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Climate Change Impacts and Solutions

Klimaendringer: Innvirkninger og Løsninger

Kevin Raj Kaushal

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Contents

List of papers

The thesis contains the following papers:

Paper 1: **Accounting for Biodiversity Loss from Climate Change in Integrated Assessment Models – A Global Delphi Value Transfer Approach**
Co-author: Ståle Navrud
Submitted to *Climate Change Economics*

Paper 2: **Taxing Consumption to Mitigate Carbon Leakage**
Co-author: Knut Einar Rosendahl
Revise-and-resubmit in *Environmental and Resource Economics*

Paper 3: **Optimal Climate Policy in the Presence of Another Region's Climate Policy**
Revise-and-resubmit in *Strategic Behavior and the Environment*

Paper 4: **Optimal REDD+ in the Carbon Market**
Co-author: Knut Einar Rosendahl

Summary

The purpose of this thesis is to assess impacts and responses to climate change. Particularly, this thesis addresses two reasons of concern related to climate change: 1) the inadequate representation of potential biodiversity impact of climate change in climate economic models, and 2) the ongoing public debate on acceptable policy strategy to mitigate carbon leakage in order to combat climate change.

Climate change will have a large impact on global biodiversity and ecosystem services, and integrated assessment models (IAMs) are among the important decision support tools for the policymakers. However, the existing IAMs either neglect or poorly assess the impacts of biodiversity and ecosystem services. The first paper responds to this problem by incorporating recent empirical estimates of the economic value of biodiversity and ecosystem services in the well-known IAM FUND (Climate Framework for Uncertainty, Negotiation and Distribution). First, biophysical assessment of impact on species loss from increased global temperature is updated in the model, based on recent studies. Then, economic damage cost estimates are transferred from a recent global Delphi Contingent Valuation (CV) study of households´ willingness-to-pay (WTP) to avoid species loss due to deforestation of the Amazon rainforest. Both of these components are fully implemented in FUND 3.9. By comparing the re-calibrated and original model, the paper suggests that the species loss is lower than what the current model projects, but the projected ecosystem service damage costs are higher. This results in a higher global damage costs of climate change. Finally, potential explanations of the results, their sensitivity and avenues for future research are discussed.

The world will still rely on unilateral action to combat climate change. Unilateral action, however, may lead to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE). The latter has strongly been advocated as an argument to search for supplemental anti-leakage measures. This is considered in the next three papers of this thesis by assessing the different policy's impact on welfare, using theoretical and numerical analyses.

Paper 2 examines the welfare effects of complementing output-based allocation (OBA) with a consumption tax on EITE goods. In particular, the paper investigates the case when only a subset of countries involved in a joint emission trading system (ETS) introduces such a tax. The paper presents a multi-sector multi-region model, and then derives the optimal consumption tax of the EITE good in one of the regulating regions. The analytical results suggest that the consumption tax would have unambiguously global welfare improving effects, and under certain conditions have

welfare improving effects for the tax introducing country as well. Numerical simulations in the context of the EU ETS support the analytical findings, including that the consumption tax is welfare improving for the single country that implements the tax.

Paper 3 extends the analyses in paper 2 by evaluating the potential outcome of climate policies in a non-cooperative policy instrument game between regions who regulate their emissions separately. In particular, the paper investigates the case when regions can choose to supplement their ETS with OBA and/or with a consumption tax, in the presence of another region's OBA and/or a consumption tax. The theoretical and numerical model is based on paper 2, but extended to examine a broader range of policies. The theoretical analysis suggests that under certain conditions the region's optimal OBA is increased and the optimal consumption tax is reduced, in the presence of another region's OBA and/or consumption tax. The numerical simulations in the context of the EU ETS and the Chinese ETS suggests that the dominant strategy for a region, when maximizing welfare, is to combine OBA with consumption tax. This is hence also the Nash equilibrium outcome.

Paper 4 examines the welfare effect of an alternative anti-leakage measure combined with an ETS. Particularly, combining the ETS with an emission offset mechanism abroad for the domestic EITE sector. The paper considers the REDD+ (Reducing Emissions from Deforestation and forest Degradation) initiative, with different conversion rates from REDD credits to ETS allowances. The paper bases the theoretical and numerical model on paper 2, but several changes are made. The analytical results suggest that under certain conditions it is globally welfare improving for a single region to introduce an emission offset mechanism. Numerical simulations in the context of the EU ETS support the analytical findings, including that the emission offset mechanism is welfare improving for the single region that implements the emission offset mechanism.

Sammendrag

Hensikten med avhandlingen er å vurdere konsekvensene av klimaendringer og tiltakene mot klimagassutslipp. Spesielt to spørsmål behandles: 1) hvordan kan en få en bedre kvantifisering og verdsetting av forventet klimarelatert tap av biologisk mangfold i integrerte klimaøkonomiske modeller, og 2) hva er akseptabel politisk strategi mot karbonlekkasje ved tiltak mot klimagassutslipp.

Klimaendringene vil ha stor effekt på global biodiversitet og økosystemtjenester, og integrerte klimaøkonomiske modeller («Integrated Assessment Models» - IAMs) er blant de viktigste verktøyene for beslutningstakere. De eksisterende IAMs neglisjerer imidlertid, eller vurderer på en ufullstendig måte, denne effekten på biodiversitet og økosystemtjenester. Den første artikkelen tar tak i dette problemet ved å bruke nye empiriske estimater av den økonomiske verdsettingen av biologisk mangfold og økosystemtjenester i den velkjente IAM FUND. Først oppdateres de biofysiske vurderingene av effekten på artsmangfold av økt global middeltemperatur i modellen, i henhold til nyere studier. Deretter overføres økonomiske verdianslag fra en ny global Delphi Betinget Verdsetting (Contingent Valuation) studie av husholdningenes betalingsvillighet for å unngå tap av artsmangfold som følge av avskoging av regnskogen i Amasonas. Begge disse komponentene blir oppdatert og implementert i FUND 3.9 (Climate Framework for Uncertainty, Negotiation and Distribution). Ved å sammenligne den oppdaterte modellen med den opprinnelige, viser artikkel 1 at tap av artsmangfold er lavere enn hva den nåværende modellen estimerer, men de forventede økonomiske skadekostnadene er høyere. Dette resulterer i høyere samlede globale skadekostnader grunnet klimaendringer. Artikkel 1 avslutter med å diskutere mulige forklaringer rundt resultatene, deres følsomhet og framtidig.

Verden vil fortsatt lene seg på regionale tiltak for å bekjempe klimaendringer. Slike tiltak kan imidlertid føre til karbonlekkasje, som for eksempel flytting av energiintensive og konkurranseutsatte sektorer. Dette har vært brukt som et hovedargument for å finne tiltak mot lekkasje. Dette vurderes i de neste tre artiklene i denne avhandlingen ved å vurdere effektene av ulike typer politikk på samfunnets velferd, basert på teoretiske og numeriske analyser.

Artikkel 2 undersøker velferdseffektene av å kombinere produksjonsbasert tildeling av utslippskvoter med en konsumavgift på energiintensive og konkurranseutsatte varer. Artikkelen undersøker effekten av at ett enkelt land, som er involvert i et felles kvotesystem, introduserer en slik avgift. Videre anvendes en global modell med flere regioner og sektorer til å undersøke den optimale konsumavgiften for energiintensive og konkurranseutsatte varer. Den teoretiske analysen

viser at konsumavgiften vil ha et utvetydig global velferdsforbedrende effekt, og under visse forhold velferdsforbedrende effekt for landet som innfører konsumavgiften. Numeriske simuleringer i sammenheng med EU ETS støtter disse analytiske funnene, blant annet at konsumavgiften er velferdsforbedrende for det enkelte landet som innfører avgiften (f.eks. Norge).

Artikkel 3 utvider analysene fra artikkel 2 ved å studere de potensielle utfallene av klimapolitikk i et politisk spill mellom regioner som regulerer sine egne utslipp via ulike typer klimapolitikk. Vi undersøker hvorvidt regioner vil velge å supplere sine kvotesystem med produksjonsbasert tildeling og / eller konsumavgift, og hvordan dette avhenger av en annen regions klimapolitikk. Den teoretiske og numeriske modellen er basert på artikkel 2, men utvidet til å undersøke et bredere spekter av klimapolitiske virkemidler. Den teoretiske analysen tyder på at under visse forhold vil en regions optimale produksjonsbasert tildeling øke og den optimale konsumavgiften reduseres, i tilstedeværelsen av en produksjonsbasert tildeling og/eller en konsumavgiften i en annen region. De numeriske simuleringene i sammenheng med EUs kvotesystem og det kinesiske kvotesystemet antyder at den dominerende strategien for begge regioner, når målet er å maksimere velferden, er en kombinasjon av produksjonsbasert tildeling med konsumavgift. Dette er derfor også Nash-likevekten i spillet.

Artikkel 4 analyserer velferdseffekten av en alternativ politikk for å hindre lekkasje, gitt et eksisterende kvotesystem. Den alternative politikken er å tillate kjøp av utslippskreditter i utlandet for den innenlandske energiintensive og konkurranseutsatte sektoren. I artikkelen vurderes spesifikt REDD+ (Reduksjon av utslipp fra avskoging og skognedbrytning), med forskjellige konverteringsfaktorer fra REDD+-sertifikater til utslippskvoter. Artikkelen baserer den teoretiske og numeriske modellen på artikkel 2, men gjør flere sentrale endringer. De analytiske resultatene tyder på at det under visse forhold vil være en global velferdsforbedring for en enkelt region å tillatte kjøp av utslippskreditter fra utlandet. Numeriske simuleringer i sammenheng med EUs kvotesystem støtter de analytiske funnene, blant annet at utslippskreditter gir en forbedring av velferden globalt og for den enkelte regionen som implementerer denne mekanismen.

Introduction

1. Motivation

There are two key reasons that motivates the thesis. First, climate economic models are often criticized for inadequately capturing the potential impacts of climate change. Second, as the world still relies on unilateral initiatives to combat climate change, these initiatives may lead to carbon leakage.

Climate change has already had observable effects, and will continue to have large impacts on the environment. Moreover, climate change impact on biodiversity and ecosystem services is a main concern (O'Neill et al., 2017). In order to assess the physical and economic damages of climate change, integrated assessment models (IAMs) are among the important decision support tools for the policymakers. The existing prominent models, however, either poorly assess or neglect the impact assessment of biodiversity and ecosystem services. Particularly, an important question that arises is how these physical and economic damages are included in IAMs. With poorly assessment or neglecting impacts, IAM-based analyses of climate policy could be misleading.

Following the Paris climate agreement from 2015, most countries in the world committed to combat climate change by reducing emissions of greenhouse gases (GHGs). However, when it comes to both their ambitions and indicated measures, the nationally determined contributions (NDCs) by each country vary greatly. Another central question is whether they will be implemented, since the NDCs are not legally binding. Thus, it is fair to conclude that the world will still rely on unilateral action to reduce GHG emissions. Unilateral action, however, may lead to carbon leakage and reduces the climate benefit of the climate policy. Since carbon leakage is an important issue in the public debate and in policy decisions, powerful and acceptable policy strategy to mitigate carbon leakage is needed in order to combat climate change.

2. Economics of climate change

The science of climate change is well established. As Stern (2008) briefly explains it, through our activities of consumption and production decisions we emit greenhouse gas (GHG) emissions, which accumulates in the atmosphere. As this overall stock of GHGs grows and exceeds earth's absorptive capabilities (through the carbon cycle) the GHGs in the atmosphere traps heat. This results in global warming, which leads to changes in climate that impacts humans and other species in many complex ways. Carbon dioxide (CO_2) makes up a large part of the human-generated

GHGs. Since the pre-industrial times (ca. year 1750) we have seen CO_2 concentrations in the atmosphere increasing rapidly, and there is strong scientific evidence indicating that the earth's climate is also changing rapidly. Two important questions that often arises among environmental economists are then: *i)* How much GHG emission should we allow, and *ii)* how can we achieve that level? In order to record the effects of human-induced climate change, its potential impact, and possible measures to prevent further changes; the climatic conditions has been tracked around the world since the Intergovernmental Panel on Climate Change's (IPCC) was established in 1988. The latest report (IPCC, 2018) estimates that human activities have caused approximately 1° Celsius (C) of global warming above pre-industrial global mean temperature level, and is likely to reach 1.5°C between year 2030 and 2050 if it continues to increase with the same pace. Limiting global warming to 1.5°C, however, requires a quick and extensive transition in many sectors.

Climate change damages that occur depends on the concentration (or stock) of GHG emission[1]. In this case, the stock is concentrated in the atmosphere, and slowly decay over time. The lifetime of CO_2 emissions is difficult to determine, because there are several processes that remove carbon dioxide from the atmosphere. Approximately 75% of the CO_2 released dissolves within a period of 300 years, while the last 25% could last forever (Archer, 2005). We cannot control the stock concentration of GHG emission directly, but we can reduce the flow of emission to the stock from year-to-year and thereby reduce the net uptake. While climate change cause primarily negative impacts, it could also be beneficial to some extent for a few parts of the world. Hence, there are also some positive effects related to unconstrained emissions. Both benefits and damages can be converted into monetary values, in order to assess the potential economic impact. In the following section, we will use a simple model from Perman et al. (2011) to illustrate the global *optimal solution* of GHG emission in an dynamic intertemporal analysis. That is, the net-present value of global welfare over time is maximized in the global optimal solution. Where the GHG emission is released is not of relevance here, but the intertemporal dimension is of importance.

Global climate change will have physical, biological, ecological, public health and financial impacts. If all these impacts are given a monetary value, we can assess the economic damage cost of climate change. The damage cost D_t at time t is determined by the size of concentration of GHG emission A_t, such that

$$D_t(A_t). \tag{1}$$

[1] The opposite is flow-emission (or rate of emission), which is emission damages that that occurs only when the emissions are being released into the environmental system.

For any level of emission target, there will be a cost of changing the production method for emission related outputs (or reducing the output of production). These are also called the benefits of unconstrained GHG emissions. To put it another way, the cost of abating emissions is identical to the benefits received from emissions. Thus, the benefits of GHG emissions is often alternatively called the cost of abatement. The benefit of emission B_t at time t is related to the flow of emission Q_t at time t, such that

$$B_t(Q_t). \tag{2}$$

The relationship between A_t and Q_t is given by:

$$\dot{A}_t = Q_t - f(A_t) \tag{3}$$

where $\dot{A}_t = \frac{dA_t}{dt}$. Mainly, the GHG emission stock $\dot{A}_t$ increases as Q_t adds to the emission stock. However, some of the existing GHG emission in the stock will decay over time and this is captured with the term $f(A_t)$. With no decay $f(A_t) = 0$, but is commonly found $f(A_t) > 0$ for climate change related GHG emissions. We keep it simple and follow Perman et al. (2011) with a constant decay rate, such that $f(A) = \beta A_t$ and $\beta > 0$.

The efficient GHG emission level in one period, is dependent on the released GHG emission in all of the other periods. Thus, the long time horizon and global nature makes climate change problem far more dynamic, complex and highly uncertain, compared to a pure flow of emission problem where the latter can be solved for only a single point in time. For the sake of intuition, we keep it simple by assuming an infinite time horizon for the intertemporal problem, and so the discounted social net benefit from a level of Q_t, for $t = 0$ to $t = \infty$ is then:

$$\int_{t=0}^{t=\infty} \left(B_t(Q_t) - D_t(A_t)\right) e^{-rt} dt \tag{4}$$

where r is the social discounted rate.

We assume a steady state condition, i.e., the emission flow and emission stock remains constant, in order to keep it simple and explaining the intuition behind this. Hence, the time subscripts can be dropped and we arrive at the following solution:

$$\frac{dB}{dQ} = \frac{dD}{dQ}\left(\frac{1}{1+\frac{r}{\beta}}\right). \tag{5}$$

$\frac{dB}{dQ}$ is the change in net benefits of a marginal unit of emission, $\frac{dD}{dQ}$ is the change in damages of a marginal unit of emission. Thus, equation (5) states that the efficient steady state level of GHG emission stock is where the net marginal benefit of a unit of GHG emission is equal to the present value of future marginal damages of a unit of GHG emission. A larger (smaller) discount value reduces (increases) the present value of the future marginal damages, while a larger (smaller) decay rate increases (reduces) the present value of the future marginal damages.

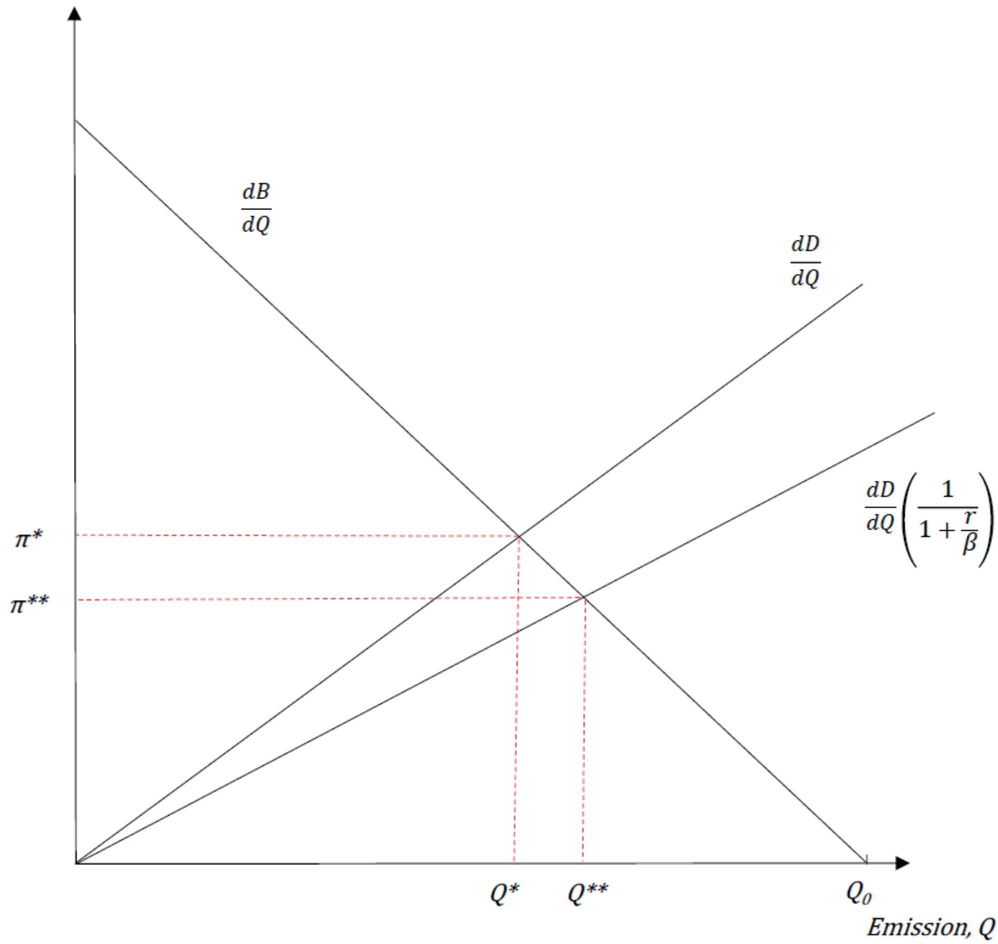

Figure 1: The global optimal solution of GHG emissions

This is illustrated in Figure 1 under two scenarios. One, if $r = 0$ and $\beta > 0$, then the optimal solution level of GHG emission is Q^* and the shadow price of emission is π^*. Second, if $r > 0$ and $\beta > 0$, then the efficient level of GHG emission is Q^{**} and the shadow price of emission is π^{**}. The Figure illustrates the importance of the social discount rate for long-term net benefits of GHG emissions, and how a change in $\frac{dD}{dQ}$ or $\frac{dB}{dQ}$ could alter the optimal solution. In the absence of any regulation, firms have no economic incentives to change their decision. That is, profit maximizing behavior by firms suggests that no additional cost would be willingly taken, i.e., zero freely abatement. In this case, we would be located to the right for the efficient emission level in Figure 1, Q_o.

Since climate change are global in scope, one country's action to reduce GHG emission would consequently benefit all of the other countries. As a result, reaching a global agreement have been with mixed outcomes as every participants expect to yield positive net benefit from the agreement. Many climate concerned countries have therefore initiated unilateral action on their own. The global abatement of such action is likely positive and will move the emission level from Q_o in Figure 1 towards an efficient level. The emission level in unregulated countries may, however, increase since the profit maximizing firms sees the opportunity to replace some of the supply of the regulated firms. As for the emission reduction, the cost of abatement would be borne by the few regulating countries, yet the damages reduced would benefit all others. This is referred to as the leakage effect, and is presented in chapter 4. To illustrate this in a global context with Figure 1 is tricky. Still, this indicates that the cost of emission mitigation increases, suggesting that $\frac{dB}{dQ}$ would shift up and out. In this case, the optimal solution moves to the right in Figure 1. However, we would still be to the right of the optimal solution, i.e., $\frac{dD}{dQ} > \frac{dB}{dQ}$.

With the Paris climate agreement, we will see more action taken by countries than ever before. The agreement however still relies heavily on unilateral action, and countries abatement target varies substantially. Whether the agreement is stable and will be held by the participants over time is yet to be seen.

3. Biodiversity impacts from climate change

Natural climate change has already begun to affect biodiversity and ecosystems, and is expected to become an even more important driver in the coming century (Díaz et al., 2006; Parmesan et al., 1999; Pounds et al., 1999; Thomas & Lennon, 1999). Ecosystem services[2] have been related to human's well-being through the goods and services they provide in terms of: i) provisioning services like fish, ii) regulatory services like pollination, and iii) cultural services like outdoor recreation, ecotourism, and non-use values (which is the economic value people put on the existence of e.g. preserving habitats for species and being able to pass this on to future generations; i.e. existence and bequest values). Loss of species could affect all these three groups of ecosystem

[2] The Millennium Ecosystem Assessment in 2005 defined Ecosystem Services as "the benefits people derive from ecosystems". See, http://www.millenniumassessment.org/en/index.html

services (Brooks & Newbold, 2014), as biodiversity is part of the supporting ecosystem services which is essential to provisioning, regulatory and cultural ecosystem services.

It is highly uncertain how species respond to future climate change. Firstly, different species may react very differently to climate change based on several factors (Davis & Shaw, 2001)[3]. Secondly, climate change will vary across regions, and therefore impact some species more than others (IPCC, 2013). Finally, while it is essential to understand the richness and distribution of species over space and time, it has, however, turned out to be very difficult to find this precise mechanism (Thomas, 2012). In recent years however, more universal theoretical frameworks from the field of ecology have been developed. The scientists now agree that species will react to climate change with three basic responses: adaptation, migration, or extinction (Brooks & Newbold, 2014). This thesis focuses on the relationship between species and the rising global mean temperature, as this is often used on a global scale in the climate economic models. Other ways that climate change would affect species are e.g., extreme weathers, droughts and change in precipitation, which are also crucial components for predicting species response in different regions (Parmesan et al., 2000).

Adaptation relates to the species' ability to cope with its new environment. For some species adaptation may require many generations, and these species are less likely to evolve and adapt to the new environment as the climate rapidly change (Kerr & Kharouba, 2007). How vulnerable different species are to climate change is still not fully understood, and some studies have found that we may be underestimating the species ability to respond to climate change (e.g., Willis and Bhagwat 2009; Urban 2015).

Migration is the movement of species leading to expansions or contractions of range. Species may avoid extinction through latitudinal or elevations migration, with shifting temperature. Studies suggests that some species have already begun their range expansion (Kerr & Kharouba, 2007; Parmesan et al., 1999). However, their ability adapt to climate changes via migration may be limited, and their ability to colonize new areas may not occur quickly enough. This could evidently lead to species collapse (Kerr & Kharouba, 2007; Malcom et al., 2002; Thomas et al., 2004).

If they cannot adapt to or migrate with the changing climate conditions, species will face extinction. These are primarily species with small ranges or narrow climatic tolerances (Kerr & Kharouba, 2007). Many studies have attempted to examine the potential loss of species diversity caused by climate change. Urban (2015) performs a meta-analysis of 131 published estimates of the number of species threatened by extinction, and reports estimates of global extinction rates related to rising

[3] Such as physical tolerances, migration, structure of population, etc.

global mean temperature. The results, see Table 1, suggest that the number of species going extinct will accelerate with rising future global mean temperature.

Table 1: Predicted species loss from climate change under four different global mean temperature increment scenarios; 0.8, 2, 3 and 4.3 °C (Urban, 2015).

Global mean temperature rise:	0.8°C	2 °C	3 °C	4.3 °C
Species extinction:	2.8 %	5.2%	8.5 %	16%

Table 1 reports species loss numbers on the global scale. Some regions will, however, have higher extinctions risk than others. In general, South America, Australia and New Zealand will have the highest risk, while the lowest risks were found for North America and Europe (Urban, 2015).

4. Climate policies

To simplify, economists refers to *market failure* as the conditions under which the free market does not produce optimal welfare level (Bator, 1958). One such important failure is *externality* (see e.g., Sidgwick 1887, Marshall 1890 and Pigou 1920), which is more or less defined as an unintended and uncompensated side effect of one agent's activities on the others. An example of such a negative externality is the GHG emission CO_2, which we produce too much of.[4] Externality is maybe the most basic concept - and closest to the heart- in the field of environmental economics (Sterner & Coria, 2012).

To correct for a negative externality such as GHG emission, economist often prefer a pure environmental charge on the party responsible for producing the negative externality. If set equal to the marginal social cost of damages, this is often referred to as the Pigouvian tax (Pigou, 1920). In chapter 2 Figure 1, the global Pigouvian tax would have been π^* or π^{**}, depending on the social discount rate. A central question that often arise is how big this tax on carbon emission (or carbon tax) should be, since estimating the damages correctly are difficult. In addition to the technical problems, we also have the political feasibility problem that may arise with taxes. A more widely used policy instrument is the emission trading system (ETS), where emissions are controlled by setting a total number of permits, and allowing the participants to trade amongst them to harmonize the marginal benefit and costs (see e.g., Coase 1960 and Montgomery 1972). If the total allowed emission in the market is set optimally and allocation of permits done correctly, then this

[4] As Stern (2008) expresses it: "GHG emissions are externalities and represent the biggest market failure the world has seen".

would produce the same outcome as an optimal carbon tax (Weitzman, 1974).[5] Most countries today who have committed to combat climate change by reducing emissions of GHGs, have proposed national or regional ETS. A prime example is the corner stone in EU's climate policy, the EU ETS, with a quite ambitious climate targets for 2030 and especially 2050.

Pure public goods are mainly characterized by non-excludability and non-rivalry, so the market alone cannot allocate the optimal use of the resource (Samuelson, 1954). The climate change problem is fundamentally a public goods problem, since it is the product of everyone's behavior. Thus, any country's action to combat the climate change problem will have a small effect compared if all countries would act together. This provides an important reason for global action against climate change damages. An international climate (environmental) agreement (IEA) is characterized to be good if it *i)* includes many (and large) countries, *ii)* reduces substantial amount of emission, and *iii)* includes punishment for withdrawal or cheating by countries. With the absent of significant punishment, the compliance is the main problem for IEAs since agreements must be self-enforcing (Barrett, 1994). As a result, several alternative climate agreement designs and strategies have been proposed to obtain a more successful outcome.

		Country B	
		Cheat	Abate
Country A	Cheat	(0, 0)	(11, -3)
	Abate	(-3, 11)	(10, 10)

Table 2: Prisoner's dilemma in the context of climate change problem

The collective action problem can be simply illustrated with the "Prisoner's Dilemma"[6] game (see Table 2) within a static framework.[7] The payoffs for the different strategy by the countries are listed in Table 2, with country A's payoff on the left and country B's to the right. A positive (negative) payoff indicates a net benefit (cost) for the country and can be thought of the benefits (costs) of reducing emission.[8] The benefits of both countries collaborating and abating emission is 10; both countries have a common interest in reducing GHG emission as long as the other one does. If one of the countries acts selfish and lets the other carry the burden of reducing emission, then the "free rider" gains 11 as long as the other country continues to abate. This would have

[5] With no uncertainty and competitive markets, they both produce the same outcome. However, the real world consists of uncertainties and asymmetric information (see e.g., Weitzman (1974)).
6 Also known as the "Social Dilemma".
7 Another (and a more complex) way to analyze these games could be in dynamic games context.
8 The values are only for illustrative purposes.

heavy impact on the abating country, resulting in -3. Both countries would maximize their own net-benefit and expect the other country to cheat. Therefore, the dominant strategy for both countries in this game is to cheat. The final outcome would then be 0 for both, which is the *Nash equilibrium* [9] in this game. However, from Table 2 we can see that the first-best outcome is when both countries collaborate and abate (10, 10). In order to reach the desirable outcome, a penalty for cheating would reduce the incentive for cheating (Ostrom, 2006). With a fine of 4 introduced for cheating, the game now has only "one" solution, which is to continue to abate for both countries.

Following the Paris climate agreement in 2015, different climate policies have emerged around the world to combat emissions of GHGs. Still, countries nationally determined contributions (NDCs) vary greatly, and an essential question is whether they will be followed up as the NDCs are not legally binding. This strongly indicates that the world will still rely on unilateral action in the coming years, increasing the concern of free-riding incentives for countries who do not commit to their emission target. The problem is still one of the most important obstacle for a successful IEA to reduce global GHG emission (see e.g., Barrett 1994; Hoel 1992; Finus 2008).

4.1 Unilateral action and anti-leakage measures

Climate policy in one (group of) country may lead to increased CO_2 emissions in other countries. This phenomenon is known as carbon leakage (Hoel, 1991; Markussen, 1975), and the leakage can be expressed as:

$$Carbon\ leakage\ rate\ (\%) = \frac{\Delta\, foreign\ emissions}{-\Delta\, domestic\ emissions} 100\%$$

The leakage occurs through several channels. The two most discussed (and familiar) ones are the *international energy markets* for fossil fuel (oil, coal and gas), and the *competitiveness market* for emission-intensive and trade-exposed (EITE) goods (e.g., steel, cement, and chemical products). The carbon leakage through the international energy market arises since climate policy reduces the demand for fossil fuels in the regulated country (or countries). This further reduces the international fuel prices, and thus stimulates fuel consumption elsewhere. Hence, emissions in other countries increases. In the competitiveness market, the leakage occurs when unilateral climate policies on carbon emissions increases the production costs for EITE producers. This reduces their competiveness in the world market, further encouraging more production (and emissions) in the unregulated

9 Nash Equilibrium is the outcome where neither player can improve without reaction from the other player

countries (Felder & Rutherford, 1993). The leakage through both of these channels depends on several factors, and numerous papers have tried to quantify the leakage effect (Babiker & Rutherford, 2005; Böhringer et al., 2012a; Zhang, 2012). While a majority of leakage comes through the energy markets, it is difficult to reduce CO_2 emissions without actually reducing the use of fossil fuel. Different variety of supplemental measures to mitigate leakage can, however, be found in the competitiveness market. This thesis focuses on the carbon leakage that occurs through the competitiveness market.

Carbon leakage is an important topic in the public debate and in policy decisions. In order to counteract the problem, policymakers have typically either exempted EITE industries from their climate regulation or implemented other second-best policy[10] for anti-leakage measures. A prime example is sectors that are regulated through an ETS and "exposed to a significant risk of carbon leakage", which are given a large number of free allowances. Similar regulation can be found in ETS' such as in EU, New Zealand, California, and China (World Bank, 2014; Xiong et. al 2017). One way to allocate these free allowances are conditional on output, often referred to as output-based allocation (OBA). With weakened incentive to substitute from carbon-intensive to carbon-free products, OBA have been criticized to stimulate too much production of the EITE good (Böhringer & Lange, 2005). Further, policymakers may be convinced by the industry to allocate too many allowances, while there are uncertainty about how big the possible leakage exposure really is (Martin et al., 2014; Sato et al., 2015).

An alternative second-best policy instrument for anti-leakage is the border carbon adjustment (BCAs). Here, the policymakers put a charge on embedded carbon imports and refunds on export of EITE goods, and studies have shown that this would outperform OBA (Böhringer et al., 2014; Fischer & Fox, 2012). BCAs may however prove to not be politically feasible, and experts seems to disagree on whether or not it is compatible with the current WTO-rules (Böhringer et al., 2012b; Böhringer et al., 2014). As a result, combining OBA with a consumption tax on the same goods has also been proposed (Böhringer et al., 2017; Kaushal & Rosendahl, 2017; Neuhoff et al., 2016). With a certain combination of OBA and a consumption tax, this have shown to be equivalent to BCA. Further, a consumption tax does not seem to face the same WTO challenges as BCA since it treats domestic and foreign goods the same. As for now, varieties of this combination can be found in for example California, China, Japan, and Korea, especially for electricity (Munnings et al., 2018).

[10] The second-best policy could be a better choice when optimality conditions cannot be satisfied with the first-best. See e.g., Lipsey and Lancaster (1956) for a more general theory of second-best.

5. Methods

The thesis relies primarily on two methods. In the first paper, we update an integrated assessment model (IAM) in order to assess global impacts from climate change with special emphasis on more comprehensive and improved valuation of biodiversity and ecosystem service damages. In the second to fourth paper, we develop a stylized computable general equilibrium (CGE) model in order to assess the welfare effect for regions or countries, who regulate their emissions in order to combat global climate change.

5.1 Integrated assessment models

Integrated assessment models (IAMs) are to some extent simplified representations of the interactions between economy and climate. Particularly, IAMs are a more detailed representation of the simplified model that was presented in chapter 2. They are one of the few economic tools that attempts to combine climate science with economics, and their primary purpose is to inform policy makers on decisions regarding climate mitigation. Impact of climate change is often translated into monetary benefits and damages in each region. The benefits are often expressed with a utility function or changes in regional GDP, while the damages are the regional costs related to climate change impacts (see chapter 2). Aggregated on a global level, these benefits and costs then maximizes the net-present value of global welfare and determines the social cost of carbon (SCC)[11] (as discussed in chapter 2 and 4), and thus the optimal global carbon taxation. Some IAMs are more natural-science oriented, while others more economic-science oriented. This thesis emphasizes on the latter type of models, which are widely used both in research and in the development of policy proposals. Particularly, three of them were extensively used under the Obama Administration (Interagency Working Group on Social Cost of Carbon, 2010): DICE (Dynamic Integrated Climate Economy), PAGE (Policy Analysis of the Greenhouse Effect) and FUND (Framework for Uncertainty, Negotiation, and Distribution). In the thesis, we use the FUND 3.9 model.[12]

FUND was originally developed to study international capital transfers in the context of climate policy, but later evolved studying impacts of climate change in a dynamic context. The model runs from year 1950 to 3000, and distinguishes 16 major world regions. While being open-access and

[11] The Social Cost of Carbon is a measure, in monetary value, of the long-term damage from emitting one ton of carbon dioxide (CO_2) in a given year (Mastrandrea, 2009). Thus, the monetary value would in principle be the optimal carbon taxation (or the Pigouvian tax).

[12] Originally developed by Richard S. J. Tol, and now co-developed by David Anthoff and Richard S. J. Tol (Anthoff & Tol, 2014)

publically available[13], FUND does not, however, have a low-threshold interface and requires real effort to understand. The climate response in FUND is translated into impacts on the economy through damage functions for each region. The model is among the most detailed IAMs, with representation of the sector and region-specific damages for agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, health, and damages from storms (see the documentation in Anthoff & Tol 2014). These climate impacts are translated into monetary values, based on different valuation studies and expert guesses, and classified as total damage cost related to climate change. For the cost-benefit analysis of climate impacts, these estimates are included alongside the regional GDP growth for each region, which is based on the EMF14 Standardized Scenario.

Only a few of the prominent economic-science oriented IAMs include ecosystem service damage costs explicitly in their model. In for instance the DICE model, the authors emphasizes that the impact of climate change on ecosystems and loss of species are one of the most important and difficult issues to assess (Nordhaus & Boyer, 2000, p. 85). However, the authors acknowledge that the methodology in their model is at a speculative stage, and that they to a large extent base the model on expert guesses (Nordhaus & Boyer, 2000, p. 86; Nordhaus, 2007). A more detailed description of the physical and economical ecosystem impact can be found in FUND. In the technical description of the model, the authors state that the ecosystem damage assessment is based on the "warm-glow" effect. They describe this warm-glow effect as "Essentially, the value, which people are assumed to place on such impacts, are independent of any real change in ecosystems, of the location and time of the presumed change, *etcetera* – although the probability of detection of impacts by the "general public" is increasing in the rate of warming" (Anthoff & Tol, 2014, p. 15). Thus, they assume that people are not able to express their actual utility from avoiding species loss in Contingent Valuation (CV) and other Stated Preference (SP) surveys. This is contrary to current evidence (see e.g. Johnston et al. 2017).

The (to some extent) simplified representation and limited available data, is a big uncertainty factor in IAMs. Particularly, the methods for quantifying, valuing and relating climate damages across space and time are highly debatable.[14] Further, these models may also lag behind the scientific research which they are based on, and remains a black-box for non-programming readers (Mastrandrea, 2009). Related to biodiversity impact of climate change, an important question is how these physical and economic damages are included in IAMs. As a result, the suggested global

[13] http://www.fund-model.org/versions
[14] See e.g., Azar and Sterner (1996), Stanton et al. (2009) and Pindyck (2013).

optimal solution of GHG emissions level suggested by IAMs are still controversial, and varies a cross the different IAM models (Greenstone et al., 2013). The model developers have, however, emphasized that specific IAMs are designed to answer specific sets of questions, and therefore one should be aware of the models intended use and limitations. Nevertheless, continuously updating the economic assessments of climate impacts can in many ways improve these models.

5.2 Computable general equilibrium models

With general equilibrium (GE) models we attempt to explain the behavior of the whole economy, in contrast to the theory of partial equilibrium where we only examine part of a market (ceteris paribus). The GE framework dates back to Léon Walras famous work in 1874 (Walras, 1954), and mainly were only theoretical analyzes. While theoretical analysis provides important insights, the actual analysis remains limited as models are highly stylized to keep analytical tractability. Computable general equilibrium (CGE) models builds upon GE theory, and have since the rise of advanced computer power (from the mid-1980s) been one of the most preferred methods for economic policy analysis at the sector-level, as well as the economy-wide level. The method is highly acknowledge for ex-ante simulation of the effects by induced policies or other changes in the economy. In the following section we intend to describe non-technically what a simple CGE model may comprise of. A more detailed description of the algebraic model and the input-data used in this thesis can be found in paper 2 to 4.[15]

In this thesis we mainly rely on the input data from the World Input Output Database (WIOD). The WIOD-dataset of the world is based on 43 regions with 56 sectors, with socio-economic and environmental indicators (such as GHG emission and land use change). All input and output values are denoted in million US dollars ($) for each sector in each region. The WIOD project (which ran from May 1, 2009 to May 1, 2012) was funded by the European Commission, Research Directorate General as part of the 7th Framework Programme, Theme 8: Socio-Economic Sciences and Humanities. The dataset from WIOD is free and publically available. [16]

The main advantage of the CGE method is that it follows the microeconomic foundation of price-dependent market interactions (Böhringer et al., 2003). The models take into account the behavior of the demand and supply side, the prices in a whole economy, as well as the interaction between the markets. On the demand side of a good we find representative agents (or households), who maximizes their utility with respect to a budget constraint. The budget constraint consists of

[15] For a more detailed presentation of CGE analysis, see also e.g., Böhringer et al. (2003).
[16] http://www.wiod.org/project

endowment such as capital and labor, which the producers demand in their production of a particular good from the agent. The producers combine these endowments (and other intermediates) with a cost-minimizing behavior, with some sort of technological constraints. The characteristics of the agent's utility and the producer's technology (e.g., functional form and elasticities) can take any form, and depends on assumption and available data. However, the constant-elasticity-of-substitution (CES) function is typically assumed for the agent's utility and producer's technology. From this simple example, the CGE model can evolve into far more complex and detailed representation of the economy by distinguishing between a numbers of regions, sectors and sub-sectors, goods and services, input and primary factors, as well as several types of household and producers.

CGE models plays a crucial part of applied economic research, but have also been criticized for its assumption of the neo-classical spirit and behavior, the parameter selection criteria and calibration procedures (see e.g., McKitrick 1998). Others have criticized that the modeling often remains closed for non-expert readers. Particularly, some scientific publications does not include a listing of the algebraic model. Even if they were fully laid out, replication of results would still require specialized programming skills and understanding. Lately however, several papers have attempted to lower this threshold by making the basic building stones of the CGE models more transparent (see e.g., Böhringer et al. 2003; Fæhn 2015).

6. Paper summaries

This section summarizes each of the papers in the thesis. The first paper examines the potential impact of climate change by updating and improving the damage cost estimates of biodiversity loss. The second, third and fourth paper examines the welfare effect of introducing different anti-leakage measures.

6.1. Paper 1. "Accounting for Biodiversity Loss from Climate Change in Integrated Assessment Models"

In this paper, we update and improve the ecosystem damage functions in the IAM FUND 3.9, based on Brooks and Newbold's (2014) suggestions. Further, we fully integrate the updated functions in FUND 3.9, and run the model to estimate the impact of ecosystem damage from climate change. The ecosystem damage component in FUND 3.9 consists of a biodiversity loss function and a biodiversity loss value function (Anthoff & Tol, 2014).

For the biodiversity loss function, we develop and calibrate the function based on the meta-analysis by Urban (2015). Further, we make the functional form more flexible so it can handle varying yearly global temperature change. For the biodiversity loss value function, we extend the analysis by Brooks and Newbold (2014) from looking at old studies of only the US households´ willingness to pay (WTP), to address the current worldwide WTP of households to avoid the global species loss due to climate change. First, we make the biodiversity value function region specific. Next, we apply and calibrate the results from a recent global Delphi Contingent Valuation (CV) study of expert estimates of households´ WTP to avoid species loss in the Amazon Rainforest (Strand et al., 2017). For the FUND 3.9 regions that are not represented in the CV study, we unit value transfer with income adjustment from other regions with similar characteristics.

The results suggest that the projected physical biodiversity loss is lower compared to the current FUND 3.9 model. However, the updated value function results in increasing global biodiversity damage costs as a fraction of regional income over time. This is true for all the regions, but biodiversity damages do vary across regions. As a result, the updated estimation of global damage is higher compared to the FUND 3.9 model. We also present the updated social cost of carbon (SCC) estimate and find them to be higher than the original FUND 3.9, when assuming lower (but still reasonable) social discount rates. This is due to the fact that the estimated biodiversity damage costs are somewhat lower in the short-run in the re-calibrated model. Later, we discuss potential explanations of the result, conduct sensitivity analyses and discuss some limitations with the FUND 3.9.

As IAMs are used as decision support and input to Benefit-Cost Analyses of climate change mitigation and adaptation measures, we conclude that our results should be used in the continuous update of these models in order to achieve the global economic optimal solution to climate change mitigation and adaptation measures.

6.2. Paper 2. "Taxing Consumption to Mitigate Carbon Leakage"

In this paper we examine the welfare effects of supplementing OBA with a consumption tax on emission-intensive and trade-exposed (EITE) goods. In particular, we investigate the case when only a subset of countries involved in a joint ETS introduces such a tax.

We present a model with three regions and three goods, where the first good is emission-free and trade-exposed, the second good is EITE, and the third good is emission-intensive and non-tradable. Same types of goods, produced in different regions, are assumed homogenous. The representative consumer in each region maximizes utility, while the competitive producers in each region maximizes profit. Two of the regions have already implemented a joint emission trading system, regulating emissions from production with OBA for the EITE sector. The third region has no climate regulating policy.

Next, we derive the optimal consumption tax of the EITE good in one of the regulating regions. The analytical results suggest that the consumption tax would have unambiguously global welfare improving effects, and under certain conditions have welfare improving effects for the tax introducing country as well.

Based on the theoretical model, we transfer our analysis to a stylized CGE model. We assume three regions calibrated according to Norway, the European Union (EU) and rest of the world. We are particularly interested in the case of Norway, which has a joint emission trading system with the European Union (EU ETS), where a variant of OBA is already in place for EITE goods. The standard calibration procedure in general equilibrium analysis is conducted, and the calibration of the model is based on WIOD data. We consider the calibrated equilibrium as the business-as-usual (BAU) scenario. The reference (REF) policy scenario is when Norway and EU together achieves a joint emission reduction target. Next, we consider the scenario with OBA for the EITE sector. And finally, the scenario where Norway implements a carbon consumption tax on the EITE good.

In the numerical simulations, we examine the effects on several key indicators. Further, we investigate the level of robustness by changing some of the main assumptions in the base simulations. The overall result supports our analytical findings, irrespective of which EU/EEA country we consider as the single region imposing a consumption tax. That is, the policy is welfare improving, both for the single country and globally.

Finally we discuss the results in the context of policy implementation, and conclude that combining OBA with a consumption tax is likely a smart and acceptable policy strategy to mitigate carbon leakage, also for individual countries involved in a more extensive emission trading system.

6.3. Paper 3. "Climate Policy in the Presence of Another Region's Climate Policy"

There are many separated carbon emission trading systems globally. This paper evaluates the potential outcome of climate policies by examining the Nash equilibrium of a non-cooperative policy instrument game between regions who regulate their emissions separately. In particular, we investigate the case when regions can choose to supplement their emission trading system with OBA and/or with a consumption tax, in the presence of another regulating region.

The theoretical analysis builds on the same model framework from paper 2. Two of the regions have already implemented separate ETSs, regulating emissions from production. The third region has no climate regulating policy. Next, we derive the optimal response of climate policy by a region, in the presence of another region's climate policy. Particularly, we derive the optimal OBA and consumption tax for one of the regions, and examine effect of introducing OBA and/or consumption tax in the other region. We find that under certain conditions, the optimal OBA is increased and the optimal consumption tax is reduced, when another region introduces OBA and/or a consumption tax.

In the numerical simulation we assess the Nash equilibrium outcomes in a non-cooperative game of policy instruments. We are interested in a game of policy instruments between China and the EU, where each region can choose to have a different variant of OBA and/or carbon consumption tax for the EITE goods. The three assumed regions are the EU, China and rest of the world, and we use the same calibration procedure as in paper 2. One policy strategy for the regions is to implement an emission reduction target with only emission pricing. Another policy strategy for the regions is to combine the emission price with different alternatives of OBA for the EITE sector. The third strategy for the regions are different variants of a consumption tax combined with OBA on the EITE good.

In the numerical simulation, we investigate the choice of climate policy in both regions based on different indicators. The motivation for this, is that policymakers could be influenced by for example strong lobbying groups who are more concerned for other indicators than maximizing the regional welfare (Sterner & Coria, 2012). Depending on the choice of indicator, the countries would choose different alternatives of policy combinations. In the context of maximizing regional welfare, the Nash equilibrium outcome is when both regions implement a consumption tax on top of the OBA. Moreover, this is also the dominant strategy for both regions. Thus, the paper concludes that combining OBA with a consumption tax is likely a strong policy strategy, even in the presence of other region's climate policy.

6.4. Paper 4. "Optimal REDD+ in the Carbon Market"

In paper 4 we examine the welfare effect of combining the ETS with an emission offset mechanism abroad. We consider the REDD+ (Reducing Emissions from Deforestation and forest Degradation) initiative which aims at reducing GHG emissions from forests in developing countries.

The theoretical analysis builds on the basic model framework from paper 2. However, the model is extended to four goods where the fourth good is the tradable forest and agricultural good. One of the regions have already implemented an ETS, and we consider a conversion rate in this region between emission allowances and offsets. The lower is the conversation rate, the more offsets must be bought to be in compliance. The second region is the supplier of REDD+, and the third region has no climate regulating policy. We look at two different cases of how the offset mechanism can be introduced into the regional ETS. First, when the regulating region only allows the EITE sector to offset their emission with REDD credits, which we refer to as scenario 1. Second, when the EITE-sector can buy and sell permits to the emission-intensive and non-trade-exposed sector as well, which we refer to as scenario 2.

We first show that increasing the conversion rate of emission offset in the first region would reduce the emission price in the ETS region. The emission offset price, however, may either increase or decrease with increasing conversion rate. Next, we also show that it is global welfare improving to increase the conversion rate of emission offset, if the global emission decreases.

For the numerical simulation, the assumed regions are the EU, Brazil, Indonesia and rest of the world. Incorporating REDD+ credit allowances in the EU ETS is of interest, as the abatement cost in this region is relatively high and carbon leakage is of concern. Brazil is considered as the supplier of REDD+. We base the standard calibration procedure on the WIOD data combined with other studies. The calibrated equilibrium is considered as the business-as-usual (BAU) scenario. The reference (REF) policy scenario is when EU achieves the emission reduction target without offsets. Finally, we consider the scenario where EITE producer can buy REDD+ credits. In the latter scenario we consider different levels of conversion rate, and examine the results in both scenario 1 and 2.

The numerical simulations confirm the result from the theoretical analysis. That is, the welfare for both the EU and the world is consistently improved when an offset mechanism is introduced, irrespective of whether the offset mechanism is introduced for only the EITE sector or for the whole EU ETS. We find the optimal conversion rate to be approximately 20%, but it depends on the parameter assumptions in the model. Finally, we discuss the results in the context of policy implementation, and conclude that complementing the 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.

7. Contribution and limitations

7.1 Contribution

The thesis contributes to the existing literature in terms of improved and updated global damage cost estimates of biodiversity loss from climate change. Another related contribution is that these changes are fully integrated in the prominent IAM FUND 3.9, in order to easily compare the results. The main results from the thesis are useful for policymakers and anyone who is interested in estimating the long-term impact of climate change.

There are relatively few papers that have examined a consumption tax related to environmental regulations, and only a few of them have examined the case where a consumption tax is combined with other instruments. Paper 2's contribution is that it examines the case for individual countries that are involved in a more extensive emission trading system. Moreover, the paper focuses on specific regions, including two regulating regions in Europe.

Although several countries are pursuing their local carbon pricing initiatives, only a few papers have investigated how climate policies in one country may or should react to climate policies in other countries. Paper 3's contribution is that it investigates a game of policy instruments between regions who regulate their emissions separately. Further, the paper focuses on the EU ETS and Chinese ETS, and investigates policy instruments such as emission pricing, OBA and/or consumption tax.

Paper 4 contributes by implementing REDD+ in a global CGE-model. Most studies of REDD+ so far have been undertaken within a more partial framework. Particularly, the paper contributes by examining the welfare effects of introducing REDD+ credits in the EU ETS, accounting for the benefits of reduced global emissions as well. Moreover, the paper examines how a conversion rate between REDD+ credits and EU ETS allowances could affect the regional and global welfare.

The results from paper 2 to 4 are useful for anyone who are interested in the public debate on unilateral climate policy action. Particularly, those who are interested in exploring the regional and global welfare effect of a unilateral climate policy action.

7.2 Limitations

Including the big uncertainty factors discussed in section 5.1 on IAMs in general, one main limitation in the first paper is that the update and improvement of the ecosystem damage function is restricted to the initial structure of the model. Particularly, while change in global mean temperature is an essential factor in order to explain the ecosystem damages, other important factors such as change in regional precipitation cannot be included. Hence, although we only update the ecosystem damage function, other parts of the model should be explored thoroughly as well. However, the complexity and FUND's high-threshold interface requires real effort to understand every component of the model. Next, the paper relies on secondary data, and some of the data were not available. For instance, because of the missing regions in the Global Delphi CV study, the households' WTP were value transferred with income adjustment from other regions with similar characteristics. A Global Delphi CV study including all the regions would likely be more optimal.

For the second to fourth paper, many of the limitations are related to the assumptions in the theoretical analysis, and the stylized multi-sector multi-region CGE model. First, the theoretical and numerical analysis does not take into account the distributional effect within the sectors and regions of imposing the different policies. A more detailed CGE model, for example, could likely capture these effects. Similar analysis on regional and sector level is therefore highly encouraged in future research. Second, the papers assume free market for all goods and services, which may not be true for all sectors and regions. Future research should look into whether or how market power may alter these results. Third, the stylized CGE model is static. That is, the total quantity of for example capital and labor in each region is fixed. Examining these results in the dynamic CGE context would likely be of interest, as factors as e.g. population growth is not taken into account in our model. Finally, the papers rely on secondary data and some were collected from several different sources. Hence, there could be uncertainties related to the parameters selection such as the Armington elasticities, which are important for the numerical results. Thus, updated and improved access to data, and improved empirical evidence on crucial parameters are vital for future research.

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Paper 1

Accounting for Biodiversity Loss from Climate Change in Integrated Assessment Models – A Global Delphi Value Transfer Approach

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Abstract:

Climate change will have a major impact on global biodiversity. However, these changes – and their economic value– is inconsistently and incompletely captured in the existing Integrated Assessment Models (IAMs). We provide improved damage cost estimates of biodiversity loss based on: i) a recent global biophysical assessment of impacts on species from increased global mean temperature, and ii) transfer of economic values from a recent global Delphi Contingent Valuation (CV) study of households´ willingness-to-pay (WTP) to avoid species loss due to deforestation of the Amazon rainforest. The Delphi CV study is the first to capture global preference for species loss; and thus can be used to account for damage costs to biodiversity in IAMs in a more consistent and transparent way. The new damage cost estimates are implemented in the FUND (Climate Framework for Uncertainty, Negotiation and Distribution) IAM, using value transfer techniques. The numerical simulations suggest that the physical global species loss is lower than the original FUND 3.9 model predicted, but the economic valuation of this species loss is larger than assumed in the original model. Thus, the damage cost from species loss is larger; but this depends on the assumed elasticity of the marginal utility of consumption in the different geographical regions and the social discount rate used. Still, this exercise clearly shows the importance of a more comprehensive accounting for the economic value of biodiversity loss in IAMs.

Keywords: Integrated Assessment Models; Delphi Contingent Valuation; Climate change; Ecosystem services; Species loss, Social Costs of Carbon Dioxide

JEL classification: Q54

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1. Introduction

In the field of economics, Integrated Assessment Models (IAMs) are among the important decision support tools in climate policymaking. These models estimate the global economic costs of climate change, often presented in terms of Social Costs of Carbon (SCC) estimates, and hence should be as complete as possible in terms of coverage of damages. The impact on biodiversity and ecosystem services are, however, not included or only partially assessed in the existing models. According to the fifth Assessment Report (5AR) of the Intergovernmental Panel on Climate Change's (IPCC), climate change will have a large impact on global biodiversity and ecosystem services, and is a key reason for concern (O'Neill et al. 2017). Thus, in order for the IAMs to be as complete as possible, it is important to quantify these losses and value the related global damage costs[1].

Brooks and Newbold (2014) propose an updated biodiversity value function for assessing economic damages in IAMs. They use new global estimates of species loss rates due to global warming to re-calibrate the species loss function, and propose a new biodiversity nonuse value function. The latter is calibrated from U.S. households´ willingness-to-pay (WTP) in a Stated Preference (SP) study of preservation of tropical rainforests (Kramer & Mercer 1997) and a meta-analysis of old (1983-2001) SP studies of endangered species in the U.S (Richardson & Loomis 2009). This extrapolation of US households´ WTP to the global population´s WTP to avoid global species loss is based on strict and unrealistic asssumptions; including U.S. households´ preferences for species loss being representative of households globally, and the relative preferences for avoiding species loss being stable over time (as the valuation studies are 15-35 year old).

In this paper, we extend Brooks and Newbold's (2014) analysis from looking at old studies of the US households´ WTP only, to address the current WTP of households worldwide to avoid the global species loss due to climate change. We achieve this by applying the results from a recent Delphi Contingent Valuation (CV) study of European, North American (USA and Canada), Oceanic (Australia and New Zealand) and South-East Asian expert estimates of households´ WTP to avoid specific scenarios for future species loss in the Amazon Rainforest (Strand et al. 2017). For the physical loss of species, we calibrate the species loss function based on the meta-analysis by Urban (2015). In contrast to Brooks and Newbold (2014) species loss function, our functional form is more flexible and can handle varying yearly global temperature change. Further, whereas Brooks and Newbold (2014) keep everything except species constant, we fully integrate the loss

[1] In the following, we will use the words "impacts" and "loss" to describe impacts in physical terms, and "(economic) damage cost" to describe the economic damage costs in monetary terms.

and economic valuation function in the FUND 3.9 IAM (Anthoff & Tol 2014b). We then run the model to estimate the global species loss and the biodiversity damage costs of climate change.

The motivation for this paper is Brooks and Newbold's (2014, p. 348) request for further economic research in order to improve the IAMs. Particularly, "better estimates of the nonuse of biodiversity values through additional research on people's willingness to pay for biodiversity protection is sorely needed". By using the Delphi CV study of households´ WTP to avoid further deforestation and species loss in the Amazon rainforest (Strand et al. 2017), we have now covered the welfare loss of more than 60% of the world's population, and about 70% of the global population outside of Latin America. For the regions that are not included in the Delphi CV study, we estimate the WTP by unit value transfer with income adjustment from the regions where we have WTP estimates. With an estimated one out of ten known species on the planet living in the Amazon rainforest (WWF 2017), it is immensely biodiverse. Hence, implementing these results in an IAM would provide a better estimate of the damage cost of climate change to the non-use values of biodiversity.[2]

This paper relies on two methods; IAMs and the CV method; each with their potential biases and limitations. IAMs are complex models, but at the same time they need to simplify due to the global coverage and limited data available. A key trade-off in IAMs are detail vs. simplification. The former is required to include all relevant processes, while the latter ensures sufficient transparency. This means that the complicated nature of both natural and social sciences is difficult to capture within the modeling framework. Moreover, each of the IAMs are designed to answer specific sets of questions, and therefore one should be aware of the models intended use.[3] Nevertheless, IAMs are one of the few economic tools that tries to combine climate science with economics to project the future, and is used both in academic research and in policy analysis. Thus, updating and improving these models based on recent ecological and economic studies is essential. The aim of this paper is only to update components related to the physical loss and loss value of biodiversity in an IAM. Hence, we do not investigate any other limitations or potential problems with the specific IAM. The CV method and other SP methods used to value species loss also have their limitations, including the challenges in describing the environmental change to be valued in simple

[2] The Delphi CV survey covers mostly the non-use values, as these distant beneficiaries from countries outside of South America have never visited the Amazon rainforest (and thus have no use value in terms of e.g. recreational use of the forest).

[3] For instance, FUND 3.9 have evolved into "...studying impacts of climate change in a dynamic context, and it is now often used to perform cost-benefit and cost-effectiveness analyses of greenhouse gas emission reduction policies, to study equity of climate change and climate policy, and to support game-theoretic investigations into international environmental agreements"(FUND 2017).

but at the same time scientifically correct terms, the choice of a realistic and fair payment vehicle, and the hypothetical nature of the valuation scenarios (See Johnston et al. (2017) for recent guidance in SP surveys). Further, there are also limitations to the Delphi CV method and the unit value transfer procedure used here to estimates household WTP globally to avoid climate induced species. Here we implicitly assume that the Delphi CV survey value the same change in the environmental good as the climate induced species loss in the IAM; and that no other factor than income affects the WTP across regions.[4]

By updating the biodiversity loss function, we show that the projected biodiversity loss is somewhat lower compared to the current FUND 3.9 model. However, the updated biodiversity loss value function estimates increasing global biodiversity damage costs as a percentage of regional income. Further, the biodiversity loss damage cost as a fraction of global damage costs increases as well. This is true for all the regions, but biodiversity service damages do vary across regions. Nevertheless, the updated estimation of global damage cost is higher compared to the original FUND 3.9 model, when assuming a lower (but reasonable) social discount rate. This is due to the fact that the estimated damages are lower in the short-run in the re-calibrated model.

The rest of the paper is structured as follows. Section 2 briefly describes how biodiversity and ecosystem damage are included in the prominent IAMs (DICE, PAGE and FUND). Section 3 updates the species loss function and WTP estimates in FUND 3.9. Section 4 implements this in FUND 3.9; and projects the biodiversity loss under different assumptions in order to test the sensitivity. Finally, section 5 concludes and outlines avenues for further research in order to improve the reliability and validity of biodiversity damage costs in IAMs.

2. Biodiversity and ecosystem damage in IAMs

In the most prominent IAMs, the climate response is usually described as impacts on society with one or more climate damage cost functions for each specific region (Mastrandrea 2009; Nordhaus & Boyer 2000; Nordhaus 2017). These damage functions are usually converted to monetary estimates of the impacts, in terms of loss of Gross Domestic Product (GDP). The main purpose of IAMs is to better understand the global economic costs of climate change, and thus the economic benefits of policy measures to mitigate these impacts on social and natural systems. Damages in IAMs are generally assumed to rise with increasing temperature, but the size and

[4] While we account for difference in income in terms of mean GDP per capita in a country, we do not account for income inequality differences which could affect WTP and the transferred values as shown by Baumgärtner et al. (2017)

functional form of these damage functions vary across the models. The global coverage and long time horizon of these IAMs necessitate a set of simplified assumptions, and there is a wide variation in how climate change damages occur in the models.

A total of 18 IAMs were involved in the Energy Modeling Forum Round 14 (EMF14) (Tol & Fankhauser 1998). Some more natural-science oriented, while others more economic-science oriented. This paper emphasizes on the latter type of models, which are widely used both in research and in the development of policy proposals. Particularly, the three models used by the U.S. government's Interagency Working Group on the Social Cost of Carbon in 2010 (Interagency Working Group on Social Cost of Carbon 2010); DICE, PAGE and FUND. In this section, we will take a closer look at how biodiversity and ecosystem service damage cost are treated in these three models.

2.1. DICE

The DICE (Dynamic Integrated Climate Economy) family of models were of the earliest IAM for climate change, and was developed in starting of 1989 (Nordhaus 1992; Nordhaus 1994). Here, the representative agent maximizes her expected discounted future utility by choosing the level of consumption, savings and investment in greenhouse gas abatement based on a global aggregated constant-return-to-scale Cobb-Douglas production function. The climate change damages felt by the agent is presented as a single global damage function, based on the climate change impact from a list of sectors dependent on the magnitude of temperature change (Mastrandrea 2009). The authors acknowledge that the methodology is at a speculative stage and that the climate change damage estimation is to a large extent based on "rough estimates" (Nordhaus & Boyer 2000, p. 86). In DICE2007, the climate change damages predicted to affect "human settlement and natural ecosystems" is estimated to be 5.7% of total damage costs from a 2.5 °C rise in global mean temperature (Brooks & Newbold 2014; Nordhaus & Boyer 2000).

2.2. PAGE

PAGE (Policy Analysis of the Greenhouse Effect) is designed to include all the five IPCC reasons for concern in an IAM (Hope 2006, p. 19). The five IPCC reasons for concern are: i) risks to unique and threatened ecosystems, ii) risks from extreme climate events, iii) distribution of impacts, iv) aggregate impacts, and v) risks from future large-scale discontinuities. The model includes mean temperature dependent damage functions, separated in 8 world regions by "market" and "nonmarket" sector. There is, however, no detailed description available or discussion about biodiversity and ecosystem damage cost, or physical losses (Hope 2006; 2008). This makes it difficult to relate the proportion of total damages to ecosystem services or biodiversity impact, and thus challenging to assess how a modified ecosystem and biodiversity impact function would change the initial results.

2.3. FUND

FUND 3.9 (Framework for Uncertainty, Negotiation, and Distribution) has the most disaggregated presentation of climate change damages among the three mentioned models (Mastrandrea 2009) Here, the damage functions are dependent on both the size and the rate of temperature increase, and the model includes both sector- and region-specific impacts. The different sectors' exposure to climate change is also assumed to be affected by socioeconomic changes, and parameters in the model are estimated based on either published documentation or expert judgment. We also find an explicit damage function for ecosystem impact of climate change. Anthoff and Tol (2014b) state that the ecosystem damage assessment is based on the "warm-glow" effect, which they describe as "Essentially, the value, which people are assumed to place on such impacts, are independent of any real change in ecosystems, of the location and time of the presumed change, *etcetera* – although the probability of detection of impacts by the "general public" is increasing in the rate of warming" (Anthoff & Tol 2014b, p. 15). Thus, they assume that people are not able to express their utility from avoiding species loss in terms of their WTP in Contingent Valuation (CV) and other Stated Preference (SP) surveys. This is, however, contrary to current evidence (see e.g. Johnston et al. 2017). FUND 3.9's open-access availability, explicitly stated assumptions and documentation of biodiversity and ecosystem services, makes it more straightforward to examine and update the ecosystem damages of climate change[5].

Since only one of these three IAMs include the biodiversity and ecosystem service damage costs explicitly, and in order to relate directly to Brooks and Newbold (2014) analysis, we use the FUND 3.9 model to illustrate how recent species loss information and global WTP estimates can be used to better account for biodiversity damage cost in an IAM. We will in the next section look closer at FUND 3.9 and its ecosystem sector.

3. Updating the ecosystem damages in FUND 3.9

The ecosystem damage function in FUND 3.9 is based on two components. The first component is the *biodiversity loss function*, which consists of a species loss function related to temperature change

[5] FUND 3.9 is written in Julia and is publically available at http://www.fund-model.org/versions

over time. The other component is the *biodiversity loss value function*, which has an economic value function linked to the species loss function. We will in the next subsections present both these components and suggest a modified and updated versions of them, while keeping the same structure of the overall model. We use standard calibration procedure, where the data presented in the following section defines the exogenous parameter values.

3.1 Biodiversity loss function

The biodiversity loss function in FUND 3.9 is specified as

$$B_t = B_{(t-1)}\left(1 - \theta - \varphi \Delta T^2_{(t-1)}\right), \tag{1}$$

where B_t is the number of species in time t on a global scale, θ and φ are parameters estimated at respectively 0.003 and 1.6 (φ with a range from 0 to 3.2), and ΔT is the temperature change (in degrees Celsius) from year $(t-1)$ to t. By examining equation (1), θ could be interpreted as the natural rate of species extinction without climate change. These parameters are described as expert guesses (Anthoff & Tol 2014b, p. 16), and FUND further assumes the number of species globally to be constant at 14 000 000 species until the year 2000. Hence, we can describe the species richness in FUND 3.9 as a function of an initial constant species loss rate θ over time (which occurs independent of climate change damages), minus an estimated parameter multiplied by the square of the year-to-year temperature change. As Brooks and Newbold (2014) argues, the simplicity of the function has both limitation and advantages. That is, the function does not characterize the heterogeneity of biodiversity in all its forms, but it can be calibrated using available quantitative studies. Brooks and Newbold op. cit. updates the biodiversity loss function, see equation (2) below, linking studies of potential impacts of climate change on species and extinction rates with the parameter φ in equation (1):

$$1 - L_t = \left(\frac{1 - \theta - \varphi \Delta T^2}{1 - \theta}\right)^t \quad , \tag{2}$$

In equation (2), $1 - L_t$ is the fraction of remaining species in some future year t, ΔT is the hypothesized constant annual temperature increase up to year t, and φ is a parameter based on existing studies of species loss under different climate change scenarios (Malcom et al. 2006; May et al. 1995; Thomas et al. 2004; Warren et al. 2011). The shortcoming of equation (2) is that it can handle only a constant ΔT over time. Furthermore, literatures like Urban (2015) suggests other projections of global species loss with rising global mean temperature. Hence, to better handle a varying year-to-year temperature change and capture the species loss projected by Urban, we present equation (3):

$$L_t = 1 - \frac{B_0 \prod_{q=1}^{t}\left(1 - \theta - \varphi \Delta T_q^2\right)}{B_0 (1-\theta)^t} = 1 - \frac{\prod_{q=1}^{t}\left(1 - \theta - \varphi \Delta T_q^2\right)}{(1-\theta)^t} \quad , \tag{3}$$

where B_0 is the initial number of species and ΔT_q is the temperature change (in degrees Celsius) at time q. We also introduce new values for θ and φ, which we calibrate according to the findings by Urban op. cit.

The prediction of species response to future climate change are highly uncertain, and several attempts have been made to estimate the species response, but with mixed results. We base our biodiversity loss function on Urban (2015), who performed a meta-analysis of 131 published estimates of the number of species threatened by extinction. The time horizon in these 131 published estimates varies from year 2020 to year 2100, with a weighted average around year 2083. Among the studies in this meta-analysis, we also find those Brooks and Newbold (2014) base their estimates on. Urban reports the results from the meta-analysis of species extinction risk from climate change under four different global mean temperature increment scenarios, which we have reproduced in Table 1.[6] The numbers are on a global scale, meaning that some regions will have higher extinctions risk than others. The meta-analysis estimates, in general, show a lower fraction of species threatened by extinction than models in Brooks and Newbold (2014) and FUND 3.9 do.

Table 1: Predicted percentage species loss from climate change under four different global mean temperature increment scenarios; 0.8, 2, 3 and 4.3 °C (Urban 2015).

Global mean temperature rise:	0.8°C	2 °C	3 °C	4.3 °C
Species loss:	2.8 %	5.2%	8.5 %	16%

Recall that the natural rate of species extinction without climate change (or the probability/risk of extinction), is denominated as θ. The parameter is estimated from fossil records and are believed to be between 10^{-7} and 10^{-6} per species per year. Moreover, it is typically assumed to be constant over geologic time (May et al. 1995). The current background extinction rate is estimated by May et al. (1995) to be approximately 10^{-3}. Pimm et al. (1995) estimates the value to be in the range of 2×10^{-4} to 2×10^{-5}. However, this value could also be close to 1.5×10^{-3}, depending on the number

[6] The relationship between species and the rising global mean temperature is often used on a global scale in the climate economic models. Other ways that climate change could affect species are e.g. extreme weathers, droughts and change in precipitation (Parmesan et al., 2000).

of threatened species that were to become extinct in the next 100 years. If we assume the lower estimates in Urban (2015) to be our current rate of species loss, then θ = 2 x 10^{-4}. This is not so unreasonable compared to estimates from Pimm et al. (1995). The unknown parameters φ is also calibrated according to Urban (2015), with value φ = 0.8347.

3.2 Biodiversity loss value function

In the biodiversity loss value function, Anthoff and Tol (2014b) define the impact of climate change on ecosystems, biodiversity, landscape etc. as:

$$E_{t,r} = \alpha P_{t,r} \frac{y_{t,r}/y^b_{t,r}}{1 + y_{t,r}/y^b_{t,r}} \frac{\Delta T_t/\tau}{1 + \Delta T_t/\tau} \left[1 + \sigma\left(\frac{B_0 - B_t}{B_t}\right)\right] \quad , \tag{4}$$

where $E_{t,r}$ is the value of loss of ecosystems at time t in region r, α is a parameter value of US \$50 per person if per capita income equals the OECD average in 1990, y denotes per capita income, y^b is a parameter set to US \$30 000,[7] P denotes population size, τ is a parameter equal to 0.025, ΔT_t denotes the yearly change in temperature (in degree Celsius), σ is 0.05, B_0 is the initial number of species set at 14 million, and B_t is the number of species in year t. E can also be interpreted as the WTP to avoid the loss of global species to climate change (Brooks & Newbold 2014). As Brooks and Newbold (2014) point out, there are some fundamental difficulties with equation (4). The damages mainly depend on the annual temperature change, and not the fraction of remaining species. Particularly, there are no damage cost if the year-to-year temperature change is zero, even if the species loss is positive. Hence, a valuation function is introduced by Brooks and Newbold (2014)[8] which has a very similar functional form to Sterner and Persson (2008) and Weitzman (2010)

$$WTP_t = y_t - \left[y_t^{1-\eta} + \beta(\eta - 1) ln\left(1 + \Delta B_t/B_t\right)\right]^{1/(1-\eta)}, \tag{5}$$

where WTP is the willingness to pay in each year t, y_t denotes per capita annual income, ΔB_t is the difference between the projected biodiversity level without climate-change in year t and the projected biodiversity level under a business-as-usual (BAU) scenario (B_t)[9], and β is a calibrated

[7] Which is the OECD average per capita income in year 1990.
[8] For a detailed presentation of equation (5), see Brooks and Newbold (2014).
[9] $\Delta B_t = (B_t^0 - B_t)$, where B_t^0 is projected biodiversity level without climate change in year t.

parameter. Brooks and Newbold (2014) describe η as the elasticity of marginal utility of consumption, which diminishes at a constant relative rate. The higher the value of η is, the less we value a dollar more of consumption (Sterner & Persson 2008; Weitzman 2010). Equation (5) derives from an indirect utility function which is assumed to include a biodiversity value component that is separable from consumption of markets goods and services. Thus, equation (5) can be viewed (loosely speaking) as representing the non-use value of biodiversity[10].

We make a one important change to equation (5) in order to make it fit better with the 16 world regions in FUND 3.9; listed in Table 2. We then use the new equation (6) to estimate the WTP per capita for each of these world regions in FUND 3.9, based on Strand et al. (2017).

$$WTP_{t,r} = y_{t,r} - \left[y_{t,r}^{(1-\eta)} + \beta_r(\eta - 1)ln\left(1 + {}^{\Delta B_t}/_{B_t}\right)\right]^{1/(1-\eta)}. \qquad (6)$$

The function is now specified for each individual regions, r. Equation (6) expresses the households' consumption of market goods and services increasing proportional to income in every period, where biodiversity is characterized as a non-market good that provides utility to individuals independent of the concurrent level of consumption of market goods and services. Given equation (6) and FUND 3.9's base assumptions of $\eta = 1$ (Anthoff & Tol 2014b, p.14) we also set $\eta \approx 1$ for all the regions as a benchmark value, which will provide a direct comparison to FUND 3.9.[11]. Table 2 lists all the regions in FUND 3.9 (Anthoff & Tol 2014a).

Table 2: The 16 geographical regions in FUND 3.9 (Anthoff & Tol 2014a).

1. USA	USA	9. Central America	CAM
2. Canada	CAN	10. South America	SAM
3. Western Europe	WEU	11. South Asia	SAS
4. Japan and South Korea	JPK	12. Southeast Asia	SEA
5. Australia and New Zealand	ANZ	13. China plus	CHI
6. Eastern and Central Europe	EEU	14. North Africa	NAF
7. Former Soviet Union	FSU	15. Sub Saharan Africa	SSA
8. Middle East	MDE	16. Small Island States	SIS

[10] Particularly, the indirect utility can be expressed as $U = \frac{y^{(1-\eta)}}{(1-\eta)} + \beta\ln(B_t)$. Thus, η is the elasticity of marginal utility of consumption, which can be derived in this way: $\frac{d(dU/dy)}{dy}\frac{y}{dU/dy} = -\eta$.

[11] $\eta = 1$ also seems to be a reasonable value as it is frequently assumed in climate change modeling. See e.g.: Scarborough (2010), Sterner and Persson (2008), Weitzman (2010) and Stern (2008).

Strand et al. (2017) use the Delphi CV method to ask over 200 environmental valuation experts from 37 countries on four continents to predict the mean and median WTP per household per year, for two specified Amazon forest preservation plans if this CV survey was conducted in their country. The CV scenarios the experts were asked to base their expert guess on are reproduced in Appendix A3. The preservation plans in the CV scenario survey are based on Soares-Filho et al. (2006), that predicts the loss of roughly 30% of the forest area and 23% of the mammal species by 2050 under the business as usual scenario. These estimates are used to specify the WTP for each region in equation (6), but is most likely in the lower range of the number of species that may face extinction risk. The estimates of WTP to avoid this species loss are presented in Table 3.

Table 3: Average annual household willingness-to-pay (WTP) to avoid species loss, reported for equation (4) and (6). Value transfer from Strand et al (2017) to geographical regions not covered by this study, is conducted using equation (7) and unity income elasticity of WTP, as found in Strand et al (2017). Results are reported as weighted average across countries in a region for each region in FUND 3.9 (see Table 2 for explanation of the abbreviations). The table also reports: i) the weighted average GDP per capita for each region, which is used as the income measure; ii) weighted average household size (needed to convert GDP per capita to a household income measure, as WTP is reported per household); iii) the calibrated parameter (β_r) based on the data collected; and iv) the average annual WTP per household, predicted by the original FUND 3.9 model. Sources: Strand et al. (2017); (Navrud & Strand 2018); Eurostat (2016); Nakono (2012); World World Bank (2017); and UN (2012). All US$ values are reported in 2012 US (see appendix A1 for inflation adjustment according to IMF).

The geographical regions in FUND 3.9 (See Table 2)	Weighted average of GDP per capita in the regions (in 2012 US$)	Weighted average of the household size in the regions (in year 2012)	Weighted average of the annual WTP per household in the regions given eq. (6) (In 2012 US$)	Calibration of the region specific parameter (β_r) from eq. (6)	The average annual WTP per household given eq. (4), i.e., initial predictions from FUND 3.9 (In 2012 US$)
USA	50 900	2.59	67.70	2.43×10^{-3}	71.29
CAN	52 200	2.55	90.20	3.21×10^{-3}	65.21
WEU	43 211	2.22	48.65	2.40×10^{-3}	53.15
JPK	40 436	2.43	45.52	2.19×10^{-3}	55.37
ANZ	62 240	2.43	41.62	1.30×10^{-3}	72.68
EEU	12 721	2.55	25.09	3.66×10^{-3}	2.24
FSU	10 094	2.72	19.91	3.43×10^{-3}	6.83
MDE	12 637	5.64	24.92	1.66×10^{-3}	3.44
CAM	8 300	3.94	30.41	4.40×10^{-3}	1.43
SAM	10 890	3.44	39.91	5.04×10^{-3}	1.68
SAS	1 404	4.13	20.95	1.71×10^{-2}	0.35
SEA	3 885	3.97	9.05	2.78×10^{-3}	0.80
CHI	6 386	3.04	23.40	5.71×10^{-3}	0.45
NAF	4 095	5.06	15.01	3.43×10^{-3}	0.81
SSA	1 766	4.59	7.00	4.09×10^{-3}	0.94
SIS	7 227	3.50	26.48	4.96×10^{-3}	1.79

The US$ values in Table 3 are listed in nominal units[12], and the regions are represented by a weighted average of the population in each country of their respective geographical regions. GDP

[12] Before using the dollar values in FUND 3.9, we adjust all values to $1995 USD according to the geographical regions, see appendix A.

per capita, household size and WTP are collected and calculated using a combination of sources (Eurostat 2016; Nakono 2012; Strand et al. 2017; UN 2012; World Bank 2017).[13] Some of the regions were not represented in Strand et al. (2017), for example, FSU, MDE, CAM, SAM, NAF, SSA and SIS. These regions' WTP are unit value transferred with income adjustment from other regions with similar characteristics, using equation (7) (Navrud & Ready 2007):

$$V_p = V_s \left({}^{Y_p}\!/_{Y_s} \right)^{\varepsilon}, \tag{7}$$

where V_p is the unknown WTP in a region p, V_s is the known WTP in region s, Y_p and Y_s are the income levels per capita, in region p and s, respectively; and ε is the income elasticity of WTP. We have used ε =1 in this unit value transfer; based on the results from Strand et al. (2017) and (Navrud & Strand 2018). Finally, with only β_r left in equation (6), we use the standard calibration procedure where the data information above defines the exogenous parameter β_r for all the regions.

In the far right column in Table 3, we run the original model to estimate the annual WTP per household in FUND 3.9.[14] We use the temperature change in year 2050 from FUND 3.9's own forecast, $\Delta T_{2050} \approx$ 0.033°C. As Table 3 shows, FUND 3.9 frequently estimates a different WTP compared to the results from Strand et al. (2017). Especially, the estimates for non-OECD countries seems to be significantly lower than Strand et al. (2017). The likely reason is: *i)* that there is only one parameter, α, which differentiates the geographical regions in FUND 3.9 into two groups (OECD and non-OECD), while in equation (6) there is one unique parameter β_r for every geographical region; and *ii)* that the WTP in the regions are mainly expressed as per capita income as a fraction of OECD average (with all other values fixed). For OECD countries ($y_{t,r} \geq y^b$ in equation (4)) we also find that WTP as a percentage of GDP per capita decreases with higher income. The opposite is true for non-OECD countries ($y_{t,r} < y^b$).

4. Model simulation

While Brooks and Newbold (2014) simulated their functions separately from the model based on some specific assumptions[15] for the globe as one region, we implement our revised and updated

[13] The damage cost are accumulated from per capita damages in FUND, so we adjust the values from per household to per capita.
[14] FUND 3.9 uses the EMF14 Standardized Scenario (Anthoff & Tol 2014b)
[15] Brooks and Newbold (2014) assumed for instance; i) a constant annual temperature change, ii) an annual income per capita of US$ 30 000, and iii) a constant annual income growth of 2%.

biodiversity damage cost function in FUND 3.9; using the 16 region specific damage costs estimates (in terms of annual WTP per household to avoid species loss) from Table 3. We then compare the different species loss projections, and run sensitivity analyses to check for robustness.

4.1 Predicted percentage species loss from climate change

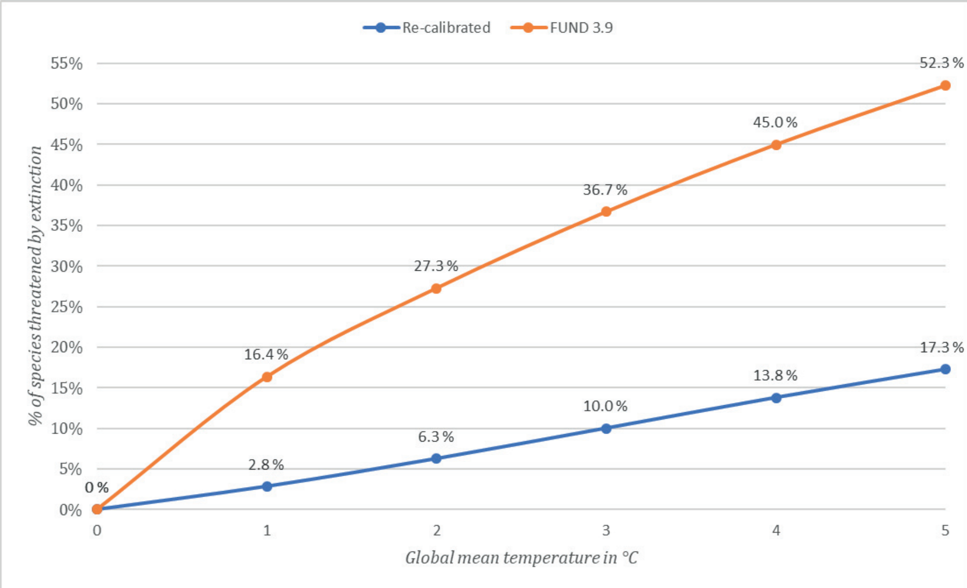

Figure 1: Projection of the percentage of species threatened by extinction with rising global mean temperature, re-calibrated and the original FUND 3.9.

Existing studies suggest that species loss due to future climate change will increase, as global temperatures rise (Urban 2015). Figure 1 shows the projected percentage of species threatened by extinction as a function of global mean temperature rise, from the original FUND 3.9 model as well as from our re-calibrated model. Here we only look at the relative rise in global mean temperature and not at the time horizon, which we will address later in Figure 2. The extinction rate in terms of % species threatened by extinction is simply projected by running the model and looking at the relative rise in global mean temperature, rather than using a year-to-year temperature change. A different scenario for the increment in annual temperature could therefore change the relationship between the global mean temperature rise and the percentage species loss in Figure 1.

The new projected species loss is *lower* than predicted in FUND 3.9, given the current temperature rise scenario. The main reason is that the meta-analysis by Urban (2015) finds a lower species loss with rising global mean temperature than predicted in FUND 3.9 using equation (1). A central assumption in FUND 3.9 is that the number of species is assumed to be constant until the year

2000 (Anthoff & Tol 2014b, p.16). Thus, if the global mean temperature rises by 2°C, the global species loss increases to 6.3% in the re-calibrated model and 27.3% in FUND 3.9. This would happen in year 2074 under the normal scenario in FUND 3.9, i.e. 74 years after the models assumes that the number of species are constant. If the Earth continues to warm up to 3°C, then the species loss rises to 10% with our estimates compared to 36.7% according to FUND 3.9. This would happen in 2097 according to the simulation. With 5°C global mean temperature rise, the species loss would be 17.3% compared to 52.3% according to FUND 3.9, in year 2142. The new estimates are approximately the same as Urban (2015) finds in the meta-analysis. However, if we in Figure 1 assume the preindustrial global mean temperature rather than year 2000 as our starting point, then we know that we have already passed the 1°C mark in year 2015 (NASA 2016). So with this assumption, in year 2015 the predicted global species loss increased to 2.8% in our estimates compared to 16.4% according FUND 3.9. Thus, this underlines the importance of the assumptions made, when projecting the global species loss.

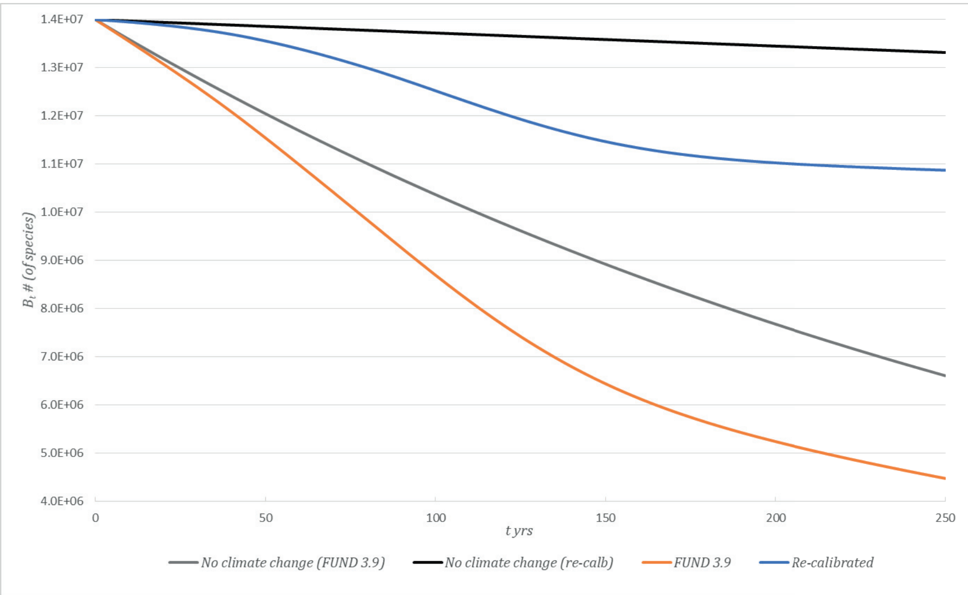

Figure 2: Projection of global species loss over time comparing scenario *no climate change (FUND 3.9)*, *no climate change (re-calibrated)*, *FUND 3.9* and *re-calibrated model*. Where number of species are constant until year 2000, i.e. year 0 in the figure.

Figure 2 shows the number of species remaining in year t, from our re-calibrated model and from the original FUND 3.9, compared to a situation with no climate change. Recall that the parameter assumption of no climate change in the re-calibrated and original FUND 3.9 model is $\theta = 2 \times 10^{-4}$ and $\theta = 3 \times 10^{-3}$, respectively for each year. In year t =200, our estimated model projects approximately 75% remaining species compared to 37% according to FUND 3.9. Assuming that there are some species projected to go extinct even with no climate change (see the "no climate change" curves in Figure 2 for both the re-calibrated and FUND 3.9), these numbers are corrected to 81% and 68%, respectively. It is important to point out that the annual temperature change in FUND is not constant, and starts to decrease approximately after t=100 years. This is why our curves in Figure 2 are not linear like Brooks and Newbold (2014), who for simplicity assumed a constant annual temperature change.

4.2 Projected biodiversity damage cost

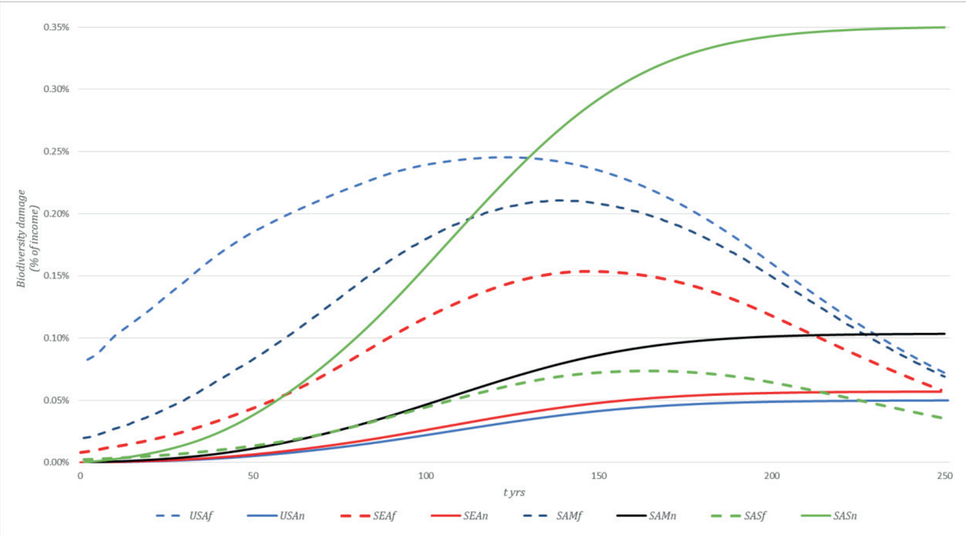

Figure 3: Projection of biodiversity damage cost as a percentage of income (GDP per capita) in different regions (USA, WEU=Western Europe, CAM=Central America, SAM=South America, and SAS = South Asia) from using FUND 3.9 and the re-calibrated model using the *new* biodiversity loss function in equation (3). *f* in the region codes (the dotted lines) denotes that we combine the new biodiversity loss function in equation (3) with the original FUND 3.9 biodiversity loss value function in equation (4). *n* in the region codes denotes that we combine the new biodiversity loss function in equation (3) with the new biodiversity loss value function in equation (6)

Figure 3 shows the predicted biodiversity damage cost in selected regions as a percentage of income (measured as their GDP per capita); both for the new biodiversity loss function in equation (3) combined with the original FUND 3.9 biodiversity loss value function in equation (4) (i.e. the dotted lines), as well as for the new biodiversity loss function in equation (3) combined with the new biodiversity loss value function in equation (6).

The biodiversity loss value function in equation (6), projects the damage costs as a percentage of income to increase over time. As stated in section 3, the original biodiversity loss value function in equation (4) depends more on the yearly temperature change than the species loss. Thus, with a declining global temperature rise over time, equation (4) predicts decreasing damage costs over time as a percentage of income giving rise to the concave form of the original FUND 3.9's prediction.

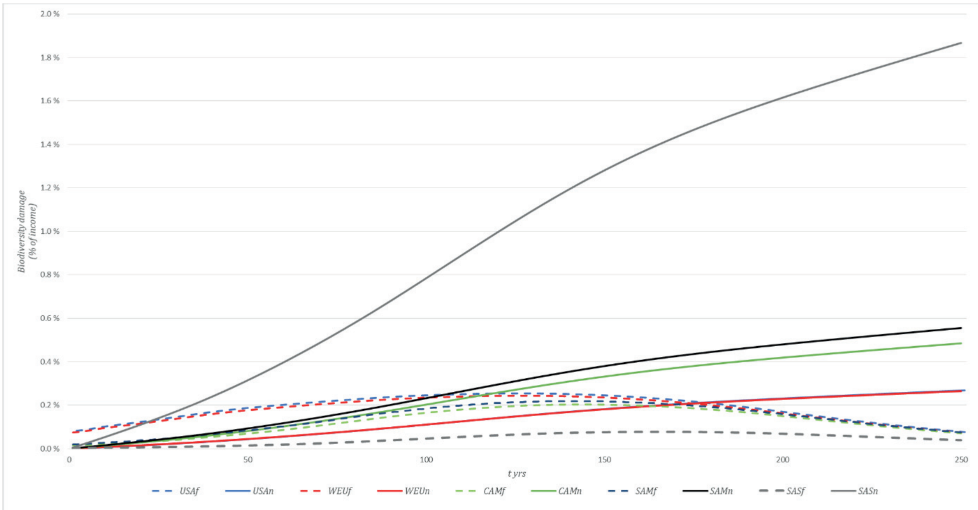

Figure 4: Projection of biodiversity damage cost as a percentage of income (GDP per capita) in different regions (USA, WEU=Western Europe, CAM=Central America, SAM=South America, and SAS = South Asia) from using FUND 3.9 and the re-calibrated model using the *old* biodiversity loss function in equation (3). *f* in the region codes (the dotted lines) denotes that we combine the old biodiversity loss function in equation (1) with the original FUND 3.9 biodiversity loss value function in equation (4). *n* in the region codes denotes that we combine the old biodiversity loss function in equation (1) with the new biodiversity loss value function in equation (6)

While Figure 3 shows the biodiversity damage costs using the new biodiversity loss function, Figure 4 illustrates the damage costs using the *old* biodiversity loss function instead. Comparing the two Figures, we see that the damage cost as a percentage of income increases more rapidly when the old biodiversity loss function is used (in Figure 4). FUND 3.9's damage cost on the other hand, does not seem to be very different from Figure 3, even with higher projected species loss. This again, as stated earlier, underlines that the biodiversity loss value function for FUND 3.9 is more dependent on the annual temperature change, rather than actual loss of species.

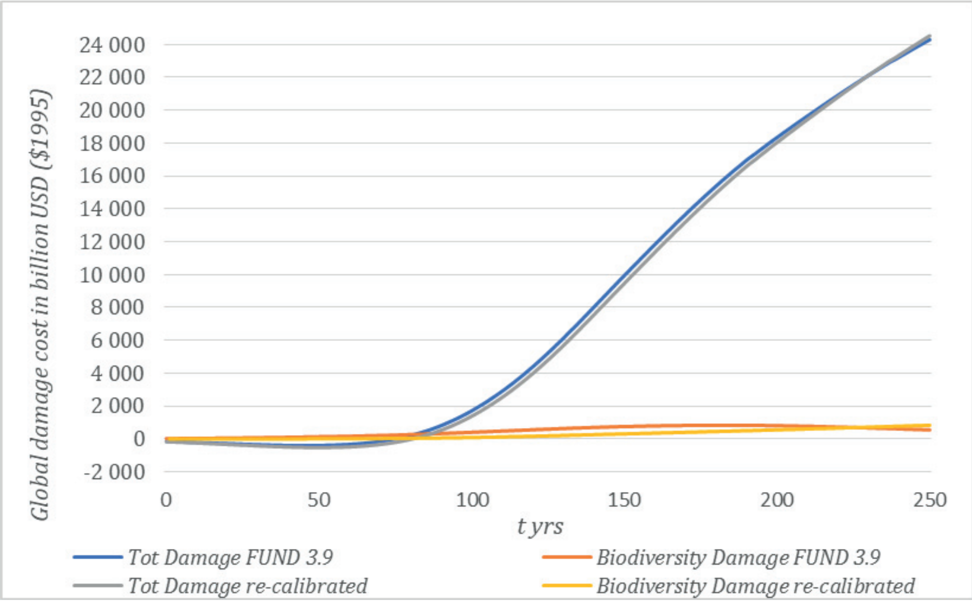

Figure 5: Projection of total damage cost and biodiversity damage cost over time, comparing FUND 3.9 and the re-calibrated model. In 1995 US $.

The total global damage costs in FUND 3.9 is divided into *economic* damage cost and *non-economic* damage cost. Species loss, and thus biodiversity damage cost, is classified as non-economic damage costs[16]. Figure 5 shows the global biodiversity damage cost and the total damage cost, for both FUND 3.9 and our re-calibrated model. While the biodiversity damage cost curve in both models is relatively flat, and higher for FUND 3.9 most of the time, the re-calibrated model surpasses FUND 3.9 after approximately 220 years. This is also reflected in the total damage cost curve. Thus, compared to FUND 3.9, the re-calibrated biodiversity damage cost represents an increasingly larger share of the total damage cost, and hence also of the non-economic damage cost[17].

By using the marginal damage cost estimated by FUND, we are also able to calculate the estimated global Social Cost of Carbon (SCC)[18]:

$$SCC = \sum_{t=2010}^{3000} \frac{1}{\prod_{s=0}^{t} 1 + \delta + \eta g_s} \sum_r MD_{tr} \quad , \tag{8}$$

[16] Appendix A.2, shows the list of categories of *economic* and *non-economic* damage cost used in FUND 3.9.
[17] The ecosystem damage cost as a percentage of non-economic damage cost is illustrated in figure A1, in appendix A.
[18] The Social Cost of Carbon Dioxide (SC-CO_2) is a measure, in US dollars, of the long-term damage from emitting one ton of carbon dioxide (CO_2) in a given year. (Mastrandrea 2009).

where *SCC* is the global social cost of carbon emission (in 1995 US $ per ton), t denotes time (in years), MD_{tr} is the marginal damage cost in year t and region r caused by carbon emission, g_s is the world per capita consumption growth rate at time s, δ is the pure rate of time preference and η is the elasticity of marginal utility of consumption (Greenstone et al. 2013). These values combined will determine the Ramsey discount rate.[19] In FUND 3.9, g_s grows yearly ≈ 2% (on average) but varies by region and year (Waldhoff et al. 2014). The value of δ is assumed 0.01%, 0.1% and 1%,[20] which gives a Ramsey discount rate of ≈ 2%, 2.1% and 3%, respectively.[21] FUND 3.9 reports SCC in metric tons of carbon, while we in this paper present SCC in metric tons of carbon dioxide (CO_2), denoted SC-CO_2.[22] The global Social Cost of Carbon Dioxide (SC-CO_2) estimates in 2010 are reported in table 4 using FUND 3.9 and the re-calibrated model.

Table 4: Estimates global Social Cost of Carbon Dioxide (SC-CO_2) in 2010 (in 1995 US $), using Ramsey discounting. *New* denotes the SC-CO_2 using the new biodiversity loss (equation (3)) and biodiversity loss value functions (equation (6)). *FUND 3.9* lists the original SC-CO_2 prediction by FUND 3.9. *New w/ eq. (1)* denotes the SC-CO_2 with the old biodiversity loss (equation (1)) and the new biodiversity loss value function (equation (6)). *FUND 3.9 w/ eq. (3)* denotes the SC-CO_2 using the biodiversity loss function (equation (3)) and the old biodiversity loss value function (equation (4)). The Ramsey discount rate is approximately 2% (δ = 0.01%), 2.1% (δ = 0.1%) and 3% (δ = 1%).

	New	**FUND 3.9**	**New w/ eq. (1)**	**FUND 3.9 w/ eq. (3)**
Global SC-CO_2 (δ = 0.01%)	$46.39	$45.77	$45.95	$37.56
Global SC-CO_2 (δ = 0.1%)	$39.14	$38.59	$38.69	$34.39
Global SC-CO_2 (δ = 1%)	$10.69	$10.81	$10.81	$10.81

Compared to other IAMs, FUND 3.9 is in the lower range of the estimated SC-CO_2 (Greenstone et al. 2013). Table 4 shows that the estimated global SC-CO_2 with δ = 0.01% and δ = 0.1% in our re-calibrated model is US $46.39 and US $39.14 (in 1995 US $), respectively.[23] These estimates are somewhat higher than FUND 3.9. FUND 3.9's estimated global SC-CO_2 is higher when δ = 1%, at US $10.81. This is due to the fact that the growing biodiversity damage costs are greater in the far future in the re-calibrated model, shown in figures 3 and 4, – as particularly the low discount rate gives a greater weight to the longer-term impacts. However, combining equation (1) with the new biodiversity loss value function from equation (6) (New w/ eq. (1)), results in a higher SC-CO_2 compared to FUND 3.9, at US $45.95 ($\delta$ = 0.01%), $38.59 ($\delta$ = 0.1%) and $10.81 ($\delta$ = 1%).

[19] The Ramsey discount rate R, is $R = \delta + \eta g_s$

[20] The assumed pure rate of time preference δ varies in the range of 0-3% (Greenstone et al. 2013).

[21] The long-term social discount rate is commonly assumed to be around 2% (Drupp et al. 2018).

[22] To convert from metric ton of CO_2 to metric ton of carbon, multiply by $\frac{12}{44}$ (Carbon Trust 2008)

[23] Roughly US $65.78 and $55.50; USA-inflation-adjusted to 2010 US $

With δ = 0.01% and δ = 0.1% (and somewhat δ = 1%), FUND 3.9's biodiversity loss value function (equation 4) seems to underestimate the biodiversity damage costs compared to our new function (equation 6), in general.

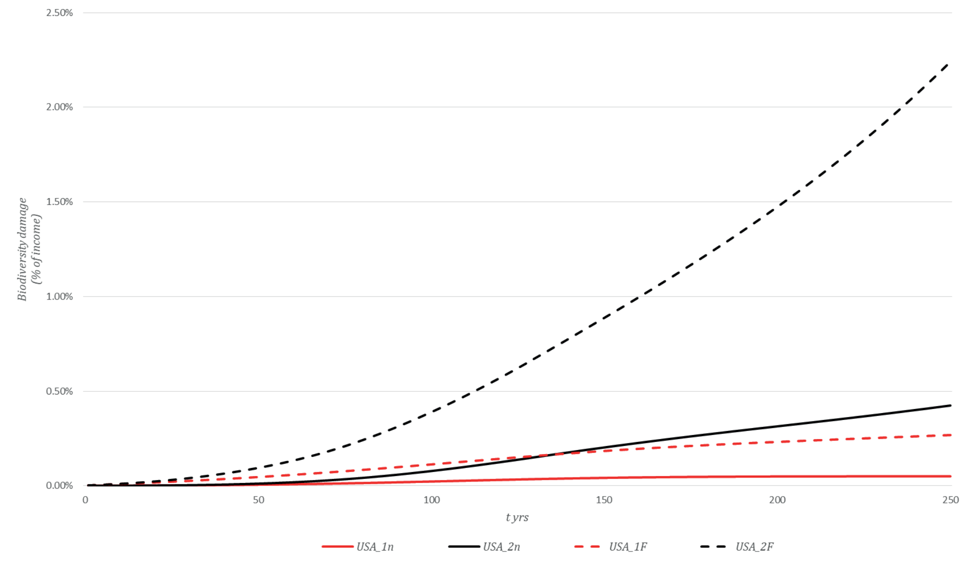

Figure 6: Projection of biodiversity damage costs as a percentage of income (GDP per capita) for one region (USA), using different values of η and different biodiversity loss functions. Regarding denotation, the numbers following "USA" refer to the assumed elasticity of marginal utility of consumption η (1 or 2). "n" is the new loss function (equation (3)) and *F* is the old loss function (equation (1)).

The correct value of the elasticity of marginal utility of consumption η, is a topic for discussion. A value between 1 and 2 is not unreasonable, but it may vary across regions. Figure 6 shows the importance of using a reasonable value for η by looking at the results for one region; USA. A lower (higher) η leads to a lower (higher) aggregated biodiversity damage cost (in percent of annual GDP per capita in the region) over time. Thus, the biodiversity damage cost could vary a lot between regions with high η (e.g. non-OECD countries), and lower η (e.g. OECD countries).

5. Concluding remarks

We update and extend both the climate change induced species loss function and the economic valuation of this species loss in the Integrated Assessment Model (IAM) FUND 3.9, in order to better account for spatial heterogeneity in both species loss and households´ willingness-to-pay (WTP) to avoid this loss. We seek to increase the global coverage and transparency of the damage cost estimates for species loss by using results from a global Delphi Contingent Valuation (CV) study together with value transfer techniques. Thus, we aim for a more comprehensive estimate of the global biodiversity damages.

The new species loss function predicts lower physical species loss than FUND 3.9. However, the improved economic valuation of species loss puts more weight on the actual physical loss for all geographical regions. Thus, by combining the updated species loss function with the updated WTP estimates, we get higher global biodiversity damage costs. This indicates that with incomplete assessment and valuation of species loss, we could underestimate the global economic damage costs of climate change.

Sensitivity analyses were also conducted in order to illustrate the uncertainty in the estimates at different stages of the damage cost function approach. The growing biodiversity damage costs are greater in the far future, and the magnitude of the economic damage cost is sensitive to the assumptions used for the social discount rate. Therefore, future analyses should look into these factors, but also evaluate the current practice in FUND 3.9 (and other IAMs) of updating global economic damages to current prices using US dollars and the US Consumer Price Index. Ideally, Purchase Power Parity (PPP) adjusted exchange rates should be used to convert damages in different regions to PPP-US $, and the regional CPIs (see Appendix A) should be used to update regional damage estimates to current values. For species loss this implies that households´ valuation of public goods like biodiversity increase at the same rate as the market prices of the basket of goods that underlies the CPI. However, people's valuation of species loss could deviate from the CPI, due to increased preferences for biodiversity preservation and increased scarcity due to the continued loss of species from climate change and other causes.

As SC-CO_2 estimates are used as decision support and input to Benefit-Cost Analyses of climate change mitigation and adaptation measures (e.g. Greenstone et al. 2013), our results should be used in the continuous update of these estimates in order to achieve the global economic optimal solution to climate change mitigation and adaptation measures.

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Appendix A

A1: Inflation adjustment

Table A1: Weighted average inflation adjustment for each geographical region (see Table 2 for the abbreviations) from 2012 US $ to 2010 US $, and from 2012 US $ to 1995US $, Source: IMF

Region	2012 US $	2010 US $	1995 US $
USA	1.00	0.95	0.67
CAN	1.00	0.95	0.72
WEU	1.00	0.96	0.71
JPK	1.00	0.98	0.73
ANZ	1.00	0.95	0.65
EEU	1.00	0.94	0.20
FSU	1.00	0.92	0.06
MDE	1.00	0.82	0.28
CAM	1.00	0.91	0.34
SAM	1.00	0.91	0.32
SAS	1.00	0.83	0.31
SEA	1.00	0.92	0.33
CHI	1.00	0.94	0.69
NAF	1.00	0.87	0.43
SSA	1.00	0.84	0.16
SIS	1.00	0.88	0.22
World	1.00	0.92	0.46

A2: Total damage in FUND 3.9

Table A2: In FUND 3.9, the total global damage cost is divided into economic damage cost and non-economic damage cost.

Total damage cost in FUND 3.9
• Economic damage cost ▪ Water ▪ Forests ▪ Heating ▪ Cooling ▪ Agricultural ▪ Costs and costal protection ▪ Tropical and extra tropical storms ▪ Income (GDP) ▪ Other economic damage cost • Non-economic damage cost: ▪ Species ▪ Human health: Diarrhea, Vector-borne diseases, Cardiovascular and respiratory mortality ▪ Wetland ▪ Other non-economic damage cost

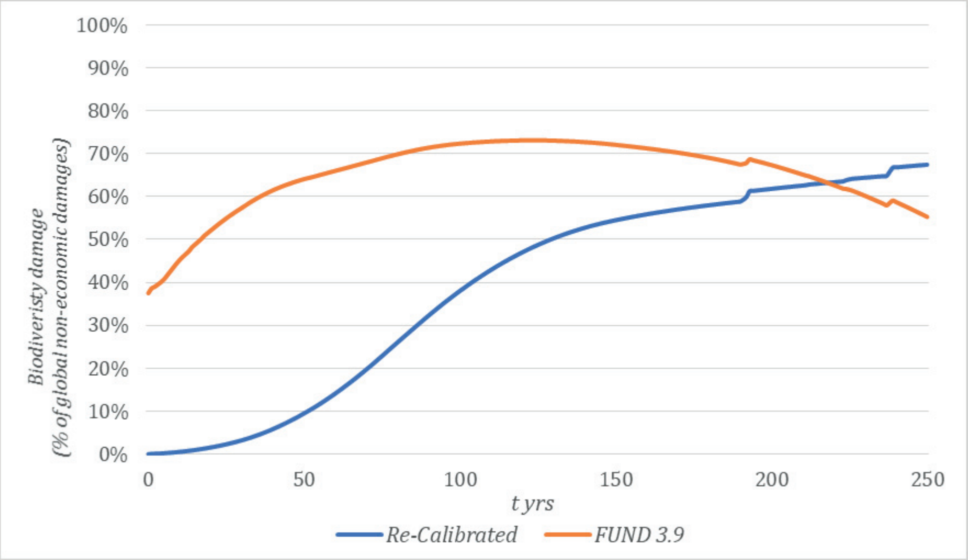


Figure A1: Projection of biodiversity damage cost as a percentage of global non-economic damages cost over time, comparing FUND 3.9 and re-calibrated model. In 1995 US $.

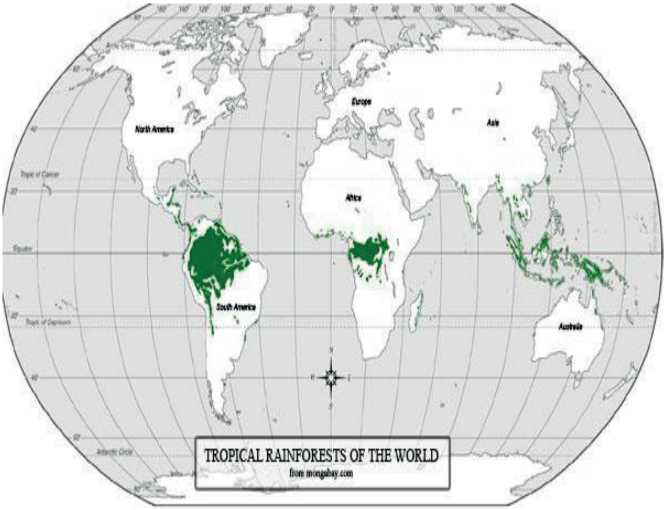
Figure A1 shows the biodiversity damage cost as a percentage of non-economic damage cost, for FUND 3.9 and the re-calibrated model. In FUND 3.9, this percentage starts at a higher share than in our re-calibrated model. Moreover, the share of biodiversity damage costs decreases after approximately 100 years run in FUND 3.9. The re-calibrated biodiversity damage on the other hand starts well below FUND 3.9, but rapidly increases over time. This increment continues beyond the time horizon in Figure A1.

A3: Valuation scenario used in the global Delphi Contingent Valuation survey (Strand et al 2017). (US version, Round 1 shown. The versions for the other regions were similar)

I. BRIEF DESCRIPTION AND VISUAL PRESENTATION OF GOOD TO BE VALUED

The map below (FIGURE 1) shows the location of the world's tropical rainforests. Rainforests cover only a small part of the earth's land surface; about 6%. Yet they are home to over half the species of plants and animals in the world. The **Amazon rainforest** is the world's largest rainforest, representing 40 percent of the global total. The Amazon is also home to the greatest variety of plants and animals on Earth. About 1/5 of all the world's plants and birds and about 1/10 of all mammal species are found there. The rainforest also serves as carbon storage, but **the carbon sequestration value is computed separately and should <u>not</u> be considered as part of your valuation assessments in this exercise.**

FIGURE 1 THE WORLD´s RAINFORESTS (IN GREEN)



For you to get an impression of the size of the Amazon rainforest, FIGURE 2 shows its size relative to the continental United States. The current total area of the Amazon rainforest is 2.2 million square miles, or about 70% of the size of the continental United States.

FIGURE 2. LOCATION AND RELATIVE SIZE OF THE AMAZON RAINFOREST

FIGURE 3. A SMALL PART OF THE AMAZON RAINFOREST AS SEEN FROM THE AIR

A recent World Bank study (Vergara, W. & S.M. Scholz (2011): *Assessment of the Risk of Amazon Dieback*) describes a development where a substantial fraction of the biomass in the standing Amazon rainforest could disappear over time if the current development continues. There are several, man-made, drivers of such a development. One central such driver is man-made deforestation in the region due to cattle ranching/grazing, other agricultural activities, and timber extraction.

The disappearing rainforest would then be transformed into less dense forest, or savannah. A significant fraction of the trees in the Amazon rainforest would dry out and die. Less oxygen would be produced, the standing biomass would shrink dramatically, the ecosystem of the rainforests would change markedly, and numerous species would disappear.

II. BASIC SCENARIO ELEMENTS

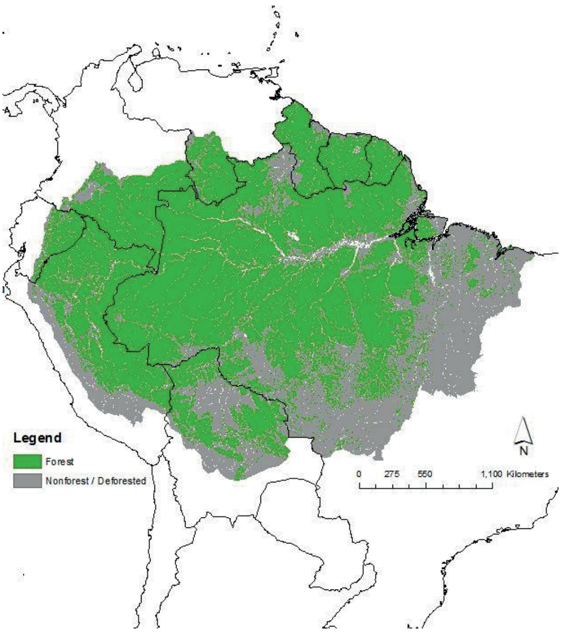
There is concern that only about 70 % of the current Amazon rainforest area will remain in 2050 **with no new preservation measures.** This means at the same time that 30% of the current forest would be lost by then.

The Brazilian Government, in collaboration with experts from international agencies, has developed two different rainforest preservation plans. These preservation plans will be expensive to carry out, since a large number of farmers and other property holders must be compensated for preserving their parts of the forest. It cannot be implemented by the Brazilian government without additional sources of support. If the funds raised by the Brazilian government and internationally exceed the costs of preservation, the preservation plans will be implemented.

Under **Plan A, no** further forest losses would occur by 2050, and the required payments will be collected from households in all contributing countries. This is the most expensive plan. It compares to the Business as Usual alternative, with no plan implemented (and thus with no implementation cost), under which only 70% of the present forest cover would remain by 2050.

Under **Plan B, some** forest losses would occur up to 2050, but about 88% of the current forest cover would still remain by then. This plan is less expensive to carry out than Plan A. Also in this case, with no plan, only 70% of the present forest cover would remain by 2050.

FIGURE 4. This represents the way the Amazon rainforest appears today



Species Loss

Along with this forest loss there are likely to be losses of species, some of which are found only in the Amazon. If nothing is done to slow the rate of deforestation in the Amazon, scientists estimate that 105 mammal species, out of 442 currently known to be found there, will (under the Business as Usual alternative) face a high risk of extinction by 2050. Eighty three (83) of these endangered species are found **only** in the Amazon. FIGURE 5, below, shows a random selection of 19 of the 105 mammal species that will be at a high risk of extinction by 2050 if no new forest protection measures are passed. A similar fraction (about 20%) of other animal species, such as birds and amphibians, will also in the same way be threatened.

Under **Plan A** (which preserves all (100 %) of the current Amazon rainforest by 2050), none of these species would be lost by 2050.

Under **Plan B** (which preserves 88% of the current Amazon rainforest by 2050), 41 of these species would face a high likelihood of extinction by 2050.

FIGURE 5. Some of the mammals threatened with extinction by 2050 with no new forest protection plan

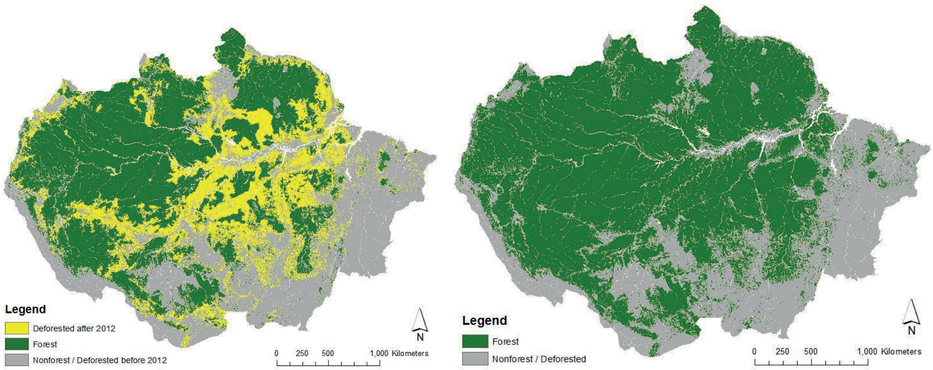
Plan A

With **PLAN A** no further deforestation would occur. The current area of the Amazon Rainforest will be maintained through 2050 and all (100%) currently existing species will be preserved.

FIGURE 6 compares the Business as Usual Scenario (to the left) to Plan A (to the right). Note that Plan A protects all forest. This is the *most ambitious and expensive plan*.

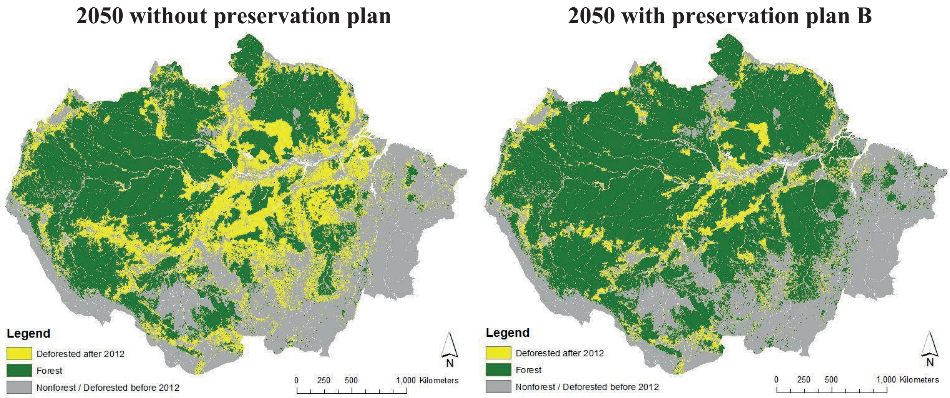
FIGURE 6. State of the Amazon Rainforest in 2050 with no new preservation plan, and with Plan A

2050 without preservation plan **2050 with preservation plan A**



With **Plan B** there will be some further losses of rainforest area, but more forest will remain by 2050 than if no measures are taken. 88% of the current rainforest area will remain in 2050, and 41 of the currently existing mammal species (10%) will face a high risk of extinction. FIGURE 7 compares the Business as Usual Scenario (to the left) to Plan B (to the right).

FIGURE 7. State of the Amazon Rainforest in 2050 with no new preservation plan, and with Plan B



III. PAYMENT MECHANISM

Households in the United States will be asked for an *annual payment per household* in terms of a national tax that would be collected by the federal government and submitted to an international Amazon Rainforest Fund. The Fund will be controlled by an international governing body, and the money will be used exclusively and fully for this Amazon Rainforest Preservation Plan (PLAN A or B). Key factors are: (1) payment *per household* rather than individual, (2) *annual* for all future years rather than a one-time payment (since the Amazon will provide these ecosystem service every year for infinity if the preservation plan is implemented), and (3) payment is *coercive* (*e.g.*, tax) rather than a voluntary contribution; (4) the plan will go through if and only if *a majority of households in high-income countries approve it*.

IV. TWO WTP ESTIMATES NEEDED FOR EACH PLAN (PLAN A and PLAN B)

All of your estimates should be provided in US$ per year. In the actual CV survey we will show a payment card indicating both monthly and annual payment amounts to the respondents. Payments are assumed to be required indefinitely or as long as the forest is to be protected. Assume that the survey design and the statistical analysis of the data would be done according to what you perceive as the current state-of-the-art. The payment card for annual payments is shown in the box below. You are free to report an amount that is not shown on the payment card if you feel it provides a better estimate of average WTP per household per year.

0 1 3 5 10 15 20 25 30 40 50 60 70 80 90 100 125 150 200 300 500 750 1000 1500
US dollars /household/year

We will first ask you to state WTP numbers for PLAN A (FIGURE 6), which preserves all (100%) of the current Amazon rainforest area from now and until 2050. Next, we ask you to state WTP numbers for the less ambitious PLAN B (FIGURE 7) which preserves 88 % of the currently forested area in 2050. Both plans should be compared to the 70% of the current forest area that is being preserved if there is no new preservation plan (the left figures in FIGURES 6 and 7)

PLAN A (FIGURE 6; the most ambitious and expensive plan, to fully protect today's rainforest)

V1. Mean per household WTP (annual payment)

___________ ( ) US$/household/ year

V2. Median per household WTP (annual payment)

___________ ( ) US$/household/ year

PLAN B (FIGURE 7; a less ambitious, and less expensive, plan than plan A, to protect only 88% of today's rainforest)

W1. Mean per household WTP (annual payment)

___________ US$/household/ year

W2. Median per household WTP (annual payment)

___________ US$/household/ year

Paper 2

Taxing Consumption to Mitigate Carbon Leakage

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Abstract:

Unilateral actions to reduce CO_2 emissions could lead to carbon leakage such as relocation of emission-intensive and trade-exposed industries (EITE). To mitigate such leakage, countries often supplement an emissions trading system (ETS) with free allocation of allowances to exposed industries, e.g. in the form of output-based allocation (OBA). This paper examines the welfare effects of supplementing OBA with a consumption tax on EITE goods. In particular, we investigate the case when only a subset of countries involved in a joint ETS introduces such a tax. The analytical results suggest that the consumption tax would have unambiguously global welfare improving effects, and under certain conditions have welfare improving effects for the tax introducing country as well. Numerical simulations in the context of the EU ETS support the analytical findings, including that the consumption tax is welfare improving for the single country that implements the tax.

Key words: Carbon leakage; Consumption tax; Emission trading system; Output-based allocation; Unilateral policy

JEL classification: D61, F18, H23, Q54

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1. Introduction

In the Paris climate agreement from 2015, almost all countries in the world committed to reduce emissions of greenhouse gases (GHGs). The countries' nationally determined contributions (NDCs) vary substantially, however, both when it comes to ambitions and indicated measures. Moreover, the NDCs are not legally binding, and it remains to be seen to what degree they will be followed up. Further, the second biggest emitter, the United States, has already signaled withdrawal from the Paris agreement. Thus, it is fair to conclude that the world will still rely on unilateral initiatives to reduce GHG emissions. Unilateral action however leads to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE). The affected industries claim that unilateral emission constraints would raise their production costs, and hence reduces their competitiveness in the world market. This induces more production and emissions in unregulated regions. As a result, the policymaker achieves lower emission level locally, but she risks losing job and industry to other regions, as well as higher GHG emissions abroad.[1]

Although the economic literature suggests that overall carbon leakage is moderate (typically in the range of 5-30%, cf. Zhang, 2012, and Böhringer et al., 2012a – somewhat higher for the EITE industry),[2] it is an important issue in the public debate and in policy decisions. Hence, policymakers have typically either exempted EITE industries from their climate regulation or implemented anti-leakage measures. For instance, sectors that are regulated by the EU Emission Trading System (EU ETS) and "exposed to a significant risk of carbon leakage",[3] are given a large number of free allowances. The allocation is based on product-specific benchmarks to maintain incentives to reduce emissions per unit of output. In order to reduce leakage exposure and limit surplus allowance, the allocation is linked to requirements such as activity level and production volumes (Neuhoff et al. 2016b). Free allowance allocation conditional on output is often referred to as output-based allocation (OBA) (Böhringer and Lange, 2005). A big share of industry sectors in the EU ETS are qualified as significantly exposed to leakage. Similar allocation rules can be found in other carbon markets such as in New Zealand and California, and in the world's biggest carbon market in China which is scheduled to be launched in late 2017(World Bank, 2014; Xiong et al., 2017).

[1] Cf. also the pollution haven literature, e.g. (Taylor 2005).

[2] 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 leakage rates for the EITE industries specifically are usually found to be somewhat higher than the overall leakage rates, see e.g. Fischer and Fox (2012). The theoretical literature on leakage goes back to Markussen (1975), and other important contributions are Hoel (1996) and Copeland (1996).

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

While a large amount of free allowances could mitigate carbon leakage, this implicit output subsidy ends up stimulating domestic production and thereby resulting in too much use of these products globally. The incentives to substitute from carbon-intensive to carbon-free products are weakened. As there is uncertainty about leakage exposure for individual sectors, policymakers may be persuaded to allocate too many permits to too many industries. Sato et al. (2015) finds for instance in the EU ETS that "vulnerable sectors account for small shares of emission", and Martin et al. (2014) concludes for the same market that the current allocation substantially overcompensates for a given carbon leakage risk. Another possible second-best policy instrument for anti-leakage is Border Carbon Adjustments (BCAs), with put charges on embedded carbon imports and refunds on export of EITE goods. Studies have shown that carbon leakage mitigation with BCAs would outperform OBA (Monjon and Quirion, 2011; Böhringer et al. 2012; Fischer & Fox 2012). BCAs may however not be politically feasible, and experts do not agree on whether or not it is compatible with WTO rules (Ismer and Haussner, 2016; Horn and Mavroidis, 2011; Tamiotti, 2011).

Recently a third approach, combining OBA with a consumption tax, has been proposed. Particularly, Böhringer et al. (2017c) shows that it is welfare improving for a country, which has already implemented a carbon tax along with output-based rebating (OBR) to EITE goods, to impose a consumption tax on top of the same EITE goods. They also show that a certain combination of OBR and a consumption tax would be equivalent to BCA. Further, whereas BCA may be politically contentious to introduce under current WTO rules, a consumption tax does not face the same challenge as it treats domestic and foreign goods symmetrically (Neuhoff et al., 2016a).[4] There are other papers as well that examine a consumption tax related to environmental regulations, both alone or combined with other instruments (Roth et al. 2016; Eichner & Pethig 2015; Holland 2012). Moreover, policymakers in for example California, China, Japan, and Korea are currently operating with a price on carbon that also regulates the embodied carbon from consumption of carbon-intensive products, especially electricity (Munnings et al. 2018;). The extra administrative costs of a consumption tax are probably limited once an OBA scheme is already in place, cf. e.g. Neuhoff (2016b).[5]

[4] Ismer and Haussner (2016) discuss the correct legal basis under EU law: "inclusion of consumption may be based on Article 192.1 of the Treaty on the Functioning of the EU and thus be adopted without unanimity voting in the Council of the EU."

[5] Neuhoff et al. (2016b) looks at 4047 commodity groups and finds that a consumption tax combined with ETS will have some administrative burdens, but could be moderate if designed correctly. Further, they conclude that "administrative efforts for 77 to 83% of imports could be avoided while still 85% to 90% of import-related carbon liabilities are included".

Our paper builds on the basic model and findings in Böhringer et al. (2017c). However, whereas the latter paper considers one regulating and one unregulating region, this paper examines the case where there is one unregulating region but two regulating regions that have a joint emission trading system with OBA to the EITE-goods. Further, only one of the two regions is considering to impose a consumption tax. The motivation for this is the current situation in Europe, where the EU/EEA countries have set quite ambitious climate targets for 2030 and especially 2050, and where EU institutions have responded enthusiastically to the Paris Climate Agreement outcome (Andresen et al., 2016). At the same time, there is significant political tension and different interests among the member states in the EU when it comes to climate policies. A prime example is the group of European countries depended on domestically produced coal, that have been critical towards EU's long-term climate goals. Other countries, especially in the north and west of Europe, are in favor of increasing the ambitions in line with the Paris agreement's requirement of gradually more ambitious targets. In the absence of cooperation to strengthen the climate policies, such as tightening the ETS further, the question is if unilateral action by a single country (or a group of countries) in the EU/EEA such as implementing a consumption tax on EITE goods would be welfare-improving or not.

We show analytically that under certain conditions it is welfare improving for a single region to introduce a consumption tax when the OBA is already implemented jointly in the two abating regions. We also find that the consumption tax has an unambiguously global welfare improving effect. Based on the analytical findings, we complement with results from a stylized numerical simulation model calibrated to data for the world economy, with three regions and three goods. As already indicated, we are particularly interested in the European context and the EU ETS, where a variant of output-based allocation is already in place for emission-intensive goods. The numerical results support our analytical findings, irrespective of which EU/EEA country we consider as the single region imposing a consumption tax. That is, the policy is welfare improving, both for the single country and globally.

As mentioned, the analytical model in our paper builds on the model framework in Böhringer et al. (2017c). However, there are several differences between the two papers. First, we examine the case with three instead of two regions. Second, we consider a broader range of policies. While Böhringer et al. consider a carbon tax in their analytical part, and a fixed global emission reduction in the numerical part, we consider the case where two of the three countries are involved in a joint emission trading system and one the two considers imposing a consumption tax. Further, our paper focuses on specific regions, including two regulating regions in Europe, whereas Böhringer et al. divide the world into two equally sized economies. A common assumption in the two papers is that producers can reduce emissions independently of output reductions. This is an important assumption, as the purpose of the policymaker typically is to reduce emissions in EITE industries without reducing the production of the same good. The latter assumption differs from other papers such as Eichner and Pethig (2015). They show that combining production and consumption-based taxes outperform only production-based taxation, but assumes a one to-one relationship between emissions and production of the emission-intensive good.

In section 2 we introduce our theoretical model, and analyze the welfare effect of a consumption tax, when a joint emission trading system combined with OBA is already in place for a subset of regions. In section 3, we transfer our analysis to a stylized multi-region multi-sector numerical model. The numerical 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

We build on the model framework in Böhringer et al. (2017c), but extend it to one more region and examine a broader range of policies. Consider a model with 3 regions, $j = \{1,2,3\}$, and three goods x, y, and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE) goods such as metal and other minerals), while z is emission-intensive and non-tradable (e.g. electricity and transport). Same types of goods, produced in different regions, are assumed homogenous. Carbon leakage may take place through relocating production of the y good, and thus OBA is considered for this sector. The market price for the goods x, y, and z in region j are denoted p^{xj}, p^{yj} and p^{zj}.

The utility for the representative consumer in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j)$, where the bar denotes consumption of the three goods. The utility function follows the normal assumptions; twice differentiable, increasing and strictly concave, i.e., the Hessian matrix is negative definite and we have a local maximum.

Production of good y in region j is $y^j = y^{1j} + y^{2j} + y^{3j}$, where y^{ij} denotes produced goods in region j and sold in region i (and similarly for the x good). The cost of producing the goods in region j is given by $c^{xj}(x^j)$, $c^{yj}(y^j, e^{yj})$ and $c^{zj}(z^j, e^{zj})$, where e^{yj} and e^{zj} denote emission from good y 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 and z is decreasing in emissions, i.e., $c_x^{xj}, c_y^{yj}, c_z^{zj} >$

0 (where $\frac{\partial c^{xj}}{\partial x^j} \equiv c_x^{xj}$ etc.). Further, $c_e^{yj}, c_e^{zj} \leq 0$ with strict inequality when emission is regulated, cost is twice differentiable and strictly convex. All derivatives are assumed to be finite.

Supply and demand give us the following market equilibrium conditions:

$$
\begin{aligned}
\bar{x}^1 + \bar{x}^2 + \bar{x}^3 &= x^1 + x^2 + x^3 \\
\bar{y}^1 + \bar{y}^2 + \bar{y}^3 &= y^1 + y^2 + y^3 \\
\bar{z}^j &= z^j
\end{aligned}
\tag{1}
$$

2.1. Climate policies

We assume that regions 1 and 2 have already implemented a cap-and-trade system, regulating emissions from production of the goods y and z in the two regions:

$$\bar{E} = e^{y1} + e^{y2} + e^{z1} + e^{z2}$$

where $\bar{E}$ is the binding cap on total emission. The emission trading market is balanced through the emission price t. We further assume that the two regions have implemented output-based allocation (OBA) to producers of the EITE good y, in order to mitigate carbon leakage to region 3, where we assume there is no climate policy imposed. OBA means that producers of good y receive free allowances in proportion to their output, which is an implicit subsidy s to production of good y in regions 1 and 2. The subsidy is proportional to the (endogenous) emission price t and the number of allowances received per unit produced. In the special case where the total number of free allowances to producers of the y good equals the total emissions from this sector, we have that $s = t(e^{y1} + e^{y2})/(y^1 + y^2)$. As the good z is not trade-exposed, there is no OBA to producers of this good.

Next, we assume that region 1 considers to implement a consumption tax v^1 on consumption of the y good, $\bar{y}^1$. The motivation for this tax is, as explained in the introduction, to counteract the negative impacts of OBA, which stimulates too much use of the y good.

The competitive producers in region j=1,2,3 maximize profits π^j such that:[6]

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

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

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

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

Since region 3 does not undertake any environmental policy, $t^3 = s^3 = 0$, whereas we have $t^1 = t^2 = t$ and $s^1 = s^2 = s$ (see above). The first order conditions are straightforward to derive, and give the following relationships (assuming interior solution):

$$\begin{gathered} p^{x1} = p^{x2} = p^{x3} = c_x^{x1} = c_x^{x2} = c_x^{x3} \\ p^{y1} + s = p^{y2} + s = p^{y3} + s = c_y^{y1} = c_y^{y2} \\ p^{y3} = c_y^{y3} \\ p^{zj} = c_z^{zj} \\ c_e^{y1} = c_e^{z1} = c_e^{y2} = c_e^{z2} = -t;\ c_e^{y3} = c_e^{z3} = 0 \end{gathered} \tag{2}$$

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

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

The representative consumer in region j maximizes utility given consumption prices and an exogenous budget restriction M^j:

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

Differentiating the *Lagrangian* function w.r.t the goods, we get the following first-order conditions:

$$\frac{\partial \mathcal{L}}{\partial \bar{x}^j} = u_{\bar{x}}^j - p^x = 0,\ \frac{\partial \mathcal{L}}{\partial \bar{y}^j} = u_{\bar{y}}^j - \left(p^y + v^j\right) = 0,\ \frac{\partial \mathcal{L}}{\partial \bar{z}^j} = u_{\bar{z}}^j - p^{zj} = 0 \tag{3}$$

where we have assumed interior solution, and normalized the utility functions so that $\lambda^j = 1$.

Further, 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 (2) that

$$p^y\left(y^j - \bar{y}^j\right) + p^x\left(x^j - \bar{x}^j\right) = 0 \tag{4}$$

2.2. The optimal consumption tax in region 1 under OBA

2.2.1. Welfare maximization in region 1

In order to evaluate the different climate policies, we need to specify the regional welfare functions. The welfare in region j can be expressed as:

$$W^j = u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{zj}(z^j, e^{zj}) - \tau^j(e^{y1} + e^{y2} + e^{y3} + e^{z1} + e^{z2} + e^{z3}) \quad (5)$$

where τ^j is region j's valuation of reduced global GHG emissions. We will refer to this as the *Pigouvian* tax.[7] The welfare consists of three elements: i) utility of consumption, ii) costs of production, and iii) costs of emissions. Note that the permit price t might vary from the Pigouvian tax.

Next, we want to derive the optimal consumption tax v^1 of good y in region 1, given that an emission trading system with OBA for sector y has already been implemented for regions 1 and 2.

By differentiating (5) with respect to v^1, subject to (4), we arrive at the following result for the optimal level of consumption tax v^{1*} in region 1:[8]

$$v^{1*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{a} \Bigg[\underbrace{s\frac{\partial y^1}{\partial v^1}}_{b} \underbrace{- \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)}_{c} + \underbrace{(-t)\left(\frac{\partial e^{y1}}{\partial y^1}\frac{\partial y^1}{\partial v^1} + \frac{\partial e^{z1}}{\partial z^1}\frac{\partial z^1}{\partial v^1}\right)}_{d} + \underbrace{\tau^1\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)}_{e}\Bigg] \quad (6)$$

The first factor (*a*) is negative since an increase in consumption tax will lead to a decrease in consumption of good y in region 1. Thus, negative (positive) terms inside the bracket tends to increase (decrease) the optimal consumption tax.

An imposed consumption tax in region 1 leads to less total demand of y, and thus the global market price falls. Hence, the production of y decreases in all the three regions and the second term (*b*) in the equation is negative. The term reflects the distortive side effects of the implicit OBA subsidy that causes too much consumption of this good.

Since the consumption of y falls, p^y decreases, i.e., $\frac{\partial p^y}{\partial v^1} < 0$. The consumer will now buy more of the relatively cheaper good x, and hence $\frac{\partial p^x}{\partial v^1} > 0$. Whether part (*c*) is negative or positive will then depend on $(y^1 - \bar{y}^1)$ and $(x^1 - \bar{x}^1)$, i.e., whether region 1 is a net exporter or importer of the

[7] 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.

[8] See Appendix A1.

two goods. For instance, if region 1 is a net exporter of good x and net importer of good y, the term becomes negative. This term therefore captures the terms-of-trade effects for the region.

The fourth part (*d*) consists of two terms, where the first term inside the parenthesis is negative as explained above. The second term is likely positive, due to interactions in the quota market. Remember that the sum of emissions from sector y and z in regions 1 and 2 must be unchanged and equal to the emission cap. Thus, emissions from production of the good z must increase as long as emissions from producing good y in regions 1 and 2 decline, and this is realized due to a lower quota price when production (and hence emissions) of y decreases. Whether joint emissions from sector y and z in region 1 increases or decreases is thus ambiguous. However, if the consumption tax in region 1 affects producers of good y in region 1 stronger (weaker) than producers in region 2, the sign of part (*d*) is likely positive (negative). Finally, we notice that the higher (lower) the permit price, the more (less) important this part becomes compared to the next part (*e*).

The last part (*e*) captures the emission effect in region 3. When global demand and the market price of good y drop, emissions related to producing this good in region 3 also decrease, $\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} < 0$. The effects on consumption of the non-tradable good z, and hence production and emissions, in region 3 are ambiguous. However, with the emission effect from production of good y as a first order effect, while impacts in sector z is a second order effect, it seems very likely that the former effect is stronger than the latter effect.[9] Thus, the sum of the two terms in part (*e*) is negative, i.e., emissions in region 3 decline when the consumption tax is imposed on good y in region 1:

$$\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right) < 0 \tag{7}$$

Recall that the first term (*a*) is negative. Then there are two negative and two ambiguous terms inside the bracket. Hence, the sign of the optimal consumption tax is in general ambiguous. However, if region 1 is not a net exporter of the y good, and if producers in regions 1 and 2 react symmetrically to the consumption tax (i.e., for the y good and the z good), then the optimal consumption tax in region 1 is unambiguously positive. Hence, we have the following proposition:

[9] We have tested the signs of d) and e) in our numerical simulations. The numerical simulation in the context of EU ETS and Norway confirms that part d) is practically zero. As for part e), we see that emission in the EITE production sector in ROW falls, while emission in the non-tradable and emission intensive sector increases. The net emission effect in ROW is still negative (as we suggested), and the sum of d) and e) is negative.

Proposition 1. Consider a region i that has a joint emission trading system with another region j, where output-based allocation is implemented for production of EITE-goods. Then it is optimal for region i to also impose a consumption tax on EITE-goods if it is not a net exporter of EITE-goods *and* producers in regions i and j react symmetrically to the consumption tax.

Proof: As explained in the text, the sign of factor (*a*) in equation (6) is strictly negative, while the signs of the terms inside the bracket of (6) are all negative (some strictly negative) if region i is not a net exporter of good y and producers in regions i and j react symmetrically to the consumption tax. Hence, the sign of v^{1*} is strictly positive, and thus the proposition is proved.

To understand the intuition behind Proposition 1, recall that there is one intended and one unintended effect of imposing OBA. The intended effect is to mitigate leakage, i.e., reduce emissions in the unregulating region. The unintended effect is that the implicit production subsidy causes too much use of the EITE good. That is, OBA hampers the switch from emission-intensive goods to less emission-intensive goods. The purpose of the consumption tax is to mitigate the unintended effect (i.e., re-establishing the switch towards less emission-intensive goods) without compromising with the intended effect of OBA. The proposition above shows that the consumption tax is welfare-improving, also for a country that is part of an emission trading system with OBA.

If the consumption tax is imposed in both region 1 and region 2 ($v^1 = v^2 = v$), and we consider the joint welfare in these two regions (assuming a common valuation of global emission reduction equal to τ), the optimal consumption tax becomes:

$$v^* = \left(\frac{\partial(\bar{y}^1+\bar{y}^2)}{\partial v}\right)^{-1}\left[s\frac{\partial(y^1+y^2)}{\partial v}+\frac{\partial p^y}{\partial v}(y^3-\bar{y}^3)+\frac{\partial p^x}{\partial v}(x^3-\bar{x}^3)+\tau\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v}+\frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v}\right)\right] \tag{8}$$

In this case, we see that part (*d*) in equation (6) has disappeared, and the optimal consumption tax (for regions 1 and 2 jointly) is positive if region 3 is not a net importer of the good y.

2.2.2. The global welfare maximization

Let us now assume that the planer in region 1 is concerned about the global welfare when imposing a unilateral climate policy in region 1, including the cost of emissions as before. Global welfare can then be expressed as followed:

$$W^G = \sum_{j=1,2,3}\left[u^j(\bar{x}^j,\bar{y}^j,\bar{z}^j)-c^{xj}(x^j)-c^{yj}(y^j,e^{yj})-c^{zj}(z^j,e^{zj})-\tau^1(e^{yj}+e^{zj})\right] \tag{9}$$

where τ^1 is still region 1's valuation of global emissions, referred to as the Pigouvian tax above.

By differentiating w.r.t. to the consumption tax in region 1 (given a joint quota market with OBA in regions 1 and 2), we find that:[10]

$$v^{1G*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{f} \left[\underbrace{s\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right)}_{g} + \underbrace{\tau^1 \left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)}_{h} \right] \tag{10}$$

From previously, we know that *(f)* is negative, $\frac{\partial \bar{y}^1}{\partial v^1} < 0$, as a consumption tax causes less demand in region 1.

Furthermore, the global market price for good y falls because of less demand and the price reduction makes it less profitable for the producers in the international market, hence *(g)* must be negative as well, $\frac{\partial y^1}{\partial v^1}, \frac{\partial y^2}{\partial v^1} < 0$. This is similar to part (*b*) in equation (6).

The last terms is identical to the last term in (6), which we argued is negative, cf. equation (7).

The social planner in region 1 was earlier concerned about the terms-of-trade effects when maximizing welfare in region 1, while this is not the case when it takes a global welfare perspective. Moreover, part (*d*) in equation (6) is also no longer present in equation (9) as the planner takes into account effects on production costs in region 2 as well.

Thus, we see that from a global welfare perspective, the optimal consumption tax in region 1 is unambiguously positive. We state this as a proposition:

Proposition 2. Consider a region i that has a joint emission trading system with another region j, where output-based allocation is implemented for production of EITE-goods. Then it is optimal from a global welfare perspective that region i impose a consumption tax on EITE-goods.

Proof: As explained in the text, the sign of factor (*f*) in equation (10) is strictly negative, while the signs of the terms inside the bracket of (10) are both strictly negative. Hence, the sign of v^{1G*} is strictly positive, and thus the proposition is proved.

Last, consider the case if region 3 is unaffected by the consumption tax in region 1[11]. Equation (9) then becomes:

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[10] See Appendix A2

[11] This could be the case if there is no trade between regions 1-2 and region 3, or if region 3 is much smaller than regions 1-2, in which case production and consumption changes in regions 1-2 are much bigger than in region 3.

$$v^{1G*} = \frac{s\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right)}{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)}$$

Since consumption of y in region 2 is likely to increase as a result of the consumption tax in region 1 (via lower price of the y good), the numerator is likely smaller than the denominator. Thus, we have $v^{1G*} < s^1$. However, the less consumption in region 2 responds to the reduced consumption in region 1, the higher is v^{1G*}. Moreover, if we return to the case with two regions (or implement the consumption tax in both regions 1 and 2), the optimal consumption tax becomes equal to the OBA subsidy: $v^{1G*} = s^1$. The latter supports the findings from Böhringer et al. (2017c) when a consumption tax is implemented on top of the OBR, in a two regions case.

3. Numerical analysis

Based on the theoretical model, we now transfer our analysis to numerical simulations with a stylized computable general equilibrium (CGE) model based on Böhringer et al. (2017c). Numerical simulations are useful to examine the ambiguous outcomes from our theoretical analysis, while also give more in-depth insights into the proportion of economic effects based on empirical data. We are particularly interested in the case of Norway, which has a joint emission trading system with the European Union (EU ETS), where a variant of output-based allocation is already in place for emission-intensive goods. Our main question here is whether it is welfare-improving for Norway to implement a consumption tax on such goods, when the effects on global emissions are also taken into account.

3.1 Model summary

We assume three regions calibrated according to Norway (NOR), the European Union (EU) and rest of the world (ROW). The three regions have four production sectors: non-carbon and tradable production x, carbon-intensive and tradable production y, carbon-intensive and non-tradable production z, and fossil energy production f. In line with the theoretical analysis, x, y and z can only be used in final consumption. Like in Böhringer et al. (2017c), f can only be used in production (of y and z) and cannot be traded between regions. Hence, we focus on the carbon leakage related to the competitive channel, in accordance with the theoretical analysis. As in the theoretical model, the tradable goods are assumed homogenous with a global price and no transportation cost.

The input factors in production are capital, labor, fossil energy and natural resources. Capital, labor and fossil energy are mobile between sectors but immobile between regions.[12] The resource is only used in fossil energy production, and is also immobile. The input factors are combined by the producers at minimum cost subject to technological constraints. Production of x, y, z is expressed by two level CES cost functions, describing the demand responsiveness for capital, labor and fossil energy input. 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 and the value-added (capital and labor) composite. At the second level, the CES value-added composite consists of substitution between capital and labor[13]. Further, emission is proportional to the use of fossil energy as input for production. Thus, the emission reduction takes place by reducing energy use through either; i) substitution of energy by the value-added composite, or ii) reducing the production output.

Each region's final consumption is determined by a representative agent who maximizes utility subject to a budget constraint. The representative agent's budget constraint is the monetary value of regional endowment of capital, labor and resource. The agent's utility is given as a constant-elasticity-of-substitution (CES) combination of final consumption goods.

3.2 Data and calibration

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

The calibration of the model is based on World input Output Database (WIOD) data (base-year 2009)[14]. We restructure the empirical data to fit the model described in Section 3.1. The WIOD-dataset of the world is based on 43 regions with 56 sectors, linked with corresponding data of CO_2 emission from each sector.[15] We map all the WIOD sectors into four merged sectors x, y, z and f.[16] Further, we stick to the presumption in the theoretical analysis that there are no carbon related

[12] We also simulate the model with capital immobile between sectors, see Section 3.5.
[13] See appendix B for CGE-summary and nesting in different sectors.
[14] The model is implemented as a Mixed Complementarity Problem in GAMS, using the PATH-solver.
[15] CO_2-data for Norway is collected from Statistics Norway (SSB).
[16] See appendix C for mapping of WIOD sectors.

emissions in sector x, and thus set emissions in this sector equal to zero.[17] Production, consumption and CO_2 emissions per sector and region are shown in Table 1.

We observe and quantify net exports in sector x and y in the base-year based on the difference between a region's production and consumption. This balance of payment constraint is incorporated in the numerical simulation model. As mentioned before, we assume no trade for the z sector. The calibrated z sector, however, is a composite of some sectors with limited trade. Thus, 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 on share form with share parameters of consumption set to base-year shares. We mainly consider the effects of assuming heterogeneous goods in the numerical simulations. That is, we follow the heterogeneous goods approach by Armington (1969) and distinguish between domestic and foreign produced goods ("Armington goods"). Like Böhringer et al. (2017c), we use a substitution elasticity of 0.5 between the three goods at the top level in the utility function. At the second level, we incorporate substitution elasticity of 8 between domestic and imported goods x and y, and at the third level we distinguish between the origin of the foreign produced goods with a substitution elasticity of 16. We also present the results with the assumption of homogenous goods, which reflects the theoretical model, while we consider heterogeneous goods to be more realistic. With infinite Armington elasticities, the heterogeneous goods case transforms into the case of homogenous goods.

	Production *(billion $)*	***Consumption*** *(billion $)*	***CO_2*** *(billion ton)*
x^{NOR}	*422*	*448*	-
y^{NOR}	*179*	*111*	*2.39×10^{-2}*
z^{NOR}	*46*	*46*	*2.26×10^{-2}*
x^{EU}	*24 645*	*24 162*	-
y^{EU}	*4 846*	*5 000*	*8.76×10^{-1}*
z^{EU}	*1 952*	*1 952*	*1.76*
x^{ROW}	*60 160*	*60 166*	-
y^{ROW}	*19 301*	*19 214*	*6.32*
z^{ROW}	*5 820*	*5 820*	*11.84*

Table 1: Base-year values from WIOD data and calibrated parameters in the numerical model

[17] In our dataset, sector x accounted for 14-15% of the global CO_2 emissions in 2009.

3.3 Policy scenarios

We consider the calibrated equilibrium in 2009 as a business-as-usual scenario, even though the EU ETS was already in place with an average ETS price of 13 Euro per ton CO_2 in 2009. Norway joined the EU ETS in 2008. Our reference (*REF*) policy scenario is when Norway and the EU together implement a joint emission reduction target for the whole economy, using an economy-wide ETS with either auctioning or unconditional grandfathering. The reduction target is set to 20 percent in the main scenarios.[18] Next, we consider the scenario where producers of the y good receive allowances in proportion to their output, i.e., output-based allocation (*OBA*). We assume that the number of free allowances to y producers is chosen so that the net purchase of allowances for y producers is zero, i.e., $s(y^1 + y^2) = t(e^{y1} + e^{y2})$.[19] Then we consider scenarios where Norway implements a carbon consumption tax on the y good (*OBA+Tax*). As a comparison, we also consider scenarios where Norway and the EU implement such a consumption tax jointly. Whereas both *OBA* and the consumption tax are directed towards the emission-intensive and trade-exposed sector y, sector z will still be competing for the available permits after the additional policies are adopted. In the *OBA+Tax* scenarios we consider different levels of the consumption tax, ranging from 0% to 200% as a fraction of the OBA rate s.

Since global emissions are different across the policy scenarios, we need to put a price on global emission reductions (as in Section 2). For the most part, we will assume that the permit price in the *REF* scenario reflects Norway's valuation of global emission reductions.

To examine the sensitivity of our findings, we present a number of sensitivity analysis in Section 3.5.

3.4 Results

We investigate the effects on key indicators such as leakage rate, welfare, permit price and production. The leakage rate is defined as percentage changes in the non-abating region's (ROW) emission, over emissions reduction in the abating regions (NOR+EU). The welfare change measure is the ratio between BAU and the different policy scenarios, where regional welfare is

[18] Given the existence of the EU ETS in 2009, we can think of this as an additional emission reduction target of 20 percent relative to the base-year emission.

[19] Although allocation in the EU ETS is based on the emission intensities of the best performing 10% of the installations (for a specific product), total allocation to industrial installations in phase 3 (since 2013) has been on average above 90% of total emissions to these industries (according to Refinitiv Carbon Research). For the most exposed industries, the share is likely even higher.

defined as the money-metric utility of consumption minus the valuation of changes in global emissions.[20]

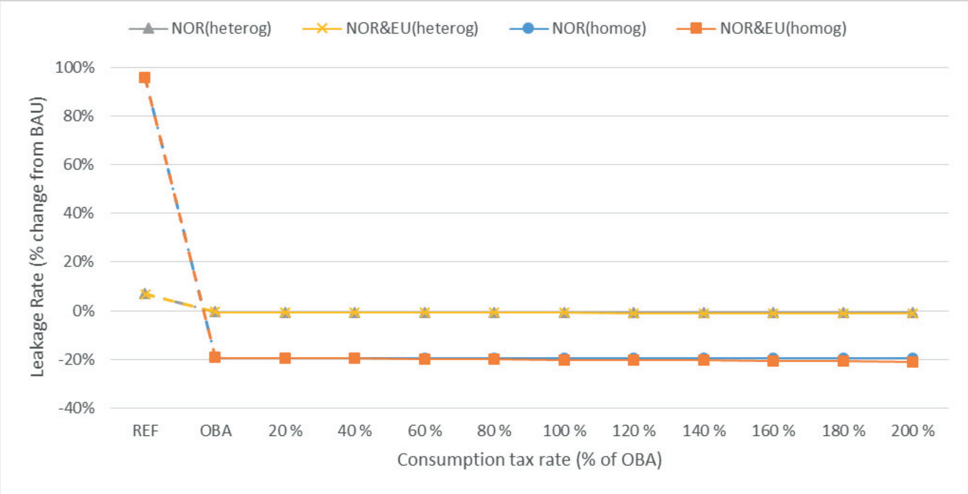

Figure 1: Leakage rate from Norway and EU under different combination of policies, and assumptions of heterogonous (heterog) and homogenous (homog) goods. "NOR" denotes consumption tax only in Norway, while "NOR&EU" denotes joint consumption tax in the two regions. The numbers on the horizontal axis indicate consumption tax rate as a share of the OBA rate.

Figure 1 shows the effects on leakage in the different scenarios. In the *REF* scenario, with only emission pricing, the leakage rate is close to 95% in the homogenous goods case, while merely 8% in the heterogeneous goods case. Since goods are less trade exposed with a lower Armington elasticity, the leakage rate is consequently lower as well. Given no energy trade in our model, leakage only happens through the market for EITE-goods (y) in our analysis. Next, the figure shows that introducing *OBA* has significant impact on leakage, which is fully eliminated. That is, *OBA* provides a perfect leakage mitigation tool in our model. With consumption tax gradually introduced in Norway, the leakage rate continues to decrease, but only slightly as Norway constitutes a small part of the abating regions.[21] However, the consumption tax has a slightly bigger impact on the leakage rate when it is introduced in both regions.

The permit price is $179 or $70 in *REF*, when we assume heterogonous or homogenous goods, respectively. As stated earlier, the *OBA* tends to simulate local production of the y good, while the consumption tax reduces the demand for the same good. This has implications for the permit market in EU and Norway, and hence for the permit price. The permit price increases under *OBA*,

[20] Compared to the welfare expression in (5), the cost functions are excluded and replaced with the endowment and technological constraints as explained above.
[21] Recall that the leakage rate is measured as emission changes in ROW divided by emission reductions in EU+NOR.

as expected: With more output of the y good produced domestically, the permit price must increase in order to clear the permit market. With gradually increasing consumption tax, the permit price decreases due to less production of the y good.

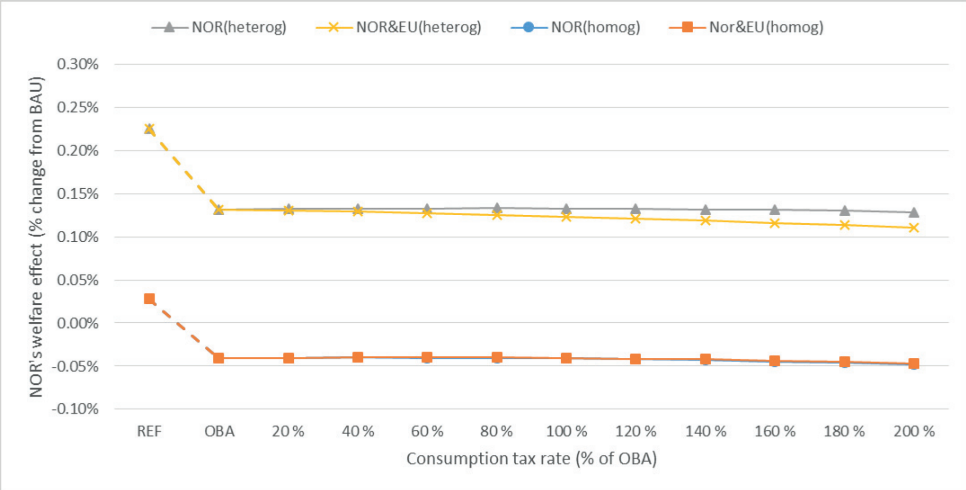

Figure 2: Norway's welfare effect under different combination of policies, and assumptions of heterogonous (heterog) and homogenous (homog) goods. "NOR" denotes consumption tax only in Norway, while "NOR&EU" denotes joint consumption tax in the two regions. The numbers on the horizontal axis indicate consumption tax rate as a share of the OBA rate.

Figure 2 shows the welfare change in Norway under the different policies. The change is displayed as a percentage change compared to the BAU scenario, also taking into account the change in global emissions, where we use the emission price from *REF* to value these changes. We attribute the welfare change related to emission to the region(s) that imposes the policy. Thus, if only Norway implements a consumption tax, the whole emission reduction (vis-à-vis *OBA*) is regarded as a welfare gain for Norway. If both Norway and the EU introduce a joint consumption tax, only a share of the emission benefits is assigned Norway, where the share is determined by Norway's initial emissions relative to that of Norway and the EU in total. As discussed in Section 2, the marginal cost of emissions τ could be different from the permit price t. Thus, a sensitivity analysis is carried out with different marginal cost of emission τ in the following section.

The *OBA* reallocates production from ROW back to the abating regions. Further, global emissions decline under the *OBA* scenario compared to *REF*, meaning less climate damages. However, with *OBA* leading to higher permit price and lower price for good y, the demand for all other goods fall in Norway. The overall results indicate a welfare declining effect of *OBA* in Norway, which is a net exporter of EITE goods. The theoretical analysis in Section 2 suggested ambiguous effects on welfare for a region that implements a consumption tax, if the region is a net exporter of the leakage-exposed good. Our numerical simulation however suggests that the consumption tax is welfare improving in Norway, with an optimal consumption tax in the range of about 80% (40%) of the *OBA*-rate when assuming heterogeneous (homogenous). The welfare impacts are generally small, however. The main drivers for the welfare improvement in Norway seem to be both lower global emissions and correction of the distortive OBA effects (as the terms of trade effects are negative for Norway). When disregarding the welfare effects of lower global emissions, the optimal consumption tax (for Norway) is still positive but somewhat lower (40% vs. 80%). If both abating regions introduce the consumption tax, Norway's welfare is practically unchanged up to a tax level of 20% of the OBA-rate when assuming heterogeneous goods, while the optimal tax for Norway is 60% of the OBA-rate when assuming homogenous goods.

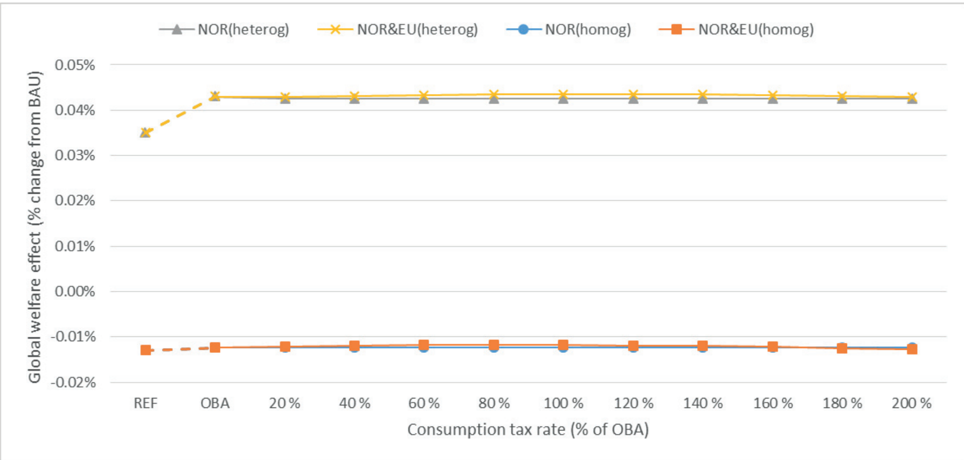

Figure 3: Global welfare effects under different combination of policies, and assumptions of heterogonous (heterog) and homogenous (homog) goods. "NOR" denotes consumption tax only in Norway, while "NOR&EU" denotes joint consumption tax in the two regions. The numbers on the horizontal axis indicate consumption tax rate as a share of the OBA rate.

According to our proposition 2, a consumption tax on top of the *OBA* in Norway, has an unambiguously positive effect from a global welfare perspective. Results illustrated in Figure 3 support this finding, and suggest an optimal consumption tax is in the range of around 120% of the *OBA*-rate when assuming heterogeneous goods. Naturally, the global welfare improvement is much stronger if both abating regions introduce the tax, and again the welfare effects are lower when assuming homogenous goods.

Figure 4 shows the welfare gains for EU and ROW when assuming Armington goods. *EU_* in the legends corresponds to EU's welfare effect, while *ROW_* corresponds to ROW's welfare effect.

Contrary to Norway, the *OBA* results in a welfare improving effect for EU[22]. This supports previous findings in e.g. Böhringer et al. (2017a), when assuming homogenous tradable goods. In the case where the consumption tax is imposed in both the EU and Norway, we notice that the EU benefits from this. In this case, we further see that ROW slightly loses.[23] Hence, the global welfare improvement shown in Figure 3 is partly due to the fact that Norway and the EU gains from terms of trade effects at the expenses of ROW (in addition to the gains from lower emissions). The welfare effect in ROW is also (slightly) negative when a consumption tax is introduced only in Norway. This result supports similar findings in Böhringer et al. (2017c). It is however important to emphasize that overall global welfare effects from the consumption tax are unambiguously positive, and thus in principle at least all regions could be better off if ROW were to be compensated through a monetary transfer.

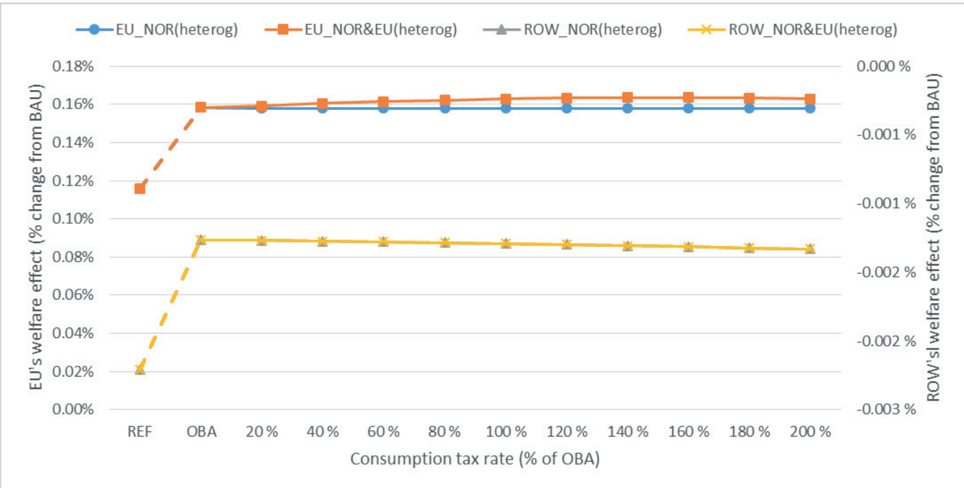

Figure 4: EU's and ROW's welfare effects under different combination of policies and assumption of heterogonous (heterog) goods. "NOR" denotes consumption tax only in Norway, while "NOR&EU" denotes joint consumption tax in the two regions. The numbers on the horizontal axis indicate consumption tax rate as a share of the OBA rate.

The effects on consumption in Norway is shown in Figure 5, under different combinations of policies where the consumption tax is only introduced in Norway. Here we consider the heterogonous goods approach. A carbon price (*REF*) increases the costs for the producers of carbon intensive goods y and z in Europe, and hence the price of these goods, which further reduces the demand for y and z in Norway (and the EU). The consumption of the carbon-free

[22] Recall from table 2, that Norway is net exporter of the emission-intensive and trade-exposed good

[23] We assume that $\tau^{ROW} = 0$ in ROW's welfare function, as there is no climate policy in this region (in our analysis).

good x, which is now relatively cheaper, increases. When *OBA* is introduced for the good y, we have the opposite effect for this good as *OBA* works as an implicit production subsidy to y. Consumption of y and x is higher than the BAU-level under *OBA*. When the consumption tax is introduced on good y, we see that the consumption of y decreases significantly, while consumption of x and z increases. Consumption of z is always below the BAU scenario, however, in our results. The increased consumption of x and z is due to the relative price changes, as well as declining permit price, and improved terms-of-trade effects. More of the y good is now exported from Norway and more is imported of x.

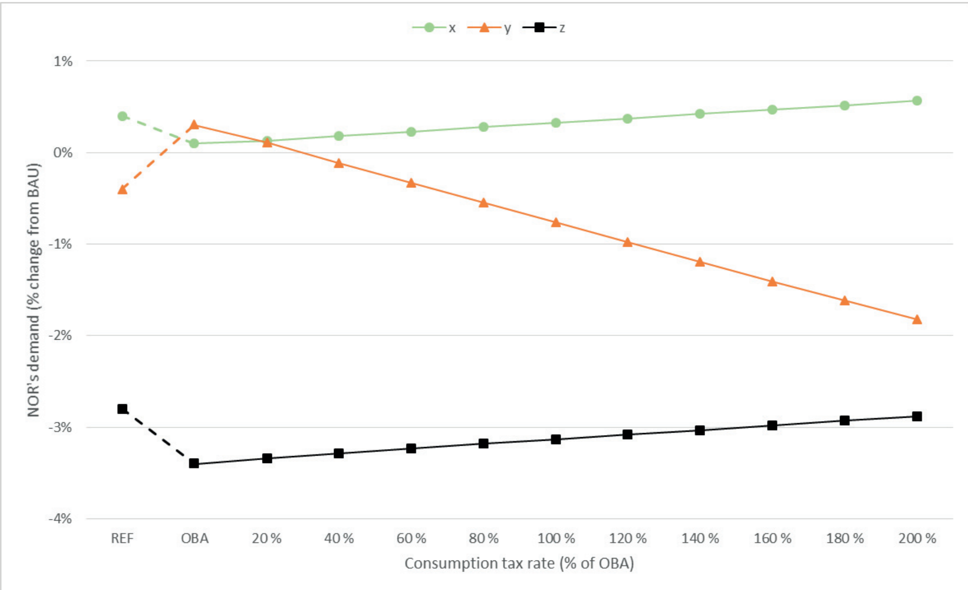

Figure 5: Consumption of the three goods in Norway under different combination of policies, and assumption of heterogonous goods. Consumption tax only imposed in Norway. The numbers on the horizontal axis indicate consumption tax rate as a share of the OBA rate.

3.5 Sensitivity analysis

How robust are our numerical results with respect to changes in our model assumptions? For instance, the theoretical analysis showed that regional welfare effects for the tax-implementing region are ambiguous, while the numerical simulations showed a positive effect for Norway. Furthermore, the simulations confirmed the unambiguous theoretical result that global welfare improves. To check the robustness of the results, we now examine the effects of changing some of our main assumptions: i) the EU tightens its emission cap in line with imposing the consumption tax, ii) the mobility of capital, iii) the optimal *Pigouvian* tax being higher than the emission price in

REF, iv) different Armington and substitution elasticity, v) and a consumption tax introduced in other European countries than Norway.

In the base assumption the overall emission in EU is unchanged after introducing the consumption tax, resulting in a reallocation of emission between EU member states. However, it could be the case that the EU decides to tighten its emission cap in order to avoid the so-called waterbed effect. EU's tightening of the emission cap has been strengthened from 1.7% to 2.2% per year in response to low emission prices. In addition, the Market Stability Reserve has been implemented, probably leading to cancellation of allowances (Perino, 2018). Thus, implementing a consumption tax could possibly lead to similar tightening of the system. One way to address this situation, where the EU does additional emission reductions in line with imposing the consumption tax, is to fix the price of emission (equal to price under OBA). By examining this case, where the consumption tax is introduced in Norway, or Norway and the EU, the results show somewhat higher welfare effect from the consumption tax in both regions compared to the baseline situation. The leakage rate is slightly higher with additional emission reduction in the EU because of unchanged emission price,[24] while global emissions are lower. However, the differences compared to the baseline simulations are only marginal for both welfare and leakage.

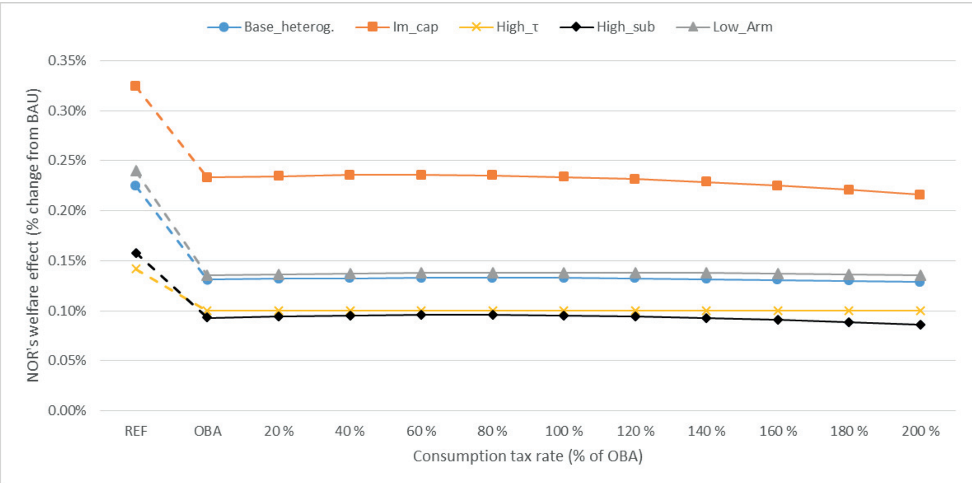

Figure 6*:* Sensitivity analysis of Norway's welfare effects of consumption tax: Baseline simulations (Base_heterog.), immobile capital (Im_cap), higher *Pigouvian* tax (High_τ), higher substitution elasticity (High_sub), and lower Armington elasticity (Low_Arm).

[24] Recall that the emission price falls with introduction of the consumption tax in the base case simulation, also resulting in lower leakage rate.

In most sectors, capital is likely immobile in the short term. Figure 6 shows the welfare effect globally and for Norway with the assumption of immobile capital between sectors but still domestically mobile labor force. With immobile capital, the leakage is less of a concern and hence the welfare changes are more beneficial under all scenarios compared with the benchmark assumption, both for Norway and globally. Further, the optimal consumption tax is around 60% of the *OBA* rate while the optimal consumption tax for global welfare is in the range of about 20% of the *OBA* rate.

In our theoretical analysis, we discussed the possibility of the *Pigouvian* tax being different from the carbon price observed in the *REF* scenario (in the benchmark simulations, we have assumed that the two are equal). In particular, given the low prices in the EU Emission Trading System over the last years, one could argue that the Pigouvian tax is higher than the current CO_2 price. In our baseline simulations, the permit price is rather high, as the emission reduction target is quite ambitious (20%). Figure 6 shows the case if EU's reduction target is set to 10% and the *Pigouvian* tax is at the same level as in the baseline simulation, the benefits of the climate policy would naturally be bigger as global emission reductions would have a greater impact on welfare. Hence for Norway, the optimal consumption tax is somewhat higher than with our benchmark assumption, now in the range of around 100% of the *OBA* rate. For the global welfare effect, the optimal consumption tax is around 120% of the *OBA* rate. The additional welfare gains from the consumption tax in Norway and globally are however about the same as in the benchmark simulations.

With a lower Armington elasticity, we now assume less trade-exposure for producer x and y. In Figure 6 we show how this assumption affects the global and Norway's welfare. The welfare effects under all the different policy scenarios are higher with a lower Armington elasticity. This is mainly a result of leakage now being more limited, and therefore the global benefits of emission reductions are bigger. The numerical simulations still suggest that the consumption tax is welfare improving for Norway. Moreover, the optimal consumption tax is now higher (100% of the *OBA* rate) than in our benchmark simulations with the Armington goods assumption (80% of the *OBA* rate). The global welfare effects are also positive, but still limited with only Norway introducing the consumption tax. The optimal consumption tax for the global welfare is still in the range of 120% of the *OBA* rate. The global welfare effects are in general higher with lower Armington elasticity, and that moving from *REF* to *OBA* has higher global welfare gains.

In our baseline simulations, we assumed a substitution elasticity value of 0.5. With a higher value (of 2) the consumption tends to shift more towards the carbon-free good x in *REF*, and to x and

z with a consumption tax. Hence, Norway's welfare gains of a consumption tax are in general lower compared to our baseline simulations. However, a consumption tax combined with OBA still has a welfare improving effect for Norway and globally. With heterogeneous goods, the optimal consumption tax is in the range of 60% of the OBA rate for Norway (vs. 80% in the baseline simulation), and 100% (vs. 120%) when considering global welfare.

How would a consumption tax introduced in another EU/EEA country than Norway affect both their regional and global welfare? In Figure 7 we list the result under various combination of policies in different EU countries. In the model, we replace the region Norway with an EU country, and include Norway in the EU region. The parameters in the model are calibrated in the same way as described in section 3.2, i.e., according to the specific country's characteristics. The Armington elasticity for the representative agent is set to the same values as in our baseline simulation in section 3.4, and the percent values in the figure is the optimal consumption tax rate for the different countries. The figure shows the same qualitative result as for Norway, when different EU countries introduce the consumption tax. That is, a consumption tax on top of *OBA* increases regional welfare for all countries. The optimal consumption tax is in the range of 80%-200%, with Bulgaria, Estonia and Lithuania having the highest rate. Because of their small economic size and the countries being net exporter of the carbon free good x, their welfare gain is substantial compared to BAU. Global welfare increases too in all these cases when a regional consumption tax is implemented. The magnitude differs depending on the policy introducing country's specific characteristics, such as the size of the economy and of the sectors. In line with our finding from section 3.4, the positive effect on welfare from the consumption tax is mainly due to its effects on emissions and terms of trade, and correction of the distortive OBA effects.

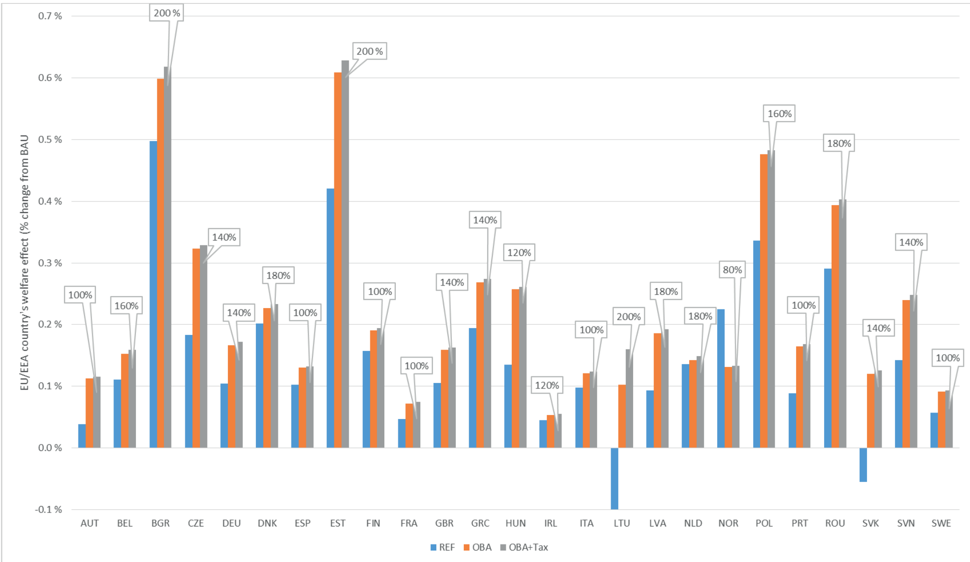

Figure 7: Regional welfare effects under different combination of policies in EU/EEA countries. Percentage changes vis-à-vis BAU. The numbers indicate optimal consumption tax rate for each country (as a share of the OBA rate).

4. Concluding remarks

As the world will still rely on unilateral action after the Paris climate agreement, many countries are considering or have introduced climate policies such as emission trading systems. Greenhouse gases however are global pollutants and unilateral action leads to carbon leakage when there is no global cap on emissions. In this paper we have focused on leakage associated with the relocation of emission-intensive and trade-exposed (EITE) industries. The economics literature have suggested different approaches to mitigate this type of carbon leakage, where border carbon adjustment in addition to emission pricing has been regarded as a second-best instrument to improve cost-effectiveness of unilateral climate policy. This instrument may not however be politically feasible, so countries and regions have either excluded such industries from their regulations or found other anti-leakage solutions, such as output-based allocation (OBA) to EITE-industries, which has been implemented e.g. in the EU ETS.

However, as OBA acts as an implicit production subsidy to domestic production, this results in too high consumption and production worldwide. Hence, an approach where OBA is combined with a consumption tax on all use of the EITE goods has been proposed by e.g. Böhringer et al. (2017c). In the current paper we have examined whether a single country, being part of a bigger ETS involving many countries where OBA to EITE-industries is already in place, should unilaterally implement such a consumption tax.

We first showed analytically that under certain conditions it is welfare improving for the single country to introduce the consumption tax, when we account for the benefits of reduced global emissions. Moreover, the consumption tax has an unambiguous global welfare improving effect. Next, we confirmed these results with a stylized numerical model calibrated to real world data, where we considered the context of the EU ETS. Individual EU/EEA members were consistently better off in welfare terms if implementing such a consumption tax.

If the tax is set equal to the output-based allocation factors ("benchmarks"), the administrative cost of adding such a consumption tax will likely be limited (Neuhoff et al., 2016a; Ismer and Haussner, 2016). Böhringer et al. (2017c) shows that the outcome of this combined policy will be equivalent to a certain variant of border carbon adjustments. However, a more differentiated variant of carbon tariffs could still be more targeted than a consumption tax, especially if the tariff is able to differentiate between firms according to their emission intensity (Böhringer et al. 2017b). First of all, it would redirect imports (and consumption) towards the least emission-intensive countries or producers, as these are less hit by the tariff. In addition, if the tariffs are firm-specific they might give these firms incentives to reduce their emission intensity. Still, the question remains about the compatibility with WTO rules. Thus, in the meantime combining output-based allocation with a consumption tax seems like a powerful and acceptable policy strategy to mitigate carbon leakage, also for individual countries involved in a more extensive emission trading system.

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Appendix A, Derivations

A1: Region welfare maximization

By differentiating the regional welfare (5) with respect to consumptions tax, we get

$$\frac{\partial W^1}{\partial v^1} = u_x^1\frac{\partial \bar{x}^1}{\partial v^1} + u_y^1\frac{\partial \bar{y}^1}{\partial v^1} + u_z^1\frac{\partial \bar{z}^1}{\partial v^1} - c_x^{x1}\frac{\partial x^1}{\partial v^1} - c_y^{y1}\frac{\partial y^1}{\partial v^1} - c_z^{z1}\frac{\partial z^1}{\partial v^1} - c_e^{y1}\frac{\partial e^{y1}}{\partial v^1} - c_e^{z1}\frac{\partial e^{z1}}{\partial v^1} - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall the conditions and assumptions from (2) and (3), and we then get

$$= p^x\frac{\partial \bar{x}^1}{\partial v^1} + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\frac{\partial \bar{z}^1}{\partial v^1} - p^x\frac{\partial x^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} - p^{z1}\frac{\partial z^1}{\partial v^1} + t^1\frac{\partial e^{y1}}{\partial v^1} + t^1\frac{\partial e^{z1}}{\partial v^1} - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

We further simplify the equation

$$= p^x\frac{\partial \bar{x}^1}{\partial v^1} - p^x\frac{\partial x^1}{\partial v^1} + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\frac{\partial \bar{z}^1}{\partial v^1} - p^{z1}\frac{\partial z^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} + p^{z1}\left(\frac{\partial \bar{z}^1}{\partial v^1} - \frac{\partial z^1}{\partial v^1}\right) - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Since there is no trade of the good z, i.e. $\left(\frac{\partial \bar{z}^1}{\partial v^1} = \frac{\partial z^1}{\partial v^1}\right)$:

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$
$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall (4), further we differentiate (4) w.r.t. consumption tax, remembering the product rule:

$$\frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + p^x\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right) = 0$$

solving this for p^x

$$p^x = \frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)}$$

we insert this into our equation for p^x

$$\frac{\partial W^1}{\partial v^1} = \left[\frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)}\right]\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1}$$
$$- (p^y + s^1)\frac{\partial y^1}{\partial v^1} + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$
$$- \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

and since

$$-\frac{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial x^1}{\partial v^1} - \frac{\partial \bar{x}^1}{\partial v^1}\right)} = \frac{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1}\right)} = 1$$

We can further simplify:

$$= p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + (p^y + v^1)\frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1)\frac{\partial y^1}{\partial v^1}$$
$$+ t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

$$= p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial \bar{y}^1}{\partial v^1} - \frac{\partial y^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + v^1\frac{\partial \bar{y}^1}{\partial v^1} - s^1\frac{\partial y^1}{\partial v^1}$$
$$+ t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall the constraint on emission in region 1 and 2, $\bar{E} = e^{y1} + e^{y2} + e^{z1} + e^{z2}$. By differentiating this w.r.t the consumption tax, we have that:

$$\frac{\partial \bar{E}}{\partial v^1} = \frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} = 0$$

By this assumption, our equation can now be expressed as:

$$= p^y\left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial \bar{y}^1}{\partial v^1} - \frac{\partial y^1}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + v^1\frac{\partial \bar{y}^1}{\partial v^1} - s^1\frac{\partial y^1}{\partial v^1}$$
$$+ t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

and simplified to

$$= v^1\frac{\partial \bar{y}^1}{\partial v^1} - s^1\frac{\partial y^1}{\partial v^1} + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + t^1\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) - \tau\left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right]$$

And we finally arrive at (6), by moving v^1 on the other side of the equal sign

$$v^{1*} = \left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}\left[s^1\frac{\partial y^1}{\partial v^1} - \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + (-t^1)\left(\frac{\partial e^{y1}}{\partial y^1}\frac{\partial y^1}{\partial v^1} + \frac{\partial e^{z1}}{\partial z^1}\frac{\partial z^1}{\partial v^1}\right) + \tau\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)\right] \quad (6)$$

A2: Global Welfare Maximization

By differentiating the global welfare w.r.t consumption tax in region 1, we get

$$\frac{\partial W^G}{\partial v^1} = \sum_{j=1,2,3} \left[u_x^j \frac{\partial \bar{x}^j}{\partial v^1} + u_y^j \frac{\partial \bar{y}^j}{\partial v^1} + u_z^j \frac{\partial \bar{z}^j}{\partial v^1} - c_x^{xj} \frac{\partial x^j}{\partial v^1} - c_y^{yj} \frac{\partial y^j}{\partial v^1} - c_z^{zj} \frac{\partial z^j}{\partial v^1} \right.$$

$$\left. - \left(\tau + c_e^{yj}\right) \frac{\partial e^{yj}}{\partial v^1} - \left(\tau + c_e^{zj}\right) \frac{\partial e^{zj}}{\partial v^1} \right]$$

From our assumption in (2), (3), (5) and (6) we get

$$\frac{\partial W^G}{\partial v^1} = \sum_{j=1,2,3} \left[p^x \frac{\partial \bar{x}^j}{\partial v^1} + \left(p^y + v^j\right) \frac{\partial \bar{y}^j}{\partial v^1} + p^{zj} \frac{\partial \bar{z}^j}{\partial v^1} - p^x \frac{\partial x^j}{\partial v^1} - \left(p^y + s^j\right) \frac{\partial y^j}{\partial v^1} - p^{zj} \frac{\partial z^j}{\partial v^1} \right]$$

$$- \left(\tau + c_e^{y1}\right) \frac{\partial e^{y1}}{\partial v^1} - \left(\tau + c_e^{z1}\right) \frac{\partial e^{z1}}{\partial v^1} - \left(\tau + c_e^{y2}\right) \frac{\partial e^{y2}}{\partial v^1} - \left(\tau + c_e^{z2}\right) \frac{\partial e^{z2}}{\partial v^1}$$

$$- \left(\tau + c_e^{y3}\right) \frac{\partial e^{y3}}{\partial v^1} - \left(\tau + c_e^{z3}\right) \frac{\partial e^{z3}}{\partial v^1}$$

$$= \sum_{j=1,2,3} \left[p^x \frac{\partial \bar{x}^j}{\partial v^1} - p^x \frac{\partial x^j}{\partial v^1} + \left(p^y + v^j\right) \frac{\partial \bar{y}^j}{\partial v^1} - \left(p^y + s^j\right) \frac{\partial y^j}{\partial v^1} + p^{zj} \frac{\partial \bar{z}^j}{\partial v^1} - p^{zj} \frac{\partial z^j}{\partial v^1} \right]$$

$$- \left(\tau - t^1\right) \frac{\partial e^{y1}}{\partial v^1} - \left(\tau - t^1\right) \frac{\partial e^{z1}}{\partial v^1} - \left(\tau - t^2\right) \frac{\partial e^{y2}}{\partial v^1} - \left(\tau - t^2\right) \frac{\partial e^{z2}}{\partial v^1} - \left(\tau + c_e^{y3}\right) \frac{\partial e^{y3}}{\partial v^1}$$

$$- \left(\tau + c_e^{z3}\right) \frac{\partial e^{z3}}{\partial v^1}$$

Since good z is non-tradable, the production in region j is equal to consumption in the same region. Also recall that $c_e^{y3} = c_e^{z3} = 0$ and $t^1 = t^2$

$$= \sum_{j=1,2,3} \left[p^x \left(\frac{\partial \bar{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1} \right) + \left(p^y + v^j\right) \frac{\partial \bar{y}^j}{\partial v^1} + p^{zj} \left(\frac{\partial \bar{z}^j}{\partial v^1} - \frac{\partial z^j}{\partial v^1} \right) - \left(p^y + s^j\right) \frac{\partial y^j}{\partial v^1} \right]$$

$$+ \left(t^1 - \tau\right) \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right) + \left(t^1 - \tau\right) \left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} \right) - \tau \left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right)$$

Again, we use our assumptions from (4), differentiate w.r.t consumption tax and solve it for p^x (*remembering the product rule*):

$$\frac{\partial p^y}{\partial v^1} \left(y^j - \bar{y}^j\right) + p^y \left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1} \right) + \frac{\partial p^x}{\partial v^1} \left(x^j - \bar{x}^j\right) + p^x \left(\frac{\partial x^j}{\partial v^1} - \frac{\partial \bar{x}^j}{\partial v^1} \right) = 0$$

$$p^x = \frac{\left(p^y\left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}\left(y^j - \bar{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \bar{x}^j\right)\right)}{-\left(\frac{\partial x^j}{\partial v^1} - \frac{\partial \bar{x}^j}{\partial v^1}\right)}$$

Insert this for p^x into our equation:

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

$$\left. + p^{zj}\left(\frac{\partial \bar{z}^j}{\partial v^1} - \frac{\partial z^j}{\partial v^1}\right) - \left(p^y + s^j\right)\frac{\partial y^j}{\partial v^1}\right] + (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

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

Since

$$\frac{\left(\frac{\partial \bar{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1}\right)}{\left(\frac{\partial \bar{x}^j}{\partial v^1} - \frac{\partial x^j}{\partial v^1}\right)} = 1$$

The equation can be simplified to

$$= \sum_{j=1,2,3}\left[p^y\left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}\left(y^j - \bar{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \bar{x}^j\right) + \left(p^y + v^j\right)\frac{\partial \bar{y}^j}{\partial v^1} - \left(p^y + s^j\right)\frac{\partial y^j}{\partial v^1}\right]$$

$$+ (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) + (t^1 - \tau)\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1}\right) - \tau\left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right)$$

$$= \sum_{j=1,2,3}\left[p^y\left(\frac{\partial y^j}{\partial v^1} - \frac{\partial \bar{y}^j}{\partial v^1} + \frac{\partial \bar{y}^j}{\partial v^1} - \frac{\partial y^j}{\partial v^1}\right) + \frac{\partial p^y}{\partial v^1}\left(y^j - \bar{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \bar{x}^j\right) + v^j\frac{\partial \bar{y}^j}{\partial v^1} - s^j\frac{\partial y^j}{\partial v^1}\right]$$

$$+ (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) + (t^1 - \tau)\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1}\right) - \tau\left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right)$$

$$= \sum_{j=1,2,3} \left[v^j \frac{\partial \bar{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} + \frac{\partial p^y}{\partial v^1}\left(y^j - \bar{y}^j\right) + \frac{\partial p^x}{\partial v^1}\left(x^j - \bar{x}^j\right) \right] + (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right)$$

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

Recall our assumption from (1):

$$\bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3$$

$$\bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3$$

And we can rewrite our equation to

$$= \sum_{j=1,2,3} \left[v^j \frac{\partial \bar{y}^j}{\partial v^1} - s^j \frac{\partial y^j}{\partial v^1} \right] + (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) + (t^2 - \tau)\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1}\right)$$

$$- \tau\left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right)$$

Since the consumption tax is only introduced in region 1, and OBA in region 1 and 2, we can re-write to:

$$= \left(v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} - s^2 \frac{\partial y^2}{\partial v^1} \right) + (t^1 - \tau)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1}\right) + (t^1 - \tau)\left(\frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1}\right)$$

$$- \tau\left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right)$$

From (2) $s^1 = s^2$ and $t^1 = t^2$

$$v^{1G*} = \left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1} \left[s^1\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right) + (\tau - t^1)\left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1}\right) + \tau\left(\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1}\right) \right]$$

Remembering our emission constraint $\frac{\partial \bar{E}}{\partial v^1} = \frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} = 0$, and we finally arrive at (9)

$$v^{1G*} = \left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1} \left[s^1\left(\frac{\partial y^1}{\partial v^1} + \frac{\partial y^2}{\partial v^1}\right) + \tau\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right) \right] \tag{10}$$

Appendix B: Summary of the numerical CGE model

Indices and sets:

Set of regions	R	NOR, EU, ROW
Set of goods	g	x, y ,z
r (alias j)		Index for regions

Variables:

S^{gr}	Production of good g in r
S^{r}_{FE}	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
$p^{g,r}$	Price of g in r
p^{r}_{FE}	Price of Primary fossil FE in r
p^{gr}_{KL}	Price of value added for g in r
p^{r}_{KLF}	Price of value added for FE in r
p^{r}_{L}	Price of labor (wage rate) in r
p^{r}_{K}	Price of capital (rental rate) in r
p^{r}_{Q}	Rent for primary energy resource in r
p^{gr}_{A}	Price of Armington aggregate of g in r
p^{gr}_{IM}	Price of aggregate imports of g in r
p^{r}_{CO2}	Price of CO2 emission in r
p^{r}_{W}	Price of consumption composite in r
o^{gr}	Output-Based Allocation on g in r
v^{gr}	Consumption tax on g in r

Parameters:

σ^{r}_{KLE}	Substitution between value-added and energy 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_{Q}^{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

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
Q_{0}^{r}	Resource endowment of primary fossil energy in region r
$CO2_{MAX}^{r}$	CO_2 emission allowance in region r
κ_{CO2}^{r}	Coefficient for primary fossil energy of CO_2 emission in region r

Zero Profit Conditions

Production of goods except for fossil primary energy:

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

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

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

Production of fossil primary energy:

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

Sector specific value-added aggregate for *FE*:

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

Armington aggregate except for *FE*:

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

Import Composite except for *FE*:

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

Consumption composite:

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

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:

$$Q_{0}^{r} \geq S_{FE}^{r} \frac{\partial \pi_{FE}^{r}}{\partial p_{Q}^{r}} \qquad \perp p_{Q}{}^{r}$$

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:

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

CO_2 Emission in region:

$$CO2_{MAX}^r \geq \kappa_{CO2}^r S_{FE}^r \qquad \perp p_{CO2}^r$$

Consumption by consumers

$$p_W^r W^r \geq p_L^r \left(\sum_g L_0^{gr} + L_{0,FE}^r \right) + p_K^r \left(\sum_g K_0^{gr} + K_{0,FE}^r \right) + p_Q{}^r Q_0^r + p_{CO2}^r CO2_{MAX}^r - S^{gr} o^{gr} + D^{gr} v^{gr}$$
$$\perp p_W^r$$

Elasticities: $\sigma_{KLE} = 0.5 \quad \sigma_{KL} = 1$

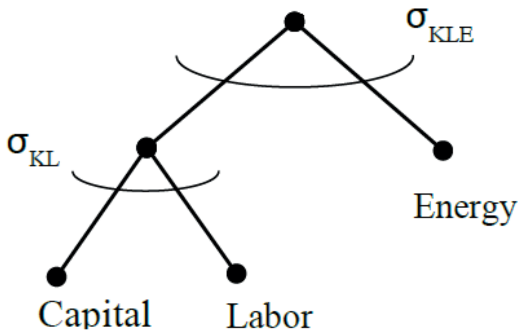


Figure B1: Nesting in production, except for fossil fuel energy

Elasticities: $\sigma_Q = 0.9 \qquad \sigma_{KL} = 1$

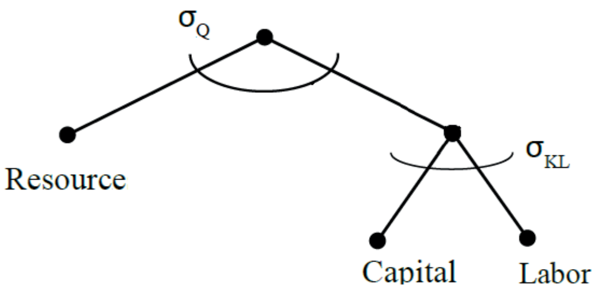
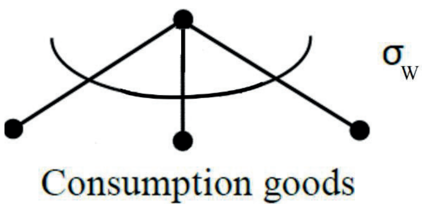


Figure B2: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$



Appendix C: 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
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.

Paper 3

Optimal Climate Policy in the Presence of Another Region's Climate Policy

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Abstract:

The allowances in an emission trading system (ETS) are commonly allocated for free to the emission-intensive and trade-exposed sector, e.g., in the form of output-based allocation (OBA). Recently an approach combining OBA with a consumption tax has been proposed to mitigate carbon leakage. This paper evaluates the potential outcome of climate policies, by examining the Nash equilibrium of a non-cooperative policy instrument game between regions who regulate their emissions separately. In particular, we investigate the case when regions can choose to supplement their ETS with OBA and/or a consumption tax, in the presence of another regulating region. The analytical results suggest that under specific conditions the optimal rate of OBA is increased and the optimal rate of consumption tax is reduced, in the presence of OBA and/or a consumption tax in another region. The numerical simulations in the context of the EU and China suggests that a combination of OBA and consumption tax is welfare improving for the regions.

Key words: Emission price; Output-based allocation; Consumption tax; Carbon leakage; Emission trading system; Unilateral policy

JEL classification: C70, D61, F18, H23, Q54

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1. Introduction

In the aftermath of the 2015 Paris climate agreement, most countries' nationally determined contributions (NDCs) includes a plan for establishing a market-based mechanism, or carbon trading system, in order to tackle climate change (Andresen et al., 2016). The policymakers in these countries however are well aware that unilateral action leads to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE). The affected industries in these countries claim that the emission restrictions raise their production costs, resulting in a competitive disadvantage on the world market. Thus, the regulating countries achieve lower emissions level locally but risks losing jobs and industry to the unregulated countries, as well as higher foreign GHG emissions (Taylor, 2005).[1] Most studies suggest a carbon leakage in the range of 5-30% (Böhringer et al., 2012; Zhang, 2012), with a somewhat higher rate for the EITE industry (Fischer & Fox, 2012).[2]

Since countries' national self-interest is a guiding principle for their NDC, policymakers have either excluded the EITE sector from regulation or found other anti-leakage solutions. In the EU emission trading system (ETS) for instance, the sectors that are significantly exposed to carbon leakage are given a large number of free allowances.[3] Similarly, the allowances for the EITE sector in China's ETS will also be allocated for free (Xiong et al., 2017). The allocation is typically based on benchmarks or requirements such as production output (Neuhoff et al., 2016b), and free allowance allocation based on output is often referred to as output-based allocation (OBA) (Böhringer & Lange, 2005). While most studies find that OBA would mitigate carbon leakage, it ends up stimulating too much production and consumption of the EITE goods. The reason is that OBA works as an implicit production subsidy, and as a consequence the incentives to substitute to less carbon-intensive products are weakened. Moreover, with uncertainty about leakage exposure for the sectors, policymakers may also overcompensate the sector with free allowances.[4]

Recently a third approach has been proposed. Particularly, Böhringer et al. (2017b) shows that it is welfare improving for a country, which has already implemented a carbon tax along with output-based rebating (OBR) to EITE goods, to introduce a consumption tax on top of the same EITE goods. Kaushal and Rosendahl (2017) also shows that it is welfare improving under specific

[1] The leakage mainly occurs through either: i) the fossil fuel markets, or ii) markets for EITE goods. This paper focuses on leakage in the latter case.
[2] Other important contribution to the theoretical literature on leakage are Markussen (1975), Hoel (1996) and Copeland (1996).
[3] In phase 3 (2013-2020) the commission estimates that 43% of the total allowances will be handed out to industrial installations exposed to a significant risk of carbon leakage (EU, 2017)
[4] E.g. Sato et al. (2015) finds that "vulnerable sectors account for small shares of emission", and Martin et al. (2014) finds that the current allocation overcompensates for a given carbon leakage risk.

circumstances for a single region to introduce a consumption tax on EITE goods, when the OBA is already implemented jointly in two regulating regions for the same EITE goods. Both Böhringer et al. (2017b), and Kaushal and Rosendahl (2017) find that the consumption tax has an unambiguously global welfare improving effect. Whereas some instruments may not be politically feasible,[5] a consumption tax may not face the same challenge (Ismer & Haussner, 2016; Neuhoff et al., 2016a; Neuhoff et al., 2016b).

Neither Böhringer et al. (2018) or Kaushal and Rosendahl (2017) examines how OBA or consumption in one region may or should react to OBA and/or consumption tax in another region. In terms of strategic policy and trade, there is a large body of literature. Brander and Spencer (1985) finds that when firms compete in quantities (Stackelberg competition), the optimal policy tends to be a subsidy to the home firm. Eaton and Grossman (1986) finds that the optimal policy tends to be a tax if the firms are price-setters (Betrand situation). In terms of environmental policy, the question has been to what extent a government should consider polices that best serves a nation's export industry (Copeland & Taylor, 2004; Greaker, 2003). Barrett (1994) finds support for the outcomes by Brander and Spencer (1985) and Eaton and Grossman (1986), but also shows that the policy implications are sensitive to assumptions about entry and market structure (Barrett, 1994; Copeland & Taylor, 2004).

This paper contributes to the extensive literature on strategic behavior related to climate policies and carbon leakage, and builds on the theoretical model and findings in Kaushal and Rosendahl (2017). Unlike the papers by Brander and Spencer (1985), Eaton and Grossman (1986), and (Barrett, 1994), this paper considers free competition on the world market and a fixed emission target for the regulating regions. The paper also look at a broader range of policies, and use a model with three different goods and three regions. Unlike the papers mentioned above, and Kaushal and Rosendahl (2017) who considers two regulating regions that have a joint emission trading system with OBA to the EITE-goods, this paper examines the Nash equilibrium of a simultaneous non-cooperative policy instrument game between regions who regulate their emissions trading systems separately. Particularly, we present a game of policy instruments with the optimal choice of climate policy for a region, based on the climate policy choice by another region. We look at the case where both of the regions can choose to supplement their emission trading system with either OBA alone or OBA combined with consumption tax. The approach is

[5] Another suggested second-best policy instrument for anti-leakage is Border Carbon Adjustments (BCAs), with charges on embedded carbon imports and refunds on export. BCA may outperform OBA with reducing carbon leakage (Böhringer et al., 2017a; Fischer & Fox, 2012; Monjon & Quirion, 2011), but experts do not agree on whether or not it is compatible with WTO rules (Horn & Mavroidis, 2011; Ismer & Haussner, 2016; Tamiotti, 2011)

motivated by the current situation, in which there are many separated carbon emission trading systems globally. For instance, the EU/EEA countries have an emission trading system, while the Chinese emission trading system is set to launch soon (Xiong et al., 2017)[6]. One region's policy choice would affect the other, and both regions consider to supplement their respectively ETS with anti-leakage measures. Thus, the policymakers may face a trade-off between securing support by national interest groups and maximizing welfare (Habla & Winkler, 2013), while still maintaining the national climate target.

We investigate with an analytic analysis the optimal response to another region's climate policy. Particularly, we show that under specific conditions the optimal OBA (consumption tax) in one region of increasing OBA or consumption tax in another region to be increased (reduced). Next, we supplement the analytical findings with a stylized numerical simulation model calibrated to data for the world economy. Mainly, we are interested in the non-cooperative game of policy instruments between EU ETS and the Chinese ETS, as both markets are considering a variant of OBA for the emission-intensive goods in their upcoming phases. We investigate the choice of climate policy in both regions based on different indicators. In the context of maximizing regional welfare, the Nash equilibrium outcome is when both regions introduce a specific combination of OBA and consumption tax on the EITE goods. The combination is also the dominant strategy for both regions.

While our analytical model is based on Kaushal and Rosendahl, there are some important differences. First, we numerically examine the case for three different regions, where two of the regions have an emission trading system. Second, while Kaushal and Rosendahl consider OBA and some shares of consumption tax based on OBA, this paper considers more policy combinations with different allocation factors for both OBA and consumption tax. Finally, this paper focuses on the non-cooperative policy instrument game of optimal climate policy for two regulating regions with separate emission trading systems, whereas Kaushal and Rosendahl look at two regions that are involved in a joint emission trading system and only one of them considers imposing a consumption tax.

We introduce a theoretical model in section 2, and analyze the effect of optimal OBA and consumption tax in the presence of a climate policy in another region. In section 3, we transfer the analysis to a non-cooperative policy instrument game, with a stylized CGE model. The

[6] Together, the EU ETS and the Chinese ETS will be the world's largest emissions trading systems in terms of regulated emissions (Böhringer et al. 2018)

numerical 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

The model builds on the framework in Böhringer et al. (2017b) and Kaushal and Rosendahl (2017). However, we also include a broader range of policy combinations across regions, and extend the model to examine the optimal OBA and consumption tax between two regions.

Consider 3 regions, $j = \{1,2,3\}$, and three goods x, y, and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE) (e.g. chemicals, metal and other minerals), and z is emission-intensive and non-tradable (e.g. electricity and transport). While produced in different regions, the same types of goods are assumed homogenous with no trade cost (for x and y). Relocating production of the y good may occur due to trade exposure, and thus OBA is considered for this sector. The market price for the goods in region j are denoted p^{xj}, p^{yj} and p^{zj}. The representative consumer's utility in region j is given by $u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j)$, where the bar indicates consumption of the three goods. The utility function follows the normal assumptions.[7]

We denote the production of good x in region j as $x^j = x^{1j} + x^{2j} + x^{3j}$, where x^{ij} is produced goods in region j and sold in region i, and similarly for the y good. The production cost of goods in region j is given by $c^{xj}(x^j)$, $c^{yj}(y^j, e^{yj})$ and $c^{zj}(z^j, e^{zj})$, where e^{yj} and e^{zj} is the emission from good y and z in the region j. The cost is assumed increasing in production, i.e., c_x^{xj}, c_y^{yj}, $c_z^{zj} > 0$ (where $\frac{\partial c^{xj}}{\partial x^j} \equiv c_x^{xj}$ etc.). Further, the cost of producing good y and z is decreasing in emissions, i.e., c_e^{yj}, $c_e^{zj} \leq 0$ with strict inequality when emission is regulated, and the cost is twice differentiable and strictly convex. All derivatives are assumed to be finite. Finally, supply and demand gives the following market equilibrium conditions:

$$\begin{gathered} \bar{x}^1 + \bar{x}^2 + \bar{x}^3 = x^1 + x^2 + x^3 \\ \bar{y}^1 + \bar{y}^2 + \bar{y}^3 = y^1 + y^2 + y^3 \\ \bar{z}^j = z^j. \end{gathered} \tag{1}$$

[7] Twice differentiable, increasing and strictly concave, i.e., the Hessian matrix is negative definite and we have a local maximum.

2.1. Climate policies

We assume that regions $j = 1, 2$ have already implemented a cap-and-trade system, regulating emissions from production of the goods y and z:

$$\bar{E}^j = e^{yj} + e^{zj},$$

where $\bar{E}^j$ is the binding cap on total emission in region j. The emission price t^j is determined through the emission trading market. The two regions can choose whether to implement OBA or not to producers of the EITE good y, in order to mitigate carbon leakage to region 3, i.e., there is no climate policy in region 3. With OBA the producers of the good y receives free allowances in proportion to their output, which we denote s^j to production of good y in regions $j = 1{,}2$. The region determines s^j with the share α^j, such that $s^j = \alpha^j t^j \left({e^{yj}}/{y^j} \right)$, where the number of free allowances to producers of the y good equals the total emissions from this sector times the subsidy share. With α^j=1, we have the special case of 100% allocation of free allowances to this sector. Since good z is not trade-exposed, there is no OBA to producers of this good.

Regions 1 and 2 can also choose to combine OBA with a consumption tax v^j on consumption of the y good, $\bar{y}^j$. The regions determines v^j as a fraction of OBA rate s^j, i.e., $v^j = \gamma^j s^j$, where γ^j is the fraction of OBA rate in region j.

The competitive producers in region j=1,2,3 maximize profits π^j:[8]

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

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

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

We have $t^3 = s^3 = 0$, since region 3 does not undertake any environmental policy. Assuming interior solution, we have the following first order conditions:

$$\begin{gathered} p^{x1} = p^{x2} = p^{x3} = c_x^{x1} = c_x^{x2} = c_x^{x3} \\ p^{y1} + s^1 = p^{y2} + s^1 = p^{y3} + s^1 = c_y^{y1} \end{gathered} \tag{2}$$

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

$$p^{y1} + s^2 = p^{y2} + s^2 = p^{y3} + s^2 = c_y^{y2}$$
$$p^{y3} = c_y^{y3}$$
$$p^{zj} = c_z^{zj}$$
$$c_e^{y1} = c_e^{z1} = -t^1 \quad ; \quad c_e^{y2} = c_e^{z2} = -t^2 \quad ; \quad c_e^{y3} = c_e^{z3} = 0.$$

With both tradable goods x and y being homogenous with no cost of trade, the interior solution requires a global price for each of the goods, such that:

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

The representative consumer in region j maximizes utility given consumption prices and an exogenous budget restriction M^j:

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

We get the following first-order conditions when differentiating the *Lagrangian* function:

$$\frac{\partial \mathcal{L}}{\partial \bar{x}^j} = u_{\bar{x}}^j - p^x = 0, \ \frac{\partial \mathcal{L}}{\partial \bar{y}^j} = u_{\bar{y}}^j - (p^y + v^j) = 0, \ \frac{\partial \mathcal{L}}{\partial \bar{z}^j} = u_{\bar{z}}^j - p^{zj} = 0, \qquad (3)$$

assuming an interior solution, and normalized the utility functions so that $\lambda^j = 1$.

The regions have a balance-of-payment constraint, i.e., the import expenditures from other regions must equal export revenues. Assuming one global price for each of the tradable goods, we have from (2) that

$$p^y(y^j - \bar{y}^j) + p^x(x^j - \bar{x}^j) = 0. \qquad (4)$$

2.2. Second-best OBA policy and consumption tax in region 1

To better understand how the sensitivity of optimal OBA and consumption tax in region 1 is affected in the presence of region 2's climate policy, we first present the optimal rate of OBA and consumption tax in region 1 when policies are kept fixed in the other regions. The analyses and results in this section are well-known and discussed by for instance Böhringer et al. (2017a), and Kaushal and Rosendahl (2017).[9]

We assess the different combinations of climate policies in the two regions, by specifying the welfare function in region j as:

[9] Also see appendix A for derivation

$$W^j = u^j(\bar{x}^j, \bar{y}^j, \bar{z}^j) - c^{xj}(x^j) - c^{yj}(y^j, e^{yj}) - c^{zj}(z^j, e^{zj}) - \tau^j(e^{y1} + e^{y2} + e^{y3} + e^{z1} + e^{z2} + e^{z3}), \quad (5)$$

where τ^j is the valuation in region j of reduced global emissions, i.e., the *Pigouvian* tax.[10]

Hence, the Pigouvian tax can be different from the permit price t^j. The welfare function consists of a utility of consumption; costs of production; and costs of emissions. Given that an emission trading system has already been implemented for regions 1 and 2, we want first to derive the optimal level of OBA in region 1.

We differentiate (5) with respect to s^1, subject to (4), and assume that all other policy instruments are kept fixed. The expression for the optimal level of OBA subsidy s^{1*} in region 1, is then:

$$s^{1*} = \underbrace{\left(\frac{\partial y^1}{\partial s^1}\right)}_{(a)}^{-1} \left[\underbrace{-\tau^1 \left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial s^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial s^1}\right)}_{(b)} + \underbrace{\frac{\partial p^y}{\partial s^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial s^1}(x^1 - \bar{x}^1)}_{(c)} \right]. \quad (6)$$

The first term (a) is positive as an introduction of s^1 will implicitly subsidize the production of good y in region 1 and consequently increase the production of y^1.

Part (b) describes the emission effect in region 3. As the market price of good y falls because of lower production cost and reallocation of production back to region 1, emissions associated with the same good in region 3 also declines, $\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial s^1} < 0$. How this affects the emissions related to production of good z in region 3 is uncertain. However, it seems likely that term (b) is positive as the second order effect on good z is presumably dominated by the first order effect on y. Hence, emissions in region 3 declines with s^1:[11]

$$\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial s^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial s^1}\right) < 0. \quad (7)$$

In the last term, the consumption of good y increases with s^1, since the price related to the same good decreases, i.e., $\frac{\partial p^y}{\partial s^1} < 0$. The consumer now buys less of the relatively expensive good x, and therefore $\frac{\partial p^x}{\partial s^1} < 0$. Term (c) captures the terms-of-trade effects for region 1, and is ambiguous. If we however assume that this term is zero, then we can elaborate that $s^1 > 0$ if the leakage is positive, and $s^1 = 0$ if the leakage is non-positive. As a result, if region 1 is a net-importer of good

[10] The Pigouvian tax is defined as the global marginal external costs of emissions. For the analytical results, it does not matter whether τ^j reflects the global or only domestic costs of global emissions.
[11] The numerical simulation in the context of EU ETS and Chinese ETS confirms that part b) is negative.

y, then $s^1 > 0$, because $\frac{\partial p^y}{\partial s^1} < 0$ and results in leakage reduction. If region 1 is a net-exporter of good y, then the sign of s^1 is ambiguous.

Thus, the optimal second-best OBA policy is in general ambiguous. However, if we assume that region 1 is a net-importer of good y, then the optimal OBA policy in region 1 is positive.

Region 1 can also supplement their OBA with a consumption tax v^1, in the presence of an emission trading system in region 2. By differentiating (5) with respect to v^1 instead, we arrive at a result very similar to Böhringer et al. (2017b) and Kaushal and Rosendahl (2017):

$$v^{1*} = \underbrace{\left(\frac{\partial \bar{y}^1}{\partial v^1}\right)^{-1}}_{(d)} \left[\underbrace{s^1 \frac{\partial y^1}{\partial v^1}}_{(e)} \underbrace{- \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1)}_{(f)} + \underbrace{\tau^1 \left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right)}_{(g)}\right]. \tag{8}$$

Since a consumption tax in region 1 will decrease consumption of good y in the same region, the first term (d) is negative. Henceforth, terms inside the bracket with negative (positive) sign tends to increase (decrease) the optimal v^1.

(e) reflects the correction by the consumption tax of an implicit OBA subsidy, which causes too much consumption of this good. The term is negative since a consumption tax in region 1 reduces the demand for good y. As a result, the global market price and hence production of good y falls in all the three regions.

The next term (f) is the familiar terms-of-trade effect for the region. We know that $\frac{\partial p^y}{\partial v^1} < 0$, from our previous discussion. With good y now being relatively more expensive than good x for consumers in region 1, the demand, and hence price, increases for good x, $\frac{\partial p^x}{\partial v^1} > 0$. Whether (f) is negative or positive will depend on whether region 1 is a net exporter or importer of the two goods. As a net exporter of good x and net importer of good y, the term becomes negative.

The emission effect in region 3 is captured in the last term (g). Global demand and the market price of good y drops, hence emissions related to producing in region 3 also decrease, $\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} < 0$. The effect on good z in region 3 is ambiguous. However like in term (b), also here it seems likely that emissions in region 3 decline when the consumption tax is imposed on good y in region 1 (Kaushal & Rosendahl, 2017):

$$\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial v^1}\right) < 0. \tag{9}$$

Hence, in general the sign of the optimal consumption tax is ambiguous. However, if region 1 is a net exporter of the x good and net importer of the y good, then the optimal consumption tax in region 1 is unambiguously positive in the presence of an emission trading system in region 2.

In the following two sections, we will first show how the optimal OBA rate in region 1 is affected by an OBA or a consumption tax in region 2, and then how optimal consumption tax in region 1 is affected by an OBA or a consumption tax in region 2. The sensitivity for the optimal OBA and consumption tax rate with respect to carbon policies in region 2 is inspired by the model set-up in Böhringer et al. (2017a). They investigate how carbon taxes in an open economy combined with OBR performs in the presence of carbon policies in a large neighboring trading partner.

We consider the optimal OBA and consumption tax rate in region 1 with the following two outcomes: i) region 2 supplements the emission price t^2 with OBA s^2, and ii) the s^2 is supplemented by a consumption tax v^2 on consumption of the y good. In the spirit to make the theoretical analysis more informal, we leave out the terms-of-trade effect from the expression of optimal OBA and consumption tax rate and focus on the leakage effect.

2.3. Second-best OBA policy in region 1, in the presence of climate policy in region 2

We simplify the notation from (6) and (8) in the following discussion by writing $\frac{\partial y^1}{\partial s^1} = y_s^1$, $\frac{\partial e^{y3}}{\partial s^1} = e_s^{y3}$ and $\frac{\partial e^{z3}}{\partial s^1} = e_s^{z3}$, and same for the derivative with respect to v^1. In (6) and (8) we presented the first order derivative with respect to s^1 and v^1, which we describe as the first order effect. The second order effect is then the second derivative of these with respect to either s^2 and v^2. Further, the main assumption in the following discussion is that lower (higher) quantity of respectively domestic production and consumption leads to reduced (stronger) effect of s and v, as we look at the effect of these policies on the corresponding quantity. The same reasoning applies to impacts on leakage too, where both s and v reduces leakage[12].

The total differentiation of (6) with respect to s^2 and v^2 and inserting for s^1, gives us:

$$ds^1 = \underbrace{\frac{\tau^1}{y_s^1}}_{(h)}\left(\underbrace{\frac{\partial y_s^1}{\partial s^2}\left(\frac{e_s^{y3}}{y_s^1} + \frac{e_s^{z3}}{y_s^1}\right)}_{(i)} - \underbrace{\left(\frac{\partial e_s^{y3}}{\partial s^2} + \frac{\partial e_s^{z3}}{\partial s^2}\right)}_{(j)}\right) ds^2 + \underbrace{\frac{\tau^1}{y_s^1}}_{(h)}\left(\underbrace{\frac{\partial y_s^1}{\partial v^2}\left(\frac{e_s^{y3}}{y_s^1} + \frac{e_s^{z3}}{y_s^1}\right)}_{(k)} - \underbrace{\left(\frac{\partial e_s^{y3}}{\partial v^2} + \frac{\partial e_s^{z3}}{\partial v^2}\right)}_{(l)}\right) dv^2, \quad (10)$$

[12] See appendix A3

where we first consider only an OBA policy in region 2, such that $ds^2 > 0$ and $dv^2 = 0$.

We initially know that (h) is positive since $y_s^1 > 0$ from (6) term (a). The bracket in term (i) is familiar from (6) term (b) and is the emission effect in region 3 of introducing s^1, which is negative. Though $\frac{\partial y_s^1}{\partial s^2}$ is ambiguous, we can elaborate that while the first order effect is positive, the second order effect is likely negative. That is, s^2 reduces the production cost of y^2 in region 2, and p^y and y^1 are likely reduced. Hence, the effect of s^1 on y^1 would now be eased. With $\frac{\partial y_s^1}{\partial s^2} < 0$, the term (i) is positive The magnitude of this effect would depend on region 2 and its y sectors size, its cost structure and demand responsiveness as well.

Term (j) also captures the emission effect in region 3, and is the derivative of (b) in (6) with respect to s^2. s^2 will reduce the emission leakage from region 2 to region 3, but how significant this would impact the leakage reduction done by s^1 is ambiguous. However, the negative effect of s^1 on emissions in region 3 would be moderated as the leakage is smaller with s^2, indicating that term (j) is positive. With a negative sign in front of (j), the term becomes negative.

Now we introduce a carbon consumption tax while keeping s^2 fixed in region 2, ($dv^2 > 0$). The bracket inside of term (k) is negative from our previous discussion. We know that v^2 reduces the demand of y in region 2, and thereby the production of y in all regions reduces. Hence, the effect of s^1 on y^1 would be eased and term (k) then becomes positive (two negative factors). The magnitude of v^2 would again depend on region 2's size, initial demand and responsiveness.

From (6) in term (b), we know that the first order effect in term (l) is negative. As v^2 reduces the leakage from region 2, the likely outcome would be that the effect of s^1 on emissions in region 3 are reduced. Hence, term (l) is positive, similar to term (j).

To sum up, although we find the overall effect on the optimal s^1 of either increasing s^2 or v^2 to be ambiguous, it seems likely that it is positive if term (i) is greater than term (j), and term (k) is greater than term (l).

2.4. Optimal consumption tax in region 1, in the presence of climate polices in region 2

We now test the sensitivity of optimal consumption tax rate in region 1 with respect to carbon policies in region 2, by holding the OBA rate s^1 fixed. We total differentiate (8) with respect to s^2 and v^2, and insert for v^1:

$$dv^1 = \underbrace{\bar{y}_v^{1^{-1}}}_{(m)}\left[\underbrace{s^1\frac{\partial y_v^1}{\partial s^2}}_{(n)} + \underbrace{\tau^1\left(\frac{\partial e_v^{y3}}{\partial s^2} + \frac{\partial e_v^{z3}}{\partial s^2}\right)}_{(o)} - \underbrace{\frac{\partial \bar{y}_v^1}{\partial s^2}\left(\frac{s^1 y_v^1 + \tau^1\left(e_v^{y3} + e_v^{z3}\right)}{\bar{y}_v^1}\right)}_{(p)}\right] ds^2$$
$$+\underbrace{\bar{y}_v^{1^{-1}}}_{(m)}\left[\underbrace{s^1\frac{\partial y_v^1}{\partial v^2}}_{(q)} + \underbrace{\tau^1\left(\frac{\partial e_v^{y3}}{\partial v^2} + \frac{\partial e_v^{z3}}{\partial v^2}\right)}_{(r)} - \underbrace{\frac{\partial \bar{y}_v^1}{\partial v^2}\left(\frac{s^1 y_v^1 + \tau^1\left(e_v^{y3} + e_v^{z3}\right)}{\bar{y}_v^1}\right)}_{(s)}\right] dv^2. \quad (11)$$

First, we let $ds^2 > 0$ and $dv^2 = 0$. The term (m) outside of the main bracket is negative from our discussion of (8) term (d), as consumption tax reduces the demand for good y.

In term (n), the first order effect is negative from the discussion of (8) term (e). The introduction of s^2 reduces the production cost of y^2 and thereby lowering the price p^y and production of y^1. Thus, it is reasonable that this (n) >0, as lower y^1 would mean less negative effect of v^1 on the production of the same good.

In the next term (o), we know from (8) term (g) that our first order effects is negative. v^1 reduces the leakage from region 1, and s^2 reduces the leakage from region 2. Since there is less leakage to region 3 with both s^2 and v^1, term (o) would likely be positive (the negative effect is dampened).

In the bracket of term (p), we recall that both term (g) from (8) and y_v^1 is negative. With the numerator and denominator being negative, this part becomes positive. Outside of the bracket, the first order effect is negative as v^1 reduces the demand for y in region 1. When it comes to the second order effect s^2 reduces p^y, which further increases $\bar{y}^1$ to some extent. Since the quantity of demanded y in region 1 is greater in the presence of s^2, it would indicate that the effect of v^1 on $\bar{y}^1$ is more negative in the presence of s^2. Hence, term (p) is likely negative. So with a negative sign in front of (p), the term becomes positive and we find the overall effect on the optimal level of v^1 of an increase in s^2 to be likely negative.

Assume now that region 2 imposes a consumption tax while keeping the other instrument fixed. In term (q) we know that y_v^1 is negative. v^2 reduces the demand for y in region 2, which reduces the price of the same good and hence the production of y. While the term is ambiguous, we can follow the same reasoning as in (n), and then the term is likely be positive, i.e., v^2 reduce the negative effect of v^1 on production of y^1.

In term (r) the first order effect inside the bracket is negative from (8) term (g). v^2 reduces the leakage to region 3 from 2, and likely also from region 1. Hence, the term (r) is likely positive since v^1 now has less negative effect on the emission in region 3.

The bracket inside of term (s) is knowingly positive from our earlier discussion. v^1 reduces $\bar{y}^1$, and reduced $\bar{y}$ in region 1 and 2 reduces p^y. Although $\frac{\partial \bar{y}_v^1}{\partial v^2}$ is ambiguous, we can use the same way of reasoning as we did for term (p). As p^y decreases with v^2, causing $\bar{y}^1$ to increase, we likely expect v^1 to have a more negative effect on $\bar{y}^1$, i.e. $\frac{\partial \bar{y}_v^1}{\partial v^2} < 0$. Hence, the last term (s) is negative.

To sum up, although (11) shows that the effect of optimal v^1 is ambiguous, it seems likely to be negative with increasing s^2 and v^2, i.e., (dv^1/dv^2, $dv^1/ds^2 < 0$).

The overall ambiguous results from chapter 2.3 and 2.4 strongly suggests that a numerical simulation is essential to give more in-depth insight. In the next chapter, we present the numerical simulations based on the theoretical model from section 2.1, and the paper by Kaushal and Rosendahl (2017).

3. Numerical analysis

Numerical simulations are useful for examining the ambiguous outcomes from the theoretical analysis. The main purpose for this analysis is to assess the Nash equilibrium outcomes in a non-cooperative game of policy instruments. Particularly, we are interested in a non-cooperative game of policy instruments in a world economy consisting of a Chinese and a European Union ETS, where each region can choose to have a different variant of OBA or carbon consumption tax for the emission-intensive and trade-exposed goods. The choice of climate policy in both regions are based on the following indicators: *i)* region maximizes regional welfare, *ii)* region minimizes leakage rate, *iii)* region maximizes global market share of good y, *iv)* region maximizes global market share of good x, and *v)* different combination of *i)* to *iv)*. The motivation for looking at a policy instrument game with different indicators is that a region's choice may be limited when making policy decisions. For example, policymakers could be influenced by strong lobbying groups who are more concerned for their global production share than regional welfare. Or, the EITE good could be of a substantially large share for the region, resulting in less flexibility for ambitious climate policies (Sterner & Coria, 2012).

3.1 Model summary

The numerical simulation model is based on the Computable General Equilibrium (CGE) model in Kaushal and Rosendahl (2017), with the assumption of the following three regions: the European Union/ European Economic Area (EU)[13], China (CHN) and rest of the world (ROW). As in the theoretical model in section 2, we find the same three goods in the different regions: a carbon free and tradable good x, carbon-intensive and tradable good y, and carbon-intensive and non-tradable good z. These goods are produced and consumed in all of the three regions, and they can only be used in the final consumption. We also include a fourth production sector, fossil energy production f, which can only be used in energy related production y and z, and cannot be traded between regions[14]. The tradable goods are assumed homogenous with a global price and no transportation cost.

Capital, labor, fossil energy and resources are the input factors in production. Further, capital, labor and fossil energy are mobile between sectors but immobile between regions. The resource is only used in the fossil energy production and is immobile between regions. The producers minimizes the cost subject to technological constraints, by combining the input factors. We describe the production of x, y, z as two level constant-elasticity-of-substitution (CES) cost functions, with the possibilities of substitution between capital, labor and fossil energy input. The two level CES cost function for producer f consists of capital, labor and resource. At the top level, we have the CES with substitution between energy/resource and value-added (capital and labor) composite. At the second level, the CES between value-added composite includes the substitution between capital and labor[15]. The emission is proportionally related to the use of energy as input for production. The emission reduction in the sectors are therefore either through; *i)* substituting energy with value-added composite, or *ii)* scaling down the production output.

We define the final consumption in each region by a representative agent who maximizes utility subject to a budget constraint. The budget constraint is determined by the monetary value of regional endowment of capital, labor and resource, and net revenues from emission regulation[16]. The agent's utility is given as a CES combination of final consumption goods.

[13] This includes all the 28 EU member states plus Iceland, Norway, and Liechtenstein.
[14] Hence in accordance with the theoretical model, we focus on the carbon leakage related to the competitive channel.
[15] See appendix B for summary of the CGE model and nesting in different sectors.
[16] The net revenues from emission regulation consists of emission price plus consumption tax, minus the cost of OBA

3.2 Calibration procedure and dataset

The calibration procedure is based on standard method in computable general equilibrium simulations, where the exogenous parameters are defined by base-year data. Like in Kaushal and Rosendahl, the other parameters are either estimated from other different studies or calibrated based on simulations of a well-established CGE-model (Böhringer et al., 2017b; Böhringer et al., 2018).

The numerical model is calibrated according to the World Input Output Database (WIOD), which is based on 43 regions and 56 sectors with related CO_2-emission from each sector. Further, we reconstruct the empirical data to fit the model from the theoretical analysis, by merging the data into the three regions and four sectors; x, y, z, and f[17]. The emissions level in sector x is set equal to zero, and thus follow the same assumption from the theoretical analysis, i.e., that there are no carbon related emissions in this sector[18]. Next, we measure the net exports in the tradable sectors in the base-year and incorporate the balance of payment constraint in the numerical model, by measuring the domestic production and consumption in each region. The calibrated sector z consists of several sectors with some trade in the dataset. Thus, we assume that produced and consumed quantity in the same region is equal, as sector z is non-tradable in the theoretical model.

The utility maximizing agent in each region is assumed to have a CES utility function calibrated to the share form, with exogenous parameters set to base-year shares from WIOD data. Like Böhringer et al. (2017b) and Kaushal and Rosendahl (2017) we set the substitution elasticity of 0.5 between goods x, y and z, with perfect substitution between locally produced and imported goods.

[17] See appendix C for mapping of WIOD sectors.

[18] Sector x accounted for 14-15% of the global CO2 emissions in 2009, according to the dataset.

	Production (billion $)	*Consumption (billion $)*	*CO_2 (billion ton)*
x^{EU}	*25 066*	*24 610*	-
y^{EU}	*5 025*	*5 111*	*0.90*
z^{EU}	*1 998*	*1 998*	*1.78*
x^{CHN}	*9 059*	*8 786*	-
y^{CHN}	*5 030*	*5 020*	*2.11*
z^{CHN}	*949*	*949*	*3.60*
x^{ROW}	*51 101*	*51 830*	-
y^{ROW}	*14 271*	*14 194*	*4.21*
z^{ROW}	*4 871*	*4 871*	*8.24*

Table 1: Base-year WIOD data values and calibrated parameters in the numerical model

3.3 Climate policy strategies and scenarios

In the following, we will consider that $j = \{CHN, EU\}$, and that calibrated base-year data from 2009 is the business-as-usual scenario. The first policy strategy (t^j) is where the region j implements an emission trading system with full auctioning. The EU ETS was already in place in 2009 with the average ETS price of €13 per ton CO_2. Thus, the considered case is where an additional emission reduction target of 20 percent is set relative to the base-year emission in the EU ETS[19]. The assumption is not unreasonable as the EU has set new and more ambitious targets for 2030 and 2050 (Andresen et al., 2016). China, however, did not have an active emission trading system in 2009. Here, the emission reduction target is set to 20 percent relative to base-year emission as well.

The next policy strategy is where region j allocates a number of allowances for free to the emission-intensive and trade-exposed (EITE) industries y, i.e. OBA (s^j). The allowances in this sector are allocated with the allocation factor α^j, ranging from 20% to 100% allocation for the industries based on output, i.e., $s^j = \alpha^j t^j \left(e^{yj} / y^j \right)$. In accordance with the theoretical analysis, sector z does not receive allowances for free.

The last policy strategy considered is where region j supplement the OBA with a consumption tax. Under this strategy, the consumption tax ranges from 20% to 100% as a fraction of the OBA

[19] The reported permit price in this chapter comes in addition to the price of €13 per ton CO_2 in 2009.

rate s^j, i.e., $v^j = \gamma^j s^j$, where γ^j is the fraction of OBA rate in region j. Hence, different combinations of OBA allocation and consumption tax can be achieved.

In line with the theoretical model, the welfare in each region consists of the regional utility and the environmental benefit of global emission reduction. We use the regional emission price t^j under the first policy strategy, to calculate the benefit of global emission reduction felt by each region under different policies. Since there are two emission trading systems in our model that are not linked, the emission price in each region is therefore different. Further, the main assumption is that negative global emission caused by one region's action, is beneficial for the other region as well.

3.4 Numerical simulations and the optimal strategies

We investigate the optimal climate policy strategy for each region by looking at the following key indicators: *i)* maximizing regional welfare, *ii)* minimizing leakage rate *iii)* maximizing global market share of y, *iv)* maximizing global market share of x, and *v)* a combination of indicators *i) – iv)*. We assume a simultaneous non-cooperative game with two players, the EU and China, who choose their climate policy based on the specific key indicators above. The optimal climate policy for each region in this game, or Nash equilibrium outcome, would then be the best choice they make given the other region's choice (Varian, 2010). To simulate all the outcomes for the different combination of policies, the model is run 961 times. A more detailed pay-off matrix for each of the tables in this section are listed in Appendix D.

		EU			
		t^{EU}	$s_{80}^{EU} v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU} v_{100}^{EU}$
CHN	t^{CHN}	*(0.14%, 0.19%)*	*(0.41%, 0.25%)*	*(0.57%, 0.19%)*	*(0.57%, 0.19%)*
	$s_{40}^{CHN} v_{80}^{CHN}$	*(0.18%, 0.23%)*	*(0.41%, 0.29%)*	*(0.59%, 0.24%)*	*(0.60%, 0.24%)*
	s_{100}^{CHN}	*(-0.07%, 0.35%)*	*(0.44%, 0.41%)*	*(0.36%, 0.39%)*	*(0.36%, 0.39%)*
	$s_{100}^{CHN} v_{100}^{CHN}$	*(-0.07%, 0.35%)*	*(0.19%, 0.41%)*	*(0.36%, 0.39%)*	*(0.36%, 0.39%)*

Table 2: China and the EU's welfare effect with different combinations of policies in the EU and China.

Results in Table 2 shows the effect on welfare in the EU and China in the presence of different combination of policies, i.e., indicator *i)*. Policy choices by the EU are on the right and China's on the left, in the brackets. t^{EU} and t^{CHN} is the scenario with only emission price in the EU and China, respectively. s and v with percent values is the correspondingly allocation factor in sector

y of OBA, and consumption tax rate as a fraction of OBA.[20] As defined earlier, the emission price in region j without any supplementing policies are equal to the valuation of reduced global GHG emissions in the same region, i.e., $t^j = \tau^j$. For EU and China, the numerical simulation suggests t^{CHN} = \$78.39 and t^{EU} = \$99.64.

The result shows that the optimal strategy when both regions maximizes welfare is to supplement OBA with a consumption tax on the EITE good, i.e., our Nash equilibrium. This outcome is in line with previous results (Kaushal & Rosendahl, 2017) since a consumption tax reduces the leakage and thereby increases the regional welfare. The Nash equilibrium outcome is $s_{40\%}v_{80\%}$ for China and $s_{80\%}v_{100\%}$ for the EU. A likely reason for the lower optimal OBA in China, is their higher emission intensity in sector y compared to the EU. Moreover, the EU is the only net exporter of good x, and therefore the higher consumption tax rate is optimal in the EU. The table further show that if one region's policy is kept fixed, their welfare increases when another region introduces a combination of OBA with a consumption tax. The main driver for the welfare increase here, is the reduction in leakage rate which benefits both regions.

The theoretical analysis in section 2 suggested in general ambiguous effects on the optimal OBA and consumption tax, when another region implements OBA and/or a consumption tax. The numerical simulation, however, suggests that the optimal rate is unaffected by an introduction of supplementing policy in the other region. That is, the optimal strategy in the Nash equilibrium outcome, is also the dominant strategy for the regions. The largest welfare effect compared to the BAU scenario for China is approximately 0.6%. In this case, China's policy is $s_{40\%}v_{80\%}$, meanwhile the EU's is $s_{100\%}v_{100\%}$. The largest welfare effect for the EU is around 0.4% if they choose $s_{80\%}v_{100\%}$ and China choose $s_{100\%}v_{100\%}$.

		EU			
		t^{EU}	$s_{80}^{EU}\,v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU}v_{100}^{EU}$
CHN	t^{CHN}	*39.8%*	*17.2%*	*4%*	*3.7%*
	$s_{40}^{CHN}\,v_{80}^{CHN}$	*34.4%*	*7.5%*	*1.2%*	*0.9%*
	s_{100}^{CHN}	*18.1%*	*2.6%*	*-7.5%*	*-7.7%*
	$s_{100}^{CHN}\,v_{100}^{CHN}$	*17.6%*	*2.3%*	*-7.8%*	*-8%*

Table 3: Leakage rate with different combinations of policies in the EU and China.

[20] For example, with $s_{80\%}v_{100\%}$ we have $\alpha = 0.8$ and $v = s$. See section 3.3.

Table 3 shows the leakage rate from the regulated regions EU and China, to the unregulated region ROW, presuming that they minimize leakage rate as their indicator, i.e., indicator *ii)*. The leakage rate is measured as the change in foreign emission over the change in the regulating region's emission, where the BAU emission is the baseline.[21] A positive (negative) number results in a positive (negative) leakage rate. Given no energy trade in our model, leakage only happens through the market for EITE-goods (y). Table 3 suggest an Nash equilibrium outcome with 100% OBA, and consumption tax to at least 100% of OBA, for both regions, i.e., $s_{100\%}v_{100\%}$. The consumption tax reduces demand for good y and thereby production and emissions in the unregulated region. Hence, in Nash equilibrium, given indicator *ii)*, both regions supplement the 100% OBA with a 100% consumption tax on the EITE good. The highest leakage rate of around 39.8% is obtained when no complementing policies are introduced in the regulating regions. The lowest leakage rate is obtained in the Nash equilibrium, around -8% leakage rate. The results indicate that a combined effort to mitigate leakage from regulated regions, results in a higher global emission reduction.

		EU			
		t^{EU}	$s_{80}^{EU}v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU}v_{100}^{EU}$
CHN	t^{CHN}	*(14.9%, 13.4%)*	*(13.1%, 22%)*	*(13.1%, 27%)*	*(13.1, 26.9%)*
	$s_{40}^{CHN}v_{80}^{CHN}$	*(17.4%, 12.8%)*	*(16.1%, 20.9%)*	*(15.3%, 25.8%)*	*(15.3%, 25.7%)*
	s_{100}^{CHN}	*(24.8%, 10.8%)*	*(23.2%, 17.5%)*	*(22.1%, 21.8%)*	*(22.2%, 21.6%)*
	$s_{100}^{CHN}v_{100}^{CHN}$	*(24.7%, 10.8%)*	*(23.1%, 17.4%)*	*(22.1%, 21.7%)*	*(22.1%, 21.6%)*

Table 4: China's and the EU's global market share of good y with different combinations of policies in the EU and China.

In accordance with earlier papers, we referred to OBA as an implicit production subsidy for producer y. If the region's main indicator had been to maximize the net production of good y, the result would consequently also have been to supplement their ETS with 100% OBA. A more motivating approach is to observe the global market share of good y, since the producers could compromise on at least maintaining the market share as the net global demand for good y declines. Table 4 shows that the highest market share of sector y is obtained when the regions allocate at least 100% OBA to the producer of EITE-good, which is also the Nash equilibrium in this game. Hence, given indicator *iii)*, the regions would supplement their ETS with at least 100% OBA. The

[21] Since the regulated regions are only concerned of the increase in emissions in the unregulated region, we express the leakage rate as $\frac{\Delta(E^{ROW})}{-\Delta(E^{EU}+E^{CHN})}$, where $E^j = e^{y^j} + e^{z^j}$ for $j = \{EU, CHN, ROW\}$.

market share in the Nash equilibrium is approximately 22.1% for China and 21.8% for the EU. The highest market share a region can achieve is when only that region supplements the ETS with OBA. Hence, this strategy for the EU and China is also the dominant strategy. The market shares for both regions are greater than a situation without any climate policy. In the BAU scenario, the result suggests a market share of approximately 20.7% for both regions.

		EU			
		t^{EU}	$s_{80}^{EU}v_{100}^{EU}$	s_{100}^{EU}	$s_{100}^{EU}v_{100}^{EU}$
CHN	t^{CHN}	*(12.3%, 31.5%)*	*(12.6%, 29.1%)*	*(12.8%, 27.7%)*	*(12.8, 27.7%)*
	$s_{40}^{CHN}v_{80}^{CHN}$	*(11.6%, 31.7%)*	*(12%, 29.4%)*	*(12.2%, 28%)*	*(12.2%, 28.1%)*
	s_{100}^{CHN}	*(9.6%, 32.2%)*	*(10%, 30.3%)*	*(10.3%, 29.1%)*	*(10.3%, 29.2%)*
	$s_{100}^{CHN}v_{100}^{CHN}$	*(9.6%, 32.2%)*	*(10.1%, 30.3%)*	*(10.4%, 29.1%)*	*(10.4%, 29.2%)*

Table 5: China's and the EU's global market share of good x with different combinations of policies in the EU and China.

If both regions maximize global market share of good x, indicator *iv)*, Table 5 shows that the they would not supplement their ETS. The emission price increases the production cost for the producer of good y and z. More demand shifts towards the relatively cheaper good x, and thereby the production of the same good increases as well. In this Nash equilibrium, the regions achieve a higher market share of good x (12.3% for China and 31.5% for the EU) than the BAU scenario (10.7% for China and 29.7% for the EU). The strategies in this Nash equilibrium outcome are also the dominant strategies for the regions. The share of good x for one region increases when the other region supplements the ETS to at least 100% OBA. Further, the share decreases somewhat if the other region introduces a consumption tax on top of the OBA.

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$(s_{40}^{CHN}v_{80}^{CHN}, s_{80}^{EU}v_{100}^{EU})$	$(s_{40}^{CHN}v_{80}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{40}^{CHN}v_{80}^{CHN}, s_{100}^{EU})$	$(s_{40}^{CHN}v_{80}^{CHN}, t^{EU})$
	ii)	$(s_{100}^{CHN}v_{100}^{CHN}, s_{80}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, s_{100}^{EU})$	$(s_{100}^{CHN}v_{100}^{CHN}, t^{EU})$
	iii)	$(s_{100}^{CHN}, s_{80}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU}v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU})$	(s_{100}^{CHN}, t^{EU})
	iv)	$(t^{CHN}, s_{80}^{EU}v_{100}^{EU})$	$(t^{CHN}, s_{100}^{EU}v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 6: A summary of the Nash equilibrium outcomes and dominant strategies based on indicators *i) – iv)*.

To sum up, we present all the Nash equilibrium outcomes from the numerical analysis in Table 6, as well as the outcomes with other combinations of indicators. The EU's indicators are listed on the right, and China's on the left, in the brackets. The numerical analysis show that the region's strategy in the Nash equilibrium outcome is also the dominant strategy for the region. This is also noticeable in Table 6 as well. That is, given the indicator, the region choses the same strategy no matter what the other region choses.

3.5 Sensitivity analysis

To check to what degree the numerical results are robust, we now examine the effects of changing some of the main assumptions. We first relax the assumption that goods produced in different regions are homogenous, and assume that domestic and foreign goods are distinguished by origin. Next, we keep the same assumptions from our benchmark simulation, but assume that the substitution elasticity for the representative agent is set to 2. Finally, we test for a Pigouvian tax being higher than the emission price.

First, we consider the heterogeneous goods approach by Armington (1969) when relaxing the assumption that goods produced in different regions are homogenous, and distinguish between domestic and foreign produced goods ("Armington goods"). We keep the same assumption at the top level of the utility function, when substituting between the goods x, y and z. At the second level, we include substitution between domestic and imported goods x and y, and finally at the third level we distinguish between the origins of the foreign produced goods.[22]

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{EU} v_{100}^{EU}, s_{100}^{EU})$	$(s_{100}^{EU} v_{100}^{EU}, t^{EU})$
	ii)	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, t^{EU})$
	iii)	$(s_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU})$	(s_{100}^{CHN}, t^{EU})
	iv)	$(t^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(t^{CHN}, s_{100}^{EU} v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 7: A summary of Nash equilibrium outcomes based on indicators *i) – iv)*, assuming Armington goods.

In Table 7 we show the different Nash equilibrium outcomes, with the assumption of Armington goods. The welfare effects under all combinations of policies are higher with Armington goods than with the homogenous goods. Mainly, this is a result of further limited leakage than with homogenous goods, and hence the global benefits of emission reductions are bigger. Compared

[22] We assume a substitution of elasticity at the top level of 0.5 (as before), at the second level of 4, and at the third level of 8. The heterogeneous goods case transforms into the case of homogenous goods with an infinite Armington elasticity setting on the second and third levels.

with Table 6 the only different strategy in a Nash equilibrium outcome, is when the region maximizes welfare. The new outcome is $(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$, which is also the dominant strategy for both regions. The welfare improves monotonically with the consumption tax to at least 100% of the OBA rate for both regions, with Armington goods. With indicator *ii)*, *iii)* or *iv)* assuming Armington goods, the results shows the same outcome as the benchmark simulations. Like in the benchmark simulations, the strategy choice in the Nash equilibrium outcomes are also the dominant strategies for the region.

		EU			
		i)	*ii)*	*iii)*	*iv)*
CHN	*i)*	$(s_{40}^{CHN} v_{60}^{CHN}, s_{60}^{EU} v_{100}^{EU})$	$(s_{40}^{CHN} v_{60}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{40}^{CHN} v_{60}^{CHN}, s_{100}^{EU})$	$(s_{40}^{CHN} v_{60}^{CHN}, t^{EU})$
	ii)	$(s_{100}^{CHN} v_{100}^{CHN}, s_{60}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, s_{100}^{EU})$	$(s_{100}^{CHN} v_{100}^{CHN}, t^{EU})$
	iii)	$(s_{100}^{CHN}, s_{60}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU} v_{100}^{EU})$	$(s_{100}^{CHN}, s_{100}^{EU})$	(s_{100}^{CHN}, t^{EU})
	iv)	$(t^{CHN}, s_{60}^{EU} v_{100}^{EU})$	$(t^{CHN}, s_{100}^{EU} v_{100}^{EU})$	(t^{CHN}, s_{100}^{EU})	(t^{CHN}, t^{EU})

Table 8: A summary of Nash equilibriums based on indicators *i) – iv)*, assuming alternative substitution elasticity.

We go back to the homogenous good assumption for the next tests. In Table 8 we list the outcome when assuming a different substitution elasticity for the representative agent. That is, we change the substitution elasticity for the representative agent from 0.5 to 2. The tests are conducted with substitution elasticity change in all the three regions. With higher substitution elasticity, the Nash equilibrium outcome given indicator *i)* is $(s_{40}^{CHN} v_{60}^{CHN}, s_{60}^{EU} v_{100}^{EU})$. That is a lower OBA rate for the EU and a lower consumption tax rate for China, than in the benchmark simulation. Higher substitution elasticity tends to shift consumption more towards the carbon-free good x. Thus, a lower OBA and consumption tax is needed in the EU and China (respectively). The welfare improvement compared to BAU scenario are in general higher with higher substitution elasticity, as the leakage rate is lower. We can see from Table 8 that the tests support the findings from our analysis in section 3.4 for indicator *ii)*, *iii)* and *iv)*. Moreover, the strategies in the Nash equilibrium outcome, are dominant strategies for the region.

The theoretical analysis in section 2.2 also discussed the possibility of the *Pigouvian* tax being different from the emission price observed under the scenario without supplementing policies to the ETS. We have assumed that the two are equal in the benchmark simulations. In the EU Emission Trading System for instance, the emission price have been fairly low over the last years. Thus, one could argue that the *Pigouvian* tax is higher than the current CO_2 price. We test for a *Pigouvian* tax that is 50 % higher (in EU and China) than the estimated carbon price from section

3.4. The increased *Pigouvian* tax does not alter our main result from section 3.4. The benefits of the climate policy, however, is now bigger as global emission reductions would have a greater impact on welfare.

4. Concluding remarks

As rest of the world closely follows the unilateral initiatives by the EU and China, the policymakers in these regions are well aware that their unilateral action leads to carbon leakage without a global initiative to reduce emissions. There are many different approaches in the economic literature to mitigate carbon leakage. A very common anti-leakage solution in emission trading systems is output-based allocation (OBA) to emission-intensive and trade-exposed (EITE) industries. OBA, however, works as an implicit production subsidy to domestic production of EITE goods. As a result, an approach to supplement OBA with a consumption tax on all use of EITE goods have been proposed (Böhringer et al., 2017b; Kaushal & Rosendahl, 2017). In this paper we have examined the choice of a climate policy instrument for a region, in the presence of another region's climate policy.

First, we showed analytically that under specific conditions the optimal OBA is increased and the optimal consumption tax is reduced, in the presence of another region's OBA and/or consumption tax. Next, we examined the choice of policy instrument for two separate regions with a stylized CGE model calibrated to real world data, where we considered the situation of the EU ETS and the Chinese ETS. We present the choice of climate policy in both regions based on different indicators. The results showed that depending on the choice of indicator, the regions would choose different variation of policy combinations. In the context of maximizing regional welfare, however, both regions would in the Nash equilibrium outcome implement a consumption tax on top of the OBA. The results suggest that the strategy in the Nash equilibrium outcomes are also the dominant strategy for the regions.

Böhringer et al. (2017b) and Kaushal and Rosendahl (2017) found that combining output-based allocation with a consumption tax may result in regional welfare improving effect. In the current situation, however, there are many separated carbon emission trading systems globally. Hence, one region's choice of climate policy would likely affect another region's climate policy. An interesting insight from our analysis is that our results support the findings of the two papers above. Thus, the paper conclude that complementing output-based allocation with a consumption tax is likely a strong policy strategy in terms of regional welfare improvement, even in the presence of another climate regulating region.

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Appendix A, Derivations

A1: Region welfare maximization with output-based allocation

By differentiating the regional welfare (5) with respect to output-based allocation, we get

$$\frac{\partial W^1}{\partial s^1} = u_x^1 \frac{\partial \bar{x}^1}{\partial s^1} + u_y^1 \frac{\partial \bar{y}^1}{\partial s^1} + u_z^1 \frac{\partial \bar{z}^1}{\partial s^1} - c_x^{x1} \frac{\partial x^1}{\partial s^1} - c_y^{y1} \frac{\partial y^1}{\partial s^1} - c_z^{z1} \frac{\partial z^1}{\partial s^1} - c_e^{y1} \frac{\partial e^{y1}}{\partial s^1} - c_e^{z1} \frac{\partial e^{z1}}{\partial s^1} - \tau^1 \left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

Recall the conditions and assumptions from (2) and (3), and we then get

$$= p^x \frac{\partial \bar{x}^1}{\partial s^1} + p^y \frac{\partial \bar{y}^1}{\partial s^1} + p^{z1} \frac{\partial \bar{z}^1}{\partial s^1} - p^x \frac{\partial x^1}{\partial s^1} - (p^y + s^1) \frac{\partial y^1}{\partial s^1} - p^{z1} \frac{\partial z^1}{\partial s^1} + t^1 \frac{\partial e^{y1}}{\partial s^1} + t^1 \frac{\partial e^{z1}}{\partial s^1} - \tau^1 \left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

We further simplify the equation

$$= p^x \frac{\partial \bar{x}^1}{\partial s^1} - p^x \frac{\partial x^1}{\partial s^1} + p^y \frac{\partial \bar{y}^1}{\partial s^1} + p^{z1} \frac{\partial \bar{z}^1}{\partial s^1} - p^{z1} \frac{\partial z^1}{\partial s^1} - (p^y + s^1) \frac{\partial y^1}{\partial s^1} + t^1 \left(\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1}\right) - \tau^1 \left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial s^1} - \frac{\partial x^1}{\partial s^1}\right) + p^y\frac{\partial \bar{y}^1}{\partial s^1} + p^{z1}\left(\frac{\partial \bar{z}^1}{\partial s^1} - \frac{\partial z^1}{\partial s^1}\right) - (p^y + s^1)\frac{\partial y^1}{\partial s^1} + t^1\left(\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1}\right)$$
$$- \tau^1\left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

Since there is no trade of the good z, i.e. $\left(\frac{\partial \bar{z}^1}{\partial v^1} = \frac{\partial z^1}{\partial v^1}\right)$:

$$= p^x\left(\frac{\partial \bar{x}^1}{\partial s^1} - \frac{\partial x^1}{\partial s^1}\right) + p^y\frac{\partial \bar{y}^1}{\partial s^1} - (p^y + s^1)\frac{\partial y^1}{\partial s^1} + t^1\left(\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1}\right)$$
$$- \tau^1\left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

Recall (4), further we differentiate (4) w.r.t. consumption tax, remembering the product rule:

$$\frac{\partial p^y}{\partial s^1}(y^1 - \bar{y}^1) + p^y\left(\frac{\partial y^1}{\partial s^1} - \frac{\partial \bar{y}^1}{\partial s^1}\right) + \frac{\partial p^x}{\partial s^1}(x^1 - \bar{x}^1) + p^x\left(\frac{\partial x^1}{\partial s^1} - \frac{\partial \bar{x}^1}{\partial s^1}\right) = 0$$

solving this for p^x

$$p^x = \frac{\left(p^y\left(\frac{\partial y^1}{\partial s^1} - \frac{\partial \bar{y}^1}{\partial s^1}\right) + \frac{\partial p^y}{\partial s^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial s^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial s^1} - \frac{\partial \bar{x}^1}{\partial s^1}\right)}$$

we insert this into our equation for p^x

$$\frac{\partial W^1}{\partial s^1} = \left[\frac{\left(p^y\left(\frac{\partial y^1}{\partial s^1} - \frac{\partial \bar{y}^1}{\partial s^1}\right) + \frac{\partial p^y}{\partial s^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial s^1}(x^1 - \bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial s^1} - \frac{\partial \bar{x}^1}{\partial s^1}\right)}\right]\left(\frac{\partial \bar{x}^1}{\partial s^1} - \frac{\partial x^1}{\partial s^1}\right) + p^y\frac{\partial \bar{y}^1}{\partial s^1}$$
$$- (p^y + s^1)\frac{\partial y^1}{\partial s^1} + t^1\left(\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1}\right)$$
$$- \tau^1\left[\frac{\partial e^{y1}}{\partial s^1} + \frac{\partial e^{y2}}{\partial s^1} + \frac{\partial e^{y3}}{\partial s^1} + \frac{\partial e^{z1}}{\partial s^1} + \frac{\partial e^{z2}}{\partial s^1} + \frac{\partial e^{z3}}{\partial s^1}\right]$$

and since

$$-\frac{\left(\frac{\partial \bar{x}^1}{\partial s^1}-\frac{\partial x^1}{\partial s^1}\right)}{\left(\frac{\partial x^1}{\partial s^1}-\frac{\partial \bar{x}^1}{\partial s^1}\right)}=\frac{\left(\frac{\partial \bar{x}^1}{\partial s^1}-\frac{\partial x^1}{\partial s^1}\right)}{\left(\frac{\partial \bar{x}^1}{\partial s^1}-\frac{\partial x^1}{\partial s^1}\right)}=1$$

We can further simplify:

$$=p^y\left(\frac{\partial y^1}{\partial s^1}-\frac{\partial \bar{y}^1}{\partial s^1}\right)+\frac{\partial p^y}{\partial s^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial s^1}(x^1-\bar{x}^1)+p^y\frac{\partial \bar{y}^1}{\partial s^1}-(p^y+s^1)\frac{\partial y^1}{\partial s^1}$$
$$+t^1\left(\frac{\partial e^{y1}}{\partial s^1}+\frac{\partial e^{z1}}{\partial s^1}\right)-\tau^1\left[\frac{\partial e^{y1}}{\partial s^1}+\frac{\partial e^{y2}}{\partial s^1}+\frac{\partial e^{y3}}{\partial s^1}+\frac{\partial e^{z1}}{\partial s^1}+\frac{\partial e^{z2}}{\partial s^1}+\frac{\partial e^{z3}}{\partial s^1}\right]$$

$$=p^y\left(\frac{\partial y^1}{\partial s^1}-\frac{\partial \bar{y}^1}{\partial s^1}+\frac{\partial \bar{y}^1}{\partial s^1}-\frac{\partial y^1}{\partial s^1}\right)+\frac{\partial p^y}{\partial s^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial s^1}(x^1-\bar{x}^1)-s^1\frac{\partial y^1}{\partial s^1}+t^1\left(\frac{\partial e^{y1}}{\partial s^1}+\frac{\partial e^{z1}}{\partial s^1}\right)$$
$$-\tau^1\left[\frac{\partial e^{y1}}{\partial s^1}+\frac{\partial e^{z1}}{\partial s^1}+\frac{\partial e^{y2}}{\partial s^1}+\frac{\partial e^{z2}}{\partial s^1}+\frac{\partial e^{y3}}{\partial s^1}+\frac{\partial e^{z3}}{\partial s^1}\right]$$

Recall the constraint on emission in region $j=\{1,2\}$, $\bar{E}^j=e^{yj}+e^{zj}$. By differentiating this w.r.t the consumption tax, we have that:

$$\frac{\partial \bar{E}^j}{\partial s^1}=\frac{\partial e^{yj}}{\partial s^1}+\frac{\partial e^{zj}}{\partial s^1}=0$$

By this assumption, our equation can now be expressed as:

$$=p^y\left(\frac{\partial y^1}{\partial s^1}-\frac{\partial \bar{y}^1}{\partial s^1}+\frac{\partial \bar{y}^1}{\partial s^1}-\frac{\partial y^1}{\partial s^1}\right)+\frac{\partial p^y}{\partial s^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial s^1}(x^1-\bar{x}^1)-s^1\frac{\partial y^1}{\partial s^1}-\tau^1\left[\frac{\partial e^{y3}}{\partial s^1}+\frac{\partial e^{z3}}{\partial s^1}\right]$$

and simplified to

$$=-s^1\frac{\partial y^1}{\partial s^1}+\frac{\partial p^y}{\partial s^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial s^1}(x^1-\bar{x}^1)-\tau^1\left[\frac{\partial e^{y3}}{\partial s^1}+\frac{\partial e^{z3}}{\partial s^1}\right]$$

And we finally arrive at (6), by moving s^1 on the other side of the equal sign

$$s^{1*}=\left(\frac{\partial y^1}{\partial s^1}\right)^{-1}\left[-\tau^1\left(\frac{\partial e^{y3}}{\partial y^3}\frac{\partial y^3}{\partial s^1}+\frac{\partial e^{z3}}{\partial z^3}\frac{\partial z^3}{\partial s^1}\right)+\frac{\partial p^y}{\partial s^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial s^1}(x^1-\bar{x}^1)\right] \quad (6)$$

A2: Region welfare maximization with consumption tax

By differentiating the regional welfare (5) with respect to consumptions tax, we get

$$\frac{\partial W^1}{\partial v^1} = u_x^1 \frac{\partial \bar{x}^1}{\partial v^1} + u_y^1 \frac{\partial \bar{y}^1}{\partial v^1} + u_z^1 \frac{\partial \bar{z}^1}{\partial v^1} - c_x^{x1} \frac{\partial x^1}{\partial v^1} - c_y^{y1} \frac{\partial y^1}{\partial v^1} - c_z^{z1} \frac{\partial z^1}{\partial v^1} - c_e^{y1} \frac{\partial e^{y1}}{\partial v^1} - c_e^{z1} \frac{\partial e^{z1}}{\partial v^1}$$
$$- \tau^1 \left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

Recall the conditions and assumptions from (2) and (3), and we then get

$$= p^x \frac{\partial \bar{x}^1}{\partial v^1} + (p^y + v^1) \frac{\partial \bar{y}^1}{\partial v^1} + p^{z1} \frac{\partial \bar{z}^1}{\partial v^1} - p^x \frac{\partial x^1}{\partial v^1} - (p^y + s^1) \frac{\partial y^1}{\partial v^1} - p^{z1} \frac{\partial z^1}{\partial v^1} + t^1 \frac{\partial e^{y1}}{\partial v^1} + t^1 \frac{\partial e^{z1}}{\partial v^1}$$
$$- \tau^1 \left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

We further simplify the equation

$$= p^x \frac{\partial \bar{x}^1}{\partial v^1} - p^x \frac{\partial x^1}{\partial v^1} + (p^y + v^1) \frac{\partial \bar{y}^1}{\partial v^1} + p^{z1} \frac{\partial \bar{z}^1}{\partial v^1} - p^{z1} \frac{\partial z^1}{\partial v^1} - (p^y + s^1) \frac{\partial y^1}{\partial v^1} + t^1 \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right)$$
$$- \tau^1 \left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

$$= p^x \left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1} \right) + (p^y + v^1) \frac{\partial \bar{y}^1}{\partial v^1} + p^{z1} \left(\frac{\partial \bar{z}^1}{\partial v^1} - \frac{\partial z^1}{\partial v^1} \right) - (p^y + s^1) \frac{\partial y^1}{\partial v^1} + t^1 \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right)$$
$$- \tau^1 \left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

Since there is no trade of the good z, i.e. $\left(\frac{\partial \bar{z}^1}{\partial v^1} = \frac{\partial z^1}{\partial v^1} \right)$:

$$= p^x \left(\frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial x^1}{\partial v^1} \right) + (p^y + v^1) \frac{\partial \bar{y}^1}{\partial v^1} - (p^y + s^1) \frac{\partial y^1}{\partial v^1} + t^1 \left(\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} \right)$$
$$- \tau^1 \left[\frac{\partial e^{y1}}{\partial v^1} + \frac{\partial e^{y2}}{\partial v^1} + \frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z1}}{\partial v^1} + \frac{\partial e^{z2}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

Recall (4), further we differentiate (4) w.r.t. consumption tax, remembering the product rule:

$$\frac{\partial p^y}{\partial v^1}(y^1-\bar{y}^1)+p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \bar{y}^1}{\partial v^1}\right)+\frac{\partial p^x}{\partial v^1}(x^1-\bar{x}^1)+p^x\left(\frac{\partial x^1}{\partial v^1}-\frac{\partial \bar{x}^1}{\partial v^1}\right)=0$$

solving this for p^x

$$p^x=\frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \bar{y}^1}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial v^1}(x^1-\bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1}-\frac{\partial \bar{x}^1}{\partial v^1}\right)}$$

we insert this into our equation for p^x

$$\frac{\partial W^1}{\partial v^1}=\left[\frac{\left(p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \bar{y}^1}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial v^1}(x^1-\bar{x}^1)\right)}{-\left(\frac{\partial x^1}{\partial v^1}-\frac{\partial \bar{x}^1}{\partial v^1}\right)}\right]\left(\frac{\partial \bar{x}^1}{\partial v^1}-\frac{\partial x^1}{\partial v^1}\right)+(p^y+v^1)\frac{\partial \bar{y}^1}{\partial v^1}$$
$$-(p^y+s^1)\frac{\partial y^1}{\partial v^1}+t^1\left(\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}\right)$$
$$-\tau^1\left[\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{y3}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}+\frac{\partial e^{z3}}{\partial v^1}\right]$$

and since

$$-\frac{\left(\frac{\partial \bar{x}^1}{\partial v^1}-\frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial x^1}{\partial v^1}-\frac{\partial \bar{x}^1}{\partial v^1}\right)}=\frac{\left(\frac{\partial \bar{x}^1}{\partial v^1}-\frac{\partial x^1}{\partial v^1}\right)}{\left(\frac{\partial \bar{x}^1}{\partial v^1}-\frac{\partial x^1}{\partial v^1}\right)}=1$$

We can further simplify:

$$=p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \bar{y}^1}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial v^1}(x^1-\bar{x}^1)+(p^y+v^1)\frac{\partial \bar{y}^1}{\partial v^1}-(p^y+s^1)\frac{\partial y^1}{\partial v^1}$$
$$+t^1\left(\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}\right)-\tau^1\left[\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{y3}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}+\frac{\partial e^{z3}}{\partial v^1}\right]$$

$$=p^y\left(\frac{\partial y^1}{\partial v^1}-\frac{\partial \bar{y}^1}{\partial v^1}+\frac{\partial \bar{y}^1}{\partial v^1}-\frac{\partial y^1}{\partial v^1}\right)+\frac{\partial p^y}{\partial v^1}(y^1-\bar{y}^1)+\frac{\partial p^x}{\partial v^1}(x^1-\bar{x}^1)+v^1\frac{\partial \bar{y}^1}{\partial v^1}-s^1\frac{\partial y^1}{\partial v^1}$$
$$+t^1\left(\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}\right)-\tau^1\left[\frac{\partial e^{y1}}{\partial v^1}+\frac{\partial e^{z1}}{\partial v^1}+\frac{\partial e^{y2}}{\partial v^1}+\frac{\partial e^{z2}}{\partial v^1}+\frac{\partial e^{y3}}{\partial v^1}+\frac{\partial e^{z3}}{\partial v^1}\right]$$

Recall the constraint on emission in region $j = \{1,2\}$, $\bar{E}^j = e^{yj} + e^{zj}$. By differentiating this w.r.t the consumption tax, we have that:

$$\frac{\partial \bar{E}^j}{\partial v^1} = \frac{\partial e^{yj}}{\partial v^1} + \frac{\partial e^{zj}}{\partial v^1} = 0$$

By this assumption, our equation can now be expressed as:

$$= p^y \left(\frac{\partial y^1}{\partial v^1} - \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial \bar{y}^1}{\partial v^1} - \frac{\partial y^1}{\partial v^1} \right) + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} - \tau^1 \left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

and simplified to

$$= v^1 \frac{\partial \bar{y}^1}{\partial v^1} - s^1 \frac{\partial y^1}{\partial v^1} + \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) + \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) - \tau^1 \left[\frac{\partial e^{y3}}{\partial v^1} + \frac{\partial e^{z3}}{\partial v^1} \right]$$

And we finally arrive at (8), by moving v^1 on the other side of the equal sign

$$v^{1*} = \left(\frac{\partial \bar{y}^1}{\partial v^1} \right)^{-1} \left[s^1 \frac{\partial y^1}{\partial v^1} - \frac{\partial p^y}{\partial v^1}(y^1 - \bar{y}^1) - \frac{\partial p^x}{\partial v^1}(x^1 - \bar{x}^1) + \tau^1 \left(\frac{\partial e^{y3}}{\partial y^3} \frac{\partial y^3}{\partial v^1} + \frac{\partial e^{z3}}{\partial z^3} \frac{\partial z^3}{\partial v^1} \right) \right] \quad (8)$$

A3: The effect of OBA and consumption tax on quantity

The revenue for the EITE producer in region 1 is given by:

$$R^1 = (p^y + s^1) y^1$$

Differentiating with respect to s^1 gives us:

$$\frac{\partial R^1}{\partial s^1} = \frac{\partial p^y}{\partial s^1} y^1 + p^y \frac{\partial y^1}{\partial s^1} + y^1 + s^1 \frac{\partial y^1}{\partial s^1} = 0$$

Further,

$$p^y \frac{\partial y^1}{\partial s^1} + s^1 \frac{\partial y^1}{\partial s^1} = -\frac{\partial p^y}{\partial s^1} y^1 - y^1$$

$$\frac{\partial y^1}{\partial s^1} = y^1 \frac{\left(-\frac{\partial p^y}{\partial s^1} - 1\right)}{(p^y + s^1)}$$

(12)

As elaborated in section 2.2, $\frac{\partial y^1}{\partial s^1} > 0$ and $\frac{\partial p^y}{\partial s^1} < 0$. With reduced y^1 in (12), $\frac{\partial y^1}{\partial s^1}$ must be smaller as well. Indicating reduced effect of s^1 on smaller quantity of y^1.

The budget constraint for the representative agent in region 1 is presented in section 2.1:

$$M^1 = p^x \bar{x}^1 + (p^y + v^1)\bar{y}^1 + p^z \bar{z}^1$$

By differentiating it with respect to the consumption tax:

$$\frac{\partial y^1}{\partial M^1} = \frac{\partial p^x}{\partial v^1}\bar{x}^1 + p^x \frac{\partial \bar{x}^1}{\partial v^1} + \frac{\partial p^y}{\partial v^1}\bar{y}^1 + p^y \frac{\partial \bar{y}^1}{\partial v^1} + \bar{y}^1 + v^1 \frac{\partial \bar{y}^1}{\partial v^1} + \frac{\partial p^z}{\partial v^1}\bar{z}^1 + p^z \frac{\partial \bar{z}^1}{\partial v^1} = 0$$

$$\frac{\partial \bar{y}^1}{\partial v^1} = \frac{\bar{y}^1\left(-\frac{\partial p^y}{\partial v^1} - 1\right) - \frac{\partial p^x}{\partial v^1}\bar{x}^1 - p^x \frac{\partial \bar{x}^1}{\partial v^1} - \frac{\partial p^z}{\partial v^1}\bar{z}^1 - p^z \frac{\partial \bar{z}^1}{\partial v^1}}{(p^y + v^1)}$$

(13)

Recall from the discussion in section 2.2 that; $\frac{\partial \bar{y}^1}{\partial v^1}, \frac{\partial p^y}{\partial v^1} < 0$, and $\frac{\partial p^x}{\partial v^1}, \frac{\partial p^z}{\partial v^1}, \frac{\partial \bar{x}^1}{\partial v^1}, \frac{\partial \bar{z}^1}{\partial v^1} > 0$. With reduced $\bar{y}^1$ on the RHS, the LHS will also be smaller (less negative). Hence, suggesting reduced effect of v^1 on smaller quantity of $\bar{y}^1$

Appendix B: Summary of the numerical CGE model

Indices and sets:

Set of regions	R	EU, CHN, ROW
Set of goods	g	x, y, z
r (alias j)		Index for regions

Variables:

S^{gr}	Production of good g in r

S_{FE}^{r} Production of fossil energy (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

$p^{g,r}$ 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_{Q}^{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}^{r} Price of CO2 emission in r

p_{W}^{r} Price of consumption composite in r

o^{gr} Output-Based Allocation on g in r

v^{gr} Consumption tax on g in r

Parameters:

σ_{KLE}^{r} Substitution between value-added and energy 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_{Q}^{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

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
Q_{0}^{r}	Resource endowment of primary fossil energy in region r
$CO2_{MAX}^{r}$	CO_2 emission allowance in region r
κ_{CO2}^{r}	Coefficient for primary fossil energy of CO_2 emission in region r

Zero Profit Conditions

Production of goods except for fossil primary energy:

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

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

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

Production of fossil primary energy:

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

Sector specific value-added aggregate for FE:

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

Armington aggregate except for FE:

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

Import Composite except for FE:

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

Consumption composite:

$$\pi_W^r = \left(\theta_W^{xr} p_A^{xr\,(1-\sigma_W^r)} + \theta_W^{yr} p_A^{yr\,(1-\sigma_W^r)} + \theta_W^{zr} p_A^{zr\,(1-\sigma_W^r)} \right)^{\left(\frac{1}{1-\sigma_W^r}\right)} \geq p_W^r \qquad \perp W^r$$

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:

$$Q_0^r \geq S_{FE}^r \frac{\partial \pi_{FE}^r}{\partial p_Q^r} \qquad \perp {p_Q}^r$$

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:

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

CO_2 Emission in region:

$$CO2_{MAX}^{r} \geq \kappa_{CO2}^{r} S_{FE}^{r} \qquad \perp p_{CO2}^{r}$$

Consumption by consumers

$$p_W^r W^r \geq p_L^r \left(\sum_g L_0^{gr} + L_{0,FE}^r \right) + p_K^r \left(\sum_g K_0^{gr} + K_{0,FE}^r \right) + p_Q{}^r Q_0^r + p_{CO2}^r CO2_{MAX}^r - S^{gr} o^{gr} + D^{gr} v^{gr}$$

$$\perp p_W^r$$

Elasticities: $\sigma_{KLE} = 0.5 \quad \sigma_{KL} = 1$

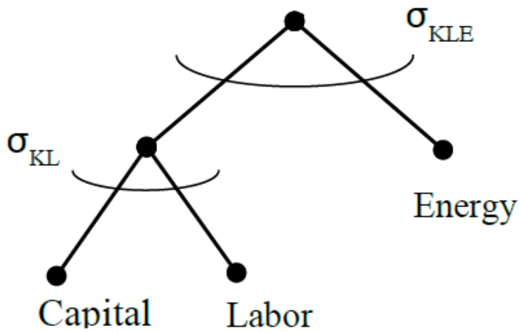

Figure 1: Nesting in production, except for fossil fuel energy

Elasticities: $\sigma_Q = 0.9 \qquad \sigma_{KL} = 1$

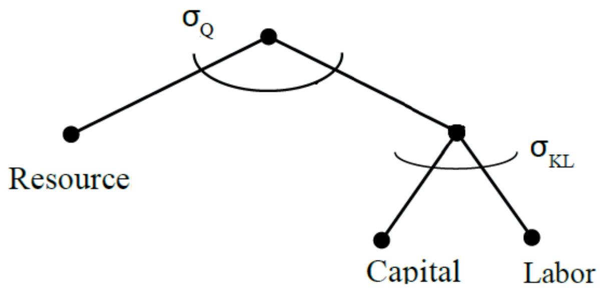

Figure 2: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$

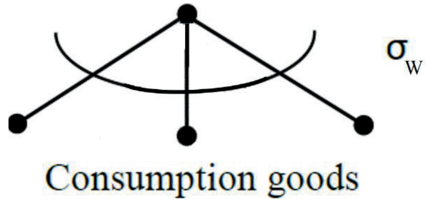

Figure 3: Nesting in consumption

Appendix C: 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
x: emission-free and tradable goods	All remaining goods and services

Table 9: Mapping of WIOD sectors to model sectors

Table 9 shows the mapping of the 56 WIOD sectors to three composite sectors in our model

Appendix D: Payoff matrices

The table listed below shows the payoffs for China and EU, given the base assumption and particular indicators in section 3.4.

	t^{EU}	$s_{20\%}$	$s_{20\%v20\%}$	$s_{20\%v40\%}$	$s_{20\%v60\%}$	$s_{20\%v80\%}$	$s_{20\%v100\%}$	$s_{40\%}$	$s_{40\%v20\%}$	$s_{40\%v40\%}$	$s_{40\%v60\%}$	$s_{40\%v80\%}$	$s_{40\%v100\%}$	$s_{60\%}$	$s_{60\%v20\%}$	$s_{60\%v40\%}$	$s_{60\%v60\%}$	$s_{60\%v80\%}$	$s_{60\%v100\%}$	$s_{80\%}$	$s_{80\%v20\%}$	$s_{80\%v40\%}$	$s_{80\%v60\%}$	$s_{80\%v80\%}$	$s_{80\%v100\%}$	$s_{100\%}$	$s_{100\%}V_{20\%}$	$s_{100\%}V_{40\%}$	$s_{100\%}V_{60\%}$	$s_{100\%}V_{80\%}$	$s_{100\%}V_{100\%}$
t^{CHN}	0.14 %	0.18 %	0.18 %	0.18 %	0.18 %	0.18 %	0.18 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.57 %	0.57 %	0.57 %	0.57 %	0.57 %	0.57 %
$s_{20\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{20\%v20\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{20\%v40\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{20\%v60\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{20\%v80\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{20\%v100\%}$	0.16 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.43 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %
$s_{40\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.33 %	0.33 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %
$s_{40\%v20\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.33 %	0.34 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %	0.60 %
$s_{40\%v40\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.33 %	0.34 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %	0.60 %
$s_{40\%v60\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.34 %	0.34 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %	0.60 %
$s_{40\%v80\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.34 %	0.34 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %	0.60 %
$s_{40\%v100\%}$	0.18 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.22 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.33 %	0.33 %	0.34 %	0.34 %	0.34 %	0.34 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.44 %	0.59 %	0.59 %	0.59 %	0.59 %	0.60 %	0.60 %
$s_{60\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.25 %	0.25 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.42 %	0.42 %	0.42 %	0.42 %	0.42 %	0.42 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{60\%v20\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.42 %	0.42 %	0.42 %	0.42 %	0.43 %	0.43 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{60\%v40\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.33 %	0.42 %	0.42 %	0.42 %	0.43 %	0.43 %	0.43 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{60\%v60\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.33 %	0.33 %	0.42 %	0.42 %	0.42 %	0.43 %	0.43 %	0.43 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{60\%v80\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.33 %	0.33 %	0.42 %	0.42 %	0.42 %	0.43 %	0.43 %	0.43 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{60\%v100\%}$	0.17 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.33 %	0.42 %	0.42 %	0.42 %	0.43 %	0.43 %	0.43 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %	0.58 %
$s_{80\%}$	0.11 %	0.14 %	0.14 %	0.14 %	0.14 %	0.14 %	0.14 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.52 %	0.52 %	0.52 %	0.52 %	0.52 %	0.52 %
$s_{80\%v20\%}$	0.11 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.52 %	0.52 %	0.52 %	0.52 %	0.53 %	0.53 %
$s_{80\%v40\%}$	0.11 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.19 %	0.19 %	0.19 %	0.20 %	0.20 %	0.20 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.37 %	0.37 %	0.52 %	0.52 %	0.52 %	0.53 %	0.53 %	0.53 %
$s_{80\%v60\%}$	0.11 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.19 %	0.20 %	0.20 %	0.20 %	0.20 %	0.20 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.37 %	0.37 %	0.52 %	0.52 %	0.52 %	0.53 %	0.53 %	0.53 %
$s_{80\%v80\%}$	0.11 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.19 %	0.19 %	0.20 %	0.20 %	0.20 %	0.20 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.37 %	0.37 %	0.52 %	0.52 %	0.52 %	0.53 %	0.53 %	0.53 %
$s_{80\%v100\%}$	0.11 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.15 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.26 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.52 %	0.52 %	0.52 %	0.52 %	0.52 %	0.53 %
$s_{100\%}$	-0.07 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.01 %	0.01 %	0.01 %	0.01 %	0.01 %	0.02 %	0.08 %	0.08 %	0.08 %	0.08 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %
$s_{100\%}V_{20\%}$	-0.07 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.37 %
$s_{100\%}V_{40\%}$	-0.06 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.20 %	0.20 %	0.36 %	0.36 %	0.36 %	0.37 %	0.37 %	0.37 %
$s_{100\%}V_{60\%}$	-0.06 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.20 %	0.20 %	0.36 %	0.36 %	0.36 %	0.36 %	0.37 %	0.37 %
$s_{100\%}V_{80\%}$	-0.07 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %
$s_{100\%}V_{100\%}$	-0.07 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	-0.03 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.02 %	0.08 %	0.08 %	0.09 %	0.09 %	0.09 %	0.09 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %

Table 10: China's welfare effect (change from BAU) with different policy combinations in China (left) and EU (top).

	t^{EU}	$s_{20\%}$	$s_{20\%v20\%}$	$s_{20\%v40\%}$	$s_{20\%v60\%}$	$s_{20\%v80\%}$	$s_{20\%v100\%}$	$s_{40\%}$	$s_{40\%v20\%}$	$s_{40\%v40\%}$	$s_{40\%v60\%}$	$s_{40\%v80\%}$	$s_{40\%v100\%}$	$s_{60\%}$	$s_{60\%v20\%}$	$s_{60\%v40\%}$	$s_{60\%v60\%}$	$s_{60\%v80\%}$	$s_{60\%v100\%}$	$s_{80\%}$	$s_{80\%v20\%}$	$s_{80\%v40\%}$	$s_{80\%v60\%}$	$s_{80\%v80\%}$	$s_{80\%v100\%}$	$s_{100\%}$	$s_{100\%}v_{20\%}$	$s_{100\%}v_{40\%}$	$s_{100\%}v_{60\%}$	$s_{100\%}v_{80\%}$	$s_{100\%}v_{100\%}$
t^{CHN}	0.19 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %	0.19 %
$s_{20\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{20\%v20\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{20\%v40\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{20\%v60\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{20\%v80\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{20\%v100\%}$	0.21 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %	0.21 %
$s_{40\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{40\%v20\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{40\%v40\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{40\%v60\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{40\%v80\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{40\%v100\%}$	0.23 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.25 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.29 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %	0.24 %
$s_{60\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %
$s_{60\%v20\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %
$s_{60\%v40\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %	0.27 %
$s_{60\%v60\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.27 %	0.28 %	0.28 %
$s_{60\%v80\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.28 %	0.28 %	0.28 %
$s_{60\%v100\%}$	0.26 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.28 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.27 %	0.27 %	0.27 %	0.28 %	0.28 %	0.28 %
$s_{80\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{80\%v20\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{80\%v40\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{80\%v60\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{80\%v80\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{80\%v100\%}$	0.30 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.31 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.33 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %	0.32 %
$s_{100\%}$	0.35 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.36 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %
$s_{100\%}v_{20\%}$	0.35 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %
$s_{100\%}v_{40\%}$	0.35 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %
$s_{100\%}v_{60\%}$	0.35 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %
$s_{100\%}v_{80\%}$	0.35 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.38 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %
$s_{100\%}v_{100\%}$	0.35 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.37 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.40 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.41 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %	0.39 %

Table 11: EU's welfare effect (change from BAU) with different policy combinations in China (left) and EU (top).

	t^{EU}	$s_{20\%}$	$s_{40\%}$	$s_{60\%}$	$s_{80\%}$	$s_{100\%}$	$v_{20\%}$	$v_{40\%}$	$v_{60\%}$	$v_{80\%}$	$v_{100\%}$
t^{CHN}	14.90 %	14.73 %	14.51 %	14.20 %	13.75 %	13.09 %	13.09 %	13.10 %	13.10 %	13.11 %	13.12 %
$s_{20\%}$	16.01 %	15.83 %	15.58 %	15.25 %	14.76 %	14.03 %	14.04 %	14.04 %	14.05 %	14.06 %	14.06 %
$s_{40\%}$	17.40 %	17.21 %	16.95 %	16.58 %	16.05 %	15.24 %	15.25 %	15.26 %	15.27 %	15.27 %	15.28 %
$s_{60\%}$	19.20 %	18.99 %	18.71 %	18.32 %	17.74 %	16.85 %	16.86 %	16.87 %	16.87 %	16.88 %	16.89 %
$s_{80\%}$	21.57 %	21.35 %	21.06 %	20.64 %	20.02 %	19.04 %	19.05 %	19.06 %	19.06 %	19.07 %	19.08 %
$s_{100\%}$	24.79 %	24.57 %	24.27 %	23.84 %	23.19 %	22.13 %	22.14 %	22.15 %	22.16 %	22.17 %	22.17 %
$v_{20\%}$	24.77 %	24.55 %	24.25 %	23.83 %	23.17 %	22.12 %	22.13 %	22.14 %	22.14 %	22.15 %	22.16 %
$v_{40\%}$	24.75 %	24.53 %	24.24 %	23.81 %	23.16 %	22.11 %	22.11 %	22.12 %	22.13 %	22.14 %	22.15 %
$v_{60\%}$	24.73 %	24.52 %	24.22 %	23.79 %	23.14 %	22.09 %	22.10 %	22.11 %	22.12 %	22.12 %	22.13 %
$v_{80\%}$	24.71 %	24.50 %	24.20 %	23.77 %	23.13 %	22.08 %	22.09 %	22.09 %	22.10 %	22.11 %	22.12 %
$v_{100\%}$	24.69 %	24.48 %	24.18 %	23.76 %	23.11 %	22.06 %	22.07 %	22.08 %	22.09 %	22.10 %	22.10 %

Table 12: China's market share of good y with different policy combinations in China (left) and EU (top).

	t^{EU}	$s_{20\%}$	$s_{40\%}$	$s_{60\%}$	$s_{80\%}$	$s_{100\%}$	$v_{20\%}$	$v_{40\%}$	$v_{60\%}$	$v_{80\%}$	$v_{100\%}$
t^{CHN}	13.40 %	14.68 %	16.37 %	18.69 %	22.03 %	27.01 %	26.98 %	26.95 %	26.92 %	26.89 %	26.86 %
$s_{20\%}$	13.12 %	14.35 %	16.00 %	18.27 %	21.55 %	26.48 %	26.45 %	26.42 %	26.39 %	26.36 %	26.33 %
$s_{40\%}$	12.75 %	13.94 %	15.52 %	17.73 %	20.93 %	25.79 %	25.76 %	25.73 %	25.70 %	25.68 %	25.65 %
$s_{60\%}$	12.27 %	13.39 %	14.91 %	17.02 %	20.12 %	24.87 %	24.84 %	24.82 %	24.79 %	24.76 %	24.73 %
$s_{80\%}$	11.64 %	12.68 %	14.08 %	16.07 %	19.01 %	23.60 %	23.57 %	23.55 %	23.52 %	23.49 %	23.46 %
$s_{100\%}$	10.78 %	11.69 %	12.94 %	14.73 %	17.44 %	21.76 %	21.74 %	21.71 %	21.68 %	21.66 %	21.63 %
$v_{20\%}$	10.78 %	11.69 %	12.94 %	14.73 %	17.43 %	21.75 %	21.73 %	21.70 %	21.67 %	21.65 %	21.62 %
$v_{40\%}$	10.77 %	11.68 %	12.93 %	14.72 %	17.42 %	21.75 %	21.72 %	21.69 %	21.67 %	21.64 %	21.61 %
$v_{60\%}$	10.77 %	11.68 %	12.93 %	14.71 %	17.41 %	21.74 %	21.71 %	21.68 %	21.66 %	21.63 %	21.60 %
$v_{80\%}$	10.77 %	11.68 %	12.92 %	14.71 %	17.40 %	21.73 %	21.70 %	21.67 %	21.65 %	21.62 %	21.59 %
$v_{100\%}$	10.77 %	11.67 %	12.92 %	14.70 %	17.40 %	21.72 %	21.69 %	21.66 %	21.64 %	21.61 %	21.59 %

Table 13: EU's market share of good *y* with different policy combinations in China (left) and EU (top).

	t^{EU}	$s_{20\%}$	$s_{40\%}$	$s_{60\%}$	$s_{80\%}$	$s_{100\%}$	$v_{20\%}$	$v_{40\%}$	$v_{60\%}$	$v_{80\%}$	$v_{100\%}$
t^{CHN}	12.30 %	12.36 %	12.42 %	12.50 %	12.62 %	12.80 %	12.80 %	12.79 %	12.79 %	12.79 %	12.79 %
$s_{20\%}$	12.01 %	12.06 %	12.13 %	12.21 %	12.34 %	12.54 %	12.54 %	12.54 %	12.54 %	12.54 %	12.54 %
$s_{40\%}$	11.63 %	11.69 %	11.76 %	11.85 %	12.00 %	12.21 %	12.21 %	12.21 %	12.21 %	12.21 %	12.21 %
$s_{60\%}$	11.14 %	11.20 %	11.27 %	11.38 %	11.53 %	11.78 %	11.78 %	11.78 %	11.77 %	11.77 %	11.77 %
$s_{80\%}$	10.49 %	10.54 %	10.62 %	10.74 %	10.91 %	11.18 %	11.18 %	11.17 %	11.17 %	11.17 %	11.17 %
$s_{100\%}$	9.58 %	9.64 %	9.73 %	9.84 %	10.02 %	10.32 %	10.32 %	10.32 %	10.32 %	10.32 %	10.31 %
$v_{20\%}$	9.59 %	9.65 %	9.73 %	9.85 %	10.03 %	10.32 %	10.32 %	10.32 %	10.32 %	10.32 %	10.32 %
$v_{40\%}$	9.60 %	9.66 %	9.74 %	9.86 %	10.04 %	10.33 %	10.33 %	10.33 %	10.33 %	10.33 %	10.33 %
$v_{60\%}$	9.61 %	9.66 %	9.75 %	9.86 %	10.04 %	10.33 %	10.33 %	10.33 %	10.33 %	10.33 %	10.33 %
$v_{80\%}$	9.61 %	9.67 %	9.75 %	9.87 %	10.05 %	10.34 %	10.34 %	10.34 %	10.34 %	10.34 %	10.34 %
$v_{100\%}$	9.62 %	9.68 %	9.76 %	9.88 %	10.05 %	10.34 %	10.34 %	10.34 %	10.34 %	10.34 %	10.34 %

Table 3: China's market share of good *x* with different policy combinations in China (left) and EU (top).

	t^{EU}	$s_{20\%}$	$s_{40\%}$	$s_{60\%}$	$s_{80\%}$	$s_{100\%}$	$v_{20\%}$	$v_{40\%}$	$v_{60\%}$	$v_{80\%}$	$v_{100\%}$
t^{CHN}	31.50 %	31.11 %	30.65 %	30.00 %	29.07 %	27.67 %	27.68 %	27.69 %	27.69 %	27.70 %	27.71 %
$s_{20\%}$	31.54 %	31.20 %	30.75 %	30.12 %	29.20 %	27.82 %	27.83 %	27.83 %	27.84 %	27.85 %	27.85 %
$s_{40\%}$	31.64 %	31.31 %	30.88 %	30.26 %	29.37 %	28.01 %	28.02 %	28.02 %	28.03 %	28.04 %	28.04 %
$s_{60\%}$	31.77 %	31.46 %	31.04 %	30.46 %	29.60 %	28.26 %	28.27 %	28.28 %	28.28 %	28.29 %	28.30 %
$s_{80\%}$	31.94 %	31.66 %	31.27 %	30.72 %	29.91 %	28.62 %	28.63 %	28.63 %	28.64 %	28.64 %	28.65 %
$s_{100\%}$	32.19 %	31.93 %	31.59 %	31.09 %	30.34 %	29.14 %	29.14 %	29.15 %	29.15 %	29.16 %	29.16 %
$v_{20\%}$	32.18 %	31.93 %	31.59 %	31.09 %	30.34 %	29.14 %	29.14 %	29.15 %	29.15 %	29.16 %	29.16 %
$v_{40\%}$	32.18 %	31.93 %	31.59 %	31.09 %	30.34 %	29.14 %	29.14 %	29.15 %	29.16 %	29.16 %	29.17 %
$v_{60\%}$	32.18 %	31.93 %	31.58 %	31.09 %	30.34 %	29.14 %	29.15 %	29.15 %	29.16 %	29.16 %	29.17 %
$v_{80\%}$	32.17 %	31.92 %	31.58 %	31.09 %	30.34 %	29.14 %	29.15 %	29.15 %	29.16 %	29.16 %	29.17 %
$v_{100\%}$	32.17 %	31.92 %	31.58 %	31.09 %	30.34 %	29.14 %	29.15 %	29.15 %	29.16 %	29.17 %	29.17 %

Table 14: EU's market share of good *x* with different policy combinations in China (left) and EU (top).

Paper 4

Optimal REDD+ in the Carbon Market

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Abstract:

Unilateral actions to reduce CO2 emissions can reduce competitiveness for emission-intensive and trade-exposed industries (EITE), causing carbon leakage through relocation of such industries. To mitigate competitiveness losses and leakage, regions often supplement an emissions trading system (ETS) with free allocation of allowances. This paper examines the welfare effects of instead introducing an emission offset mechanism for the EITE sector, where EITE producers may have to acquire more than one offset credit to balance one ETS allowance. The analytical results suggest that under certain conditions it is globally welfare improving for a single region to introduce such an offset mechanism. Numerical simulations in the context of the EU ETS and REDD+ credits support the analytical findings, and suggest that it is optimal for the EU to require EITE producers to acquire several REDD+ credits to offset one EU ETS allowance.

Key words: Carbon leakage; emission trading system; unilateral policy; REDD+

JEL classification: D61, F18, H23, Q54

1. Introduction

In order to reduce emissions of greenhouse gases (GHGs), many countries (and regions) consider or have introduced unilateral climate policies. However, unilateral action may lead to carbon leakage, such as relocation of emission-intensive and trade-exposed industries (EITE) to unregulated regions[1]. Emission pricing increases the domestic firms' production cost, which could lead to firm closures and job losses, as well as more production and emission in unregulated regions.

In the economic literature, the overall carbon leakage is suggested in the range of 5-30%, and somewhat higher for the EITE industry (see e.g., Zhang, 2012; Böhringer et al. 2012; Fischer and Fox 2012). While these numbers are quite moderate, EITE industries are typically either exempted from the regulation or considered for other anti-leakage measures. A prime example is the EU Emission Trading System (EU ETS), where sectors that are exposed to a significant risk of carbon leakage are given a large number of free allowances conditional on output. This is often referred to as output-based allocation (OBA) (Böhringer & Lange, 2005). A big share of industry sectors in the EU ETS are qualified as significantly exposed to leakage. OBA has shown to be politically feasible, and commonly used in other ETS markets, too[2]. This allocation method could, however, end up stimulating too much domestic production and further moderate the incentives to substitute from carbon-intensive to carbon-free products (Böhringer & Lange, 2005; Böhringer et al., 2017; Kaushal & Rosendahl, 2017).

An alternative way to make emissions pricing more politically feasible could be to allocate permits in proportion to investment in abatement technology, often referred to as *expenditure-based* allocation (Sterner & Coria, 2012). The industry then receives permits in the ETS market subject to a benchmark of their abatement expenditure. For instance, Hagem et al. (2015) shows theoretically that to achieve a given abatement target, the refunded fee level with OBA[3] exceeds the standard carbon price, whereas the opposite is the case for expenditure-based allocation.

In the context of the EU ETS, the abatement cost is generally greater than in other regions. Thus, even with expenditure-based allocation, the impact on competiveness for the EITE firms may be adverse. An alternative to the expenditure-based allocation could be expenditure on abatement

[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] Similar allocation rules can be found in other carbon markets such as in New Zealand, California, and China (World Bank, 2014; Xiong et al., 2017).

[3] Strictly speaking, Hagem et al considers carbon taxes and rebating rather than emission trading and allocation of permits, but this should be equivalent when there is no uncertainty.

abroad. In the first phases of the EU ETS, regulated firms have had the option to use CDM (Clean Development Mechanism) credits to offset some of their emissions. This option will end after 2020, however[4]. Another alternative is REDD+ (Reducing Emissions from Deforestation and forest Degradation), which aims at reducing GHG emissions from forests in developing countries. The idea is based on use of financial incentives to change the behavior of forest users, i.e., pay the forest actors to conserve the forest (Angelsen et al., 2012). Since deforestation and land use change stand for about 11% of the global carbon emission (IPCC, 2014) and is far less costly than any other abatement action (Anger & 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, 2014). There are some studies that have explored the effects of including REDD+ credits in a global carbon market (Angelsen et al., 2014; Anger & Sathaye, 2008; 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. 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 and carbon leakage. 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 (2017), 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 emission-intensive and trade-exposed sector can offset their emissions through REDD+ credits. Further, we examine the welfare effects of introducing REDD+ credits in the EU ETS, accounting for the benefits of reduced global emissions as well. We consider different conversion rates between REDD+ credits and EU ETS allowances, meaning that the EU ETS producers may need more than one REDD+ credit to offset one unit of emissions. 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 (Angelsen et al., 2014; Angelsen et al., 2017). Our question is if unilateral action by the EU combined with REDD+ credits for the EITE producer would be welfare-improving or not, both for the EU and for the world as a whole.

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

We show analytically that under certain conditions it is globally welfare improving for a single region to introduce an emission offset mechanism for the emission-intensive and trade-exposed sector, when the emission price is already implemented in the region. We also find this to be true when the offset mechanism is introduced for all the participants in the regional carbon market. Based on the analytical findings, we supplement with results from a stylized computable general equilibrium (CGE) model calibrated to data for the world economy, with four regions and four goods. 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, regardless of whether the offset mechanism is introduced for only the trade-exposed sector or for the whole EU ETS. The optimal conversion rate, however, is far below one according to our simulations, as it implies lower global emissions.

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 goods x, y, q and z. Good x is emission-free and tradable, y is emission-intensive and tradable (EITE), q is the tradable forest and agricultural good, while z is emission-intensive and non-tradable. The same types of goods produced in different regions, are assumed homogenous in this analysis. Carbon leakage may take place through two channels; i) increased production of the q good from non-REDD+ regions when credits are introduced in REDD+ regions, and ii) relocating production of the y good. 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). 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, c_e^{yj}, c_e^{qj}, $c_e^{zj} \leq 0$ with strict inequality when emission is regulated, cost is twice differentiable and strictly convex. All derivatives are assumed to be finite.

Supply and demand give us the following market equilibrium conditions:

$$\begin{aligned} \bar{x}^1 + \bar{x}^2 + \bar{x}^3 &= x^1 + x^2 + x^3 \\ \bar{y}^1 + \bar{y}^2 + \bar{y}^3 &= y^1 + y^2 + y^3 \\ \bar{q}^1 + \bar{q}^2 + \bar{q}^3 &= q^1 + q^2 + q^3 \\ \bar{z}^j &= z^j \end{aligned} \tag{1}$$

2.1. Emission price and carbon offset credit

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 only allows the emission-intensive and trade-exposed sector to offset their emission with REDD+ credits, which we will refer to as scenario 1. Next, we allow the sector to buy and sell permits to the emission-intensive and non-trade-exposed sector as well, which we will refer to as scenario 2.

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

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

where the emission price t^1 balances the emission trading market. e_0^{q2} is the initial emission from producer q in region 2, and it is assumed that $\left(e_0^{q2} - e^{q2}\right) \geq 0$. α determines the conversion rate between emission allowances and offsets, that is, one offset corresponds to α allowances, where $0 < \alpha \leq 1$.[5] Thus, the producer of good y can either buy allowances through the emission market, or buy emission offset through REDD+ credits. The lower is α, the more offsets must be bought

[5] With $\alpha = 1$, we have the special case of perfect offset of emission for producer y in region 1 through REDD+ credits.

to be in compliance. As the z sector is not trade-exposed, we first consider the case where there is no offset considered to producer of this good, 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 producer 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 supplier, producer q^2, and demand from producer who want to offset their emission, producer y^1. The suppliers reduce their emissions, as long as they receive a payment for these services that outweigh their costs.[6] The price of REDD+ credits r, which is the price per unit emission reduction for producer q in region 2, balances the supply and demand of credits.[7] The total cost of reducing emission through REDD+ credits is then for producer y in region 1:

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

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

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

Thus, the competitive producers in region j=1,2,3 maximize profits π^j such that:[8]

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

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

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

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

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

7 We will later show that r is determined by the marginal abatement cost for producer q^2.

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

As explained above, we have that $t^{y2} = t^{z2} = t^{y3} = t^{z3} = r^1 = r^3 = 0$. Thus, producer of good y in region 2 and 3 do not buy REDD+ credits r^2. 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 producer 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 producer q:

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

From equation (3) and (4), the first line shows that the price for the good is equal to the marginal cost of producing that same good. In the second line in (3), the left-hand side shows that the marginal abatement cost of emission is equal to the emission price in region 1 for producer y. 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 of emission for the producer of good q^2, i.e., $r^2 = -c_e^{q2}$. The last line in (3) and (4) shows that the marginal abatement cost of emission is (as expected) equal to zero for the non-regulated regions and unregulated sectors.

Next, we derive the first order conditions for producer x and z:

$$\frac{\partial \pi_1^x}{\partial x^1} = p^{x1} - c_x^{x1} = 0; \ \frac{\partial \pi_2^x}{\partial x^2} = p^{x2} - c_x^{x2} = 0; \ \frac{\partial \pi_3^x}{\partial x^3} = p^{x3} - c_x^{x3} = 0$$
$$\frac{\partial \pi_j^z}{\partial z^j} = p^{zj} - c_z^{zj} = 0$$
$$\frac{\partial \pi_1^z}{\partial e^{z1}} = c_e^{z1} + t^{z1} = 0 \tag{5}$$
$$\frac{\partial \pi_2^z}{\partial e^{z2}} = c_e^{z2} = 0; \ \frac{\partial \pi_3^z}{\partial e^{z3}} = c_e^{z3} = 0$$

We see that the 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:

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

Differentiating the *Lagrangian* function w.r.t the goods, we get the following first-order conditions:

$$\frac{\partial \mathcal{L}}{\partial \bar{x}^j} = u_{\bar{x}}^j - p^x = 0, \qquad \frac{\partial \mathcal{L}}{\partial \bar{y}^j} = u_{\bar{y}}^j - p^y = 0, \frac{\partial \mathcal{L}}{\partial \bar{q}^j} = u_{\bar{q}}^j - p^q = 0,$$
$$\frac{\partial \mathcal{L}}{\partial \bar{z}^j} = u_{\bar{z}}^j - p^{zj} = 0 \tag{6}$$

where we have assumed interior solution, and normalized the utility functions so that $\lambda^j = 1$.

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

$$p^y(y^j - \bar{y}^j) + p^x(x^j - \bar{x}^j) + p^q(q^j - \bar{q}^j) = 0 \tag{7}$$

2.2 Change in emission price

In this section, we will show how the change in α affects the emission price t for the producer of good y in scenario 2. However, the results also holds for the emission price t^y in scenario 1. As discussed in the introduction, the assumption is that abatement through REDD+ credits for producer y is less costly than reducing emission on their own. With a single emission market in region 1 and thus one emission price for both sectors, we have established with equation (2) – (5)

that the relationship between the emission price t^1, REDD+ credit price r^2, and α is $t^1 = \frac{r^2}{\alpha}$. Both t^1 and r^2 are endogenous, balancing their respective markets, and depend on the marginal abatement cost; c_e^{y1}, c_e^{z1} and c_e^{q2}. The emission price for producer of good y (t^1) will decrease with increasing α. This can be shown by first taking the derivative of (2) and $t^1 = \frac{r^2}{\alpha}$ with respect to α:

$$\frac{\partial \bar{E}^1}{\partial \alpha} = \frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} + \alpha \frac{\partial e^{q2}}{\partial \alpha} - \left(e_0^{q2} - e^{q2}\right) = 0$$

$$\frac{\partial r^2}{\partial \alpha} = t^1 + \alpha \frac{\partial t^1}{\partial \alpha}$$

To show that t^1 decreases with α, let us first assume the opposite, i.e., $\frac{\partial t^1}{\partial \alpha} \geq 0$. Higher or unchanged emission price implies that the demand for emission permits in the region decreases or stay unchanged, i.e., both e^{y1} and e^{z1} would decrease or remain the same. From the second equation above, we see that $\frac{\partial t^1}{\partial \alpha} \geq 0$ 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 $\frac{\partial \bar{E}^1}{\partial \alpha}$ above. As the expression must be equal to zero, this doesn't add up. Therefore, we must have that the emission price t^1 will decrease with increasing share of α. It is straightforward to show that this is also true for t^{y1} in scenario 1. Hence, we have the following result:

Lemma 1. *Let 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 in region i from region j,* α*, be given by equations (2) - (5), i.e.,* $t^i = \frac{r^j}{\alpha}$*. Further, assume that the conversion rate in region i is* $0 < \alpha \leq 1$*. Then, increasing the conversion rate in region i would reduce the emission price in region i.*

Proof. *The lemma follows from equations (2) - (5) as explained above.*

2.3 The global welfare effect

We express the global welfare as:

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

where τ^1 is region 1's valuation of reduced global GHG emissions. We will refer to this as the *Pigouvian* tax.[9]

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 the global welfare be given by equation (8). Then the global welfare effect of increasing the conversion rate* α *for producer of good* y *is given by:*

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1 \frac{\partial e^{q2}}{\partial \alpha} - \tau^1 \left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \tag{9}$$

Proof. *See Appendix A.*

Given our assumption of $0 < \alpha \leq 1$ and $\left(e_0^{q2} - e^{q2}\right) > 0$, equation (10) shows that if $\tau^1 = 0$ then $\frac{\partial W^G}{\partial \alpha} > 0$. That is, if we disregard the damage cost of emissions, then the global welfare effect is positive with increasing offset conversion rate. In this case, the positive welfare effect of increasing α is simply a pure global cost saving.

It is of course more reasonable to assume that $\tau^1 > 0$. If the domestic emission price is equal to the *Pigouvian* tax, the first term becomes zero since $t^1 = \frac{r^2}{\alpha}$. As t^1 is reduced when offsets are introduced, we may well have that $\tau^1 > \frac{r^2}{\alpha}$. Hence, it seems likely that:

$$\left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) \leq 0 \tag{10}$$

[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.

From Lemma 1 we know that t^1 decreases with α, and hence we must have $\frac{\partial e^{y1}}{\partial \alpha} > 0$. It is more uncertain what happens with e^{q2} though when α increases. Initially, starting from $\alpha = 0$, it must obviously decrease. When $\alpha > 0$, it is more ambiguous what happens when α is further increased. We see from (2) that $\alpha \frac{\partial e^{q2}}{\partial \alpha} = \left(e_0^{q2} - e^{q2}\right) - \frac{\partial e^{y1}}{\partial \alpha}$. As mentioned, the latter term is negative, while the former is positive (when $\alpha > 0$).

The intuitive explanation is that as α increases from a certain level, fewer credits are needed to offset emission by y^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. Hence, $\frac{\partial e^{q2}}{\partial \alpha}$ is in general ambiguous. As α approaches 1, we see that the size of the second term approaches zero. If $t^1 = \tau^1$, the welfare effect then comes down to the very last bracket of equation (9).

The last bracket consists of the leakage effects, and we must consider what will happen with production and hence emissions in unregulated regions and sectors. Increasing α reduces the production cost for producer y in region 1. This would strengthen their competitiveness level on the world market and further lower the price of the good p^y. Production from region 2 and 3 of good y would now be less profitable. Hence, it is likely that:

$$\frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} < 0 \tag{11}$$

From our previous discussion, increasing the share of α would have an ambiguous effect on the abatement for producer q^2. If $\frac{\partial e^{q2}}{\partial \alpha} < 0$, some of this abatement would likely be through lower production. It then seems reasonable that the price p^q increases somewhat, and hence production of q^1 and q^3 increases slightly as well. This would suggest that $\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} > 0$. If instead $\frac{\partial e^{q2}}{\partial \alpha} > 0$, we will have the opposite situation, i.e., $\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} < 0$. In any case, the second term in (9) and this leakage effect go in different directions with respect to welfare, and the sum of these is 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. Hence:

$$\frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha} \leq 0 \tag{12}$$

To sum up, although the effects on emissions in the q market is ambiguous, it seems quite likely that unregulated emissions will decrease when α increases, in which case the last term in (9) is positive.

Based on the discussion of equation (9), we have the following result:

Proposition 1. *Consider a region i that has an emission trading system, where the producer of emission-intensive and trade-exposed goods, y, can offset their emissions through emission credits from a sector q in region j with a conversion rate α. Assume further that the emission price for producer y is equal to or below the Pigouvian tax. Then it is global welfare improving to increase the conversion rate α if the emission from sector q in region j decreases or is unaffected by this increase.*

Proof. *The proposition follows from equations (7) - (12).*

In Appendix A we show that Proposition 1 also holds in scenario 2, i.e., the producer in region 1 sector y can sell their permits to sector z in the same region

3. Numerical analysis

The stylized theoretical analysis explains some of the outcomes of introducing REDD+ credits in a carbon markets. In order to get a more in-depth insights into the proportion of economic effects and the ambiguous results, we now transfer our analysis to numerical simulations with a stylized computable general equilibrium (CGE) model. Incorporating REDD+ credit allowances in EU ETS is of particular interest, as the abatement cost in this region is relatively high and carbon leakage is of concern. Further, we are interested in both Brazil and Indonesia as regions, since they both have a quite dense rainforest whose deforestation is a major source of CO2 emissions. Particularly Brazil is considered as the supplier of REDD+ credits. By separating these two regions we are able to capture the possible leakage effect (and trade patterns) related to participating in REDD+ (Gan & McCarl, 2007; Sun & Sohngen, 2009). 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 emission-intensive and trade-exposed sector, when the effects on global emission and carbon leakage, as well as trade patterns are taken into account.

3.1 Model summary

The model consists of four regions calibrated according to the European Union/ European Economic Area (EU), Brazil (BRA), Indonesia (IDN) and rest of the world (ROW). The four regions have five production sectors: 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 an 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 the carbon leakage related to the competitive channel for the goods z and q (the latter related to the REDD+ market). We distinguish between domestic and foreign produced goods, with no 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 a technological constraints. Production of x, q, y and z 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[10]. Fossil related emission is proportional to the use of fossil energy as input for 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.

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

3.2 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)[11], and we further reconstruct the empirical data to fit the model from the theoretical analysis. 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, q, y, z and f.[12] Further, we stick to the same 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[13]. For the agriculture and forestry sector, we combine the data of land use from WIOD with other studies. Carbon sequestration in the different regions related to forest and land use change are collected from Malhi et al. (1999), IPCC (2000), Gan and McCarl (2007), Sun and Sohngen (2009), Kindermann et al. (2008) and FAOSTAT (2018). While we base the values on these studies, it is important to note that the sequestration rate varies and depends on the age and the types of forest. Further, the land prices in the regions are based on data from EUROSTAT (2016), USDA (2018), SEAB (2016), and Dislich et al. (2018). These data where relatively difficult to collect, and ideally an open-access database will be beneficial for similar future studies[14]. Finally, we structure the production function for sector q and calibrate the substitution between land use and value-added composite (capital and labor), and we calibrate the marginal abatement cost estimates according to the collected data.

The net exports in sector x, q and y in the base-year is 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. 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. We distinguish between domestic and foreign

[11] The model is implemented as a Mixed Complementarity Problem in GAMS, using the PATH-solver.
[12] See appendix C for mapping of WIOD sectors.
[13] In the WIOD dataset, sector x accounted for 14% of the global (fossil related) CO_2 emissions in 2009.
[14] Coomes et al. (2018):"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."

goods by origin, based on Armington's approach (Armington, 1969). 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 x, q and y. Finally at the third level, we differentiate between the origins of the foreign produced goods. At the second level for goods x and y the substitution elasticity is set to 16, and 32 at the third level. For good q the substitution elasticity at the second level is set to 4, and the third level to 8. The size of the substitution elasticities determine how close goods produced with different origins are.[15] Hence, we implicitly assume that the agricultural and forest good q is less trade-exposed than the emission-intensive (manufacturing) good y and the non-carbon good x. However, there are uncertainties related to how trade-exposed the q good is. Particularly, the output response by other regions and carbon leakage that occurs in this sector depends on forest type, product variety, international transport costs, and carbon up take (García et al., 2018). Hence, we will also consider alternative assumptions about the Armington elasticities in the sensitivity analysis.

3.3 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 scenario[16]. 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. The reduction target is set to 20 percent.[17] Next we consider the same scenarios as discussed in the theoretical analysis, where producer y can buy REDD+ credits to offset its 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. We consider both scenarios examined in the theoretical analysis, where: *1)* only producer y can offset its emissions through REDD+ credits and *cannot* resell emission allowances to sector z, and *2)* producer y can offset its emissions through REDD+ credits and *can* resell emission allowances to sector z. We consider only Brazil (BRA) as the supplier of REDD+ credits, and further assume that the CO_2 emission level for Brazil

[15] Thus, with an infinite Armington elasticity on the second and third levels, it would be possible to transform it into perfect substitution between locally produced and imported goods.
[16] In 2009 the ETS price was roughly 13 Euro per ton CO_2
[17] We can think of this emission target as an additional emission reduction target of 20 percent 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.

producer q in the *REF* scenario is taken as the reference level for offsets. Hence, the cap in the EU ETS is endogenously increased by $\alpha\left(e_{ref}^{qBRA} - e^{qBRA}\right) \geq 0$.

Finally, 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. Finally, to examine the sensitivity of our findings, we also present a number of sensitivity analysis in Section 3.5.

3.4 Results

In this chapter, 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 *BAU* and the different policy scenarios. The welfare is defined by the CES utility function for the representative agent minus the valuation of changes in global emissions.

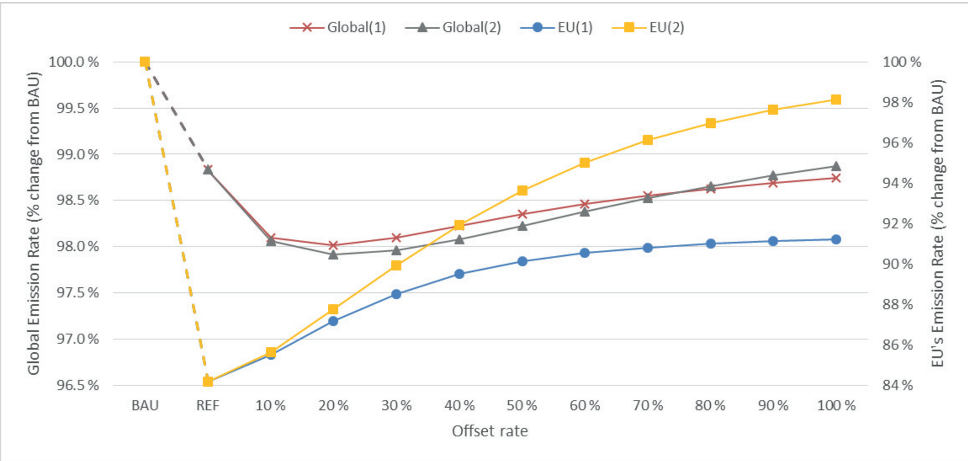

Figure 1: Global and EU's emission rate under different combination of policies in scenario 1 and 2.

Figure 1 shows the effect on the global emission and EU's emission in the different scenarios. The numbers *1* and *2* in the parenthesis behind the legend corresponds to scenario *1* and *2* from our theoretical analysis. Here, we measure the emission rate from both fossil energy and land use change. With only emission pricing in the EU, emissions in the EU declines by 16 %, leading to a 1.2% reduction in global emissions. Since 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).

Next, the figure shows that allowing for offsets has a significant impact on global emission, which has a minimum when α is 20%, i.e., one REDD+ credit translates into 0.2 ETS allowances. The global emission rate is a little lower in scenario 2 than in scenario 1, that is, up to an offset rate of 70%. This is due to relatively more offset credits being bought in scenario 2. It follows that EU's emission rate is higher under scenario 2 than scenario 1.

Figures 2 show the effects on leakage in scenario 1 and scenario 2, that is, 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_f* shows the leakage rate to energy-intensive producers y and z in other regions, *EU_fq* shows the leakage rate from the EU ETS to all other sector (y, z and q), and finally *BRAq*, shows the leakage rate from agriculture and forestry producer q in Brazil to sector q in other regions.

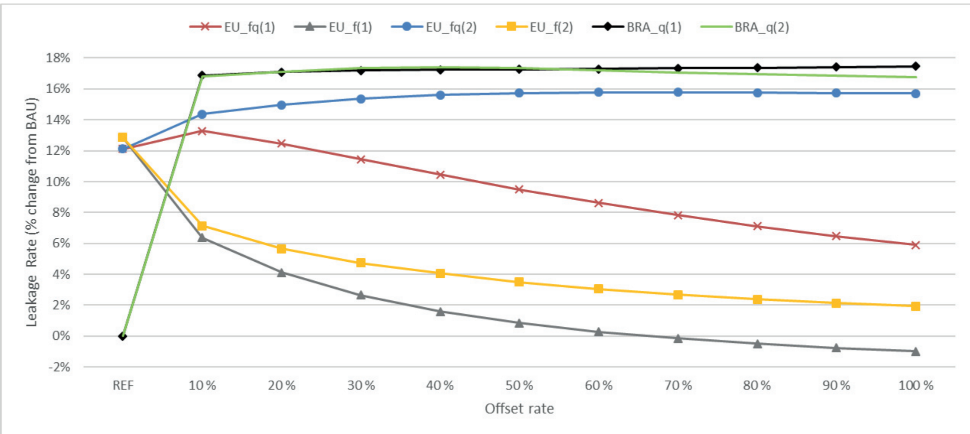

Figure 2: Leakage rate from y and z in EU and q in BRA under different combination of policies in scenario 1 and 2.

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 the demand for inputs from other production sectors including sector q. Further, by 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), which becomes negative above 60% offset in scenario 1. Leakage to sector q actually contributes more to overall leakage in all offset scenarios. It reaches a maximum at 40% offset rate in scenario 1, while increases monotonically with the offset rate in scenario 2. This is due to more demand for offsets in scenario 2, which reduces the production of good q in BRA more than in scenario 1. As a consequence, the producer of good q in the other regions increase their production, and hence emission, even more. Therefore, introducing an offset possibility leads to a bigger reduction in the leakage rate in scenario 1 than scenario 2.

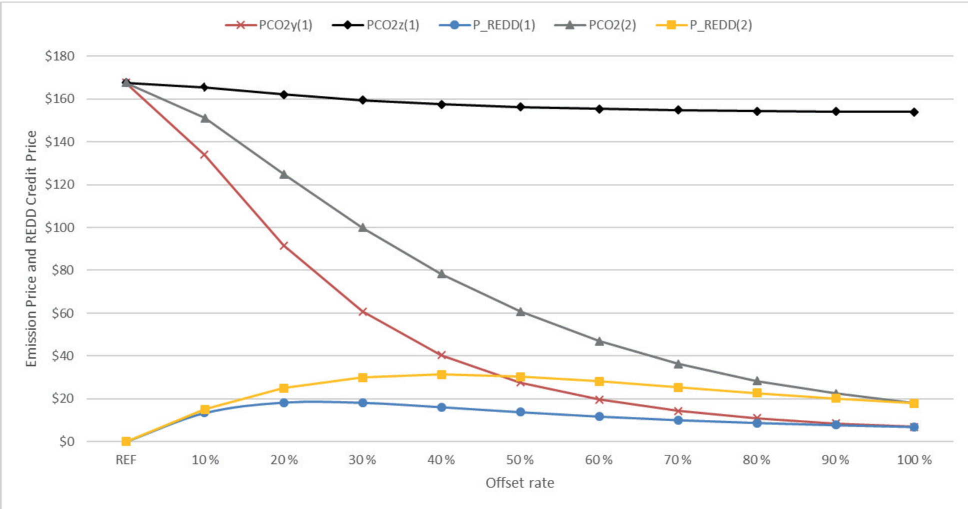

Figure 3: Price of emission and REDD+ credit under different combination of policies in scenario 1 and 2.

As mentioned before, the main reason why leakage from the regulating region decreases is that the REDD+ credits make it less costly to reduce emission. Hence, 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 emission price for producer y and z, and the REDD+ credit price, in scenario 1. In line with our theoretical analysis, the offset possibility lowers the emission price substantially for the producer of good y. The emission price for the producer of good z decreases to some degree, as consumers now shift their consumption towards the relatively cheaper good y. The same pattern is seen in scenario 2, where producers of good y and z in the EU have one common emission price. Here, too, the emission price decreases rapidly, but less than in scenario 1. Figure 3 show that an increasing offset 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 top point, however, of around \$19 with 25% offset rate in scenario 1, and \$32 with 40% offset rate in scenario 2. Recall from our theoretical analysis that the price of REDD+ credits could indeed either increase or decrease with increasing offset rate. On the one hand, a higher offset rate makes REDD+ credits more valuable, leading to higher demand. On the other hand, a higher offset rate also means that fewer REDD+ credits are needed to offset a given amount of emissions. As illustrated by the figures, the former effect is dominating at low offset rates, while the latter is dominating at high rates. Finally, as discussed earlier, demand for REDD+ credits is relatively higher in scenario 2 since both sector y and z benefit from the offset possibilities. As a result, this increases the REDD+ credit price more than in scenario 1.

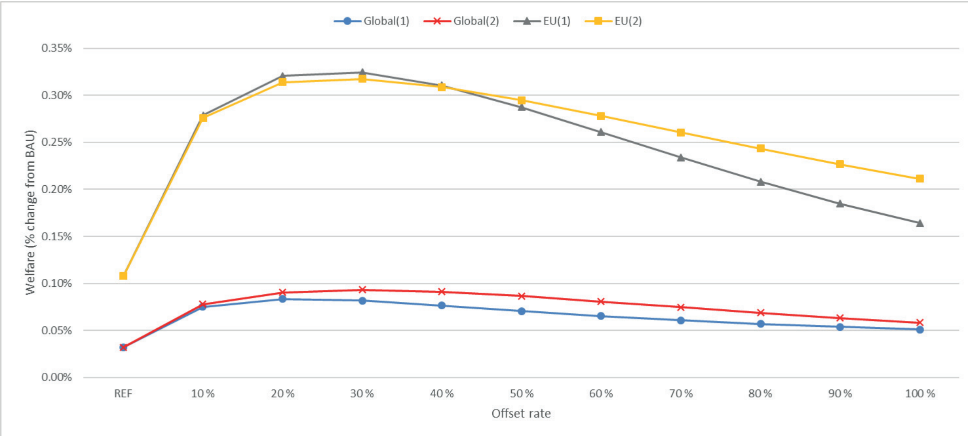

Figure 4: Global and EU's welfare effect under different combination of policies in scenario 1 and 2.

The offset mechanism reallocates production of good y from the unregulating regions back to the EU. Further, global emissions decline with the offset scenario, at least for relatively small offset rates, meaning less climate damages. Figure 4 shows the global welfare change and the welfare change in the EU under the different policies in scenario 1 and 2. The change is shown as a percentage change compared to *BAU*. Here we take into account the change in global emissions, where we use the emission price from *REF* to value these. 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 offset rate in the range of 20% in scenario 1 and 25% in scenario 2 for global welfare. These are also the offset rates where global emission is at the lowest, see Figure 1. For the EU, the optimal offset rate is in the range of 25% in both scenarios. If we were to ignore the welfare effects of lower global emissions, the optimal offset rate (both globally and for the EU) increases to 100%. The reason is that the offset possibility is a cost saving policy for the abating region, and hence the welfare gain in the EU (and globally) is highest in scenario 2 when both y and z producers can use offsets. To sum up, from a pure economic perspective, 100% offset 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 offset rate is optimal when the benefits of global emission reductions are also accounted for.

3.5 Sensitivity analysis

In the sensitivity analysis, we now examine the effects of changing some of our main assumptions: i) a lower Armington elasticity on traded goods, ii) infinite Armington elasticity (homogenous goods), where domestic and foreign goods are not distinguished by origin anymore, and iii) including Indonesia in the REDD+ market. We only examine scenario 1 in the sensitivity analysis.

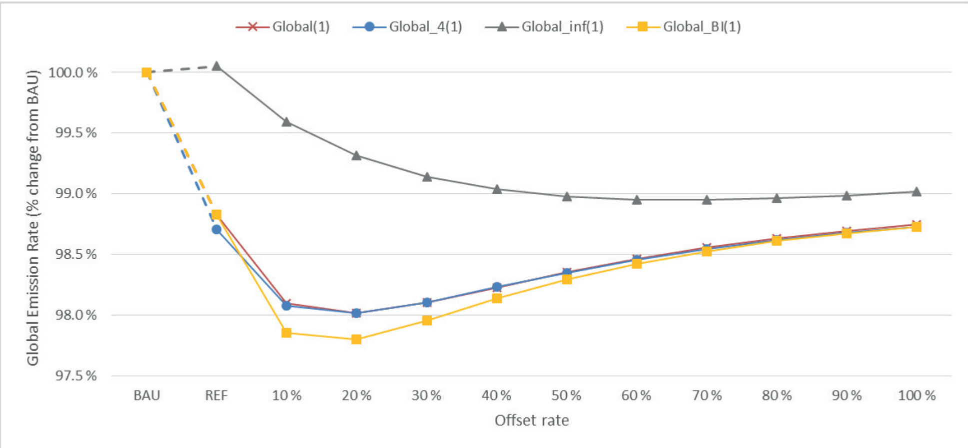

Figure 5: Global emission rate with assumption of lower Armington elasticity (_4), homogenous goods (_inf), and including Indonesia in the REDD+ market (_BI) under different combination of policies in scenario 1.

With a lower Amington elasticity, we now assume less trade-exposure for producer x, y and q. At the top level in the utility function, we keep the same assumption as before. At the second level for goods x and y the substitution elasticity is set to 4, and 8 at the third level. For good q the substitution elasticity at the second level is set to 2, and the third level to 4. In the case of homogenous goods, we still assume a substitution elasticity of 4 and 8 only for good q, at second and third level respectively. Hence, producer q is still less trade-exposed than producer x and y. In Figure 5 we show how this assumption affects the global emission rate compared to our benchmark assumption in scenario 1. The global emission rate under all the different policy scenarios are lower than the benchmark simulations with higher Armington elasticity. This is mainly a result of less trade-exposure, which limits the leakage more. Further, the numerical simulations still suggest that the offset rate that minimizes global emission is in the range of 20 % offset. In the case of homogenous goods, however, more trade exposure (and hence leakage) leads to much lower global emission reductions, and the offset rate that minimizes global emission is much higher (approximately 70%). Moreover, Figure 5 shows that the global emission in fact (slightly) *increases* from *BAU* to the *REF* scenario, and then decreases when REDD+ is introduced.

We show in Figure 6 how the choice of the Armington elasticity affects the global welfare. In general, the lower the Armington elasticity, the higher are the welfare gains under all the different policy scenarios. This is mainly the result of lower global emission, and hence the global benefits of emission reductions being bigger. The optimal offset rate is similar to or slightly higher than the offset rate that minimizes global emissions. With heterogeneous goods, the optimal rate is around 20%, while in the homogenous good case the optimal offset rate is in the range of 90%. The optimal offset rate is slightly higher than the rate that minimizes global emissions as the benefit of lower abatement cost increases with the offset rate (as discussed in section 3.4).

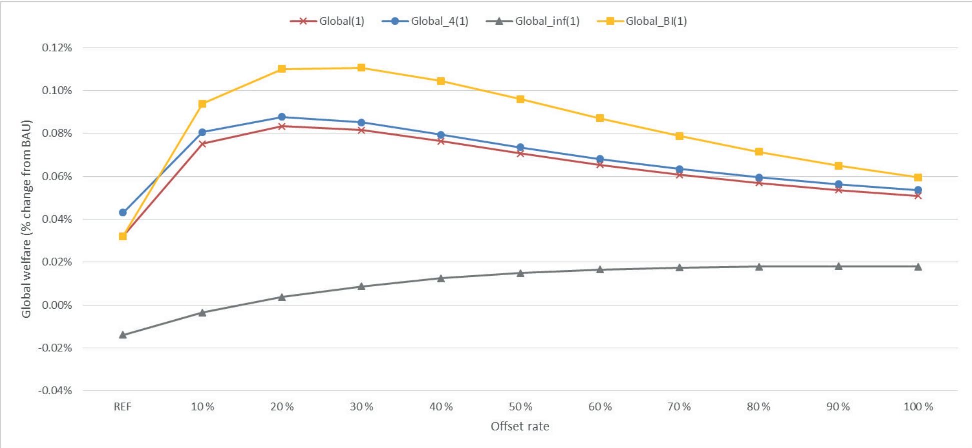

Figure 6: Global welfare effect with assumption lower Armington elasticity (_4), of homogenous goods (_inf),and including Indonesia in the REDD+ market (_BI) under different combination of policies in scenario 1.

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 emission and global welfare? In the model, we now replace the reference level of CO_2 emission in Brazil for producer q, with both Brazil and Indonesia, such that $\alpha(e_{ref}^{qBRA} + e_{ref}^{qIDN} - e^{qBRA} - e^{qIDN}) \geq 0$. Figure 5 shows that global emission is lower than in all the other scenarios considered. The offset rate that minimizes global emission is still in the range of 20%. The lower global emission is due to relatively more offset credits being bought, as the REDD+ credit price is now even lower. That is, with both Brazil and Indonesia supplying REDD+ credits, a similar emission reduction can now 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. Also here, Figure 6 suggests that the optimal offset rate is in the range of 20%.

4. Concluding remarks

Countries that introduce unilateral action to reduce greenhouse gas (GHG) emissions, may face the risk of reduced competitiveness for emission-intensive and trade-exposed (EITE) industries, and corresponding carbon leakage. As a result, countries have either excluded the EITE industries from their regulations or implemented other anti-leakage measures. The economics 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 instead allowing for Reducing Emissions from Deforestation and Forest Degradation (REDD+) credits to offset domestic GHG emission for the EITE industries. In particular, we have looked into the effects of requiring that the EITE producers may have to acquire more than one offset credit to balance one ETS allowance.

We have shown analytically that under certain conditions 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 calculations, we include the benefits of reduced global emissions. We also find this to be the case when the offset mechanism is introduced for all participants in the domestic carbon market. Next, we have confirmed these results with a stylized computable general equilibrium model calibrated to real world data in the context of the EU ETS and REDD+ credits from Brazil. In particular, the welfare for both the EU and the world as a whole were 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. The simulations further suggest that it is optimal for the EU to require EITE producers to acquire several REDD+ credits to offset one EU ETS allowance, as this leads to bigger global emission reductions. The numerical simulation also showed that the offset mechanism had a significant impact on the leakage rate to the energy-intensive goods. This was also true for lower conversion rates between REDD+ credits and EU ETS allowances. Further, the leakage rate from agricultural and forestry sector in the REDD+ countries, were positive for all the conversion rates. However, the leakage rate decreased 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 exposer and land prices do vary, there could to some extent be uncertainties related to the parameters selection in the numerical simulations. Further, the paper does also not take into account the issues related to additionality and implementation, which is a large literature on its own (Angelsen et al., 2017; Boer, 2018; Brockhaus et al., 2014; Cadman et al., 2017)

As of the Paris climate agreement, the national determined contributions (NDCs) by many tropical rainforest countries, includes a future of REDD+. Particularly, 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, were pushed to COP25 (Conference of the Parties) 2019 in Chile (Evans & 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.[18]

Böhringer et al. (2017) and Kaushal and Rosendahl (2017) showed that OBA combined with emission pricing may result in regional and global welfare improving effect, 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.

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

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Appendix A, Derivations

A1: Global welfare change in scenario 1

By differentiating with respect to α, we arrive have that:

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

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

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

We use our assumptions from (7), differentiate w.r.t α and solve it for p^x:

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

Insert this for p^x into our equation:

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

Can be simplified to:

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

Further:

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

By combining this with equation (1) we have that:

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

$c_e^{y1} = -\frac{r^2}{\alpha}$, $c_e^{q2} = -r^2$ and $c_e^{z1} = -t^{z1}$ from equation (3) - (5) gives us:

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

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

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

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, (9) can be expressed as:

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\left(e_0^{q2} - e^{q2}\right) - \tau^1\left(\left(e_0^{q2} - e^{q2}\right) - \alpha\frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

Further:

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - \tau^1\left((1-\alpha)\frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

And we finally arrive at (9):

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1\frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \quad (9)$$

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 (13):

$$\frac{\partial W^G}{\partial \alpha} = \frac{r^2}{\alpha}\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha}\right) + r^2 \frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{y1}}{\partial \alpha} + \frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{z1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{q2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right) \quad (13)$$

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 assumption as previously we arrive at equation (9) again:

$$\frac{\partial W^G}{\partial \alpha} = \left(\frac{r^2}{\alpha} - \tau^1\right)\left(e_0^{q2} - e^{q2}\right) - (1-\alpha)\tau^1 \frac{\partial e^{q2}}{\partial \alpha} - \tau^1\left(\frac{\partial e^{q1}}{\partial \alpha} + \frac{\partial e^{y2}}{\partial \alpha} + \frac{\partial e^{z2}}{\partial \alpha} + \frac{\partial e^{y3}}{\partial \alpha} + \frac{\partial e^{q3}}{\partial \alpha} + \frac{\partial e^{z3}}{\partial \alpha}\right)$$

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^r_{FE}	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 CO_2 emission allowance in region r
$CO2_{0}^{gr}$	Land use related CO_2 emission for good g in region r
γ_{CO2}^{r}	Coefficient for land use CO_2 emission in region r
κ_{CO2}^{r}	Coefficient for primary fossil energy of CO_2 emission in region r

Zero Profit Conditions

Production of goods except fossil primary energy:

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

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

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

Production of fossil primary energy:

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

Sector specific value-added aggregate for FE:

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

Armington aggregate except for *FE*:

$$\pi_A^{gr} = \left(\theta_A^{gr}(p^{gr})^{(1-\sigma_A^{gr})} + (1-\theta_A^{gr})p_{IM}^{gr\,(1-\sigma_A^{gr})}\right)^{\left(\frac{1}{1-\sigma_A^{gr}}\right)} \geq p_A^{gr} \qquad \perp A^{gr}$$

Import Composite except for *FE*:

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

Consumption composite:

$$\pi_W^r = \left(\theta_W^{qr} p_A^{qr\,(1-\sigma_W^r)} + \theta_W^{xr} p_A^{xr\,(1-\sigma_W^r)} + \theta_W^{yr} p_A^{yr\,(1-\sigma_W^r)} + \theta_W^{zr} p_A^{zr\,(1-\sigma_W^r)}\right)^{\left(\frac{1}{1-\sigma_W^r}\right)} \geq p_W^r \qquad \perp W^r$$

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 CO_2 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 CO_2 emission in region by q:

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

Fossil fuel related CO_2 emission in region by g:

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

CO_2 emission offset through REDD credits in region:

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

Consumption by consumers:

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

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

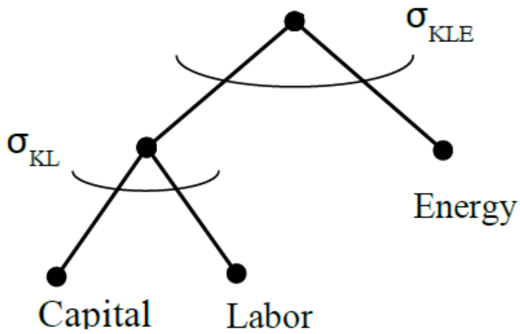

Figure B1: Nesting in production of x, y and z

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

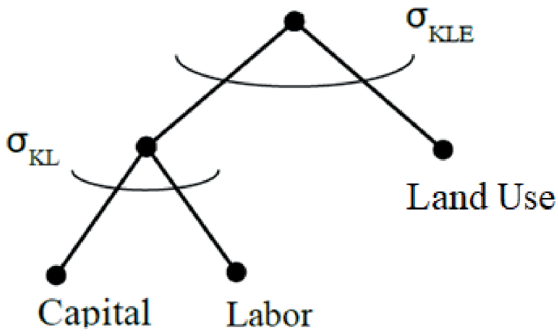

Figure B2: Nesting in production of agriculture and forestry good

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

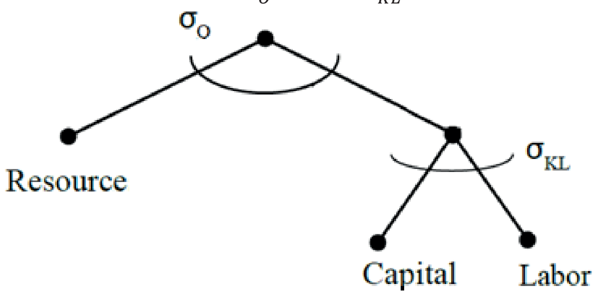

Figure B3: Nesting in production of fossil fuel energy

Elasticity: $\sigma_W = 0.5$

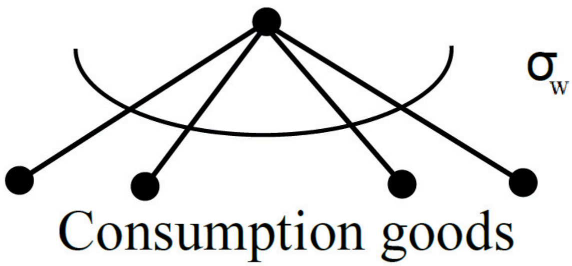

Figure B4: Nesting in final consumption

Appendix C: 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.

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Kevin R. Kaushal was born in Oslo, Norway 1990. He holds a BSc. degree in Business and Administration at Oslo University college (2013) with specialization in Economics from University of Oslo (2012), and a MSc. Degree in Business and Administration at the Norwegian University of Life Sciences (2015).

The thesis consists of an introduction and four research papers assessing impacts and responses to climate change. Particularly, there are two key reasons that motivates the thesis. First, climate economic models are often criticized for their representation of potential biodiversity impact of climate change. Second, as the world still relies on unilateral initiatives to combat climate change, these initiatives may lead to carbon leakage.

Paper 1 incorporates recent empirical estimates of the economic value of biodiversity and ecosystem services in a well-known Integrated Assessment Model (IAM). Paper 2 examines the welfare effects of complementing the anti-leakage measure output-based allocation (OBA) with a consumption tax on emission-intensive and trade-exposed (EITE) goods. Paper 3 extends the analyses in paper 2 by evaluating the potential outcome of climate policies in a non-cooperative policy instrument game between regions who regulate their emissions separately. Finally, paper 4 examines the welfare effect of combining an emission trading system with an emission offset mechanism abroad for the domestic EITE sector.

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