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HOW MUCH COULD ARTICLE 6 ENHANCE NATIONALLY DETERMINED CONTRIBUTION AMBITION TOWARD PARIS AGREEMENT GOALS THROUGH ECONOMIC EFFICIENCY?

JAMES EDMONDS*, SHA YU† and HAEWON MCJEON‡

Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352, USA
**jae@pnnl.gov*
†sha.yu@pnnl.gov
‡Haewon.McJeon@pnnl.gov

DIRK FORRISTER

International Emissions Trading Association
24, rue Merle d'Aubigné
CH-1207 Geneva, Switzerland
forrister@ieta.org

JOSEPH ALDY

Harvard Kennedy School, Harvard University
79 John F. Kennedy Street
Cambridge, MA 02138, USA
joseph_aldy@hks.harvard.edu

NATHAN HULTMAN‡ and RYNA CUI§

Center for Global Sustainability
School of Public Policy, University of Maryland
3101 Van Munching Hall
College Park, MD 20742, USA
‡hultman@umd.edu
§ycui10@umd.edu

STEPHANIE WALDHOFF

Pacific Northwest National Laboratory
P.O. Box 999, Richland, WA 99352, USA
stephanie.waldhoff@pnnl.gov

*Corresponding author.

LEON CLARKE

Center for Global Sustainability
School of Public Policy, University of Maryland
3101 Van Munching Hall
College Park, MD 20742, USA
lclarke@umd.edu

STEFANO DE CLARA[¶] and CLAYTON MUNNINGS[‖]

International Emissions Trading Association
24, rue Merle d'Aubigné
CH-1207 Geneva, Switzerland

Energy and Resources Group
University of California Berkeley
310 Barrows Hall, Berkeley, CA 94720
[¶]*declara@ieta.org*
[‖]*clayton_munnings@berkeley.edu*

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The Paris Agreement of 2015 uses Nationally Determined Contributions (NDCs) to achieve its goal to limit climate change to well below 2°C. Article 6 allows countries to cooperatively implement NDCs provided they do not double-count mitigation. We estimate that economic efficiency gains from cooperative implementation of existing NDC goals using Article 6 could reduce the cost of achieving NDC goals in 2030 to all parties by $\sim\$300 \times 10^9$, which if reinvested in additional emissions mitigation could add 9 billion tons CO_2/year mitigation, beyond the 8 billion tons CO_2/year currently pledged in 2030. We estimate that more than half of the 2030 gains could come from nature-based measures, but long-term potential for nature-based measures is more limited. How much or even if this economic potential can be realized is uncertain and will depend on both the rules and their implementation.

Keywords: Paris agreement; article 6; market mechanisms; emissions trading; enhanced ambition.

1. Introduction

The Paris Agreement of 2015 (United Nations, 2015) established under the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992) aims to hold "the increase in global average temperature to well below 2°C above pre-industrial levels and [to pursue] efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (United Nations, 2015). Under the Paris Agreement, each country pledges a Nationally Determined Contribution (NDC) reflecting near-term (through 2025 or 2030) intentions to reduce national emissions toward meeting the long-term Paris goal (UNFCCC, 2015). Current pledges are insufficient to limit the average surface temperature to 1.5°C (IPCC, 2018). The intent of Article 6 of the Paris Agreement is to facilitate enhanced ambitions through gains in efficiency by reducing the variability in the marginal cost of abatement across countries (Aldy *et al.*, 2016; Mani *et al.*, 2018; UNFCCC, n.d.), allowing parties to cooperatively implement NDCs either working together directly or using internationally transferred mitigation outcomes, as long as parties avoid double-counting (Schneider *et al.*, 2019). Article 6 allows for many cooperative systems, including linkage among homogeneous policies (e.g., multiple market-based policies), linkage among heterogeneous policies (e.g., carbon tax and performance standards) (Bodansky *et al.*, 2016; Mehling *et al.*, 2018), and potentially other innovative approaches (e.g., regional carbon clubs) (Nordhaus, 2015, 2019; Keohane *et al.*, 2017). The lower abatement costs realized through co-operation may increase political appetite for more ambitious targets when NDCs are reviewed (Keohane and Oppenheimer, 2016). Approximately half of the NDCs signal interest in using forms of international cooperation through Article 6 (World Bank Group and Ecofys, 2018).

Negotiators at the 25th Conference of the Parties to the UNFCCC (COP25) remained unable to reach consensus on the rules for Article 6 (UNFCCC, 2018) and mandated parties to continue efforts toward developing rules for COP26. Despite intense focus by diplomats and analysts on how to implement Article 6, with the exception of Fujimori *et al.* (2016), Hof *et al.* (2017), and Edmonds *et al.* (2019), little work has focused on quantifying the potential economic and environmental opportunities offered by Article 6. We analyze two primary questions. What are the potential cost savings from full cooperation in implementing the NDCs? And if the cost savings were reinvested in additional ambition, how much additional emissions mitigation could be enabled?

In exploring these questions, we will include all carbon emissions including both viz. those arising from fossil fuel and industrial sources and those arising from land-use change. In the latter case, we track emissions and absorption. We will report the marginal cost of implementing NDCs independently, cooperatively, and in an ENHANCED AMBITION case in which the ambition is enhanced by applying the cost savings from the cooperative implementation of NDCs.

We will examine the aggregate and geographic distribution of Article 6 economic efficiency gains, potential re-allocation of emissions mitigation, the distribution of transactions between land-use change and fossil fuel mitigation, and the associated financial flows. We will estimate the potential for enhanced ambition at regional scales. We will then recalculate physical and financial flows, and the distribution of transactions involving fossil fuel and industrial mitigation as compared to nature-based mechanisms.

While this paper focuses primarily on the potential benefits of cooperative implementation of NDCs, we recognize the critical role that the rules play in achieving all or part of that benefit. Well-written rules can enable reduced costs and enhanced ambition. But poorly written rules could open the door to mischief such as double-counting, reduced ambition, and increased emissions.

2. Approach

We simulate a reference and three alternative scenarios. We adopt the shorthand notation given in Table 1 to identify the four different cases.

Table 1. Scenario notation.

Scenario Short Name	Scenario
REFERENCE	Reference scenario assuming no additional actions to reduce CO_2 emissions beyond those in place in 2010
INDEPENDENT	Independently implemented unconditional NDCs
COOPERATIVE	Cooperatively implemented unconditional NDCs
ENHANCED AMBITION	Enhanced ambition potentially enabled if all savings from cooperative implementation of NDCs were deployed to enhance NDC ambition

We use the Global Change Analysis Model (GCAM), v.5.13 (Joint Global Change Research Institute, 2017, 2018) to develop the four scenarios. GCAM is an open-source, integrated assessment model, with a global scope with disaggregation to 32 geopolitical regions (Calvin *et al.*, 2019; Clarke and Edmonds, 1993; Edmonds and Reilly, 1983). It links the energy, economy, agriculture, and land-use systems within a unified computational framework that solves all systems simultaneously and consistently. The REFERENCE scenario that is our counterfactual benchmark uses the GCAM representation of the Shared Socioeconomic Pathways Scenario 2 (SSP2), reported in Calvin *et al.* (2017). The analysis was prepared prior to the onset of the COVID-19 pandemic and therefore does not include the effect of year 2020 shutdowns nor the potential enduring effects of a possible post-2020 recession. The analysis remains relevant in that it is examining potential benefits. And, by using the SSP2 scenario, it is comparable to other studies in the literature.

In the independently implemented NDC scenario, INDEPENDENT, we assume regions implement their unconditional NDC contributions. Regional NDCs are estimated using individual country NDCs (UNFCCC, n.d.). We use the approach first employed in Fawcett *et al.* (2015) (see: https://science.sciencemag.org/content/sci/suppl/2015/11/24/science.aad5761.DC1/aad5761_Fawcett-SM.pdf). This approach is briefly summarized as follows. Because national NDC submissions are heterogeneous, regional emissions limits are built up offline, country by country, for 2020, 2025, and 2030. For contributions that are prescribed relative to a baseline, we use either a business-as-usual (BAU) scenario if it is provided in the NDC submission or our REFERENCE scenario. For regions with multiple countries, we calculate each country's implied emissions limit from its NDC and sum up to obtain the regional limit.

For post-2030 emissions, we assume that countries continue to decarbonize at the same annual rate required to meet their NDCs between 2020 and 2030. If a decarbonization rate is below 2% per year, we set the rate of decarbonization to 2% per year.

We track all anthropogenic net carbon emissions including net changes to terrestrial carbon stocks resulting from actions to achieve NDCs. We enforce the "no double-counting" requirement both in domestic mitigation and in international transactions under Article 6. As we will discuss later in the paper, double-counting and implicit reductions in NDC ambition are major issues in negotiations.

The REFERENCE scenario includes 2010 policies, but not additional measures intended to achieve NDC outcomes. NDCs are not anticipated to be achieved in our REFERENCE scenario. The REFERENCE scenario serves as a counterfactual scenario to compare with the mitigation scenarios described below.

NDCs are generally defined in terms of an outcome in a specific compliance year, e.g., 2025 or 2030. Emission limitations or other policies are generally not defined for interim, non-compliance year states. We assume that progress toward achieving NDC goals occurs linearly with time. In our COOPERATIVE implementation scenarios, we act as if the non-compliance year limits are a linear interpolation between 2015 emissions and the NDC in the compliance year. Similarly, for countries with compliance years prior to 2030, we assume that post-compliance year-implicit NDCs are an extension of the linear interpolation to 2030.

By construction, global CO_2 emissions are the same in the INDEPENDENT and COOPERATIVE scenarios. Countries in the COOPERATIVE scenario are allowed to combine their obligations and cooperatively achieve their combined decarbonization goals so as to minimize combined mitigation cost.

The marginal abatement costs associated with achieving NDC goals independently vary widely across countries. For some countries it is more cost effective to cooperate with other countries that have lower marginal abatement costs than to reduce emissions domestically. While global emissions are identical in INDEPENDENT and COOPERATIVE scenarios, emissions in individual countries are different. Some countries emit more than their NDC but offset those increases with purchases of additional emissions mitigation from other regions. Thus, there is no net change in emissions across the aggregation of all countries. Similarly, each country keeps the same level of ambition in the INDEPENDENT and COOPERATIVE scenarios.

We calculate the marginal cost of a country's emissions mitigation in its INDEPENDENT implementation case as the idealized marginal cost of achieving its emissions mitigation in an economically efficient manner. This is the approach taken by the studies listed in Table 2, for example, Fujimori *et al.* (2016), Hof *et al.* (2017), and Edmonds *et al.* (2019), making our results comparable to other studies. But all studies utilizing this approach, including this one, underestimate the marginal cost of achieving NDC carbon mitigation goals independently when heterogeneous measures are utilized. In addition, they do not capture marginal ancillary benefits accruing to the use of individual policy instruments, e.g., fuel economy standards, to improve multiple metrics simultaneously such as carbon emission reductions, local air-quality benefits, and energy independence. Our assumption should thus be treated as a simplifying approximation.

The reduction in total mitigation costs in the COOPERATIVE scenario, as compared to INDEPENDENT scenario, is distributed among the countries as it were utilizing international trade via a carbon market, with each country "buying" or "selling" the difference between its NDC and the international distribution of global least cost mitigation. Article 6 allows carbon markets, but also allows other cooperative mechanisms.

To estimate the potential increase in ambition that could be enabled by Article 6 we create an ENHANCED AMBITION scenario. The ENHANCED AMBITION scenario is created by calculating region-by-region savings from economic efficiency offered by Article 6 and then reinvesting those savings in additional emissions mitigation.

To create our ENHANCED AMBITION scenario, we first sum the total cost of achieving NDC goals independently. We use this amount as the global emissions mitigation budget. Emissions in the ENHANCED AMBITION scenario are the emissions that would have been achieved had the cooperative total net emissions mitigation cost been as large as the total cost of achieving NDC goals independently. We then calculate the individual regional emissions ambition that leaves each region with the identical emissions cost as experienced in the INDEPENDENT scenario.

Mechanically, we obtain the global cost of achieving NDCs as the sum of regional costs in our INDEPENDENT scenario. That sum becomes the global emissions mitigation budget. We then find the common global carbon price that exhausts that mitigation cost budget. This creates our ENHANCED AMBITION scenario. At the end of this process, the total global cost of emissions mitigation is identical in both the INDEPENDENT and ENHANCED AMBITION scenarios. But the ENHANCED AMBITION scenario is obtained in an economically efficient manner and thus exhibits greater global emissions mitigation than the INDEPENDENT scenario.

The ENHANCED AMBITION scenario is in a sense the complement to the COOPERATIVE scenario. The INDEPENDENT and COOPERATIVE scenarios share common global physical emissions but have different regional and global total costs. The INDEPENDENT and ENHANCED AMBITION scenarios share a common global total cost but have different global emissions. The increase in global emissions mitigation in the ENHANCED AMBITION scenario compared to the INDEPENDENT scenario is the potential for enhanced global ambition.

We can distribute those potential enhancements back to individual regions by using the domestic regional cost differences between the INDEPENDENT and ENHANCED AMBITION scenarios and then backing out the transfer necessary to leave each region with the same total cost as in its INDEPENDENT scenario. Those transfers can then be translated into emission transfers, which can in turn be combined with each region's ENHANCED AMBITION domestic mitigation to calculate the implied level of ENHANCED AMBITION in each region. The difference between the original INDEPENDENT ambition and the calculated ENHANCED AMBITION is a region's enhanced ambition.

A mathematical description of this calculation is provided in the Supplementary Material.

Our calculation is constructed as if emissions mitigation were an issue that can be isolated from other societal consequences. It takes no account of either ancillary benefits or costs. If NDCs were intended to achieve multiple benefits including nonclimate goals, for example, improved local air quality or energy security, then net emissions mitigation costs (mitigation cost less the value of ancillary benefits or costs) could diverge from mitigation costs. We discuss this further later in the paper.

3. Results

Emission mitigations across all sources are allowed to be traded in a carbon market regardless of whether the underlying activities reduced fossil fuel and industrial or net land-use change emissions.

3.1. *Cost savings from cooperation implementation of NDCs*

We first consider independent implementation of NDC goals for each of the 32 GCAM regions for 2030, the INDEPENDENT scenario. In the figures, we order and color the 32 regions into regional subsets such as North America, Africa, and OECD Pacific, based on geospatial proximity and similarity of economies as shown in Fig. 1(a).

CO_2 emissions for the INDEPENDENT scenario are displayed in Fig. 1(b), while the corresponding distribution of marginal costs for the 32 GCAM regions is reported in Fig. 1(c). The wide divergence in shadow prices for carbon emissions mitigation creates the opportunities for trade to lower the total societal costs of emission reductions from our reference (current policies only) emissions pathway. This is the classic gains to trade economic principle. Countries with high marginal costs can reduce costs with a trade at any price lower than their marginal cost, and countries with low marginal costs can gain by undertaking greater emissions mitigation and transferring the credit for the associated emissions to the high-marginal-cost region at any price above their marginal cost of emissions mitigation. The marginal cost at which there are no additional opportunities to lower costs by redistributing emissions between the economies is shown in *red* in Fig. 1(c).

Regional changes in emissions in the COOPERATIVE scenario relative to INDEPENDENT scenario are shown in Fig. 1(d). The sum of positive values (regions with increases in mitigation) represents the size of the virtual physical (as opposed to financial) carbon market, approximately between 4 net $GtCO_2$/year and 5 net $GtCO_2$/year are exchanged in 2030, representing roughly half of total global mitigation. A cooperatively implemented, efficient emissions mitigation effort would redistribute roughly 10% of the total global emissions in 2030. Both the INDEPENDENT and COOPERATIVE cases deliver approximately 8 $GtCO_2$/year in 2030 calculated as the difference between reference emissions and INDEPENDENT and COOPERATIVE emissions.

The net effect of the cooperative implementation scenario is to redistribute emissions mitigation patterns in two dimensions. More emissions mitigation occurs in non-OECD countries and less emissions mitigation occurs in OECD countries. This shifts investments in lower-emissions energy technology from the high-marginal-cost regions, principally the OECD regions, toward low-marginal-cost regions, principally the non-OECD regions.

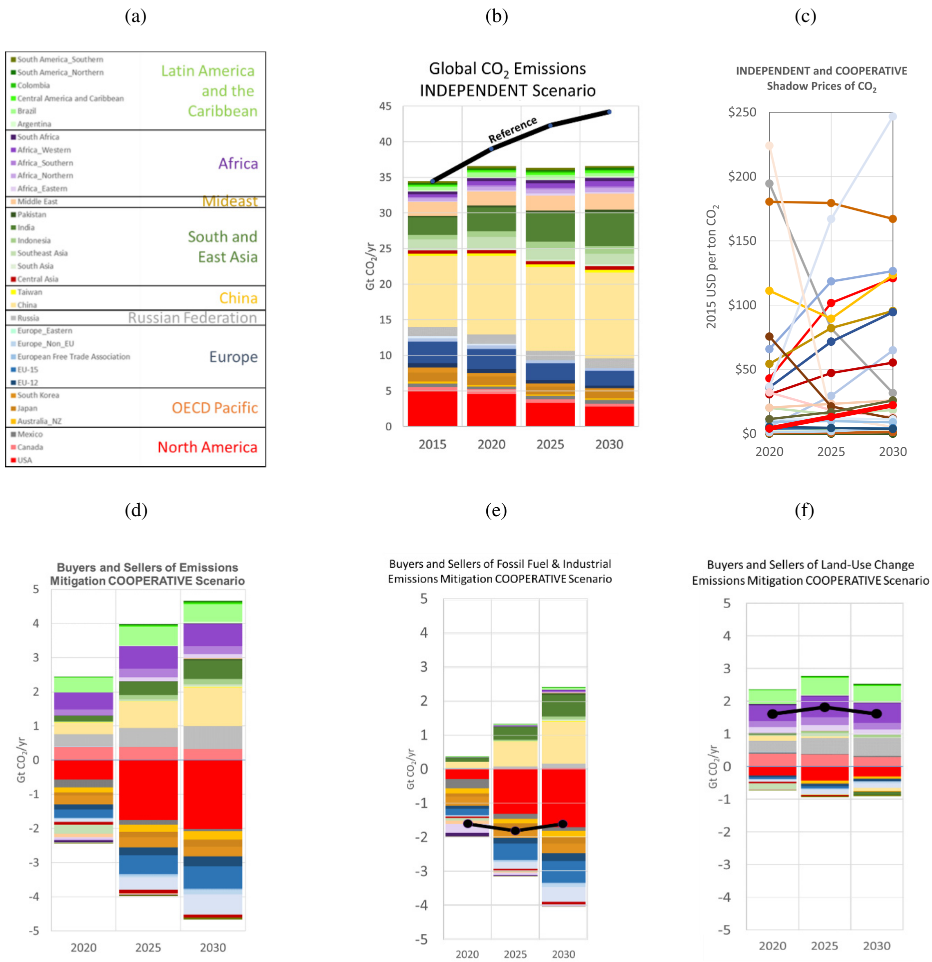

Figure 1. (Color online) CO_2 emissions (2015–2030). Panel (a) provides the regional key. Panel (b) shows regionally disaggregated emissions for the INDEPENDENT scenario. Panel (c) shows the shadow prices for carbon by region (INDEPENDENT scenario) and the solid red line indicating the common cooperative marginal cost for carbon in the COOPERATIVE scenario. Panel (d) shows the change in emissions associated with the transition between the INDEPENDENT and COOPERATIVE scenarios. Positive values denote increased emissions mitigation, while negative values are reductions in domestic mitigation. The sum of negative and positive values is zero in panel (d). Panel (e) shows the change in fossil fuel emissions included in panel (d). Panel (f) shows the change in land-use change carbon emissions represented in panel (d). The black line in panels (e) and (f) show the net change in global emissions between the INDEPENDENT and COOPERATIVE scenarios for fossil fuel and industrial emissions [panel (e)] and global land-use change emissions [panel (f)].

Emissions mitigation is also shifted from fossil fuel and industrial emissions mitigation toward land-use change emission reductions. Figure 1(e) shows a negative net change in fossil fuel and industrial emissions, *black* line. Figure 1(f) shows the corresponding positive net change in land-use change emissions, *black* line.

Table 2. COOPERATIVE collaborative carbon prices (2015-USD per ton CO_2).

Year	2020	2025	2030
This study	**$4**	**$13**	**$22**
Fujimori *et al.* (2016)	—	—	$9
AIM/CGE 2.0 ADVANCE	$10	$29	$73
POLES ADVANCE	$3	$19	$38
WITCH-GLOBIOM 4.4 CD-LINKS	$0	$11	$28
POLES CD-LINKS	$6	$14	$23
REMIND-MAgPIE 1.7–3.0 CD-LINKS	$2	$16	$16
REMIND 1.7 ADVANCE	$2	$15	$15
MESSAGEix-GLOBIOM 1.0 CD-LINKS	$0	$29	$10

Source: Fujimori *et al.* (2016), the Â IAMC 1.5Â°C Scenario Explorer hosted by IIASA, https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.

The near-term, 2030, carbon prices are shown in Table 2. These results align well with Fujimori *et al.* (2016), which estimated the carbon price in 2030 to be $9/t$CO_2$, and Hof *et al.* (2017), that estimated that costs could be reduced between 56% and 44%, depending upon whether unconditional or conditional NDCs were used.

The financial flows, valued at the COOPERATIVE common carbon price, are shown in Figs. 2(a)–2(c). Total market volume is around 100×10^9 2015-USD per year in 2030. Our 2030 estimate falls within the range of the World Bank's estimate of \$100–400 $\times 10^9$ 2015-USD in 2030 (Kossoy *et al.*, 2015), but is significantly greater than Fujimori *et al.*'s (2016) estimate of $58 billion (2015-USD) in 2030.

We report the direct economic cost by region in Fig. 2 for the INDEPENDENT scenario [panel (d)] and COOPERATIVE scenario [panel (e)]. Total global direct economic costs across all regions decline significantly between INDEPENDENT and COOPERATIVE scenarios. Direct economic costs are increasing for countries that are emissions mitigation sellers, while decreasing for emissions mitigation buyers. The net cost reduction by region is calculated as the difference in regional direct total cost, negative for sellers and positive for buyers, plus the value of emissions mitigation sales, positive for sellers and negative for buyers. The net change in cost including transfers is reported in Fig. 2(f).

Note that the larger the participation in the trading market the greater the benefit to participation. This follows from the fact that participation in the carbon market is the direct result of large differences in marginal cost of mitigation and hence the largest gains to trade. Regions with shadow prices for carbon close to the COOPERATIVE collaborative value have little potential to gain from trade.

3.2. *Application of cost reductions from economic efficiency to enhanced ambition*

We employ our region-by-region estimates of net economic cost reductions (reduction or increase in emissions mitigation cost plus net sales from offsets) shown in Fig. 2

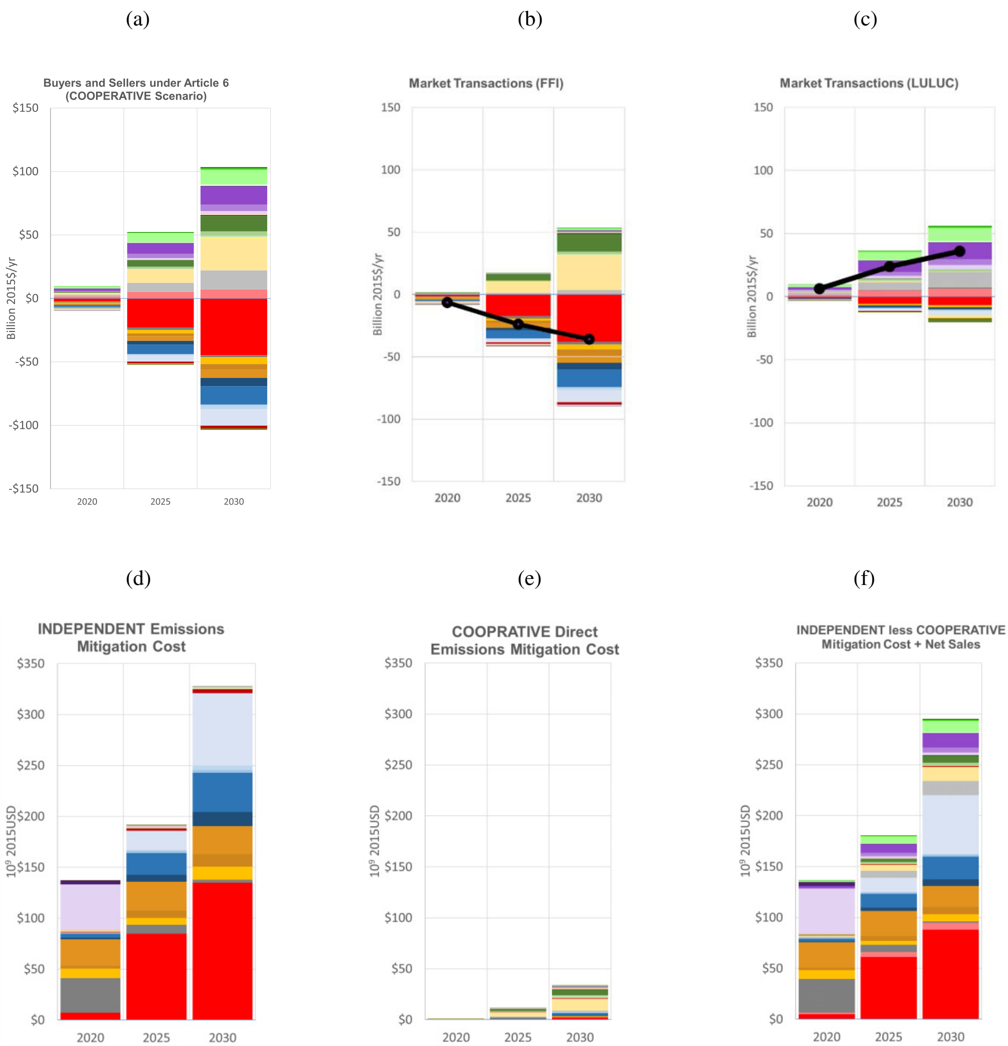

Figure 2. Transfer payments associated with cooperative implementation calculated as the COOPERATIVE scenario carbon price multiplied by the corresponding change in emissions. Negative values represent purchases. Positive values represent sales. Panel (a) shows the value of total global net market transactions induced by cooperation. Panel (b) shows the value of net global transactions from fossil fuel and industrial sources alone. Net global change from fossil fuel and industrial activities is shown by the black line. Panel (c) shows the value of net global transactions from land-use change sources alone. Net global change from land-use change activities is shown by the black line. Panel (d) shows the INDEPENDENT emissions mitigation cost by region. Panel (e) shows the COOPERATIVE emissions reduction costs incurred by region. These costs do not include the value of cooperation-induced transfers. Panel (f) shows the change in cost by region: INDEPENDENT direct mitigation cost less COOPERATIVE direct mitigation cost plus net sale (purchase if less than zero) of offsets. Note that the regional color key can be found in Fig. 1(a).

resulting from cooperative implementation of NDCs to estimate the potential enhanced ambition that could be enabled by fully cooperative implementation of emission mitigation if all savings were reinvested in additional emissions mitigation under a fully cooperative scenario. This is our ENHANCED AMBITION scenario. A detailed description of the calculation method can be found in Supplementary Material at the end of the paper.

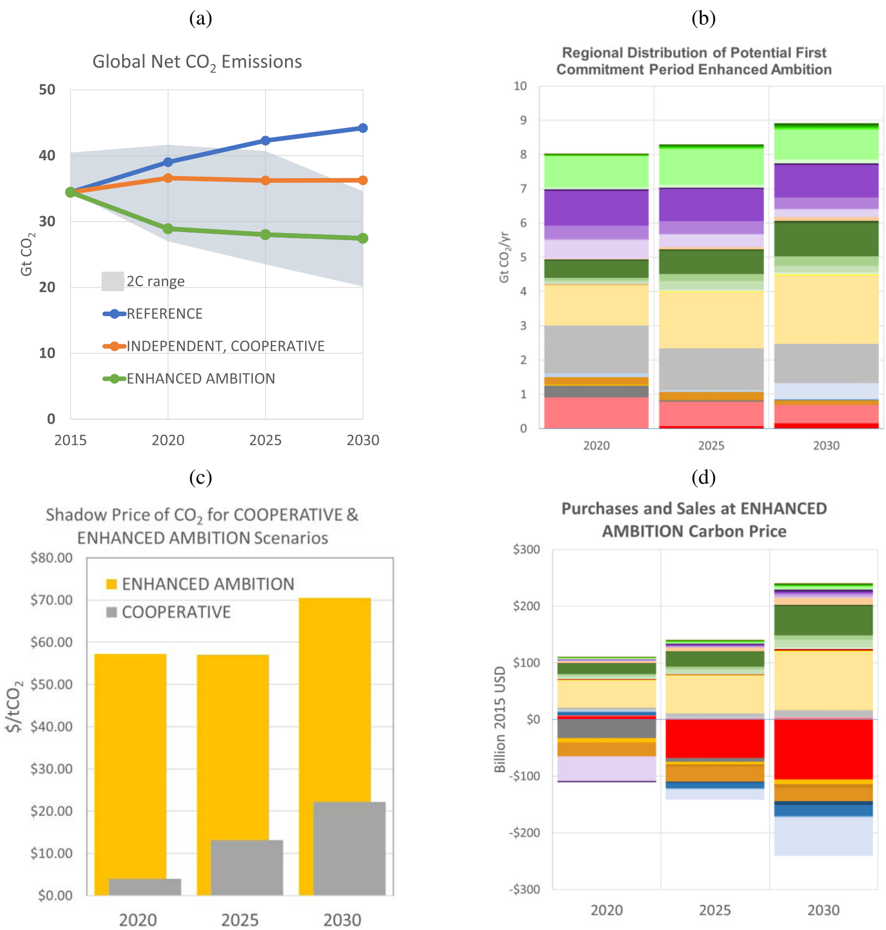

Figure 3. Enhanced ambition enabled by Article 6. Panel (a) compares the global emission trajectories of INDEPENDENT scenario, which is identical to the COOPERATIVE scenario, with ENHANCED AMBITION and the REFERENCE scenarios and the 2°C-consistent, open-literature scenario range. Panel (b) shows the increase in emissions mitigation between ENHANCED AMBITION and INDEPENDENT scenarios, disaggregated by region. Panel (c) compares the shadow price of carbon in the COOPERATIVE and ENHANCED AMBITION scenarios. Panel (d) shows the financial transactions that correspond to the physical mitigation under an ENHANCED AMBITION scenario (Sales > 0 and Purchases < 0). Note that the regional color key can be found in Fig. 1(a).

Results of these calculations are shown in Fig. 3. Figure 3(a) shows the global ENHANCED AMBITION scenario emissions compared to the REFERENCE and INDEPENDENT/COOPERATIVE scenarios. As background, we show the range of open-literature 2° emission scenarios. While INDEPENDENT ambition in 2030 lies outside the range of open-literature Paris-consistent scenarios, the ENHANCED AMBITION scenario emissions are within the range found in the open literature for the year 2030.

Emissions mitigation in 2030, defined as the increase in emissions mitigation in the ENHANCED AMBITION scenario relative to the INDEPENDENT scenario, is more than doubled. Figure 3(b) shows the regional emission mitigation enhancement in the ENHANCED AMBITION scenario relative to the INDEPENDENT scenario. It is worth noting that the increase in ambition is greatest for the seller regions observed in Fig. 2(a).

The common carbon price that enables enhanced ambition is shown in Fig. 3(c). The ENHANCED AMBITION scenario adds roughly \$50/tCO_2 to the cooperative global carbon price in 2030 compared to the COOPERATIVE scenario. The requisite financial transfers to leave each region with identical total cost as in the INDEPENDENT scenario are shown in Fig. 3. The carbon market financial flows are larger in the ENHANCED AMBITION scenario than in the COOPERATIVE scenario, both because the carbon price is higher and the physical flows of emissions mitigation transfers are also larger.

3.3. *The role of nature-based solutions*

Article 6 collaborative emissions mitigation shifts emissions mitigation toward nature-based solutions as shown in Fig. 1. This increases the land area that is engaged in emissions mitigation. However, there are limits to land-use change emissions to offset fossil fuel-based emissions. We assume that the same ambition exhibited in first contribution period continues into the future. Under that assumption land-use emissions mitigation declines steadily over time until 2050, at which point land-use change emissions are greater in the INDEPENDENT scenario than in the COOPERATIVE scenario, Fig. 4.

Figure 4(c) shows the fraction of enhanced ambition accounted for by land-use change emissions mitigation. Through the first NDC contribution period, 2030, land-use change contributes more than 50% of the total emissions mitigation. However, under the continued ambition scenario assumption, land-use change emissions decline as a share of total enhanced emissions mitigation. Land-use change emissions remain a component of emission enhancements relative to the INDEPENDENT scenario throughout the century. By 2050 the share has fallen to less than 20%, and by 2100 is only 5% of enhanced ambition.

There are several factors at work shaping the relatively greater near-term impact of including nature-based solutions in the mitigation mix. First, nature-based solutions

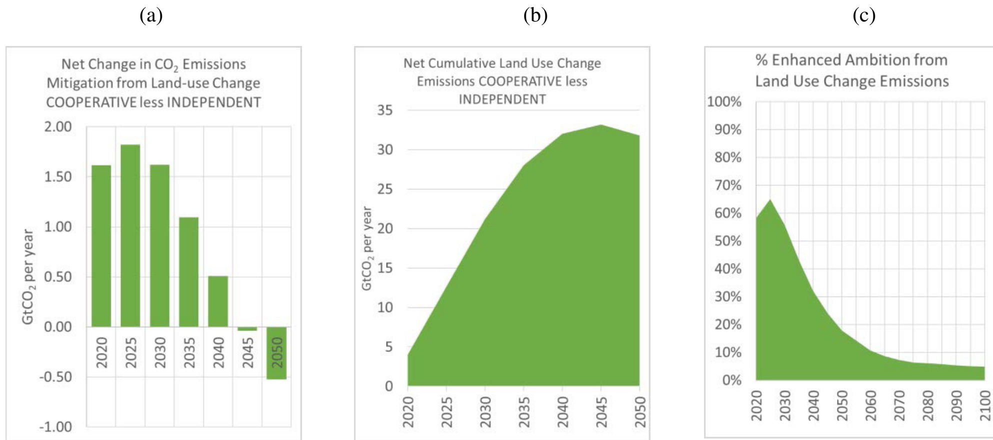

Figure 4. Increased land-use change CO_2 emission reductions induced under the COOPERATIVE scenario compared with the INDEPENDENT scenario. Panel (a) shows the annual change induced by Article 6 while panel (b) aggregates the net increase in emissions mitigation over time under the COOPERATIVE scenario. Panel (c) shows the fraction of enhanced ambition accounted for by transfers of emissions mitigation derived from land-use change emissions mitigation. The fraction of enhanced ambition attributable to land-use change (change in land-use CO_2, ENHANCED AMBITION less INDEPENDENT, compared to the overall increase in ambition, ENHANCED AMBITION less INDEPENDENT).

have relatively low marginal costs. They have relatively low capital requirements and they involve the transition of one land use to another, e.g., from crops or grazing land to forests. So, the transition can occur relatively rapidly.

Carbon accumulation also occurs relatively rapidly in above-ground system, e.g., forests, which are the systems we consider here, grow to maturity in a matter of a few decades, depending on the locale and specie. Natural systems grow to maturity and then become a carbon stock, with little additional net carbon flow. The exceptions to this rule are systems that are harvested and replanted, e.g., bioenergy systems, which remove carbon from the atmosphere which in turn is captured and stored, allowing the system to act as a virtual atmospheric carbon vacuum indefinitely. However, our carbon accounting treats bioenergy as carbon-neutral and reports net atmospheric removal in the industrial sector where the bioenergy-use emissions are captured.

In addition, nature-based solutions are limited in scale by the need to maintain land for other purposes, specifically unmanaged lands and food cropping. One of the major sources of lands for carbon storage and bioenergy that occurs in our results is through a marginal shift in diet away from high carbon-intensive food, driven by relative food prices. There are limits to the ability of prices to shift diets and eventually nature-based solutions reach the limit of low-cost opportunities. Once a nature-based land-use saturates its carbon uptake potential, it ceases to be able to continue to absorb carbon.

4. Discussion

Our principal conclusion is that Article 6 holds substantial potential for parties to work together via Article 6 to either lower the costs of achieving their NDCs under the Paris Agreement and/or increase their ambition in the first contribution period. If its full potential could be reached, Article 6 could reduce cost and/or increase ambition for all parties. Nature-based solutions broaden the scope of opportunities available to enhance ambition in the first contribution period. Achieving the full potential of Article 6 at global scales remains a formidable challenge.

In the near-term, just writing the rules has proved difficult. It is not obvious how to facilitate the creation and trade of emissions mitigation under Article 6 given the heterogeneity in targets and policies across NDCs (Das, 2015; Hood and Soo, 2017; Mehling *et al.*, 2018; Rose *et al.*, 2018). Metcalf and Weisbach (2011) initiated an active vein of the economics literature (Bodansky *et al.*, 2016; Mehling *et al.*, 2018, 2019) that investigates how to establish linkages between disparate programs, such as emissions trading systems and carbon taxes or regulatory schemes while avoiding double-counting, emissions leakage, and "hot air".

It is not obvious that even such mechanisms were to be agreed, whether they could be scaled up to the levels that we consider here. Experience in earlier international market mechanisms, such as the Clean Development Mechanism or the Kyoto Protocol's Article 17, which often had high transaction costs (Hepburn, 2007; Michaelowa and Jotzo, 2005; Fichtner *et al.*, 2003; Michaelowa *et al.*, 2003), provides a cautionary note. On the other hand, new approaches that aggregate and standardize projects provide some reason to expect that at least some of the challenges could be addressed successfully. Finally, it is not clear if equity concerns, either in the domestic or international contexts, would create significant opposition that would slow, or halt, scaled expansion of market mechanisms.

The rule book needs to be written carefully. Article 6 is intended to both reduce costs and enhance ambition. Creating rules that inadvertently, through indirect effects (e.g., leakage or double-counting), increase global emissions relative to independent implementation are a real danger (Calvin *et al.*, 2015). Rulesets need to be tested in numerical simulation models before they are tested in the real world to avoid costly miscalculations, though we recognize the imperfect nature of such tests. Rules need to be assessed both on their potential to reduce costs and enhance ambition as well as for other ancillary consequences such as effects on local air quality, food security, income distribution, economic development, and water.

Our estimate of the potential enhancement to ambition available to parties through the use of Article 6 was based on a calculation in which we increased ambition in all parties so that the net domestic costs of emissions mitigation were exactly the same as they would have been had that party implemented its NDC independently. Implicit in this calculation is the assumption that each country's cost of independently implementing its NDC reflects its willingness to pay for climate-related emissions mitigation. However, national motivations may be more complex (Ostrom, 2010; Lutter and Shogren, 2002). Some countries may not want to become net importers of transfers and reduce the quantity of their domestic CO_2 emission abatement because they value the co-benefits (e.g., local air-quality benefits). Thus, inclusion of local air-quality benefits in buying regions could reduce the demand for imports while it could operate to increase the supply of emissions mitigation instruments in selling regions, which would receive additional local air-quality benefits.

Similarly, the decision to avoid international transfers may reflect regulatory capture by domestic stakeholders (environmental groups, select industries) who secure greater rents from excessive domestic regulation. On the other side, some countries may not opt for increasing their domestic abatement even if co-benefits would justify it because of domestic regulatory capture that aims to minimize domestic regulatory costs.

Finally, we note that employing Article 6 would have long-term dynamic effects on technology deployment and capital investment. In general, the buyers of emissions mitigation would deploy less low-emissions technology in the near term than they would were they to independently implement their NDC. This could reduce the incentive for and pace of technological change in those countries. On the other hand, Article 6 will have the opposite effect in seller countries. That is, it will increase investment in emissions mitigation technology and build a stronger technological foundation for future emissions mitigation in those regions. Using Article 6 cost savings to enhance ambition will lead to greater capital investment in the global aggregate, though not necessarily in every country of the world.

While we note above the prospect for regulatory capture to weaken a country's interest in Article 6 transfers — and such incentives may also result in economically inefficient domestic policies — transparent evidence of the welfare benefits of more cost-effective implementation — domestically and internationally — could shine a light on domestic policy design. Such analysis could undermine the stakeholders attempting to capture the regulator and may drive a country toward more welfare-enhancing policies as noted by Becker (2000).

In order to meet the Paris goals, initial contributions need to be enhanced in second and subsequent contribution periods. In order to limit climate change to 1.5°C or 2°C, it is essential that these cost savings translate into enhanced ambition, rather than simply rewarding lack of further ambition after countries achieve initial pledges (Fawcett *et al.*, 2015). Rules to guard against this could include options such as limiting sales of emissions mitigation instruments by an inverse proportion to actual emissions or the phase-in of ratcheting mechanisms. Article 6 might also provide peer pressure insofar as climate clubs emerge, since many countries say that they will only link or import from countries that have credible NDCs (Keohane *et al.*, 2017; Nordhaus, 2015; Sabel and Victor, 2017; Stua, 2017).

The challenges to realizing the full potential cost savings and enhanced ambition opportunities of Article 6 should not be underestimated. However, Article 6 could be an important tool for increasing mitigation ambition. National policies and measures that are currently in place do not appear to be capable of delivering NDC outcomes (Olhoff and Christensen, 2018). In the longer-term NDCs eventually will need to deliver near-zero and negative emissions. Heterogeneous national capabilities to produce negative and zero aggregate emissions point toward a potential cost-reducing or ambition-enhancing role for Article 6 throughout the century.

The Paris Agreement Rulebook, under development and with potential adoption at the 2021 COP, is expected to elaborate the rules and implementation guidance needed to operationalize Article 6 of the Paris Agreement. Wisely written rules could result in substantial cost savings that translate into enhanced mitigation, while poorly written rules could undercut and frustrate the performance of the Paris Agreement. A coherent and robust set of rules, with ability to adjust based on experience, will therefore be an essential element of minimizing risks from cooperative emissions strategies that could see more rapid and cost-effective global reductions to achieve Paris goals.

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