Optimal discounting of forest offsets in the carbon market

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Abstract:

Unilateral actions to reduce CO_2 emissions can be costly and may lead to carbon leakage through relocation of emission-intensive and trade-exposed industries (EITE). This paper examines the welfare effects of introducing an emission offset mechanism for the EITE sector, where EITE producers may have to acquire more than one offset credit to balance one emission allowance. The analytical results suggest that it is globally welfare improving for a region to introduce such an offset mechanism, with an optimal conversion rate below one. Moreover, numerical simulations in the context of the EU ETS and REDD+ credits support the analytical findings.

1. Introduction

In order to reduce emissions of greenhouse gases (GHGs), many countries (and regions) consider or have introduced unilateral climate policies such as emissions trading systems (ETS). However, unilateral action raises at least two types of concerns. First, the cost of reducing global emissions is higher than necessary as cheap mitigation options in unregulated regions are forgone. Second, the climate policy may lead to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE) to unregulated regions,[1] reducing the effectiveness of the unilateral policy.[2] The two concerns are related – the more costly unilateral action is, the higher is typically leakage. As a response to these concerns, emission trading is often supplemented with access to offsets or free allocation of emission allowances.

In the context of the EU and its emission trading system (EU ETS), the abatement cost is generally greater than in other regions, and carbon leakage is of great concern. To prevent leakage, the EU hands out a large number of free allowances to the sectors that are exposed to significant risk of carbon leakage.[3] The allocation to individual firms is directly linked to each firm's production level (Neuhoff et al. 2016) – often referred to as output-based allocation (OBA). Hence, the competitiveness for the exposed sectors is improved (compared to auctioning of allowances) and carbon leakage is mitigated. There is a large literature analyzing OBA (e.g., Martin et al. 2014; Fischer and Fox 2012; Böhringer et al. 2017).

Access to offsets can decrease the domestic costs of complying with the regulation and hence reduces the carbon leakage. An essential assumption here is that the offset credits are cheaper than reducing emission domestically. Firms regulated by the EU ETS have had the option to use CDM (Clean Development Mechanism) credits to offset some of their emissions. CDM is a mechanism under the Kyoto Protocol, allowing industrialized countries to pay for mitigation projects in developing countries as an alternative to own emissions reductions. This option will end after 2020, however, as the EU then has a *domestic* emission reduction target.[4] There has also been a lot of criticism against CDM credits, especially related to additionality (Carmichael et al. 2016). That is, it is difficult to verify whether or not a CDM project would have taken place in the absence of CDM. Leakage has also been highlighted as a challenge with the CDM (Rosendahl and Strand 2011).

An alternative option to CDM in a carbon market is REDD+ (Reducing Emissions from Deforestation and forest Degradation), which aims at reducing GHG emissions from forests in developing countries (Lund et al. 2017). Since deforestation and land use change stand for about 11% of the global carbon emissions (IPCC 2014), and reducing these emissions is less costly than most other abatement options (Anger and Sathaye 2008; Myers 2007; Nepstad et al. 2007), forest offsetting has been recognized as an important strategy against climate change (Kindermann et al. 2008; van der Werf et al. 2009). Since the 2007 Bali Action Plan, the aim has been to make REDD+ a part of a global climate agreement, where REDD+ credits could be used as offsets in carbon markets (Angelsen et al. 2014). The idea is that use of financial incentives can change the behavior of forest users, as they are paid by conserving the forest (Angelsen et al. 2012). REDD+ credits suffer from many of the same challenges as CDM, however, such as additionality and leakage.

In this paper, we examine the impacts of introducing an offset mechanism into a carbon market, first analytically and then numerically in the context of the EU ETS and REDD+. Using offsets implies reduced demand for ETS allowances, and (hence) lower emission price in the ETS. We consider the effects of discounting offset credits, so that the conversion rate between a REDD+ credit and ETS allowances may be less than one. With a conversion rate less than one, the regulated firms in the ETS may need more than one REDD+ credit to offset one unit of their domestic emissions. Hence, global emissions are further reduced. If the conversion rate is not set too low, and offsets are significantly cheaper than domestic reductions, the result can be a combination of bigger global emission reductions and lower total costs, i.e., a win-win situation.

In the analytical part of the paper, we show that an increased conversion rate leads to a lower emission price and particularly examine what is the optimal conversion rate. We show that it is globally welfare improving to increase the conversion rate as long as it leads to lower global emissions, and most likely increase the rate a bit more. The welfare measure accounts for the value of reductions in global emissions. It follows that the conversion rate that minimizes global emissions is lower than the conversion rate that maximizes global welfare. The relationship between the conversion rate and global emissions is likely to be U-shaped. The reason is that one unit higher domestic emissions must be balanced by more than one unit lower emissions related to offsets when the conversion rate is below 1, while if the conversion rate is too close to zero using offsets becomes too expensive. We also discuss implications for leakage and how this may affect global emissions, and explain why it is likely that leakage will decline with higher conversion rate.

Next, we supplement with results from a stylized computable general equilibrium (CGE) model calibrated to data for the world economy. The numerical results support our analytical findings in the context of the EU ETS. That is, the REDD+ offset mechanism is welfare improving, both for the EU and the world. In our benchmark simulations, the conversion rate that minimizes global emissions is 18%. For higher conversion rates there is a tradeoff between emissions and costs, as higher rates imply higher global emissions but lower mitigation costs. In our main simulations, the optimal conversion rate (from a global or EU perspective) is 22-23%, i.e., not much higher than the conversion rate that minimizes global emissions. With this conversion rate, carbon leakage from emission-intensive producers in the EU is largely mitigated. Further, the emission price for the EITE producer is halved while the REDD+ credit price is maximized in this case. However, these results depend on several uncertain assumptions, such as the international trade and leakage exposure of both EITE goods as well as forest and agricultural goods. In most realistic cases, however, the optimal conversion rate is far below one, as it implies lower global emissions. The exception is if goods in different regions were perfect substitutes with one global price – then the optimal conversion rate would be close to one.

There are some studies that have explored the effects of including REDD+ credits in a carbon market (Angelsen et al. 2014; Anger and Sathaye 2008; Bosello et al. 2015, Bosetti et al. 2011; Den Elzen et al. 2009; Dixon et al. 2008; Eliasch 2008; Murray et al. 2009). They overall suggest an emission price reduction in the range of 22-60%, depending on the scope and rules for REDD+ credit inclusion. Particularly for this paper, the work by Angelsen et al. (2014) and Bosello et al. (2015) are highly relevant.

Angelsen et al. (2014) discuss the major concern of market flooding when including REDD+ credits in a carbon market. They argue that REDD+ inclusion should be additional to existing efforts, to avoid full crowding out of domestic emission reductions.[5] They further highlight (at least) five possible ways to ensure a balanced introduction of REDD+ into a global carbon market: *i)* partial inclusion of REDD+ credits (e.g., through discounting, as explored in our paper), *ii)* REDD+ inclusion along with a flexible emission cap, *iii)* banking of REDD+ credits from the current to later periods, *iv)* restrictions on demand and/or supply of REDD+ credits, and *v)* a continuously update of the REDD+ reference level which determines the amount of credits that REDD+ countries can sell to the market. Angelsen et al. then explore some of these options in ten different scenarios using the FAIR model, which includes a set of marginal abatement cost (MAC) curves in different sectors and regions of the world. Assuming a global carbon market, a two degrees scenario and a 50% conversion rate for REDD+ credits, they find that REDD+ trading increases overall global abatement while reducing global abatement costs. However, neither welfare effects nor the impacts of leakage due to non-global carbon market or different conversion rates are explored.

Bosello et al. (2015) examines the effect of introducing REDD+ credits in the EU ETS, and finds that reduced deforestation both decreases climate change policy costs via lower ETS prices, and carbon leakage as the costs for domestic EITE producers decline making them less likely to relocate. They consider different conversion rates between REDD+ credits and ETS allowances. However, as they do not consider the benefits of lower global emissions, they find that the optimal conversion rate is 100%. The study is one of very few that have explored some of the effects of introducing REDD+ in the EU ETS.

Our paper builds on the basic model in Kaushal and Rosendahl (2020), and the basic idea in Bosello et al. (2015) of introducing REDD+ credits offset in the EU ETS. However, whereas the latter paper does not distinguish between trade-exposed and non-trade-exposed sectors, we consider the case where only the EITE sector can offset their emissions through REDD+ credits. The motivation for this approach is the concern about carbon leakage in the EITE sector mentioned above, and thus an alternative to free allocation of allowances or other anti-leakage measures. A crucial question then is whether EITE producers should be allowed to resell offsets to the non-trade-exposed sector, and we consider both alternatives in our paper. Full flexibility basically means that all ETS sectors get access to offsets, directly or indirectly, while no such flexibility most likely implies higher emission prices for the non-trade-exposed sector than for the EITE sector. Further, we examine the welfare effects of introducing REDD+ credits in the EU ETS, accounting for the benefits of reduced global emissions as well. Introducing REDD+ credits into the EU ETS would provide large-scale funding for REDD+ programs, and higher global emission reductions can be achieved for a lower mitigation cost if the conversion rate is set below one (Angelsen et al. 2014; Angelsen et al. 2017).

The remainder of this paper is organized as follows. In section 2 we introduce our theoretical model, and analyze the welfare effect of an emission offset mechanism, when an emission trading system is already in place in the policy region. In section 3, we transfer our analysis to a stylized computable general equilibrium model. The model is based on the theoretical model in section 2 and calibrated to data for the world economy. Finally, section 4 concludes.

2. Theoretical model

Consider a theoretical model with 3 regions, $j = \{1,2,3\}$, and four sectors and goods x, y, q and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE) such as steel, cement, and chemicals, q is the tradable forest and agricultural good, while z is emission-intensive and non-tradable (e.g., electricity and transport). The same types of goods produced in different regions, are assumed homogenous in this analysis. An emission trading system (ETS) is implemented in region j=1, and the region considers allowing offsets in terms of REDD+ credits from region j=2. Due to international trade in q and y goods, carbon leakage may take place through two channels; i) relocating production of the q good to non-REDD+ regions (j=1,3) when credits are introduced in the REDD+ region j=2 (i.e., the region offering REDD+ credits), and ii) relocating production of the y good from region j=1 to other regions. The market price for the goods x, y, q and z in region j are denoted p^{xj}, p^{yj}, p^{qj} and p^{zj}.

The representative consumer's utility in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{q}^j, \bar{z}^j)$, where the bar denotes consumption of the four goods. The utility function follows the normal assumptions; twice differentiable, increasing and strictly concave.

Production of good y in region j is denoted $y^j = y^{1j} + y^{2j} + y^{3j}$, where y^{ij} denotes produced goods in region j and sold in region i (and similarly for the x and q good).[6] The cost of producing the goods in region j is given by $c^{xj}(x^j)$, $c^{yj}(y^j, e^{yj})$, $c^{qj}(q^j, e^{qj})$ and $c^{zj}(z^j, e^{zj})$, where e^{yj}, e^{qj} and e^{zj} denote emission from good y, q and z in the region j. We assume that the cost is increasing in production for all goods, and that the cost of producing good y, q and z is decreasing in emissions, i.e., $c_x^{xj}, c_y^{yj}, c_q^{qj}, c_z^{zj} > 0$ (where $\frac{\partial c^{xj}}{\partial x^j} \equiv c_x^{xj}$ etc.). Further, cost is twice differentiable and strictly convex in production, and $c_e^{yj}, c_e^{qj}, c_e^{zj} \leq 0$ with strict inequality when emission is regulated. All derivatives are assumed to be finite.

Supply and demand give us the following market equilibrium conditions:

$$\begin{gathered} \bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3 \\ \bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3 \\ \bar{q}^1 + \bar{q}^2 + \bar{q}^3 = q^1 + q^2 + q^3 \\ \bar{z}^j = z^j \end{gathered} \qquad [1]$$

Emission price and carbon offset credits

In the following sections, we will look at two different cases of how the offset mechanism can be introduced into the regional emission trading system. First, we assume that the regulating region allows only the EITE sector y to offset its emission with REDD+ credits, and refer to this as scenario 1. Next, we allow the EITE sector to buy and sell permits to the emission-intensive and non-trade-exposed sector *z* as well, and refer to this as scenario 2.

We assume that region 1 already regulates emission from production of the *y* and *z* goods through an ETS. Region 2 is where REDD+ is introduced, while region 3 has no climate policy. In order to reduce mitigation costs and counteract carbon leakage, the regulating region implements the possibility for the EITE sector y to offset emissions through REDD+ credits. The binding cap on total emission in region 1, $\bar{E}^1$, is then:

$$\bar{E}^1 = e^{y1} - \alpha\left(e_0^{q2} - e^{q2}\right) + e^{z1} \qquad [2]$$

where the emission price t^1 balances the emission trading market and the conversion rate α defines the offset of emission through REDD+.

We first consider the case where there is no offset considered to sector z, and sector y cannot resell permits to sector z. This implies that when offsets are allowed, there will be separate (binding) caps on emissions in the two sectors, $\bar{E}^{y1}$ and $\bar{E}^{z1}$, where $\bar{E}^{z1} = e^{z1}$ and $\bar{E}^{y1} = e^{y1} - \alpha\left(e_0^{q2} - e^{q2}\right)$. Consequently, the emission market is separated for the two sectors but the cap on total regional emission is still fixed. The producers can buy and sell permits within their sector but not across sectors, which necessitates the emission price to be sector specific in region 1, t^{y1} and t^{z1}.

The REDD+ credit market in region 2 consists of the suppliers, producers of good q in region 2, and demand from producers who want to offset their emissions, producers of good y in region 1. The suppliers have incentives to reduce their emissions as long as they receive a payment for these services that outweigh their costs.[7] The price of REDD+ credits r^2, which is the price per unit emission reduction for sector q in region 2, balances the supply and demand of credits. The total cost of reducing emissions through REDD+ credits is then for sector y in region 1:

$$r^2\left(e_0^{q2}-e^{q2}\right).$$

This is also the payment that the sector q in region 2 receives for abatement. Based on the amount of REDD+ credits bought by sector y in region 1, the sector would need fewer emission permits to comply such that their cost savings are:

$$\alpha t^1\left(e_0^{q2}-e^{q2}\right).$$

Assuming competitive producers, the representative producers in region j=1,2,3 maximize their profits π^j:[8]

$$Max_{x^{ij}}\,\pi_j^x=\sum_{i=1}^{3}\left[p^{xi}x^{ij}\right]-c^{xj}(x^j)$$

$$Max_{y^{ij},e^{yj},e^{q2}}\,\pi_j^y=\sum_{i=1}^{3}\left[p^{yi}y^{ij}\right]-c^{yj}\left(y^j,e^{yj}\right)-t^{yj}e^{yj}+\alpha t^{yj}\left(e_0^{q2}-e^{q2}\right)-r^2\left(e_0^{q2}-e^{q2}\right)$$

$$Max_{q^{ij},e^{qj}}\,\pi_j^q=\sum_{i=1}^{3}\left[p^{qi}q^{ij}\right]+r^j\left(e_0^{qj}-e^{qj}\right)-c^{qj}\left(q^j,e^{qj}\right)$$

$$Max_{z^j,e^{zj}}\,\pi_j^z=\left[p^{zj}z^j-c^{zj}\left(z^j,e^{zj}\right)-t^{zj}e^{zj}\right].$$

As explained above, we have that $t^{y2} = t^{z2} = t^{y3} = t^{z3} = r^1 = r^3 = 0$. Thus, producers of good y in regions 2 and 3 do not buy REDD+ credits. While we will now present the case in scenario 1, it is essential to note that by assuming $t^{y1} = t^{z1} = t^1$, we transform the expressions from scenario 1 to the case in scenario 2.

Assuming interior solution, we derive the first order conditions for producers of good y:

$$\begin{gathered}
\frac{\partial \pi_1^y}{\partial y^1} = p^{y1} - c_y^{y1} = 0; \;\; \frac{\partial \pi_2^y}{\partial y^2} = p^{y2} - c_y^{y2} = 0; \;\; \frac{\partial \pi_3^y}{\partial y^3} = p^{y3} - c_y^{y3} = 0 \\
\frac{\partial \pi_1^y}{\partial e^{y1}} = c_e^{y1} + t^{y1} = 0 \\
\frac{\partial \pi_1^y}{\partial e^{q2}} = \alpha t^{y1} - r^2 = 0 \\
\frac{\partial \pi_2^y}{\partial e^{y2}} = \frac{\partial \pi_3^y}{\partial e^{y3}} = c_e^{y2} = c_e^{y3} = 0
\end{gathered} \tag{3}$$

and the first order conditions for producers of good q:

$$\begin{gathered}
\frac{\partial \pi_1^q}{\partial q^1} = p^{q1} - c_q^{q1} = 0; \;\; \frac{\partial \pi_2^q}{\partial q^2} = p^{q2} - c_q^{q2} = 0; \;\; \frac{\partial \pi_3^q}{\partial q^3} = p^{q3} - c_q^{q3} = 0 \\
\frac{\partial \pi_2^q}{\partial e^{q2}} = c_e^{q2} + r^2 = 0 \\
\frac{\partial \pi_1^q}{\partial e^{q1}} = c_e^{q1} = 0; \;\; \frac{\partial \pi_3^q}{\partial e^{q3}} = c_e^{q3} = 0
\end{gathered} \tag{4}$$

The first line of equations [3] and [4] shows that the marginal cost of producing the good is equal to the price of the same good. The second line of [3] shows that the marginal abatement cost is equal to the emission price for producers of good y in region 1. From the third line in [3] and second line in [4] we have that the interior solution requires that the price of REDD+ credits in region 2 is equal to the marginal abatement cost for the producer of good q in that region, i.e., $r^2 = -c_e^{q2}$. The last line in [3] and [4] shows that the marginal abatement cost is (as expected) equal to zero for the unregulated regions and sectors.

Next, we derive the first order conditions for producers of goods x and z:

$$\frac{\partial \pi_1^x}{\partial x^1} = p^{x1} - c_x^{x1} = 0; \ \frac{\partial \pi_2^x}{\partial x^2} = p^{x2} - c_x^{x2} = 0; \ \frac{\partial \pi_3^x}{\partial x^3} = p^{x3} - c_x^{x3} = 0$$

$$\frac{\partial \pi_j^z}{\partial z^j} = p^{zj} - c_z^{zj} = 0$$

$$\frac{\partial \pi_1^z}{\partial e^{z1}} = c_e^{z1} + t^{z1} = 0 \qquad [5]$$

$$\frac{\partial \pi_2^z}{\partial e^{z2}} = c_e^{z2} = 0; \ \frac{\partial \pi_3^z}{\partial e^{z3}} = c_e^{z3} = 0$$

We see that interior solution requires that the prices of the three tradable goods x, y and q are equalized across regions, as they are homogenous with no cost of trade, i.e., we may define:

$$p^x \equiv p^{xj}, \qquad p^y \equiv p^{yj}, \qquad p^q \equiv p^{qj}$$

The representative consumer in region j maximizes utility given consumption prices and an exogenous budget restriction M^j, leading to the following *Lagrangian* function:

$$\mathcal{L}^j = u^j\left(\bar{x}^j, \bar{y}^j, \bar{q}^j, \bar{z}^j\right) - \lambda^j\left(p^x\bar{x}^j + p^y\bar{y}^j + p^q\bar{q}^j + p^z\bar{z}^j - M^j\right)$$

Differentiating this function w.r.t. consumption of each good, we get the following first-order conditions:

$$\frac{\partial \mathcal{L}}{\partial \bar{x}^j} = u^j_{\bar{x}} - p^x = 0, \qquad \frac{\partial \mathcal{L}}{\partial \bar{y}^j} = u^j_{\bar{y}} - p^y = 0,$$
$$\frac{\partial \mathcal{L}}{\partial \bar{q}^j} = u^j_{\bar{q}} - p^q = 0, \qquad \frac{\partial \mathcal{L}}{\partial \bar{z}^j} = u^j_{\bar{z}} - p^{zj} = 0 \qquad [6]$$

where we have assumed interior solution, and normalized the utility functions so that $\lambda^j = 1$, which means that we measure utility in monetary terms (money metric utility).

Finally, we assume that the regions have a balance-of-payment constraint. The net export from a region is equal to domestic production minus domestic consumption. Given the assumption of one global price for each of the tradable goods, we have from [3], [4] and [5] that

$$p^y\left(y^j - \bar{y}^j\right) + p^x\left(x^j - \bar{x}^j\right) + p^q\left(q^j - \bar{q}^j\right) = 0 \qquad [7]$$

Change in emission price

In this section, we will show how the change in the conversion rate α affects the emission price t^{y1} for the producer of good y in region 1 in scenario 1. From equation [3] we have the following relationship between the emission price t^{y1}, the REDD+ credit price r^2, and the conversion rate α: $t^{y1} = \frac{r^2}{\alpha}$. Both t^{y1} and r^2 are endogenous, balancing their respective markets, and depending on the marginal abatement cost; c_e^{y1} and c_e^{q2}. The emission price t^{y1} decreases with increasing α. This can be shown by differentiating both [2] (disregarding e^{z1} since we consider scenario 1) and $t^{y1} = \frac{r^2}{\alpha}$ with respect to α:

$$\frac{\partial \bar{E}^{y1}}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} + \alpha \frac{\partial e^{q2}}{\partial \alpha} - \left(e_0^{q2} - e^{q2}\right) = 0$$

$$\frac{\partial r^2}{\partial \alpha} = t^{y1} + \alpha \frac{\partial t^{y1}}{\partial \alpha}$$

To show that t^{y1} decreases with α, let us first assume the opposite, i.e., $\frac{\partial t^{y1}}{\partial \alpha} \geq 0$. Higher or unchanged emission price implies that the demand for emission permits in the region decreases or stay unchanged, i.e., e^{y1} would decrease or remain the same. From the second equation above, we see that $\frac{\partial t^{y1}}{\partial \alpha} \geq 0$ would further imply that r^2 increases with increasing α, i.e., $\frac{\partial r^2}{\partial \alpha} > 0$. This further implies that emission from producer of good q in region 2, e^{q2}, would decrease. With $\left(e_0^{q2} - e^{q2}\right) \geq 0$, we thus have one strictly negative term and the remaining terms non-positive in the expression for $\frac{\partial \bar{E}^{y1}}{\partial \alpha}$ above. As the expression must be equal to zero, this doesn't add up. Therefore, we must have that the emission price t^{y1} decreases with increasing α. It is straightforward to show that this is also true for t^1 in scenario 2. Hence, we have the following result:

Lemma 1. Consider the emission price in region i, t^i, the price of emission offset credits in region j, r^j, and the conversion rate between offsets and allowances, α, so that $t^i = \frac{r^j}{\alpha}$. Further, assume that the conversion rate is $0 < \alpha \leq 1$. Then, increasing the conversion rate reduces the emission price in region i.

Proof. The lemma follows from equations [2] – [3] as explained above.

Global welfare effects

We express global welfare as:

$$W^G = \sum_{j=1,2,3} \left[u^j(\bar{x}^j, \bar{y}^j, \bar{q}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{qj}(q^j, e^{qj}) - c^{zj}(z^j, e^{zj}) - \tau^1(e^{yj} + e^{qj} + e^{zj})\right] \quad [8]$$

where τ^1 is region 1's valuation of reduced global GHG emissions. We will refer to this as the *Pigouvian* tax.[9] As mentioned above, utility is measured in monetary terms, and the welfare expression can also be interpreted as the sum of global consumer and producer surplus minus the monetary value of global emissions (strictly speaking, we are only interested in the value of *changes* in global emissions, not the total value of global emissions).

We first consider scenario 1, so that t^{y1} and t^{z1} may differ. By differentiating with respect to α, we arrive at the following result:

Lemma 2. Let global welfare be given by equation [8]. Then the global welfare effect of increasing the conversion rate α is given by:

$$\frac{\partial W^G}{\partial \alpha} = t^{y1}\left(e_0^{q2} - e^{q2}\right) - \tau^1 \frac{\partial E}{\partial \alpha} \quad [9]$$

where E denotes global emissions.

Proof. See Appendix A.

The first term in [9] is clearly positive. Hence, if an increase in α leads to lower global emissions, then an increase in α increases global welfare. However, the opposite is not necessarily true. As explained below, the relationship between α and global emissions is likely to have a U-shape (this is also the case in the simulations). Hence, the level of α that maximizes global welfare (α^W) is likely to be higher than the level of α that minimizes global emissions (α^E). However, the higher is the valuation of global emissions (τ^1), the closer is α^W to α^E, as the second term in [9] becomes more important.

Before continuing, we summarize our finding in the following proposition (in Appendix A we show that the proposition also holds in scenario 2):

Proposition 1. Consider a region i that has an emission trading system, where producers of EITE goods, y, can offset their emissions through credits from a sector q in region j with a conversion rate α. Then it is global welfare improving to increase the conversion rate α if this leads to lower global emissions.

Proof. The proposition follows directly from equation [9].

Why is the relationship between α and global emissions likely to have a U-shape? To see this, it is useful to focus on emissions that are directly affected by the ETS, i.e., from sectors *y* and *z* in region 1 and sector *q* in region 2 (we return to leakage effects below, but these are likely to be of second order). Consider first the level of emissions when $\alpha = 1$ and when α is very close to zero. When $\alpha = 1$, total emissions are the same as without offsets, as one unit of offset credits replaces exactly one unit of domestic emissions in region 1. When α is very close to zero, using offsets is very expensive, and producers in region 1 will buy no or very few offsets – hence, we are practically in a situation without offsets. On the other hand, when α is between these two extremes, offsets are (more than marginally) used, and for every unit of offset used, global emissions are reduced by $1/\alpha - 1$ units.

We may in fact have a similar pattern for emissions from sector *q* in region 2. Increasing α from zero, these emissions must obviously decrease as producers in region 1 begins to use offsets. However, eventually the effect of increasing α further might be the opposite. That is, the sign of $\frac{\partial e^{q2}}{\partial \alpha}$ is in general ambiguous. We see from equation [2] that $\alpha \frac{\partial e^{q2}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \frac{\partial e^{y1}}{\partial \alpha}$. While the latter term is negative (since t^1 decreases with α, cf. Lemma 1), the former becomes positive as soon as offsets are being used. The intuitive explanation is that as α increases from a certain level, fewer credits are needed to offset emissions by producers in region 1. Thus, if for instance e^{y1} only increases marginally when α is increased, then we may have $\frac{\partial e^{q2}}{\partial \alpha} > 0$, i.e., both e^{y1} and e^{q2} may increase if α increases.

Why is the optimal conversion rate α^W higher than the conversion rate that minimizes global emissions (α^E)? The reason is of course that welfare also consists of consumer and producer surplus. Increasing α from α^E indirectly relaxes the overall emission constraint, which is an advantage when disregarding the environmental benefits. In the hypothetical case of $\tau^1 = 0$, we see that $\frac{\partial W^G}{\partial \alpha} > 0$. That is, if we disregard the damage cost of emissions, then global welfare increases with increasing conversion rate. In this case, the positive welfare effect of increasing α is simply a pure global cost saving.

It is also of interest to discuss impacts on leakage, although they are likely to be of second order. To examine leakage effects, we must consider what will happen with production and hence emissions in unregulated regions and sectors. Increasing α reduces the production cost for producers of good y in region 1, strengthening their competitiveness level in the world market and lowering the global price of this good, p^y. Production of good y in regions 2 and 3 would then be less profitable, likely reducing emissions in (i.e., leakage to) those sectors and regions.

From our previous discussion, increasing the share of α has an ambiguous effect on emissions for producers of good *q* in region 2. If $\frac{\partial e^{q2}}{\partial \alpha} < 0$, some of this emission reduction would likely be related to lower production. It then seems reasonable that the price p^q, and hence production of *q* in regions 2 and 3, increases somewhat. If instead $\frac{\partial e^{q2}}{\partial \alpha} > 0$, we will have the opposite situation. Thus, the effects on leakage through the market for the good *q* are ambiguous.

As the price of good y decreases, consumers in all regions will buy more of this relatively cheaper good. The effect on p^q on the other hand is ambiguous, as just explained. Still, it is likely that consumption of the z good decreases in all regions as p^y decreases, in which case also production and emissions decreases. However, these effects are likely to be small as they are of second or third order. To sum up, although the effects on emissions in the market for good *q* is ambiguous, it seems quite likely that unregulated emissions will decrease somewhat when α increases, that is, total leakage is likely to decrease somewhat, strengthening the case for a higher α.

3. Numerical analysis

The stylized theoretical analysis explains some of the outcomes of introducing REDD+ credits in a carbon market. In order to get more in-depth insights into the effects, we now transfer our analysis to numerical simulations with a stylized computable general equilibrium (CGE) model.

Incorporating REDD+ credits in EU ETS is of particular interest, as the abatement cost in this region is relatively high and carbon leakage is of concern. There are many countries in the world with rainforest and REDD+ programs. We are particularly interested in Brazil and Indonesia, which are the two countries with the biggest tropical forest loss (Pendrill et al. 2019). Particularly Brazil is considered as the supplier of REDD+ credits. By separating Brazil and Indonesia, we are able to capture possible leakage effects (and trade patterns) related to participating in REDD+ (see e.g. Alix-Garcia et al. 2012; Gan and McCarl 2007; Fortmann et al. 2017; Sun and Sohngen 2009; Velly et al. 2017). Our main question here is whether it is welfare-improving for the EU, and from a global perspective, to implement such an offset mechanism for the EITE sector, and what the optimal conversion rate is, when the effects on global emission are taken into account.

Model summary

The model consists of four regions, the European Union/ European Economic Area (EU/EEA), Brazil (BRA), Indonesia (IDN), and Rest of the world (ROW). Each region has five production sectors[10]: non-carbon and tradable production x, carbon-intensive and tradable production y, carbon-intensive and non-tradable production z, agriculture and forestry production q (tradable), and fossil energy production f (non-tradable). Consistent with the theoretical analysis, x, y, z and q can only be used in final consumption, while f can only be used in production (of y and z). Hence, in line with the theoretical analysis, we focus on carbon leakage related to the competitive channel for the goods y and q (the latter related to the REDD+ market). We distinguish between domestic and foreign produced goods, disregarding transportation cost.

Capital, labor, fossil energy, fossil resources and land are the input factors in production. Capital, labor and fossil energy are mobile between sectors but immobile between regions. The fossil resource is only used in fossil energy production, while land is only used in agriculture and forestry production. Both fossil resource and land are immobile between sectors and regions. The producers combine the input factors at minimum cost subject to technological constraints. Production of x, y, z and q is expressed by two level constant-elasticity-of-substitution (CES) cost functions, describing the substitution possibilities between capital, labor, fossil energy and land use. For *f* production, the two level CES cost function consists of capital, labor and resource. At the top level, we have the CES function with substitution between energy/resource/land and the value-added (capital and labor) composite. At the second level, the CES value-added composite consists of substitution between capital and labor[11]. Fossil related emission is proportional to the use of fossil energy as input in production, and emission related to land use change is proportional to the use of land in production of good q. Thus, the total emission reduction takes place by reducing energy or land use through either; i) substitution of energy/land by the value-added composite, or ii) reducing the production output.

The final consumption in each region is determined by a representative agent's utility, which is maximized subject to a budget constraint. The agent's utility is given as a CES combination of final consumption of domestic and imported goods, and the budget constraint is the monetary value of regional endowment of capital, labor, resource and land.

For a detailed description of the data and calibration procedure for the CGE model, see Appendix C.

Policy scenarios

The latest available WIOD data with corresponding CO_2 emission level for different sectors is from 2009. Even though the EU ETS was already in place, we consider the calibrated equilibrium in 2009 as a business-as-usual (*BAU*) scenario[12]. The reference (*REF*) policy scenario is when the EU/EEA imposes an emission reduction target, using an economy-wide ETS with either auctioning or unconditional grandfathering. We will refer to this as EU ETS despite the differences vis-à-vis the real EU ETS (especially when it comes to sectoral coverage). The reduction target is set to 20%.[13]

Next, we consider the same scenarios as discussed in the theoretical analysis, where producers of good y can buy REDD+ credits to offset their CO_2 emissions. In the offset scenarios we consider different levels of α, where $1/\alpha$ is the number of REDD credits needed to offset one ton of emissions. α is ranging from 0% to 100%, and from Section 2 we know that the price of REDD+ credits will be equal to α times the emission permit price t in the EU ETS. In the following subsection we only consider scenario 1 from the theoretical analysis, that is, where only producers of good y can offset their emissions through REDD+ credits and *not* being allowed to resell emission allowances to sector z. Scenario 2 is dealt with together with some sensitivity analysis. We consider only Brazil (BRA) as the supplier of REDD+ credits, and further assume that the CO_2 emission level for Brazilian producers of good q in the *REF* scenario is taken as the reference level for offsets. Hence, the cap on domestic emissions in the EU ETS is endogenously increased by $\alpha\left(e_{ref}^{qBRA} - e^{qBRA}\right) \geq 0$. As the global emissions are different across the policy scenarios, we will assume that the emission permit price in the *REF* scenario reflects EU/EEA's valuation of global emission reductions.

Results

In this section, we examine the effects on some key indicators such as emission, leakage rate, welfare, and permit and REDD+ credit prices. We define the leakage rate as changes in emissions in the unregulated regions and sectors divided by emissions reductions in the abating regions and sectors. This is explained in more detail below. The welfare change measure is the ratio between welfare in the different policy scenarios vis-à-vis welfare in the *BAU* scenario. Welfare is defined by the CES utility function for the representative agent, where utility is measured in monetary terms, minus the monetary valuation of changes in global emissions.[14]

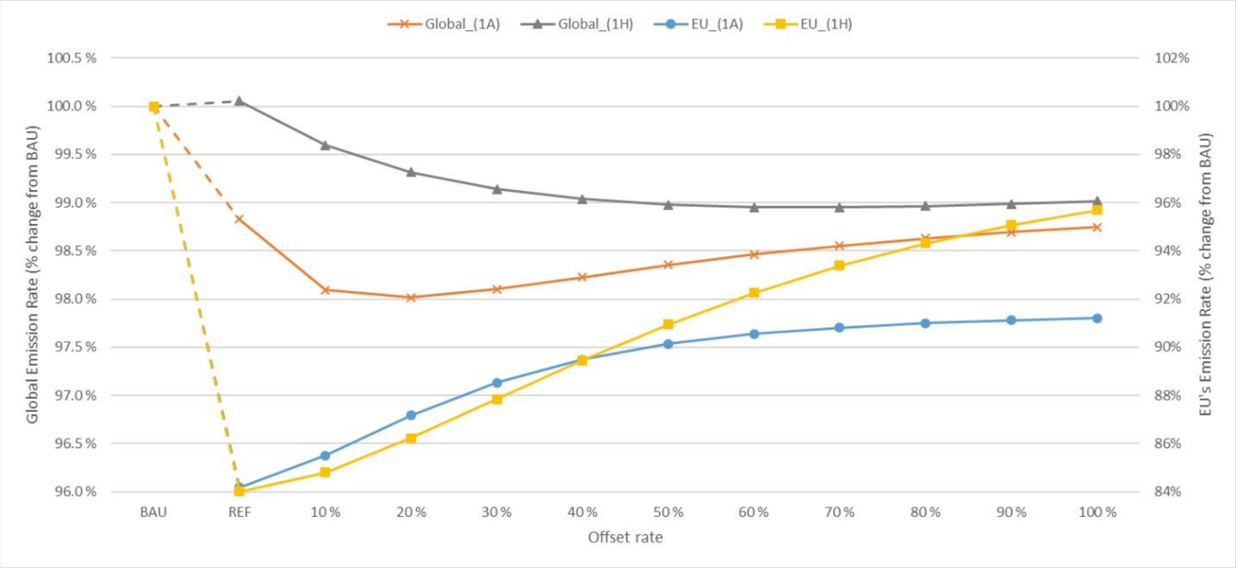

Figure 1: Global and EU's emission rate under different combination of policies.

Figure 1 shows the effects on global emissions and EU's emissions, both with the Armington (*A*)[15] approach and the homogenous goods (*H*) approach. We consider the former approach most realistic, and thus emphasize those results (and refer to them as the benchmark results).[16] Emissions include emissions from both fossil energy and land use change. With only emission pricing in the EU (*REF*), emissions in the EU decline by 16% vis-à-vis *BAU*, leading to a 1.2% reduction in global emissions. Since the sector q is not part of the EU ETS, emission from this sector increases slightly as consumption shifts towards the relatively cheaper goods (x and q). Due to substantial leakage effects, global emissions are practically unchanged when domestic and foreign goods are homogenous (see Figure 2).

Next, the figure shows that allowing for offsets has a significant impact on emissions. Emissions in the EU increase significantly with α, and is merely 4% below *BAU* emissions when $\alpha = 100\%$. As indicated in section 2, we obtain a U-shaped curve for global emissions, with a minimum when α is 18%, i.e., one REDD+ credit translates into 0.18 ETS allowances. Hence, from a pure environmental perspective, the optimal conversion rate is 18% (α^E = 0.18). However, we notice from the figure that α^E is much bigger when domestic and foreign goods are homogenous (α^E = 0.66). Thus, although the latter approach seems less realistic, it illustrates that the optimal conversion rate may depend substantially on the leakage exposure of traded goods (see also the sensitivity analysis). Emissions from the *q* sector in Brazil have a minimum level when α is 24% (in the 1A scenario), confirming that the impacts of higher conversion rate on these emissions is ambiguous (cf. the discussion in section 2).

Figure 2 shows the effects on leakage from regulated sectors in the EU ETS (y and z) to unregulated sectors and regions (both in the EU and other regions). In the *REF* scenario, the unregulated regions and sectors consist of all emissions outside the EU plus emissions from the q sector in the EU. In the offset scenarios, emissions from the q sector in Brazil is no longer treated as unregulated – instead changes in these emissions (vis-à-vis *REF*) are treated as regulated emissions together with the EU ETS emissions (changes in these emissions from *BAU* to *REF* are still treated as unregulated). In the figures, EU_yz shows the leakage rate to energy-intensive producers y and z in other regions, EU_yzq shows the leakage rate from the EU ETS to all other sector (y, z and q), and finally BRA_q, shows the leakage rate from agriculture and forestry producer q in Brazil to sector q in other regions.

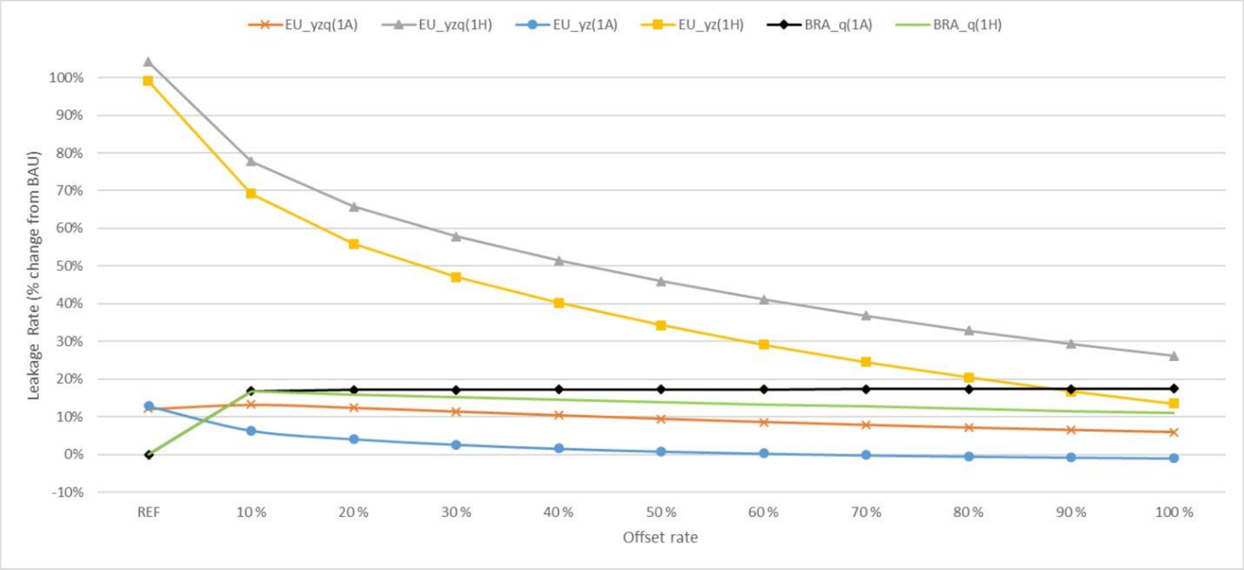

Figure 2: Leakage rate from y, z (and q) in the EU and from q in BRA under different combination of policies.

In the *REF* scenario, the leakage rate is 13% if we only account for leakage to sector y and z outside the EU. Given no energy trade in our model, (fossil) carbon leakage only happens through the market for EITE-goods. The leakage rate to sector q is however slightly negative, as increased production of good y in the unregulated regions tends to shift demand for inputs from other production sectors including sector q. When introducing the offset possibilities in the EU ETS, the figure shows that this has a significant impact on the leakage rate to energy-intensive goods (y and z). The leakage rate decreases with the conversion rate, which is what we expected in section 2, and becomes negative when α exceeds 60%. With homogenous goods, the leakage rate is around 100% in the *REF* scenario, then declines sharply when offsets are introduced and the conversion rate increased, but remains positive even when α is 100%.

Leakage to sector q actually contributes more to overall leakage in all offset scenarios. This leakage rate is only marginally affected by the conversion rate, but reaches a maximum when α is 40% (in section 2 we concluded that the effect of higher α on this type of leakage is ambiguous).

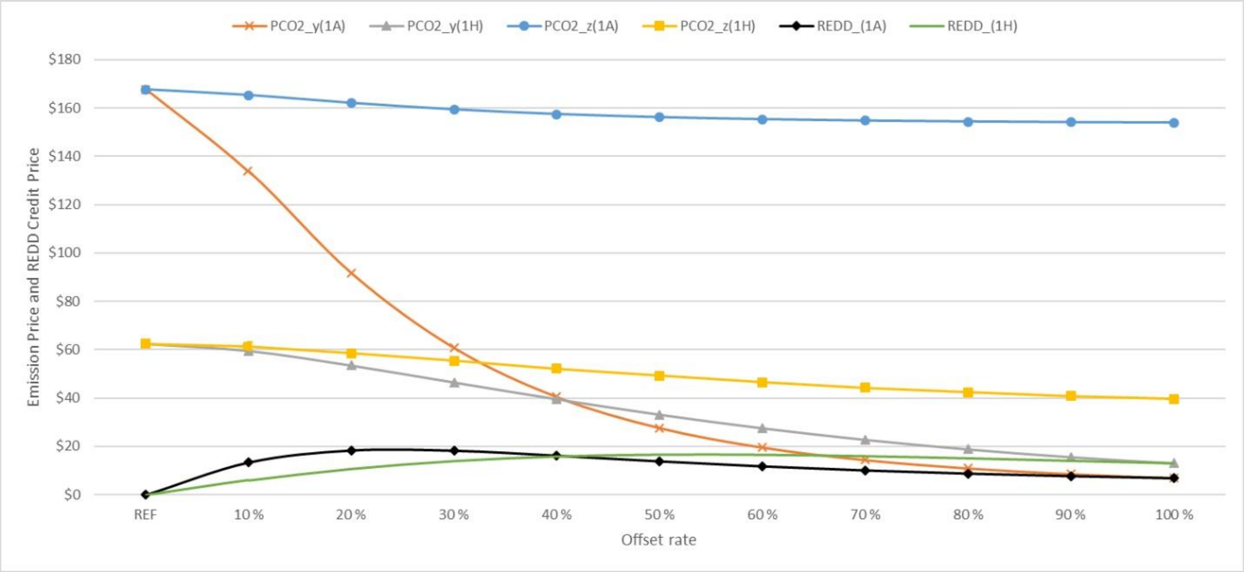

Figure 3: Price of emission and REDD+ credit under different combination of policies.

As explained in section 2, the main reason why leakage from the regulating region decreases is that the REDD+ credits make it less costly to comply with the emission regulation. That is, the offset possibility will tend to decrease the emission price for producers of good y and z in the EU. Figure 3 shows the endogenous ETS prices together with the REDD+ credit price. In line with our theoretical analysis, the offset possibility lowers the emission price substantially for the producers of good y. The emission price for the producers of good z decreases to some degree, as consumers now shift their consumption towards the relatively cheaper good y. Thus, the production of good y in the EU increases by around 7% (when $\alpha = 1$) vis-à-vis *REF* (and is about the same as in *BAU*), while the production of good z decreases marginally in scenario 1. Emission intensities in the EU increase slightly for good *y* and marginally for good *z*.

Figure 3 further shows that an increasing conversion rate increases the REDD+ credit price initially, as more emission reductions from sector q increase the marginal abatement cost. The REDD+ credit price reaches a maximum, however, of around \$19 with 25% conversion rate. Recall from our theoretical analysis that the price of REDD+ credits could indeed either increase or decrease with increasing conversion rate. On the one hand, a higher conversion rate makes REDD+ credits more valuable, leading to higher demand. On the other hand, a higher conversion rate also means that fewer REDD+ credits are needed to offset a given amount of emissions. As illustrated by the figure, the former effect is dominating at low conversion rates, while the latter is dominating at high rates. The reason is likely that at very low conversion rates, using offsets is quite costly as explained above. Hence, demand for offsets is rather low. As the conversion rate increases, using offsets become more and more interesting, stimulating demand. This effect is also existing at higher conversion rates, but less so, and then the other effect (fewer offsets are needed to compensate emissions) is dominating. To a large degree, the offset price is inversely related to the effects on global emissions (cf. Figures 1 and 3).

In the case with homogenous goods, the initial emission price is much lower as higher costs for EU producers to a larger degree make them less competitive (cf. the effects on leakage above). Still, we recognize the same pattern as with heterogeneous goods, except that the REDD+ credit price reaches its maximum at a much higher conversion rate. This is consistent with Figure 1, showing that EU emissions continue to increase significantly with α also when α is high, indicating continued increase in demand for offsets (as opposed to in the benchmark results).

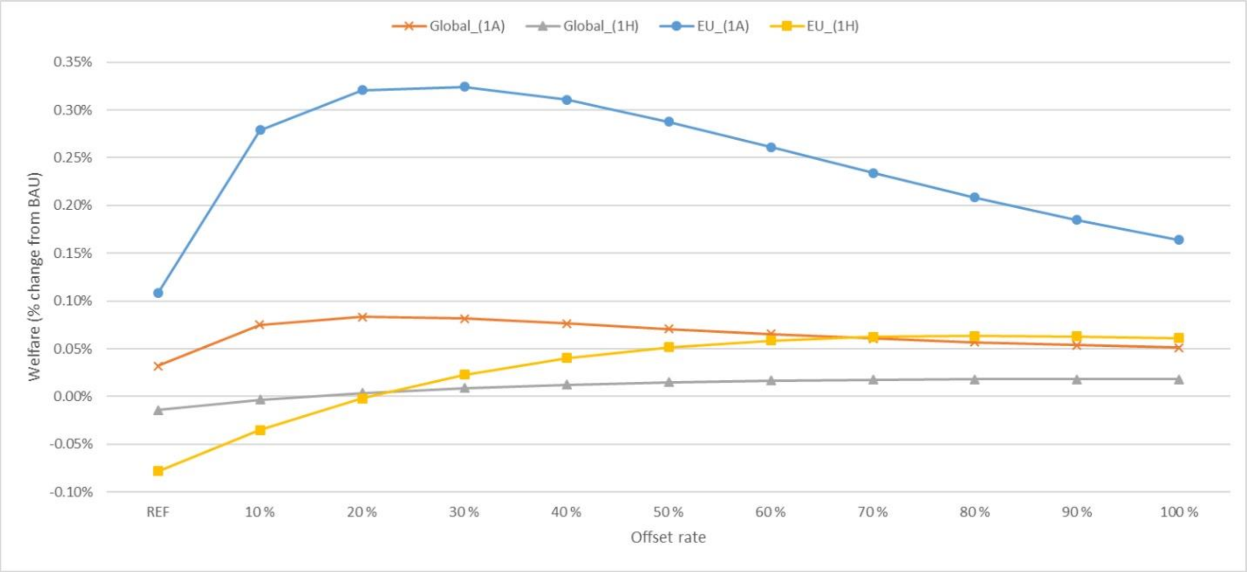

Figure 4: Global and EU's welfare effect under different combination of policies.

The offset mechanism reallocates some production of good y from the unregulating regions back to the EU. Further, global emissions decline with the introduction of offsets, with a minimum when the conversion rate is 18%, meaning lower costs of climate change. Figure 4 shows the global welfare change and the welfare change in the EU under the different policies, shown as percentage changes compared to *BAU*. As explained above, the value of changes in global emissions are taken into account, using the emission price from *REF* as the value per ton emissions. Note that we credit the effort of emission reduction through REDD+ to the policy region EU. As shown in the figure, emission pricing alone (*REF*) is welfare improving both for the EU and globally. Furthermore, the results suggest an optimal conversion rate of 22% from a global welfare perspective (23% from an EU perspective). This confirms our analytical result in section 2, i.e., that the optimal conversion rate from a welfare perspective (α^W) is higher than the conversion rate that minimizes global emissions (α^E). However, we also notice that α^W is quite close to α^E.

If we were only concerned about economic welfare effects, and not the impacts on global emissions, the optimal conversion rate (both globally and for the EU) increases to 100%, which also confirms what we concluded in the theoretical analysis. The reason is that the offset possibility is a cost saving policy, and the cost savings are maximized when producers are facing the same emission price across sectors. To sum up, from a mitigation costs perspective, 100% conversion rate is optimal as it equalizes marginal abatement costs between the y and z sectors in the EU and the q sector in Brazil, while a lower conversion rate is optimal when the benefits of global emission reductions are also accounted for.

In the homogenous goods case, the optimal conversion rate is much higher, which is consistent with the result in Figure 1 that global emissions are minimized at a much higher conversion rate in this case.

Sensitivity analysis

In the sensitivity analysis, we consider scenario 2 (open permit trade between sector y and z) and examine the effects of changing some of our main assumptions (in scenario 1): i) a lower Armington elasticity on traded goods, ii) including Indonesia in the REDD+ market, and iii) only 50% additionality of REDD+ credits (i.e., net abatement is only half of what is reported). In the figures below, we also show the benchmark results, i.e., scenario 1 with heterogeneous goods. We focus on global emissions and global welfare.

Starting with scenario 2, global emissions are slightly lower than in scenario 1 as more offset credits are being bought when also sector z indirectly can buy offsets (see Figure 5). It follows that EU's emissions are higher in scenario 2 than scenario 1, and only 2% below *BAU* emissions when α is 100%. The conversion rate that minimizes global emissions is 21%. From Figure 6 we see that global welfare increases even more in scenario 2, which is not surprising given that both sectors have access to offsets. The conversion rate that maximizes global welfare is 30%. However, EU's welfare is not higher in scenario 2 than scenario 1, which seems surprising at first as then also the *z* sector has access to offsets. The reason is probably that the offset price then increases more than in scenario 1, due to higher demand. Since the EU is the only buyer of REDD+ credits, it is in EU's interest to restrict demand for offsets in order to keep the offset price at a lower level (cf. Rosendahl and Strand 2015).

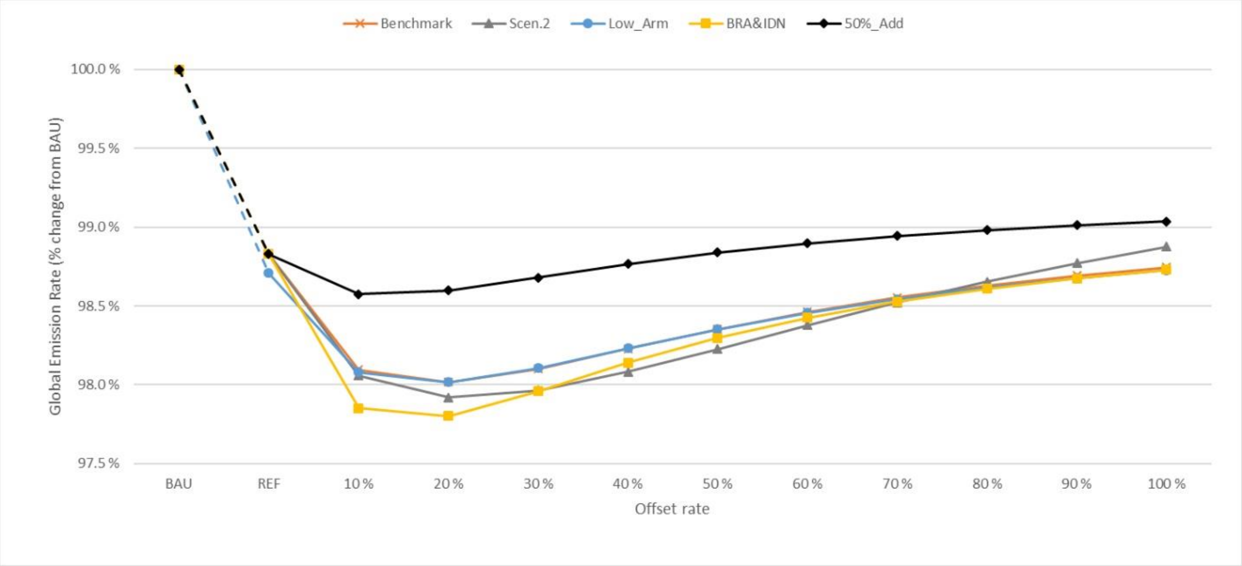

Figure 5: Global emission rate in Benchmark (Scenario 1), Scenario 2, and with assumption of lower Armington elasticity (Low_Arm), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add).

The size of the Armington elasticity determines how close goods produced in different regions are, and hence implicitly the good's trade exposure (see Appendix C). Thus, with a lower Armington elasticity we assume less trade exposure for producer x, y and q. From Figure 5 we see that global emissions are very close to the benchmark results. The effects on global welfare are also very similar, see Figure 6, with almost the same optimal conversion rate ($\alpha^W = 0.21$). Hence, it seems that the

Armington elasticities are not as important as long as they are not too big (and hence close to homogenous goods).

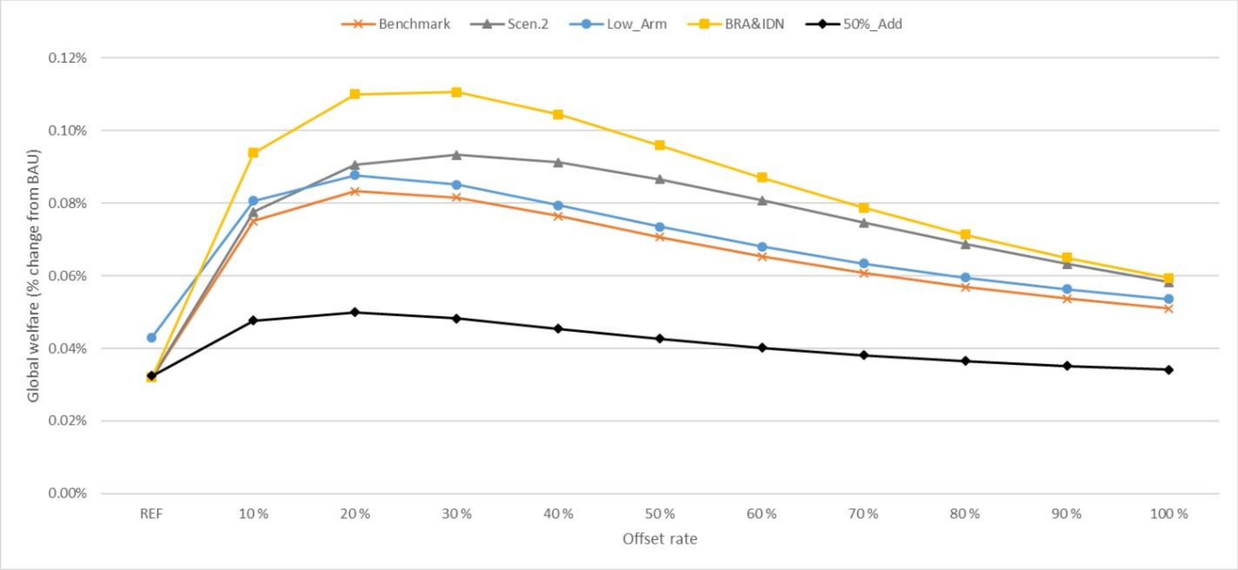

Figure 6: Global welfare effects in Benchmark (Scenario 1), Scenario 2, and with assumption of lower Armington elasticity (Low_Arm), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add).

In the benchmark simulations we only consider Brazil as the supplier of REDD+ credits. However, Indonesia is also a country with large rainforests, and among the countries that may participate in a REDD+ initiative. How would an offset mechanism introduced for both Brazil and Indonesia affect global emissions and global welfare? In the model, we now replace the reference level of CO_2 emission in Brazil for producer q, with corresponding emissions for both Brazil and Indonesia, such that $\alpha\left(e_{ref}^{qBRA}+e_{ref}^{qIDN}-e^{qBRA}-e^{qIDN}\right)\geq 0$. Figure 5 shows that global emission is then lower than in all the other scenarios considered. The conversion rate that minimizes global emission is still in the same range as in the benchmark simulations (α^{E}= 0.16 versus α^{E}= 0.18). The lower global emissions are due to relatively more offset credits being bought, as the REDD+ credit price is now even lower with more cheap abatement options available. That is, with both Brazil and Indonesia supplying REDD+ credits, a similar emission reduction can be achieved at a lower cost. Figure 6 shows that this has a positive global welfare effect, as the welfare increase is greater than in the benchmark simulations. Again, the optimal conversion rate is not much changed, however ($\alpha^W =$ 0.18).

In the last sensitivity analysis, we assume that the net emission reduction in Brazil for producer q is 50% less than reported, that is, the additionality of REDD+ credits is only 50%. This can be due to asymmetric information between the buyer and seller of credits (Angelsen et al. 2014). In other words, when *y* producers in the EU pay for two REDD+ credits, the effect on the ground in Brazil is the same as when they pay for one credit in the other scenarios. Each credit can still be balanced against one unit of domestic emissions, which means that the environmental integrity of the offsets is reduced. All other assumptions are in line with our benchmark simulations. The simulation results suggest that allowing for offsets still has an impact on global emission, but less than in the benchmark case with 100% additionality (cf. Figure 5). Moreover, global emissions have a minimum at a lower conversion rate, i.e.,13% (compared to 18% in the benchmark simulations). The global emission rate remains lower than *REF* for conversion rates up to 50% – with higher conversion rates the global emissions are inflated by introducing REDD+ offsets. As for global welfare, Figure 6 suggests an optimal conversion rate of 19%, again somewhat lower than in the benchmark case. In general, global welfare is lower than in the benchmark simulations, which is due to higher global emissions (and implicitly higher costs of reducing emissions through REDD+).

4. Concluding remarks

Countries that introduce unilateral action to reduce greenhouse gas (GHG) emissions, may face high abatement costs as well as the risk of reduced competitiveness for emission-intensive and trade-exposed (EITE) industries, and corresponding carbon leakage. The economic literature has suggested different approaches to mitigate this type of carbon leakage, and a widely used approach in existing emission trading systems (ETS) is output-based allocation (OBA). In the current paper, we have examined the impacts of allowing for REDD+ credits to offset domestic GHG emission for the EITE industries. The use of offsets can improve the efficiency of the ETS by lowering the overall cost of compliance, mitigate carbon leakage, and functioning as a bridge for large scale funding of REDD+. However, a major concern of including the offset mechanism is market flooding which can reduce the incentives for low-carbon technology. We have especially examined the effects of requiring that the EITE producers must acquire more than one offset credit to balance one ETS allowance, i.e., a conversion rate below one.

We have shown analytically that it is globally welfare improving for a single region to introduce such an emission offset mechanism for the EITE sector, when an ETS is already implemented in the region. In the welfare expression, we include the benefits of reduced global emissions. Moreover, we have shown that it is optimal to increase the conversion rate (at least) as long as it leads to lower global emissions, and hence that the optimal conversion rate from a global welfare perspective is higher than the conversion rate that minimizes global emissions.

Next, we have confirmed these results using a stylized computable general equilibrium model for the world economy, calibrated to real world data in the context of the EU ETS and REDD+ credits from Brazil. We found that welfare for both the EU and the world as a whole was consistently improved when an offset mechanism was introduced, irrespective of whether the offset mechanism is introduced for only the trade-exposed sector or for the whole EU ETS. In the former case, we found that global emissions are minimized with a conversion rate of 18%, whereas global and EU welfare is maximized with conversion rates of respectively 22% and 23%. The low optimal conversion rate is due to its beneficial impact on global emissions. This is contrary to previous results such as Bosello et al. (2015), who find that a conversion rate of 100% would be optimal for the EU, illustrating the significant difference between our welfare concept accounting for global emission reduction and Bosello et al's welfare concept accounting only for changes in GDP.

Whereas global welfare is slightly higher when all ETS sectors have access to offsets, EU's welfare is in fact higher when only EITE producers have access, due to lower prices of offset credits. Moreover, EU's domestic emissions are lower in this latter case, due to less overflow of REDD+ credits in the EU ETS. Together, this may suggest that restrictions on access to offsets to only EITE producers (with a conversion rate well below one) may in fact be a preferred policy for the EU even if it implies different emission prices within the region. However, this is due to EU's role as the sole buyer of offsets and hence strong influence on the price of offsets, and thus from a global perspective full access to offsets for all sectors in the EU ETS is slightly preferred.

The numerical simulations account for international trade, and showed that the offset mechanism has a significant impact on the leakage rate for EITE goods, and that this depends crucially on the trade exposure of these goods. If goods in different regions were perfect substitutes with one global price, then the optimal conversion rate would be close to one. However, we find this quite unrealistic, and with more realistic assumptions about trade exposure the optimal conversion rate is much below one. Further, the leakage rate from agricultural and forestry goods in the REDD+ countries is positive irrespective of the conversion rate. However, we found that the leakage rate decreases with increasing conversion rate.

Data from different sources were collected to estimate and calibrate the production function's structure for the agricultural and forestry producer. However, as the literature on carbon uptake, trade exposure and land prices do vary, there are some uncertainties related to the parameter selection in the numerical simulations. Moreover, our model is rather stylized with one aggregate sector for agricultural and forest goods, and future work could benefit from a more disaggregated modeling of this sector (as well as of other sectors and of regions). For instance, the trade and leakage exposure vary quite a lot between different forest and agricultural goods, which our model does not capture. Further, the paper does also not take into account issues related to implementation, which is a large literature on its own (see e.g. Angelsen et al. 2017; Boer 2018; Brockhaus et al. 2014; Cadman et al. 2017; Doupe 2015).

When it comes to the Paris climate agreement, many tropical rainforest countries have included REDD+ efforts into their national determined contributions (NDCs). That is, these countries aim to implement REDD+ as part of their contribution to combat climate change. Moreover "positive incentives for activities relating to reducing emissions from deforestation and forest degradation" is also specifically mentioned under article 5 of the agreement (Paris Climate Agreement 2015). However, none of the potential donor countries have mentioned support for such an emission offset mechanism in their NDCs (Hein et al. 2018). Moreover, the parties are still undecided on the handbook for how Paris climate agreement will measure and interpret a country's emissions and commitments. Further, the rules for international carbon markets and the new sustainable development mechanism, both under Article 6 of the agreement, have been pushed into future COP (Conference of the Parties) meetings (Evans and Timperley 2018). As for now, a report by Streck et al. (2017) does suggest that countries that are parties to the Paris climate agreement could cooperate to implement REDD+ in a carbon market under Article 6, as long as the parties agree on how to deduct from the national emission account of the forest country. It is also worth mentioning that the EU aims to reach its NDC for 2030 through domestic emission reductions. Hence, allowing for REDD+ credits in the EU ETS may be more realistic in a scenario where the EU decides to strengthen its ambitions, which is currently a topic of discussion in the EU.[17]

Böhringer et al. (2017) and Kaushal and Rosendahl (2020) showed that OBA combined with emission pricing may result in regional and global welfare improving effects, when the EITE goods are highly exposed to foreign competition. However, they also find that the opposite might be true when the goods are less exposed. We have shown that a low conversion rate for the emission offset mechanism, combined with emission pricing, could improve the global and regional welfare. Moreover, we find this to be true no matter how trade-exposed the EITE goods are. Thus, we conclude that complementing emission pricing with a certain conversion rate for the emission offset mechanism, seems like a good strategy in terms of regional and global welfare improvement. Future research could to a large degree compare different compensation mechanisms within a consistent framework, and even try to derive the optimal combination of different mechanisms.

Acknowledgements

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Appendix A

A1: Global welfare change in scenario 1

By differentiating with respect to α, we have that:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3} \left[u_x^j \frac{\partial \bar{x}^j}{\partial \alpha} + u_y^j \frac{\partial \bar{y}^j}{\partial \alpha} + u_q^j \frac{\partial \bar{q}^j}{\partial \alpha} + u_z^j \frac{\partial \bar{z}^j}{\partial \alpha} - c_x^{xj} \frac{\partial x^j}{\partial \alpha} - c_y^{yj} \frac{\partial y^j}{\partial \alpha} - c_q^{qj} \frac{\partial q^j}{\partial \alpha} - c_z^{zj} \frac{\partial z^j}{\partial \alpha} \right.$$
$$\left. - \left(\tau^1 + c_e^{yj}\right) \frac{\partial e^{yj}}{\partial \alpha} - \left(\tau^1 + c_e^{qj}\right) \frac{\partial e^{qj}}{\partial \alpha} - \left(\tau^1 + c_e^{zj}\right) \frac{\partial e^{zj}}{\partial \alpha} \right]$$

Since good z is non-tradable, the production in region j is equal to consumption in the same region. Also recall that $c_e^{q1} = c_e^{y2} = c_e^{z2} = c_e^{y3} = c_e^{q3} = c_e^{z3} = 0$:

$$\frac{\partial W^G}{\partial \alpha} = \sum_{j=1,2,3} \left[p^x \left(\frac{\partial \bar{x}^j}{\partial \alpha} - \frac{\partial x^j}{\partial \alpha} \right) + p^y \left(\frac{\partial \bar{y}^j}{\partial \alpha} - \frac{\partial y^j}{\partial \alpha} \right) + p^q \left(\frac{\partial \bar{q}^j}{\partial \alpha} - \frac{\partial q^j}{\partial \alpha} \right) \right] - \left(\tau^1 + c_e^{y1}\right) \frac{\partial e^{y1}}{\partial \alpha}$$
$$- \left(\tau^1 + c_e^{z1}\right) \frac{\partial e^{z1}}{\partial \alpha} - \left(\tau^1 + c_e^{q2}\right) \frac{\partial e^{q2}}{\partial \alpha}$$
$$- \tau^1 \left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha} \right)$$

We next differentiate [7] w.r.t α:

$$\frac{\partial p^x}{\partial \alpha} (x^j - \bar{x}^j) + p^x \left(\frac{\partial x^j}{\partial \alpha} - \frac{\partial \bar{x}^j}{\partial \alpha} \right) + \frac{\partial p^y}{\partial \alpha} (y^j - \bar{y}^j) + p^y \left(\frac{\partial y^j}{\partial \alpha} - \frac{\partial \bar{y}^j}{\partial \alpha} \right) + \frac{\partial p^q}{\partial \alpha} (q^j - \bar{q}^j) + p^q \left(\frac{\partial q^j}{\partial \alpha} - \frac{\partial \bar{q}^j}{\partial \alpha} \right) = 0$$

We solve this for p^x, and insert for p^x into the equation above:

$$\frac{\partial W^G}{\partial\alpha} = \sum_{j=1,2,3}\left[\frac{\left(\frac{\partial p^x}{\partial\alpha}(x^j-\bar{x}^j)+p^y\left(\frac{\partial y^j}{\partial\alpha}-\frac{\partial\bar{y}^j}{\partial\alpha}\right)+\frac{\partial p^y}{\partial\alpha}(y^j-\bar{y}^j)+\frac{\partial p^q}{\partial\alpha}(q^j-\bar{q}^j)+p^q\left(\frac{\partial q^j}{\partial\alpha}-\frac{\partial\bar{q}^j}{\partial\alpha}\right)\right)}{-\left(\frac{\partial x^j}{\partial\alpha}-\frac{\partial\bar{x}^j}{\partial\alpha}\right)}\left(\frac{\partial\bar{x}^j}{\partial\alpha}\right.\right.$$

$$\left.\left.-\frac{\partial x^j}{\partial\alpha}\right)+p^y\left(\frac{\partial\bar{y}^j}{\partial\alpha}-\frac{\partial y^j}{\partial\alpha}\right)+p^q\left(\frac{\partial\bar{q}^j}{\partial\alpha}-\frac{\partial q^j}{\partial\alpha}\right)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial\alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial\alpha}$$

$$-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial\alpha}-\tau^1\left(\frac{\partial e^{q1}}{\partial\alpha}+\frac{\partial e^{y2}}{\partial\alpha}+\frac{\partial e^{z2}}{\partial\alpha}+\frac{\partial e^{y3}}{\partial\alpha}+\frac{\partial e^{q3}}{\partial\alpha}+\frac{\partial e^{z3}}{\partial\alpha}\right)$$

This can be simplified to:

$$\frac{\partial W^G}{\partial\alpha} = \sum_{j=1,2,3}\left[\frac{\partial p^x}{\partial\alpha}(x^j-\bar{x}^j)+p^y\left(\frac{\partial y^j}{\partial\alpha}-\frac{\partial\bar{y}^j}{\partial\alpha}\right)+\frac{\partial p^y}{\partial\alpha}(y^j-\bar{y}^j)+\frac{\partial p^q}{\partial\alpha}(q^j-\bar{q}^j)+p^q\left(\frac{\partial q^j}{\partial\alpha}-\frac{\partial\bar{q}^j}{\partial\alpha}\right)\right.$$

$$\left.+p^y\left(\frac{\partial\bar{y}^j}{\partial\alpha}-\frac{\partial y^j}{\partial\alpha}\right)+p^q\left(\frac{\partial\bar{q}^j}{\partial\alpha}-\frac{\partial q^j}{\partial\alpha}\right)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial\alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial\alpha}-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial\alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial\alpha}+\frac{\partial e^{y2}}{\partial\alpha}+\frac{\partial e^{z2}}{\partial\alpha}+\frac{\partial e^{y3}}{\partial\alpha}+\frac{\partial e^{q3}}{\partial\alpha}+\frac{\partial e^{z3}}{\partial\alpha}\right)$$

Further:

$$\frac{\partial W^G}{\partial\alpha} = \sum_{j=1,2,3}\left[p^y\left(\frac{\partial y^j}{\partial\alpha}-\frac{\partial\bar{y}^j}{\partial\alpha}+\frac{\partial\bar{y}^j}{\partial\alpha}-\frac{\partial y^j}{\partial\alpha}\right)+p^q\left(\frac{\partial q^j}{\partial\alpha}-\frac{\partial\bar{q}^j}{\partial\alpha}+\frac{\partial\bar{q}^j}{\partial\alpha}-\frac{\partial q^j}{\partial\alpha}\right)+\frac{\partial p^x}{\partial\alpha}(x^j-\bar{x}^j)+\frac{\partial p^y}{\partial\alpha}(y^j-\bar{y}^j)\right.$$

$$\left.+\frac{\partial p^q}{\partial\alpha}(q^j-\bar{q}^j)\right]-\left(\tau^1+c_e^{y1}\right)\frac{\partial e^{y1}}{\partial\alpha}-(\tau^1+c_e^{z1})\frac{\partial e^{z1}}{\partial\alpha}-\left(\tau^1+c_e^{q2}\right)\frac{\partial e^{q2}}{\partial\alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial\alpha}+\frac{\partial e^{y2}}{\partial\alpha}+\frac{\partial e^{z2}}{\partial\alpha}+\frac{\partial e^{y3}}{\partial\alpha}+\frac{\partial e^{q3}}{\partial\alpha}+\frac{\partial e^{z3}}{\partial\alpha}\right)$$

By combining this with equation [1] we have that:

$$\frac{\partial W^G}{\partial\alpha} = -\left(c_e^{y1}+\tau^1\right)\frac{\partial e^{y1}}{\partial\alpha}-(c_e^{z1}+\tau^1)\frac{\partial e^{z1}}{\partial\alpha}-\left(c_e^{q2}+\tau^1\right)\frac{\partial e^{q2}}{\partial\alpha}$$

$$-\tau^1\left(\frac{\partial e^{q1}}{\partial\alpha}+\frac{\partial e^{y2}}{\partial\alpha}+\frac{\partial e^{z2}}{\partial\alpha}+\frac{\partial e^{y3}}{\partial\alpha}+\frac{\partial e^{q3}}{\partial\alpha}+\frac{\partial e^{z3}}{\partial\alpha}\right)$$

$c_e^{y1} = -t^1$, $c_e^{q2} = -r^2$ and $c_e^{z1} = -t^{z1}$ from equation [3] – [5] gives us:

$$\frac{\partial W^G}{\partial \alpha} = \left(t^1 - \tau^1\right)\frac{\partial e^{y1}}{\partial \alpha} + (r^2 - \tau^1)\frac{\partial e^{q2}}{\partial \alpha} + (t^{z1} - \tau^1)\frac{\partial e^{z1}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

With sector separated emission markets, emission from sector z in region 1 is fixed. Thus, $\frac{\partial e^{z1}}{\partial \alpha} = 0$:

$$\frac{\partial W^G}{\partial \alpha} = t^1\frac{\partial e^{y1}}{\partial \alpha} + r^2\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

By differentiating the emission from sector y in region 1 and set it equal to zero, we have that:

$$\frac{\partial \bar{E}^{y1}}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} - e_0^{q2} + e^{q2} + \alpha\frac{\partial e^{q2}}{\partial \alpha} = 0$$

$$\frac{\partial e^{y1}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \alpha\frac{\partial e^{q2}}{\partial \alpha}$$

Thus, the expression above can be simplified to (using that $r^2 = \alpha t^1$):

$$\frac{\partial W^G}{\partial \alpha} = t^1\left(e_0^{q2} - e^{q2}\right) - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) = t^1\left(e_0^{q2} - e^{q2}\right) - \tau^1\frac{\partial E}{\partial \alpha}$$

where *E* denotes global emissions. Hence, we have derived equation [9] in Lemma 2.

A2: Global welfare change in scenario 2

A single emission price t^1 balances the region emission market. Since $t^1 = \frac{r^2}{\alpha}$, then we get [A1]:

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha}\right) + r^2\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \qquad \text{[A1]}$$

With the assumption of regional emission, we differentiate with respect to α:

$$\frac{\partial \bar{E}^{y1}}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} - e_0^{q2} + e^{q2} + \alpha \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} = 0$$

$$\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \alpha \frac{\partial e^{q2}}{\partial \alpha}$$

Further, by simplifying with the same assumptions as above, we can easily derive equation [9] again.

Appendix B: Summary of the numerical CGE model

Indices and sets:

Set of regions	R	EU, BRA, IDN, ROW
Set of goods	*g*	q, x, y, z
r (alias *j*)		Index for regions

Variables:

S^{gr}	Production of good *g* in *r*
S_{FE}^{r}	Production of FE in *r*
D^{gr}	Aggregated consumer demand of good *g* in *r*
KL^{gr}	Value-added composite for *g* in *r*
KLF^{r}	Value-added composite for *FE* in *r*
A^{gr}	Armington aggregate of *g* in *r*
IM^{gr}	Import aggregate of *g* in *r*
W^{r}	Consumption composite in *r*
$CO2^{qr}$	Land use related CO_2 emission in region r

p^{gr}	Price of *g* in *r*
p_{FE}^{r}	Price of Primary fossil *FE* in r
p_{KL}^{gr}	Price of value added for g in r
p_{KLF}^{r}	Price of value added for FE in r
p_{L}^{r}	Price of labor (wage rate) in *r*
p_{K}^{r}	Price of capital (rental rate) in *r*

p_O^r	Rent for primary energy resource in *r*
p_A^{gr}	Price of Armington aggregate of *g* in *r*
p_{IM}^{gr}	Price of aggregate imports of *g* in *r*
p_{CO2}^{gr}	Price of CO2 emission in *r*
p_{REDD}^{gr}	Price of REDD credits in *r*
p_W^r	Price of consumption composite in *r*
LA^{gr}	Land use endowment in sector *g* in region r

Parameters:

α^r	Offset share allowance in region *r* through REDD credits from BRA
σ_{KLE}^{gr}	Substitution between value-added and energy/land *g* in *r*
σ_{KL}^r	Substitution between value-added *g* in *r*
σ_Q^r	Substitution between value-added and natural resource in *FE* in *r*
σ_{LN}^r	Substitution between value-added in *FE* in *r*
σ_A^{gr}	Substitution between import and domestic *g* in *r*
σ_{IM}^{gr}	Substitution between imports from different *g* in *r*
σ_W^r	Substitution between goods to consumption

θ_{FE}^{gr}	Cost Share of FE in production of *g* in *r*
θ_{KL}^{gr}	Cost Share of labor in production of *g* in *r*
θ_O^r	Cost Share of natural resource in production of *FE* in *r*
θ_{LN}^r	Cost Share of labor in production of *FE* in *r*

θ_A^{gr}	Cost Share of domestic goods *g* in consumption in *r*
θ_{IM}^{gr}	Cost Share of different imports goods *g* in consumption in *r*

p_{LA}^r	Price of land (rental rate) in *r*
L_0^{gr}	Labor endowment in sector *g* in region r
$L_{0,FE}^r$	Labor endowment in *FE* in region r
K_0^{gr}	Capital endowment in sector *g* in region r
$K_{0,FE}^r$	Capital endowment in *FE* in region r
O_0^r	Resource endowment of primary fossil energy in region r
$CO2_{MAX}^r$	Fossil related CO₂ emission allowance in region r
$CO2_0^{gr}$	Land use related CO₂ emission for good *g* in region r
γ_{CO2}^r	Coefficient for land use CO₂ emission in region r
κ_{CO2}^r	Coefficient for primary fossil energy of CO₂ emission in region r

Zero Profit Conditions

Production of goods except fossil primary energy:

$$\pi_S^{gr} = \left(\theta_{FE}^{gr}\left(p_{FE}^r + \kappa_{CO2}^r p_{CO2}^{gr}\right)^{\left(1-\sigma_{KLE}^{gr}\right)} + \theta_{LA}^{gr}\left(p_{LA}^r\right)^{\left(1-\sigma_{KLE}^{gr}\right)} + \left(1-\theta_{FE}^{gr}-\theta_{LA}^{gr}\right)p_{KL}^{gr\left(1-\sigma_{KLE}^{gr}\right)}\right)^{\left(\frac{1}{1-\sigma_{KLE}^{gr}}\right)} \geq p^{gr} \quad \perp S^{gr}$$

Sector specific value-added aggregate for *q, x*, *y* and *z*:

$$\pi_{KL}^{gr} = \left(\theta_{KL}^{gr} p_L^{r\left(1-\sigma_{KL}^{gr}\right)} + \left(1-\theta_{KL}^{gr}\right)p_K^{r\left(1-\sigma_{KL}^{gr}\right)}\right)^{\left(\frac{1}{1-\sigma_{KL}^{gr}}\right)} \geq p_{KL}^{gr} \qquad \perp KL^{gr}$$

Production of fossil primary energy:

$$\pi_{FE}^{r} = \left(\theta_{O}^{r} p_{O}^{r\,(1-\sigma_{O}^{r})} + (1-\theta_{Q}^{r}) p_{KLF}^{r}{}^{(1-\sigma_{O}^{r})}\right)^{\left(\frac{1}{1-\sigma_{O}^{r}}\right)} \quad \geq p_{FE}^{r} \qquad \perp S_{FE}^{r}$$

Sector specific value-added aggregate for *FE*:

$$\pi_{KLF}^{r} = \left(\theta_{LN}^{r} p_{L}^{r\,(1-\sigma_{LN}^{r})} + (1-\theta_{LN}^{r}) p_{K}^{r\,(1-\sigma_{LN}^{r})}\right)^{\left(\frac{1}{1-\sigma_{LN}^{r}}\right)} \quad \geq p_{KLF}^{r} \qquad \perp KLF^{r}$$

Armington aggregate except for *FE*:

$$\pi_{A}^{gr} = \left(\theta_{A}^{gr} (p^{gr})^{(1-\sigma_{A}^{gr})} + (1-\theta_{A}^{gr}) p_{IM}^{gr\,(1-\sigma_{A}^{gr})}\right)^{\left(\frac{1}{1-\sigma_{A}^{gr}}\right)} \quad \geq p_{A}^{gr} \qquad \perp A^{gr}$$

Import Composite except for *FE*:

$$\pi_{IM}^{gr} = \left(\sum_{j \neq r} \theta_{IM}^{gjr} \left(p^{gj}\right)^{(1-\sigma_{IM}^{gr})}\right)^{\left(\frac{1}{1-\sigma_{IM}^{gr}}\right)} \quad \geq p_{IM}^{gr} \qquad \perp IM^{gr}$$

Consumption composite:

$$\pi_{W}^{r} = \left(\theta_{W}^{qr} p_{A}^{qr\,(1-\sigma_{W}^{r})} + \theta_{W}^{xr} p_{A}^{xr\,(1-\sigma_{W}^{r})} + \theta_{W}^{yr} p_{A}^{yr\,(1-\sigma_{W}^{r})} + \theta_{W}^{zr} p_{A}^{zr\,(1-\sigma_{W}^{r})}\right)^{\left(\frac{1}{1-\sigma_{w}^{r}}\right)} \quad \geq p_{W}^{r}$$

$$\perp W^{r}$$

Market Clearing Conditions

Labor:

$$\sum_{g} L_{0}^{gr} + L_{0,FE}^{r} \geq \sum_{g} KL^{gr} \frac{\partial \pi_{KL}^{gr}}{\partial p_{L}{}^{r}} + KLF^{r} \frac{\partial \pi_{KLF}^{r}}{\partial p_{L}{}^{r}} \qquad \perp p_{L}{}^{r}$$

Capital:

$$\sum_g K_0^{gr} + K_{0,FE}^r \geq \sum_g KL^{gr} \frac{\partial \pi_{KL}^{gr}}{\partial {p_K}^r} + KLF^r \frac{\partial \pi_{KLF}^r}{\partial {p_K}^r} \qquad \perp {p_K}^r$$

Primary fossil energy resource:

$$O_0^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_O^r} \qquad \perp {p_O}^r$$

Land use resource:

$$LA^{gr} \geq S^{gr} \frac{\partial \pi_S^{gr}}{\partial P^{gr}} \qquad \perp {p_{LA}}^r$$

Value-added except *FE*:

$$KL^{gr} \geq S^{gr} \frac{\partial \pi_S^{gr}}{\partial p_{KL}^{gr}} \qquad \perp p_{KL}^{gr}$$

Value-added *FE*:

$$KLF^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_{KLF}^r} \qquad \perp p_{KLF}^r$$

Armington Aggregate:

$$A^{gr} \geq W^r \frac{\partial \pi_W^r}{\partial p_A^{gr}} \qquad \perp p_A^{gr}$$

Import Aggregate:

$$IM^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p_{IM}^{gr}} \qquad \perp p_{IM}^{gr}$$

Supply-demand balance of goods, except *FE*:

$$S^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p^{gr}} + \sum_{j \neq r} IM^{gj} \frac{\partial \pi_{IM}^{gj}}{\partial p^{gj}} \qquad \perp p^{gr}$$

Supply-demand balance of *FE*:

$$S_{FE}^r \geq \sum_g S^{gr} \frac{\partial \pi_S^{gr}}{\partial \left(p_{FE}^r + \kappa_{CO2}^r p_{CO2}^{gr}\right)} \qquad \perp p_{FE}^r$$

Demand of goods:

$$D^{gr} \geq A^{gr} \frac{\partial \pi_A^{gr}}{\partial p^{gr}} + IM^{gr} \frac{\partial \pi_{IM}^{gr}}{\partial p^{gr}} \qquad \perp D^{gr}$$

Allowed CO₂ emission in region, with offset from region BRA:

$$CO2_{MAX}^r \geq \kappa_{CO2}^r S_{FE}^r - \alpha^r \left(CO2_0^{qBRA} - CO2^{qBRA}\right) \qquad \perp p_{CO2}^r$$

Land use related CO₂ emission in region by *q*:

$$CO2^{qr} \geq \gamma_{CO2}^r LA^{qr} \qquad \perp CO2^{qr}$$

Fossil fuel related CO₂ emission in region by *g*:

$$CO2^{qr} \geq \kappa_{CO2}^r S_{FE}^r \qquad \perp CO2^{gr}$$

CO₂ emission offset through REDD credits in region:

$$\alpha^r p_{CO2}^r \geq p_{REDD}^{BRA} \qquad \perp p_{REDD}^{BRA}$$

Consumption by consumers

$$p_W^r W^r \geq p_L^r \left(\sum_g L_0^{gr} + L_{0,FE}^r \right) + p_K^r \left(\sum_g K_0^{gr} + K_{0,FE}^r \right) + p_O{}^r O_0^r + P_{LA}^r LA^{qr} + p_{CO2}^r CO2_{MAX}^r$$
$$- p_{REDD}^{BRA} \left(CO2_0^{qBRA} - CO2^{qBRA} \right) \qquad \perp p_W^r$$

Elasticities: $\sigma_{KLE}^x, \sigma_{KLE}^y, \sigma_{KLE}^z = 0.5 \qquad \sigma_{KL} = 1$

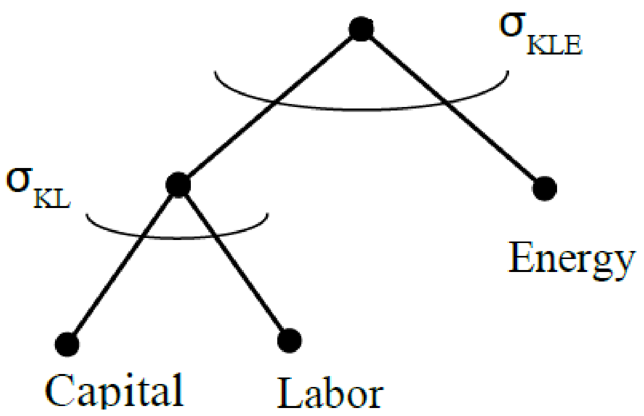

Figure B1: Nesting in production of *x*, *y* and *z*

Elasticities: $\sigma_{KLE}^q = 0.1 \qquad \sigma_{KL} = 1$

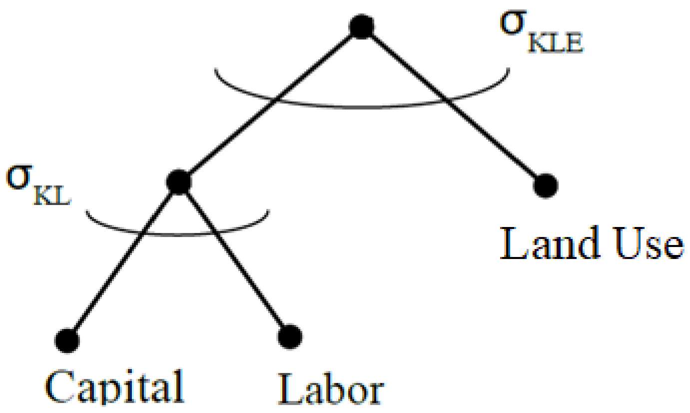

Figure B2: Nesting in production of agriculture and forestry good

Elasticities: $\sigma_O = 0.9 \quad \sigma_{KL} = 1$

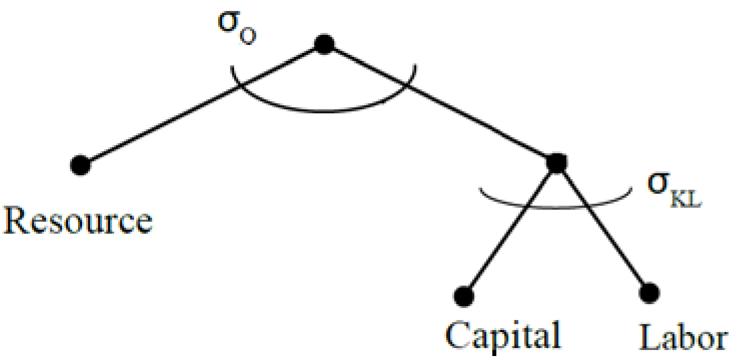

Figure B3: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$

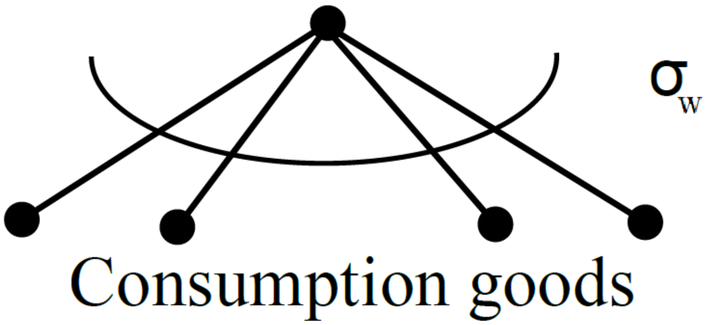

Figure B4: Nesting in final consumption

Appendix C: Data and Mapping

C1: Mapping of WIOD sectors

Model Sectors	WIOD Sectors
y: emission-intensive and tradable goods	Oil; Mining and Quarrying; Chemicals and Chemical Products; Basic Metals and Fabricated Metal; Other Non-Metallic Mineral; Transport Equipment; Textiles and Textile Products; Food, Beverages and Tobacco; Pulp, Paper, Paper , Printing and Publishing
z: emission-intensive and non-tradable goods	Transport Sector (air, water, rail, road); Electricity
q: agricultural and forestry goods	Crop and Animal production; Forestry and Logging
x: emission-free and tradable goods	All remaining goods and services

Table C1: Mapping of WIOD sectors to model sectors

Table C1 shows the mapping of the 56 WIOD sectors to three composite sectors in our model.

C2: Data and Calibration

The calibration procedure for the general equilibrium analysis is standard, where base-year data defines some of the exogenous parameter values. For other parameters, we either use estimates from other studies or calibrate them based on simulations of a well-established large-scale CGE-model (Böhringer et al. 2017).

We base the calibration of the model on World Input Output Database (WIOD) data (base-year 2009)[18], and further reconstruct the empirical data to fit the model with the theoretical model. The WIOD dataset of the world is based on 43 regions with 56 sectors, linked with corresponding data of fossil related CO_2 emission from each sector. We map all the WIOD sectors into five merged sectors x, y, z, q and f. Further, we stick to the assumption from the theoretical analysis that there are no carbon related emissions in sector x, and thus set emissions in this sector equal to zero[19].

For the agriculture and forestry sector, we need to calibrate the production function so that it captures the costs of reduced deforestation (in terms of carbon sequestration). For this purpose, we need to determine (for each region) the value share of land, the substitution elasticity between land use and the value-added composite (capital and labor), and the relationship between land use and carbon. From WIOD we have data for hectare (ha) land used in agriculture and forestry sectors (based on FAOSTAT 2018). We combine this with information about land prices in different countries, such as EUROSTAT (2016), USDA (2018), SEAB (2016), Flexor and Leite (2017) and Dislich et al. (2018),[20] and an assumed annual rent as a percentage of the land price. Together, this gives us an estimate for the value share of land in this sector in the different regions.

Next, from Malhi et al. (1999), IPCC (2000), Gan and McCarl (2007) and Sun and Sohngen (2009), we have information about ton of CO2 per ha per year related to (reduced) deforestation in different types of forest (e.g., tropical vs. temperate vs. boreal forest). Moreover, Kindermann et al. (2008) provide estimates of marginal abatement costs related to reduced deforestation in different regions of the world, which we use to calibrate the substutition elasticity between land and other inputs to production. There are several uncertainties involved in this calibration, both with respect to land prices and CO2 sequestered per ha, implying that the numerical results should be interpreted with some caution.

Net exports in sector x, y and q in the base-year are based on the difference between a region's production and consumption, and the balance of payment constraint is incorporated in the CGE model. The calibrated z sector consists of some sectors with (fairly limited) trade according to the WIOD dataset. Because there is no trade for the z sector in the theoretical analysis, we simply assume that produced quantity in a region is the same as consumed quantity in the same region.

The representative agent is assumed to have a CES utility function, which is calibrated with share parameters of consumption set to base-year shares. At the top level in the CES utility function, we use a substitution elasticity of 0.5 between the four goods x, q, y and z. At the second level we integrate a substitution between domestic and imported goods for x, q and y. Here we consider two alternative approaches for sectors x and y. One approach (denoted *H*) follows the assumption in the theoretical analysis, i.e., that domestic and foreign goods are homogenous goods (perfect substitutes).

The other approach (denoted *A*) assumes that domestic and foreign goods are heterogeneous goods (imperfect substitutes), based on Armington's approach (Armington, 1969). In this case, we also differentiate between the origins of the foreign produced goods (at the third level of the CES function). The substitution elasticities (for goods x and y) at the second and third levels are set to 16 and 32, respectively. The size of these elasticities determines how close substitutes goods produced in different origins are.

In both cases (*H* and *A*) we assume that domestic and foreign q goods are heterogeneous, and the substitution elasticities at the second and third levels are set to 4 and 8, respectively. Hence, we implicitly assume that the agricultural and forest good q is less trade-exposed than the emission-intensive (manufacturing) good y and the carbon-free good x.

We consider the approach with heterogeneous goods (*A*) more realistic than the approach with homogenous goods (*H*), and will therefore refer to the former as the benchmark case. However, there are of course uncertainties related to how trade-exposed the goods are. Thus, considering both homogenous and heterogeneous goods is useful. In addition, we consider an alternative with lower Armington elasticities for all sectors in the sensitivity analysis. Here, the second and third levels in the CES utility function the substitution elasticities are set to 4 and 8, respectively, for goods x and y, and to 2 and 4, respectively, for good q. For instance, the output response by other regions and carbon leakage that occurs in the *q* sector depends on forest type, product variety, international transport costs, and carbon uptake (García et al. 2018).

References

Alix-Garcia, J. M., Elizabeth, S., and Sims, K. 2012. "Forest conservation and slippage: evidence from Mexico's national payments for ecosystem services program." *Land Economics* 88 (4): 613-638.

Angelsen, A., Brockhaus, M., Sunderlin, W. D., and Verchot, L. V. 2012. *Analysing REDD+ Challenges and choices*. Bogor, Indonesia: Center for International Forestry Research (CIFOR).

Angelsen, A., Gierløff, C. W., Beltrán, A. M., and Elzen, M. d. 2014. *REDD credits in a global carbon market: Options and impacts*. Copenhagen, Denmark: Nordic Council of Ministers.

Angelsen, A., Brockhaus, M., Duchelle, A. E., Larson, A., Martius, C., Sunderlin, W. D., Verchot, L., Wong, G., and Wunder, S. 2017. "Learning from REDD+: a response to Fletcher et al." *Conserv. Biol.* 31 (3): 718-720.

Anger, N., and Sathaye, J. 2008. "Reducing Deforestation and Trading Emissions: Economic Implications for the Post-Kyoto Carbon Market." ZEW Discussion Papers, 08-016. Mannheim, Germany: ZEW.

Armington, P. S. 1969. "A Theory of Demand for Products Distinguished by Place of Production." *International Monetary Fund Staff Papers* 16 (1): 159-178.

Boer, H. J. 2018. "The role of government in operationalising markets for REDD+ in Indonesia." *Forest Policy and Economics* 86: 4-12.

Bosello, F., Parrado, R., Rosa, R., and Eboli, F. 2015. "REDD in the Carbon Market: A General Equilibrium Analysis." *Environmental Modeling & Assessment* 20: 103-115.

Bosetti, V., Lubowski, R., Golub, A., and Markandya, A. 2011. "Linking reduced deforestation and a global carbon market: Implications for clean energy technology and policy flexibility." *Environment and Development Economics* 16 (4): 479-505.

Brockhaus, M., Gregorio, M. D., and Mardiah, S. 2014. "Governing the design of national REDD+: An analysis of the power of agency." *Forest Policy and Economics* 49: 23-33.

Böhringer, C., Rosendahl, K. E., and Storrøsten, H. B. 2017. "Robust policies to mitigate carbon leakage." *Journal of Public Economics* 40: 459-476.

Cadman, T., Maraseni, T., Ma, H. O., and Lopez-Casero, F. 2017. "Five years of REDD+ governance: The use of market mechanisms as a response to anthropogenic climate change." *Forest Policy and Economics* 79: 8-16.

Carmichael, D.C., Lea, K.A., and Balatbat, M.C.A. 2016. "The financial additionality and viability of CDM projects allowing for uncertainty." *Environment, Development and Sustainability* 18: 129–141.

Coomes, O. T., Macdonald, G. K., and Waroux, Y. L. P. D. 2018. "Geospatial Land Price Data: A Public Good for Global Change Science and Policy." *BioScience* 6 (7): 481-484.

Copeland, B. R. 1996. "Pollution content tariffs, environmental rent shifting, and the control of cross-border pollution." *Journal of International Economics* 40: 459-476.

Den Elzen, M. G. J., Beltran, A. M., Piris-Cabezas, P., and Vuuren, D. P. V. 2009. *Analysing the International Carbon Market and Abatement Costs by 2020 for Low Concentration Targets: Policy Choices and Uncertainties*. Bilthoven, The Netherlands: Netherlands Environmental Assessment Agency.

Dislich, C., Hettig, E., Salecker, J., Heinonen, J., Lay, J., Meyer, K. M., Wiegand, K., and Tarigan, S. 2018. "Land-use change in oil palm dominated tropical landscapes - An agent-based model to explore ecological and socio-economic trade-offs." *PLOS ONE* 1. https://doi.org/10.1371/journal.pone.0190506

Dixon, A., Anger, N., Holden, R., and Livengood, E. 2008. *Integration of REDD into the International Carbon Market: Implications for Future Commitments and Market Regulation*. Wellington, New Zealand: New Zealand Ministry of Agriculture and Forestry.

Doupe, P. 2015. "The Costs of Error in Setting Reference Rates for Reduced Deforestation." *Land Economics* 91 (4): 723-738.

Eliasch, J. 2008. *Climate Change: Financing Global Forests*. Norwich, United Kingdom: The Stationery Office.

EUROSTAT. (2016). *Agricultural Land Prices and Rents data for the European Union*. The European Union: Directorate E: Sectoral and regional statistics, Unit E-1: Agriculture and fisheries.

Evans, S., and Timperley, J. 2018. "COP24: Key outcomes agreed at the UN climate talks in Katowice." *Carbon Brief*, March 19, 2019. Available at https://www.carbonbrief.org/cop24-key-outcomes-agreed-at-the-un-climate-talks-in-katowice.

FAOSTAT. 2018. Rome, Italy. Food and Agriculture Organization of the United Nations. Available at http://www.fao.org/faostat/en/.

Fischer, C., and Fox, A. K. 2012. "Comparing policies to combat emissions leakage: Border carbon adjustments versus rebates." *Journal of Environmental Economics and Management* 64 (2): 199-216.

Flexor, G., and Leite, S. P. 2017. "Land Market and Land Grabbing in Brazil during the Commodity Boom of the 2000s". *Contexto Internacional* 39(2): 393-420.

Fortmann, L., Sohngen, B., and Southgate, D. 2017. "Assessing the role of group heterogeneity in Community Forest concessions in Guatemala's Maya biosphere reserve." *Land Economics* 93: 423-432.

Gan, J., and McCarl, B. A. 2007) "Measuring transnational leakage of forest conservation." *Ecological Economics* 64 (2): 423-432.

García, J. H., Orlov, A., and Aaheim, A. 2018. "Negative leakage: The key role of forest management regimes." *Journal of Forest Economics* 33: 8-13.

Hein, J., Guarin, A., Frommé, E., and Pauw, P. 2018. "Deforestation and the Paris climate agreement: An assessment of REDD + in the national climate action plans." *Forest Policy and Economics* 90: 7-11.

Hoel, M. 1996. "Should a carbon tax be differentiated across sectors?" *Journal of Public Economics* 59: 17-32.

IPCC. 2000. *IPCC Special Report: Land Use, Land-Use Change, and Forestry*. Cambridge, United Kingdom: Cambridge University Press.

IPCC. 2014. Agriculture, Forestry and Other Land Use (AFOLU).

Kaushal, K. R., and Rosendahl, K. E. 2020. "Taxing consumption to mitigate carbon leakage." *Environmental and Resource Economics* 75: 151-181.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S., and Beach, R. 2008. "Global cost estimates of reducing carbon emissions through avoided deforestation." *PNAS* 105 (30): 10302-10307.

Lund, J. F., Sungusia, E., Mabele, M. B., and Scheba, A. 2017. "Promising Change, Delivering Continuity: REDD+ as Conservation Fad." *World Development* 89: 124-139.

Malhi, Y., Baldocchi, D. D., and Jarvis, P. G. 1999. "The carbon balance of tropical, temperate and boreal forests." *Plant, Cell and Environment* 22: 715-740.

Martin, R., Muûls, M., de Preux, L.B., and Wagner, U. J. 2014. "Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme." *American Economic Review* 104: 2482–2508.

Markussen, J. R. 1975. "International externalities and optimal tax structures." *Journal of International Economics* 5: 15-29.

Murray, B. C., Lubowski, R., and Sohngen, B. 2009. *Including International Forest Carbon Incentives in Climate Policy: Understanding the Economics*. Durham, North-Carolina: Nicholas Institute for Environmental Policy Solutions.

Myers, E. C. 2007. "Policies to Reduce Emissions from Deforestation and Degradation (REDD) in Tropical Forests: An Examination of the Issues Facing the Incorporation of REDD into Market-Based Climate Policies." RFF Discussion Paper, 07-50. Washington, DC: Resources for the Future.

Nepstad, D., Soares-Filho, B., Merry, F., Moutinho, P., Rodrigues, H. O., Bowman, M., Schwartzman, S., Almeida, O., and Rivero, S. 2007. "The Costs and Benefits of Reducing Carbon Emissions from Deforestation and Forest Degradation in the Brazilian Amazon." Presented at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP), Bali, Indonesia, December 3-14.

Neuhoff K., Owen A., Pauliuk S., and Wood R. 2016. "Quantifying impacts of consumption based charge for carbon intensive materials on products." Discussion papers 1570: DIW. Berlin, Germany.

Paris Climate Agreement. (2015). United Nations.

Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., and Wood, R. 2019. "Agricultural and forestry trade drives large share of tropical deforestation emissions." *Global Environmental Change* 56: 1-10.

Rosendahl, K.E., and Strand, J. 2011. "Carbon Leakage from the Clean Development Mechanism." *The Energy Journal* 32 (4): 27-50.

Rosendahl, K.E., and Strand, J. 2015. "Emissions Trading with Offset Markets and Free Quota Allocations." *Environmental and Resource Economics* 61: 243-271.

SEAB. 2016. *PREÇOS MÉDIOS DE TERRAS AGRÍCOLAS – detalhamento por caracteŕistica e município de 2006 a 2016 em Reais por hectare*. Brazil: SECRETARIA DE ESTADO DA AGRICULTURA E DO ABASTECIMENTO - SEAB, DEPARTAMENTO DE ECONOMIA RURAL – DERAL, DIVISÃO DE ESTATÍSTICAS BÁSICAS.

Streck, C., Howard, A., and Rajão, R. 2017. *Options for Enhancing REDD+ Collaboration in the Context of Article 6 of the Paris Agreement*. Washington, DC: Meridian Institute.

Sun, B., and Sohngen, B. 2009. "Set-asides for carbon sequestration: implications for permanence and leakage." *Climatic Change* 96 (3): 409-419.

Taylor, S. M. 2005. "Unbundling the Pollution Haven Hypothesis." *The B.E. Journal of Economic Analysis & Policy* 4 (2): 1-30.

USDA. 2018. *Land Values, 2018 Summary*. Washington, DC: United States Department of Agriculture, National Agricultural Statistics Service.

van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G. J., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J., and Randerson, J. T. 2009. "CO_2 emissions from forest loss." *Nature Geoscience* 2: 737–738.

Velly, G. L., Sauquet, A., and Sortina-Villar, S. 2017. "PES impact on leakages over several cohorts: the case of the PSA-H in Yucatan, Mexico." *Land Economics* 93: 230-257.

Figure titles

Figure 1: Global and EU's emission rate under different combination of policies.

Figure 2: Leakage rate from y, z (and q) in the EU and from q in BRA under different combination of policies.

Figure 3: Price of emission and REDD+ credit under different combination of policies.

Figure 4: Global and EU's welfare effect under different combination of policies.

Figure 5: Global emission rate in Benchmark (Scenario 1), Scenario 2, and with assumption of lower Armington elasticity (Low_Arm), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add).

Figure 6: Global welfare effects in Benchmark (Scenario 1), Scenario 2, and with assumption of lower Armington elasticity (Low_Arm), including Indonesia in the REDD+ market (BRA&IDN), and 50% additionality of REDD+ (50%_Add).

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[1] Leakage mainly occurs through two channels, i.e., i) fossil fuel markets; and ii) markets for EITE goods. This paper focuses on leakage in the latter case. The theoretical literature on leakage goes back to Markussen (1975), and other important contributions are Hoel (1996) and Copeland (1996).

[2] The effectiveness is reduced as unilateral emission constraints would raise local producers' cost, and therefore reduce their competitiveness in the world market. As a result, the regulating region achieves lower emission level locally, but risks higher production and emissions abroad (Taylor, 2005).

[3] https://ec.europa.eu/clima/policies/ets/allowances/leakage_en

[4] https://ec.europa.eu/clima/policies/ets/credits_en

[5] Full crowding out means that emission reductions from offsets fully replace domestic emission reductions.

[6] This is not the case for the non-tradable good z.

[7] Services such as forest conservation, sustainable forest management, improving the forest carbon stocks or other projects.

[8] To simplify notation, we replace $\sum_{i=1}^{3} x^{ij}$ with x^{j} in the equations.

[9] The correct definition of the Pigouvian tax is the global marginal external costs of emissions. Whether τ^{j} reflects this, or only domestic costs of global emissions, does not matter for the analytical results.

[10] See appendix C for mapping of the sectors.

[11] See appendix B for CGE-summary and nesting in different sectors.

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[12] In 2009 the ETS price was roughly 13 Euro per ton CO_2

[13] We can think of this emission target as an additional emission reduction target of 20% relative to the base-year emission. Further, the permit price in this chapter is reported without taking into account the 13 Euro per ton CO_2 in 2009.

[14] In equation [8] in section 2, we deduct production costs in the welfare expression. This is not necessary in the numerical model, as the model instead incorporates resource constraints on production (labour, capital, fossil resources, land) in addition to the terms-of-trade constraint.

[15] Based on Armington's approach (Armington, 1969).

[16] See Appendix C

[17] https://www.euractiv.com/section/climate-strategy-2050/news/eu-parliament-votes-for-55-emissions-cuts-by-2030/

[18] The model is implemented as a Mixed Complementarity Problem in GAMS, using the PATH-solver.

[19] In the WIOD dataset, sector x accounted for 14% of the global (fossil related) CO_2 emissions in 2009.

[20] These data where relatively difficult to collect, and ideally an open-access database will be beneficial for similar future studies. Coomes et al. (2018) write: "An open-access, global land price database would enable policymakers, scientists, and civic society to better grapple with the economic, social, and environmental challenges posed by global change."