited to the industrial and energy sectors. In the scenario with market-based REDD+, overall ambition could thus increase by 70 GtCO_2e or almost double (91%) relative to the base case, while keeping total costs the same. Relative to current Paris pledges, this increase in ambition enables about 60% versus 30% of the total mitigation required under the 2°C-consistent scenario.

These results indicate that market-based REDD+ could play a pivotal role in enabling greater global climate ambition because of its large potential supply and relatively low mitigation costs. The cost savings from REDD+ enable 38 GtCO_2e (or 54%) of the total increase in ambition of 70 GtCO_2e possible with full global trading. Including market-based REDD+ in the global market not only lowers costs significantly, but also provides a large additional pool of low-cost reductions that can be "bought" with the resulting cost savings. These additional reductions are over and above the contributions from REDD+ in the domestic policy base case scenario where reductions in emissions from tropical forests comprises 27% of the estimated reductions under current levels of NDCs. In total, REDD+ amounts to 52% of the cost-effective reductions over 2020–2035 in the case of global cost break-even ambition with full global trading. REDD+ accounts for 55% of the total cost-effective emissions reductions under current levels of NDC ambition over 2020–2035. The relative share of reductions stemming from REDD+ fall at higher levels of ambition, as more reductions are required from both REDD+ as well as the other sectors worldwide, as discussed in Section 3.2.

Modeling policy uncertainty via a risk premium on the interest rate increases costs by 18% to $131 billion (in current dollar terms) in the case of a full global market with REDD+. Even so, this still achieves 95% of the cost savings as under the case of full certainty and thus enabling equivalent increases in the level of mitigation ambition.

We next examine the potential to enable greater ambition through cost savings under the more limited scenarios for international market development.

3.1.4. International markets with partial country participation

We find that, among the partial coverage scenarios applied to the NDC-consistent emissions targets, the global heat map, Asia-Pacific, and Americas scenarios reduce global costs by 51%, 49%, and 51% relative to the base case without markets. The cost savings rise to 63%, 56%, and 59%, respectively, when trading includes market participation from additional countries (beyond those in each scenario) via REDD+. The Americas and Asia-Pacific scenarios lead to 47% and 52% of global coverage by carbon markets by 2030 respectively.

Notably, the cost savings from the Asia-Pacific and Americas markets are similar, despite the lower coverage of global emissions under the former scenario. This similarity stems from the more ambitious NDCs in the U.S. and Canada, compared to those in China, as shown by the estimated carbon prices in Table 3 above. This is because the gains from trade result from the interaction of both demand and supply for reductions—that is, not only the availability of low-cost reductions but also the demand for these

Table 4
Summary of modeled carbon prices under alternative global market scenarios (\$/tCO_2e).

	REDD+*	Ambition	2020	2025	2030	2035
Global	No	Current NDC	\$7.4	\$9.4	\$12.0	\$15.3
	Global	Current NDC	\$3.7	\$4.7	\$5.9	\$7.6
	Global	Extended (cost break-even compared to current NDC)	\$10.4	\$13.2	\$16.9	\$21.6
	No	Enhanced NDCs consistent with 2°C	\$90.4	\$115.4	\$147.3	\$188.0
	Global	Enhanced NDCs consistent with 2°C	\$49.6	\$63.2	\$80.7	\$103.2
	Global	Extended (cost break-even compared to enhanced NDC consistent with 2°C)	\$112.0	\$143.0	\$182.5	\$233.0

* Scenarios without REDD+ still include the role of tropical forests for meeting NDCs domestically but without the potential to trade additional reductions internationally.

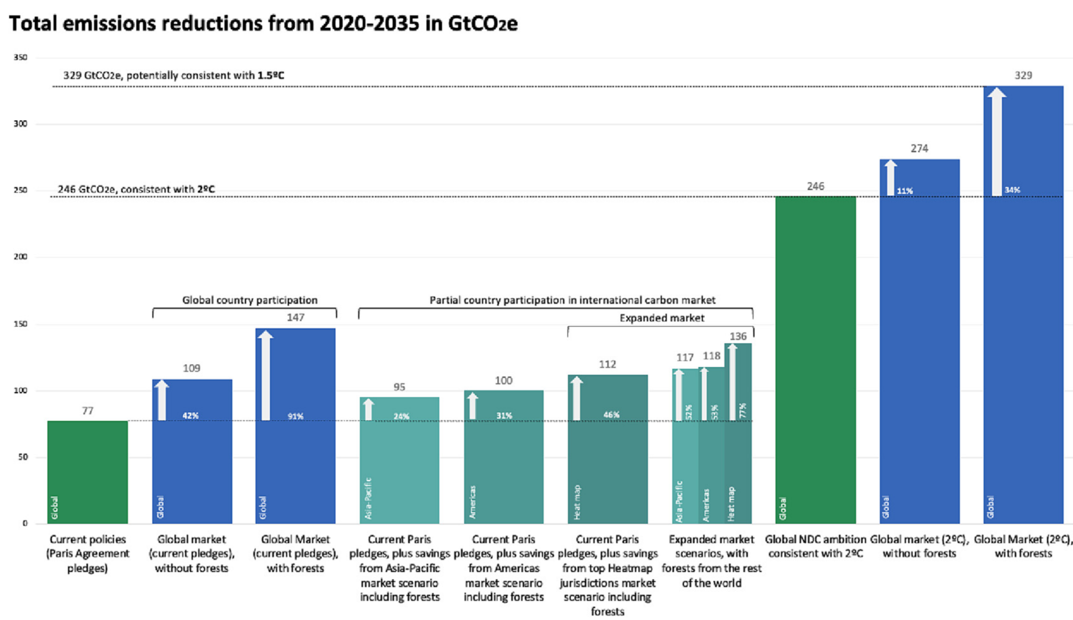

Fig. 3. Increase in total emissions reductions from reinvesting cost savings from emissions trading under different market configurations and Paris Agreement pledge ambition. Note: Cumulative mitigation over 2020–2035 shown in blue under global market scenarios and turquoise under partial market scenarios, keeping overall costs constant relative to the base case without markets (except in EU plus Norway and United Kingdom), shown in green.

reductions driven by more ambitious NDCs and higher costs in countries that would be net buyers in a market.

Our results with partial market coverage are summarized in Fig. 3 above, including a comparison to the break-even ambition enabled by a full global market, as discussed above. We find that the Asia-Pacific and Americas markets both enable similar increases in ambition, enabling about a quarter to a third of the increase in ambition relative to the case of full global trading. This enables the world to reach about two-thirds of the total potential reductions under the case of full trading.

The global market with all the heat map countries enables about half of the increase in ambition, enabling the world to reach more than three quarters of the level of ambition attainable in the case of full trading (without increasing costs relative to the base case of the current Paris Agreement pledges). When additional countries can participate via REDD+ (Fig. 3), the gap is further narrowed such that the two regional market scenarios and the 'Heat map' market scenario enable 57–59% and 84% of the increase in ambition, respectively, relative to the full trading case. This represents an increase of 52%, 53% and 77%, respectively, relative to total emissions reductions under current policies as depicted in Fig. 3. In these cases, the world can reach 80% to 92% of the total reductions under the full trading case.

3.2. Potential to increase ambition relative to enhanced NDCs consistent with 2°C

3.2.1. Base case without international markets

Cumulative reductions under the 2°C case amount to 246 $GtCO_2e$ from 2020 to 2035. Given this 2°C scenario, the global abatement cost for each country to limit its emissions in the least cost manner domestically, but without the benefit of international carbon trading, is estimated at \$950 billion in present discounted terms. This is about 80% more than the base case of current NDC ambition, despite about triple the total emissions reductions. The less than proportionate increase in costs is explained as costs are discounted and most of the difference between the NDC and 2°C trajectories occurs towards the end of the period, as shown in Fig. 1. The significant mitigation from tropical forests contributing to NDCs in the 2°C case further contains the increase in costs.

3.2.2. Full global markets

A fully global carbon market excluding and including tropical forests reduces total presented discounted abatement costs by 29 and 65%, respectively, relative to the case where the enhanced 2°C NDCs are achieved without international cooperation. The scenario without REDD+ results in average transaction volumes estimated at 2.0 $GtCO_2e$/year compared to 1.1 $GtCO_2e$/year in the case of a global market without REDD+ based on current NDC ambition. However, annual financial flows average at $179.0 billion per year, an order of magnitude greater than in the current ambition case, due to significantly higher carbon prices, as shown in Table 4. In the case where REDD+ is included in the international market, the international trading volumes doubles again, from 2.0 to 3.8 $GTCO_2e$/year, without and with REDD+, respectively, and the average financial flows rise from $179.0 to $188.3 billion per year, despite the lower prices when reduced deforestation emissions are part of the market.

Reinvesting the cost savings from a global market into greater emissions reductions could increase cumulative reductions from 2020 to 2035 by about 11%, in the case without REDD+, and by 34% in the case with REDD+, for the same total present discounted cost as without an international market (Fig. 3). A global market without and with REDD+, respectively, offers the opportunity to raise total cumulative reductions over 2020–2035 from 246 to 274 and 329 $GtCO_2e$, without any added costs compared to the 2°C ambition case without international markets. As in the case of current NDC targets, including REDD+ in international markets enables the largest share of these ambition gains, even though the contribution of REDD+ to meeting domestic targets has also been increased. Introducing REDD+ enables 55 $GtCO_2e$ or two-thirds out of 83 $GtCO_2e$ of total added reductions, holding constant the total cost of mitigation as in the case without international trading. Notably, this increase in global mitigation ambition is sufficient to put the world on a trajectory that keeps open options for limiting warming to the 1.5°C, based on modeled pathways from the European Commission (Keramidas et al., 2018).

3.3. Carbon prices

Tables 2 below summarizes modeled carbon price signals across the different global market scenarios discussed above. Under a globally integrated carbon market that excludes REDD+, estimated carbon prices range from $7.4/$tCO_2e$ to $58.7/$tCO_2e$ in 2020 (rising 5% per year afterwards), depending on whether market demand is set by only the current NDCs or from an expectation of required action consistent with 2°C. In the cases where REDD+ is included, prices range from $3.7 to $33.9/$tCO_2e$ in 2020 (rising 5% per year afterwards) in the current and NDC 2°C scenarios, respectively. Under the "cost break-even" scenario where global mitigation ambition is increased in line with the cost savings resulting from international market cooperation, including REDD+, the carbon price starts at $10.4 in 2020 (rising 5% per year afterwards). This is higher than in the case of a market without REDD+ but where ambition is limited to current pledges.

Table 5 below summarizes the modeled carbon prices under alternative partial market scenarios to achieve current levels of NDC ambition. In general, prices are lowest in the case of a global market that includes all "Heat map" countries, ranging from $6.6 to $9.2 in 2020 (with and without REDD+) compared to $9.5-$10.9 and $8.4-$13.5 in the Asia-Pacific and Americas market scenarios, respectively. Prices are also sensitive to the extent of inclusion of REDD+ in international trading. For the "cost break-even" scenarios, with REDD+ supply limited to the core market participants, market prices range between $13.5 and $16.8 per ton of CO_2e in 2020 rising 5% per year afterwards. With extended REDD+ supply from additional countries, market prices range between $11.4 and $14.2 per ton of CO_2e in 2020 rising 5% per year afterwards.

4. Discussion

In the case of current NDCs, our results of the potential cost savings from a fully global market range from 62 to 79%, depending on the inclusion of REDD+. Our idealized global market results are consistent with other studies, notably Fujimori et al. (2016), despite different methodologies. Fujimori et al.'s study is based on Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) and estimates that a global market, inclusive of land use, based on current NDCs would reduce global welfare loss by 75% and produce a price of around $9/$tCO_2$ in 2030, comparable with our estimates.

Our results on the potential for reinvested cost-savings from a fully global carbon market to increase climate ambition are also consistent with results from the Edmonds et al. (2021) and Thube et al. (2022) studies, which estimated these potential gains, albeit for only one year (2030), rather than cumulatively over time. Edmonds et al. (2021) estimate that cost-savings from international cooperation can enhance global mitigation by 113% in 2030 compared to the pledged NDCs, with more than half of those gains coming from nature-based solutions. This compares to our estimate of a potential 91% increase in global climate ambition and a 54% share for REDD+ for the period 2020–2035. While Thube et al. (2022) only considered CO_2 emissions from burning fossil fuels and excluded other sources of emissions, they found that global cooperation in reaching the NDCs could lower total costs by 60% in 2030, compared to our estimate of 62% over 2020–2035.

Our estimated percentage savings are also in line with Rose et al. (2018) analysis of a global carbon market for power and industry sectors that evolves in a stepwise manner to help meet NDCs. They estimate cost savings ranging from 59%, 75% and 72%, as markets progressively integrate by 2020, 2025 and 2030, up to the point where 50% of global emissions are covered. Nevertheless, Rose et al.'s study generates significantly higher prices compared to our idealized case. Potential explanations may be that their analysis considers a market with a more restricted scope in terms of sectors and gases and is not intertemporal in nature.

While not including any land-use activities, under their mid-range emissions scenario, Hof et al. (2017) find that global emissions trading can reduce the costs of NDC implementation by 56% for unconditional NDC targets and by 44% for conditional NDC targets. The World Bank, Ecofys and Vivid Economics (2016) estimate that international emission trading of cardon dioxide from energy and industrial sectors could reduce the total abatement costs of achieving 2°C by about a third by 2030 and half by 2050. These estimated cost savings are more modest than our findings, perhaps given that our analysis (along with Fujimori's) considers a broader range of mitigation activities as well as a longer time-period (2020–2035, versus 2030 only in the World Bank study).

Our analysis still potentially underestimates the benefits of markets, as we did not consider opportunities for trading of non-CO_2 emissions from agricultural activities and we limited our consideration of forestry to reducing deforestation and degradation, without including the potential of reforestation and improved forest management. Furthermore, our analysis only considers cost savings from an equalization of expected marginal abatement costs across countries, without consideration of the potential benefits from ongoing buffering idiosyncratic market or policy shocks across countries, which Doda and Taschini (2017) estimate can produce significant added savings. Our analysis also does not examine food security, forest conservation, sustainable development, and other potential non-climate benefits of international climate cooperation.

Moreover, our estimated increase in ambition is mostly due to the gains from international trade, and not the increase in use of domestic markets to meet national targets. Expanding the use of markets from the base case to the "full trading" scenario can be divided into two steps: first, broadening the use of emission trad-

Table 5
Summary of modeled carbon prices under alternative partial market scenarios (\$/tCO_2e).

	REDD+*	Ambition	2020	2025	2030	2035
Heat map	No	Current NDC	\$9.2	\$11.8	\$15.0	\$19.2
	Heat map countries	Current NDC	\$6.6	\$8.4	\$10.8	\$13.7
	Heat map countries	Extended (cost break-even)	\$13.5	\$17.2	\$22.0	\$28.1
	Global	Extended (cost break-even)	\$11.6	\$14.8	\$18.9	\$24.1
Asia-Pacific	No	Current NDC	\$10.9	\$14.0	\$17.8	\$22.8
	Asia-Pacific countries	Current NDC	\$9.5	\$12.1	\$15.4	\$19.7
	Asia-Pacific countries	Extended (cost break-even)	\$15.8	\$20.1	\$25.7	\$32.8
	Global	Extended (cost break-even)	\$11.4	\$14.6	\$18.6	\$23.8
Americas	No	Current NDC	\$13.5	\$17.3	\$22.0	\$28.1
	Americas countries	Current NDC	\$8.4	\$10.8	\$13.7	\$17.5
	Americas countries	Extended (cost break-even)	\$16.6	\$21.1	\$27.0	\$34.4
	Global	Extended (cost break-even)	\$14.2	\$18.2	\$23.2	\$29.6

* Scenarios without REDD+ still include the role of tropical forests for meeting NDCs domestically but without the potential to trade additional reductions internationally.

ing as an instrument of domestic policy, with the "full trading" scenario assuming that every country in the world uses an internal carbon market to meet its NDC; second, linking those markets through international trading. Both steps yield cost savings, and thus potential increases in ambition. Our modeling suggests that the predominant share of the gains from global markets are due to international linking, with a much smaller share coming from increased use of domestic carbon markets. This suggests that carbon pricing policies that encourage international cooperation—such as carbon markets—may be able to capture significantly more cost savings, and thus increased ambition, than carbon pricing policies that are less prone to linkage. Furthermore, our results indicate that increasing ambition increases, rather than decreases, the overall size of the market for international trades. This highlights that international trading will be increasingly important as deeper reductions are needed.

These findings come with an important qualification due to the nature of our model. While the model is fairly disaggregated among countries, it is relatively coarse within countries, because only four sectors are modeled: energy, transport, industry, and forestry and land-use. Because the model assumes least-cost abatement in each sector within each country (including within the EU-region aggregate), it effectively assumes the use of within-sector emission trading or other market-based policies, rather than more costly command-and-control measures. More fine-grained sectoral coverage would yield greater estimated cost savings due to greater within-country trading. Nonetheless, virtually the entire cost savings (96%) in our analysis are due to international linking, with just 4% of estimated cost savings coming from increased use of domestic trading. At the least, this suggests that the potential for gains from international trade are significantly greater than the gains from intersectoral trade within each country.

This study also focuses on the implications of international cooperation for emissions abatement costs, without considering impacts of international emissions trading on markets for other goods and services, both internationally and domestically. While our analysis yields qualitatively similar results to some general equilibrium studies (e.g. Fujimori et al., 2016), future model intercomparison efforts (e.g. Böhringer et al., 2021) are needed to examine sensitivities to specific model frameworks and data. Studies could further examine the potential for different international market scenarios to increase ambition, as well as other co-benefits of climate mitigation, in a general equilibrium context. Such analyses could identify lower as well as higher costs for particular countries given changes in terms of trade for other goods and services that could negate the benefit of trading (Babiker et al., 2004). General equilibrium analyses could also analyze impacts on international emissions leakage across countries and explore alternative policies such as border carbon adjustments and other market designs to address these issues (PMR and ICAP, 2016).

Another caveat of our study is that it does not capture the recent decline in global emissions, notably from international aviation, and the potential longer-term implications for the global economy resulting from the COVID-19 pandemic. These changes could either facilitate or hinder further reductions in line with NDCs depending on the strength, speed and characteristics of the economic recovery and the extent to which stimulus spending and other public policy measures align with climate priorities. Examination of these issues are priorities for future work.

Finally, a fully global carbon market is unlikely in the medium term, given differences in country readiness as well as political hurdles to linking markets, particularly when these could entail large financial resource transfers among countries. There may also be environmental justice concerns over trading that could, at least in the short run, increase emissions in buying countries (and reduce associated air quality and other local benefits) in exchange for mitigation abroad. Even so, our partial sector coverage models indicate that even limited trading conditions evolving around regional lines—potentially consistent with ongoing cooperation on trade, environmental quality, migration, and other regional strategic issues—can significantly boost global climate ambition.

Significant practical hurdles also remain to operationalize a large-scale market with environmental integrity and low transaction costs, including on the development of common standards for monitoring, reporting and verification (MRV). Nevertheless, there has been major progress. The LEAF Coalition, a public–private partnership that has mobilized over \$1 billion to date to pay for emissions reductions from tropical forest protection at large national and subnational scales, provides a potential model for high-integrity standards for enhanced ambition both on the supplier side, as well as on the buyer side (Lubowski, 2021).

5. Conclusion

Our findings suggest that the development of well-designed and high-integrity approaches for international market cooperation, as envisioned under Article 6 of the Paris Agreement, as well as the inclusion of REDD+, merit significant policy attention as a means of closing the global emissions gap. We find that the global use of emissions trading, based on well-designed accounting rules and the banking (carry-forward) of emissions units over 2020–2035 could allow the world to nearly double climate ambition without increasing aggregate costs relative to countries' acting purely independently to achieve their NDCs. Most of these potential gains come from the inclusion of REDD+, suggesting it is an immediate priority for international market development.

While international emissions trading and REDD+ offer major potential to boost climate ambition, the cost savings from carbon markets in the "break-even" scenarios based on current NDCs do not yield enough ambition relative to what is necessary to avoid warming of less than 2°C. On the one hand, breaking even on costs compared to current levels of ambition is a low bar for increasing future commitments. Nevertheless, just based on this requirement, global trading gets 60% of the way to the 2 °C scenario. Total ambition could be further increased by expanding global carbon market coverage through the development of high-integrity approaches that can realize cost-effective emissions reductions from nature-based climate solutions not contemplated in this modeling exercise, including from agriculture.

Our study also suggests that international markets, including forests, can play a potentially even more critical role as global ambition increases, with roughly double the volume of international transactions and ten-fold the value of trading if countries' Paris pledges are scaled up to limit warming to 2°C. Under this scenario, global use of carbon markets lowers costs by two thirds, enabling one third more mitigation for the same cost as without international markets, a gain sufficient to keep options open for limiting warming to 1.5°C.

In summary, our study points to the potential role of international climate cooperation to facilitate more cost-effective achievement of targets, easing political hurdles to increasing climate ambition. Nevertheless, it is not automatic that countries will translate cost savings from markets into greater ambition. Future research is needed on policy designs and processes that can best ensure continued ratcheting of ambition as envisioned under the Paris Agreement and to build confidence in this dynamic. If forward-looking market actors can anticipate this eventual ratcheting-up of ambition, they would have incentives to act early to take advantage of lower cost abatement opportunities in order to avoid future cost increases. This has the potential to activate a virtuous circle that could further help close the ambition gap and put the world on track towards meeting the Paris Agreement goals.

CRediT authorship contribution statement

Pedro Piris-Cabezas: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Ruben N. Lubowski:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Gabriela Leslie:** Methodology, Formal analysis, Writing – review & editing, Visualization.

Data availability

The authors do not have permission to share data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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