The Green Paradox in Open Economies

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Abstract

This paper explains how, in the context of incomplete coordination among all countries, unilateral policies that might at first sight seem pro-green could actually turn out to harm the global environment. The free-riding motives and the difficulty of reaching an effective international environmental agreement are reviewed. As a first step, the various channels that lead to carbon leakage in static models of open economies are identified, and some simulation results are reported. This is complemented by a review of the possibility of green paradox outcomes in dynamic open-economy models with an exhaustible resource exploited by far-sighted firms. It is shown that border tax adjustments can lead to a green paradox outcome. Directions for future research are suggested.

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Introduction

How to mitigate the climate change is one of the most important problems facing the world today. Efforts to secure cooperation by all countries have failed because of the incentive to free ride. The first best outcome is therefore not feasible. The world is thus left with an assortment of proposed policy options that at first sight might look like second best or third best measures to improve welfare relative to the "business-as-usual" (BAU) scenario. However, as often is the case, a careful analysis would reveal that some policies that seemingly would do the job could actually turn out to have an adverse effect on the environment, contrary to the good intention of the policy makers. Such outcomes are called green paradox outcomes (Sinn, 2008a,b, 2012). There is by now a large body of literature that identifies various channels by which well-intentioned environmental policies may lead to green paradox outcomes.

The main purpose of this paper is to show how green paradox outcomes may arise in a world where climate-change policies are adopted by individual countries or sub-coalitions of countries, in the absence of a grand coalition that would ideally adopt first best policy measures. We will in particular explore the contexts in which international trade and international factor movements may play a role in magnifying or attenuating the green paradox.

In the recent economic literature, the term green paradox has been used both in a broad sense and in a more narrowly defined sense. In the broad sense, any environmental policy that is formulated with the intention of improving environmental quality that turns out to have adverse consequences for the environment is called a green paradox outcome. In a more narrowly defined sense, the green paradox refers to environmental policy failure owing to the failure to recognize the intertemporal supply behavior of extractors of fossil fuel resources. According to this narrower sense, policies that affect resource demand can turn out to be counterproductive because of incorrect analysis of the supply side of the resource market, which is inherently dynamic. As Bretschger and Smulders (2012) put it, "If a policy is not well designed for resource markets it might result in worsening the conditions for sustainability, counteracting the intention of policy makers. This was recently popularized under the title of the `green paradox' (Sinn, 2008b), but known in the literature much earlier (Long and Sinn, 1985). It may be exactly the intertemporal arbitrage conditions driving basic resource extraction which evoke this kind of market reactions undermining climate policies."

In this paper, we take the views that, as a first step, one can discuss some green paradox results without an explicit recognition of the intertemporal optimization behavior of owners of fossil resource stocks, and that ultimately a deeper understanding of the green paradox literature would require an appreciation of the theory of supply of fossil fuels firmly grounded on the microeconomics of the resource extracting industry.

Accordingly, the plan of the remaining part of this paper is as follows. In the next section, we analyse the green paradox for open economies in a static framework without an explicit analysis of the exhaustibility of fossil resources. This will be followed by a section that explicitly takes into account intertemporal supply behavior of resource extracting firms, where we reveal dynamic sources of green paradox outcomes in a trading world.

Green Paradox in Static Models of Open Economies

While the center piece of Sinn's analysis of the green paradox is intertemporal supply behavior of owners of stocks of fossil fuels, it is possible to construct simple examples of green paradox outcomes in a purely static framework. In an interesting model that abstracts from the time dimension, Hwang and Mai (2004) show that an increase in the pollution tax can increase the pollution damages to residents of a central business district (CBD). This is clearly a green paradox result (though the term was not invented until 2008). The model assumes that a firm's location is endogenous. Assume there is a monopolist that buys its inputs from two suppliers (e.g. two farms) located at two points on the periphery of a region and ships his output to the CBD. The monopolist's plant is located somewhere between the CBD and the location of the input suppliers. Its exact location is determined by balancing the cost of shipping inputs to the plant, and the cost of shipping output to the CBD. The pollution generated by the firm is caused by emissions from the plant. Assume that pollution is proportional to output. The pollution as measured at the center of the CBD is only a fraction of the pollution generated at the plant. This fraction is a decreasing function of the distance between the plant and the CBD. An increase in an emission tax rate will make the firm produce less output, and thus its total emissions are reduced. Suppose the production function exhibits decreasing returns to scale. Then as the firm cuts back its production, less of each input is needed per unit of output. Cost minimization (balancing input transport costs with output transport cost) then dictates that the firm moves closer to the CBD. As a result, even though total emissions fall, the pollution damages inflicted on the CBD may rise. This is a green paradox outcome. This outcome would not arise if the tax is based on pollution damages at the CBD and not on the emissions at the plant.

While the model of Hwang and Mai (2004) does not deal with open economies, by endogenizing the choice of a firm's location, it is pointing out to a root of the green paradox: policy makers quite often fail to take into account the full ability of firms or individuals to make spatial or intertemporal adjustments to their plans in response to policy measures. The literature on "carbon leakage" is based on the same insight. For example, the carbon-leakage model by Babiker (2005) assumes spatial competition among Cournot oligopolists, a feature that has been exploited in modeling firms' locational choice (Markusen and Venables, 1988, Markusen et al., 1993, 1994).

Hoel (1997) also explored the issue of endogenous plant locations between two countries, and showed that the Nash equilibrium of the environmental-policy game between two countries is generally not Pareto optimal.

Eichner and Pethig (2011) define carbon leakage as the phenomenon where "the effort of abating countries will be offset to some extent by increasing emissions in non-abating countries." The co-existence of abating countries and non-abating countries is a fact of life. The explanation of this phenomenon is the free riding incentive. Earlier discussions of this issue include Bohm (1993), Hoel (1992, 1994), Carraro and Siniscalco (1993), and Barrett (1994).

Why don't countries cooperate?

Barrett (1994) and others have shown that if countries decide whether to participate in an international environmental agreement (IEA) based on their own selfish interest, then even in the simple case of identical countries, very few countries will want to join an IEA. A grand coalition (i.e. a coalition in which all countries are members) will not arise unless the number of countries in the world is very small.[1]

Limited participation in international cooperation lies at the heart of many green paradox effects. Actions that are motivated by good intention may have bad consequences if others do not follow.

Does the possibility of trade lead to expansion of the size of a stable IEA? Eichner and Pethig (2013) show that the answer is in the affirmative, in the case where the IEA acts as a Stackelberg leader. However, the aggregate emissions turn out to be not much different from the business as usual scenario.

When countries are heterogeneous, cooperation is even more unlikely. Hoel (1992) considers the case where countries have identical cost of emission reductions, but they differ with respect to their evaluation of the benefit of the public good. Countries can elect to join an IEA. Members will vote on a uniform reduction that they must carry out. The equilibrium rate of reduction is the outcome of the median voter mechanism. Hoel showed numerically that in a world consisting of 100 countries, only 2 countries will join an IEA, and their emission reduction is very negligible.

In the IEA literature, once an IEA forms, two scenarios are possible: (a) the IEA members are assumed to act simultaneously with the other non-signatories, or (b) the IEA members are assumed to have the ability to move first and announce their emissions policies before the non-signatories choose their respective emissions policies. Both scenarios lead to the same pessimistic outcome: very few will join an IEA, and the IEA's cut in pollution will be largely offset by increasing emissions of non-members. This is an instance of "carbon leakage" even when there is no trade among countries (for example when there is only one final good and inputs are not traded internationally).

In a recent contribution, Buchholz et al. (2012) allow IEA members to make a different kind of commitment, which enables them to act as the first mover relative to non-members. In their

1 Barrett (1994) used a linear-quadratic model, with quadratic damage costs. If damage costs are linear, as was assumed in some of this literature, then non-members have a dominant strategy, and leakages do not occur. The result that participation to IEA is low may be due to the functional forms assumed. Karp and Simon (2012) use a non-parametric model and show that participation can be large. Battaglini and Hardstad (2012) find high participation in a model of multistage participation game with investment.

formulation, members agree to a matching rule: if a member contributes a flat amount g_i to a public good (abatement), then other members will jointly match this contribution at a rate ρ so that the contribution g_i induces $(1+\rho)g_i$. They find that there are parameter values that imply $\rho < 0$ in equilibrium. Then if an IEA coalition is not a grand coalition, its formation will actually result in more pollution for the world. In this model, when $\rho < 0$, it is the coalition that exploits the non-members. In a way, this is another green paradox result: when a first best action (here, full cooperation by all countries) is not available, actions that might resemble a second best solution (forming an IEA with a few members) may actually be worse than no action at all.

The intuition behind the result of Buchholz et al. (2012) is as follows. Emission reductions are strategic substitutes, in the sense that if one player contributes more to a public good, then other players will respond by contributing less. A subset of players can therefore gain if it can act as a first mover, declaring that it contributes less, so that others will contribute more.[2] The choice of ρ, which is made before all players make their contributions, amounts to a commitment device by the coalition, turning it to a Stackelberg leader.

The above models rely on the non-cooperative game theory. Authors using the cooperative game theory offer a more optimistic view concerning IEA. Chandler and Tulkens (1995) use the concept of the gamma-core as solution concept for their cooperative approach to IEA. They find that the grand coalition is the equilibrium outcome, therefore the carbon leakage problem does not arise. The gamma-core approach basically assumes that each member of an IEA perceives that if it leaves the coalition, then all existing members will follow suit. This is a strong deterrent against leaving. The static model of Chandler and Tulkens (1995) has been modified by Germain et al. (2003) to take into account the dynamics of pollution, and transfers among countries in a dynamic setting. In this formulation, in any period, a country may decide to join a grand coalition, or to stay outside. It is assumed that if it chooses the second alternative, then it will expect that in the following period, a grand coalition will be formed. Thus this formulation retains the basic optimism of the static model of Chandler and Tulkens (1995).[3] There is no surprise then that the conclusion of the paper is that there exists a transfer scheme that supports full cooperation.

It seems that the approach typified by Barrett (1994) and that of gamma core are at two opposite extremes. The former assumes that quitting is not punished, the latter assumes that quitting is met with maximum punishment. As some critics have said, the truth lies somewhere in between.

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[2]Long (1992) shows that this is the case even in a dynamic game: A player that can act as Stackelberg leader will contribute less than it would if it were playing the simultaneous move game.

[3]Martimort and Sand-Zantman (2013) develop a model in the tradition of Chandler and Tulkens (1995), where participation is high (essentially by assumption) but abatement may be low because of asymmetric information.

In the formulation of Barrett's IEA game, each of N countries must choose to join or not to join a coalition. An IEA among M countries determines M abatement levels, one for each coalition member, so as to maximize the sum of their payoffs. If $M = N$ the coalition is called the grand coalition. Barrett adopts the concept of coalitional stability originally proposed by d' Aspremont et al. (1983) for cartel stability. Under this formulation, when a country considers joining or leaving a coalition, it assumes that the rest of the countries in the coalition will maintain their membership status and will continue to cooperate, choosing their action to maximize their joint welfare. Let $\pi^s(M)$ and $\pi^{ns}(M)$ denote the equilibrium payoffs of signatory and non-signatory countries when the coalition has M identical members. A coalition with M members is said to be internally stable if no signatory would gain by leaving the coalition, i.e., if $\pi^s(M) \geq \pi^{ns}(M-1)$, and it is said to be externally stable if a non-signatory would not gain by joining it, i.e. $\pi^{ns}(M) \geq \pi^s(M+1)$. An IEA is called stable if and only if it is both internally and externally stable.

Some authors have argued that the external and internal stability criterion is based on the premise that agents are myopic. This concept of stability has been referred to by de Zeeuw (2008) as "myopic stability" since a player does not foresee any change that might occur in the coalition following its defection. A more sophisticated player would anticipate that by defecting, other players' incentives to defect might be affected. Diamantoudi and Sartsetakis (2008) and Osmani and Tol (2009) adopt the concept of a " farsighted stable IEA". This concept is borrowed from developments in coalition formation theory (Chwe,1994, Xue, 1998).

In their pioneering work on farsighted stable IEAs, Diamantoudi and Sartsetakis (2008) extended the existing literature by endogenizing the reaction of the IEA members to a deviation by a member or group of members. Thus, when a country contemplates leaving or joining an agreement, it takes into account the reactions of other countries. The authors identified conditions under which there always exists a unique set of farsighted stable IEAs. They showed that farsighted IEAs can be significantly larger than the stable IEAs under the internal external stability criterion. While a formal definition of the concept of far-sighted stability would require a lot of preliminary definitions that are heavy in mathematical symbols and set-theoretic concepts, a rough idea can be obtained by considering the case of a world consisting of four countries. Suppose countries 1,2, and 3 form an IEA. Then country 3 considers withdrawing from it. Suppose that this withdrawal would be gainful to country 3 if countries 1 and 2 would remain members of a two-country coalition. If we use the internal and external stability criterion of d'Aspremont et al. (1983), then it follows that the three-country coalition is not stable. On the contrary, under far-sighted stability, country 3 cannot presume that once it has left, countries 1 and 2 would remain in a two-country coalition. These two may well contemplate leaving the two-country coalition, because this could destroy country 3's hope of free riding, and thus inducing it to rejoin the three-country coalition. Thus a three-country coalition can be stable in the sense of far-sighted stability, though it is unstable in the sense of internal and external stability of d'Aspremont et al. (1983). Whether a three-country coalition in a four-country world is far-sightedly stable or not depends on specifications of parameters of the damage function and the production functions. Numerical examples of farsightedly stable three-country coalition in the four-country world can be found in Benchekroun and Ray Chaudhury (2013), where both the static pollution framework of Barrett (1994), and the dynamic pollution accumulation framework (as in Long (1992), Dockner and Long (1993), Ploeg and de Zeeuw (1992)) are considered. It is important that countries 1 and 2 make credible threats to country 3. This issue is explained in Benchekroun and Ray Chaudhury (2013).

The above models did not consider negotiations. Hoel (1991) considered international negotiations. He reported a carbon leakage result: when a country unilaterally reduces its emissions, this will generally affect the outcome of international negotiations about emission reductions. The final outcome may well give rise to higher total emissions when one country reduces its emissions than when all countries act selfishly. This will be the case if countries restrict their negotiations to equal or proportional abatements.[4]

Carbon leakage in a trading world: static models

Unilateral reduction of emissions by one country or one subset of countries can lead to a problem called "carbon leakage" via reduction of fuel prices. Assuming that fuels are traded in the world market, Bohm (1993) and Felder and Rutherford (1993) were among the first authors to discuss this issue, though Bohm did not use this terminology. As Bohm points out, "such unilateral actions or international treaties among a limited number of countries would tend to reduce world-market fuel prices and, hence, increase fuel consumption in non-signatory countries" (p. 258). This consideration is later referred to as the "fuel price effect" (FPE).[5] Using a static model, and taking into account both the demand side and the supply side, Bohm suggests that the carbon leakage problem through the fuel price effect could be mitigated if signatories buy or lease fossil fuel deposits from fuel exporting countries and store such oil in their original deposits. This would reduce the fossil-fuel supply to non-signatories. Harstad (2012) offers a formal model along these lines. Another channel through which carbon leakage can arise is the relocation of plants in response to emissions taxes or regulations (Markusen et al., 1993, 1995). A third channel is the change in a country's comparative advantage induced by

[4]For a more technical review of IEA issues, see Benchekroun and Long (2012).

[5]Bohm also points out another problem: many poor fuel-exporting countries could be seriously hurt, with undesirable political consequences for the world.

its adoption of tougher environmental policies (Copeland and Taylor, 2003, 2004, Krishna, 2010).[6]

In Bohm's model, there is no trade in the final goods among countries. When there is trade in final goods, a country that unilaterally imposes an emission tax on its (fossil-fuel-using) final good industry will find that consumers will switch their expenditure to the untaxed foreign final-good substitutes. Output of these goods will therefore go up to meet the demand, creating more emissions in the non-abating countries. This "expenditure switching effect" (ESE) from taxed dirty domestic goods to untaxed dirty foreign goods tends to reinforce the carbon leakage effect found in models without trade.[7]

On the other hand, if the dirty good uses both carbon and a clean input (say, a composite factor K) which is an imperfect substitute for carbon, and if this clean input is internationally mobile, the pollution tax in a country may increase its demand for the clean input, so that less of this input will be available in the foreign countries. This may to some extent reduce the output of foreign goods. This is a negative leakage effect that mitigates the positive leakages mentioned above. This effect has been termed "abatement resource effect" (ARE) by Fullerton et al. (2011) and Elliott and Fullerton (2012). Negative leakage can also occur if technology adoption is endogenous. An increase in carbon tax in one country that leads to R&D in abatement can lead to adoption of the new technology in other countries or sectors (Golombek and Hoel, 2004, Gerlagh and Kuik, 2007, Di Maria and Smulders, 2004, Di Maria and van der Werf, 2008).[8]

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[6]However, Chau (2003) points out that more stringent environmental policies can increase the demand for factors used in abatement. If these factors are used intensively in the clean sector, this resource-pull away from the claen good sectot can decrease the supply of the clean good and increase its relative price, creating a comparative advantage for the dirty good. Karp (2012) expands on this idea, and shows that the Copeland-Taylor-Krishna finding that higher emission tax increases the autarchic price of the dirty good depends crucially on the assumption that the production function of the dirty good is separable in capital, labor, and emissions, such that production and abatement use the same capital-labor ratio. Karp (2012) demonstrates that when this assumption is relaxed, the opposite result can occur.

[7]In the carbon leakage model of Ishikawa and Kiyono (2006), there is no international market for fuels. Each country produces outputs using a composite factor (say labor) and a dirty input that is freely available, except there are taxes for using this dirty input.

[8]Endogenous policy responses by governments of non-participating countries can mitigate the leakages when income effects are taken into account. See Copeland and Taylor (2005).

The magnitude of the carbon leakage associated with a unilateral carbon tax depends on the magnitude of various parameters. Leakage increases with the consumer's elasticity of substitution between the domestic dirty goods and the foreign dirty goods, but decreases with the polluting firm's elasticity of substitution between carbon (or carbon-intensive inputs) and the clean composite input. There are of course other relevant parameters such as the degree of competition among firms, the supply elasticity of fossil fuels, and so on. Using a computable general equilibrium model, Babiker (2005) found that the leakage could be as high as 130%, because of relocation of carbon-intensive industries away from rich countries that undertake stricter environmental policies. [9] With relocation, unilateral action by one country leads to a green paradox outcome. Babiker's model allowed for spatial competition by Cournot oligopolists. Babiker made use of a data set based on the Global Trade Analysis Project (GTAP) data together with data from the International Energy Agency. The model, being static, does not take into account the inter-temporal supply behavior of firms in the fossil fuels sector. Exogenous assumptions are made on the price elasticity of supply for fuel.

Most CGE models however produce smaller estimates of carbon leakages. Winchester et al. (2011), using the EPPA4 model in Paltsev et al. (2005), found in their simulations of a U.S. carbon policy that the leakage would be only around 10%. Elliot et al. (2010) found that the increase in emissions by non-Annex B countries of the Kyoto Protocol relative to the emission reduction by Annex B countries is within the range of 15% to 25%. Burniaux and Martin (2012) emphasized that carbon leakages are small because of the assumption that the supply of coal is fairly elastic over the medium term. [10]

Since OECD countries are net importers of embodied emissions from non-OECD countries, it has been suggested that carbon tariffs could reduce leakage. Carbon tariffs are also known as border tax adjustments (BTA). Advocates for BTA include economists such as Stiglitz and Krugman. Keen and Kotsogiannis (2011) define BTA as differential taxation of traded goods that is motivated by differences in underlying carbon prices. In particular, they consider the

[9]The model employed by Babiker (2005) is based on the MIT's "Emissions Prediction and Policy Analysis" (EPPA) model described in Paltsev (2001).

[10]Econometric estimates by Aichele and Felbermayr (2012) found that Kyoto membership reduces carbon emissions and increases carbon imports, but does not change the level of emissions embodied in consumption and investment of members. Presumably non-members' consumption of the dirty goods may fall, so one cannot say that the leakage rate is 100%. See Karp (2012) for further discussions on this point.

possibility of "setting a charge on imports equal to some notion of carbon tax `not paid' abroad, and remitting tax on exports in similar fashion." (p. 2)

Böhringer, Carbone and Rutherford (2011) simulated the effects of embodied carbon tariff. They found that carbon leakage is reduced thanks to the BTA. Similar simulation results are surveyed in Elliott and Fullerton (2012). These studies found that the main effect of BTA is to shift the burden of climate policies to less developed countries. On the other hand, Jacob et al. (2013) reported that, based on empirical data for the year 2004, full BTA applied by the European Union on imports from and exports to China would actually increase carbon leakage, because China's production would be shifted from the export sector to the non-export sector, which is more carbon intensive.

Karp (2012) uses a static partial equilibrium model to provide an example in which BTA can create negative leakage, where he defines leakage as the number of units of outsiders' increased emissions per unit of insiders' decreased emissions (p. 16). In the initial situation, there are n identical countries that produce a carbon-intensive good, and there is no trade. Suppose the governments of m of these countries agree to introduce a carbon tax. Then these member countries begin to import the dirty good from the non-participating countries, a leakage. Suppose the m member countries impose a BTA that sets a charge per unit import equal to the price of carbon times the carbon content of the imported good. Since the demand for the dirty good in the member countries fall (because of the carbon tax), the BTA on top of the carbon tax causes the member countries to become exporters of the dirty good. In this case, the BTA is in effect an export subsidy instead of an import tax. Karp (2012, p. 21) describes this as a negative leakage, and notes that in this case insiders lose and outsiders gains (ignoring environmental considerations). [11]

Dynamic Multi-country Models with Inter-temporal Supply Emphasis

About 75% of anthropogenic carbon emissions are accounted for by the burning of fossil fuels. Thus, it is imperative to take into account the behavior that governs the extraction decisions of owners of fossil-fuel deposits. Bohm (1993) was among the first to point out that climate policy

[11] McKibbin and Wilcoxen (2009) also find examples of negative leakages caused by BTA, using a CGE model, although the mechanism is not clear.

discussions should take into account the supply side. However, he did not offer a formal model to account for the inter-temporal supply responses of sellers of fossil fuels to policy changes. Sinclair (1992) explicitly points out the need for such a model: "the key decision of those lucky enough to own oil wells is not so much how much to produce as when to extract it." Sinclair (1994) and others have studied the time path of first best carbon price under alternative specifications of damage costs. While it is true that, in a world without political constraints, the optimal price of a ton of carbon emissions at any point of time is equal to the present value of all future marginal damage costs, realistically such a policy cannot be implemented. Policy makers are likely to feel more comfortable with a gradual approach, where significant carbon taxes are delayed into the future. However, such gradualism can be counter-productive. As Sinn (2008a, p. 360) points out, if suppliers of fossil fuels "feel threatened by a gradual greening of (demand-reducing) policies in in the Kyoto countries that would damage their future prices, they will extract their stocks more rapidly, thus accelerating global warming." Sinn calls such an outcome a green paradox. Gerlagh (2011) makes a distinction between "weak green paradox" and "strong green paradox". The former refers to increases in near-term emissions, while the latter refers to increases in the present value of all future damage costs.

While there is by now a large literature on the green paradox with an inter-temporal-supply-side emphasis, almost all authors restrict attention to the case of a single country. This modeling strategy ignores an important real world element: we live in a multi-country world, with a diverse array of climate policies. It is important to know whether good-intentioned actions by one country may lead to bad outcome because of lack of actions by other countries.

Carbon leakage in two-country models with a fixed resource stock to be extracted over time and a renewable substitute

We now turn to two models of carbon leakage involving two countries, a finite stock of fossil-fuel resource to be extracted over time, and a clean, perfect substitute for fossil fuel. The first model, proposed by Hoel (2011), assumes that the perfect substitute can be produced at constant unit cost, and this technology is available to both countries. In contrast, the second model, proposed by Grafton et al. (2012), assumes that the perfect substitute is produced under increasing cost, and this technology is available to one country only. Both models deliver the result that apparently good-intentioned policies can lead to unfavorable climate outcomes.

Hoel (2011) proposes a two-country model that takes into account the fact that resource extraction involves the inter-temporal optimization by resource extracting firms. This model assumes that goods (including oil) flow freely between the two countries: there are no tariffs. The policy instruments available to a country are taxes on the domestic consumption of the dirty energy, and production subsidies for a perfect substitute (e.g. solar energy) that is not internationally traded. The perfect substitute is available at a constant unit cost, b, and this constant cost technology is available to both countries. The size of the aggregate fossil-fuel resource stock to be exhausted is exogenously given. Extraction cost is zero for simplicity. Resource owners are perfectly competitive: extractive firms do not think that they can influence the price. Oil is traded internationally, while the substitute is not tradable. In this model, it is irrelevant where the resource deposits are located. The aggregate resource stock will be exhausted at some time in the future. This time is endogenously determined. Policies can only affect the time path of extraction, not the total cumulative emissions (which are fixed, because the fossil fuel stock will be exhausted). The consumer price of oil in each country is equal to the oil producer price plus the unit carbon tax imposed by that country. When the consumer price of a country reaches the value b, consumers in that country will switch to the perfect substitute. Resource owners can sell oil to either market. It follows that the resource rents in the two markets are equalized, and they rise over time at an exponential rate equal to the rate of interest. The resource rent at time zero is an endogenous variable; it depends on the carbon tax rates.

Assume that country i imposes a constant tax rate θ_i per unit of carbon consumed, where θ_i is smaller than b. Then consumers in country i will switch to the clean substitute at time T_i where T_i satisfies the condition that the country i consumers' price of oil at time T_i just equals the price of the perfect substitute. [12]

Consider first the simple case where both countries have identical demand curves and impose the same carbon tax rate. Then, obviously the two switching times coincide, and if both countries increase their carbon tax rate by the same amount, the consumer's price of oil at each date will be higher, implying that less will be demanded at each point of time. Consequently the time of exhaustion of the fossil fuel stock will be delayed. This reduces the present value of total damage costs. The "green policy" is working correctly in this case.

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[12] $\psi_0 \exp(rT_1) + \theta_1 = b$, and $\psi_0 \exp(rT_2) + \theta_2 = b$ by Hotelling Rule, where ψ_0 is the the resource rent at time zero. This pair of conditions and the condition that the sum of the cumulative demands for oil in the two countries must equal the fixed stock of oil X_0 determine the three endogenous variables, ψ_0, T_1 and T_2.

However, when countries do not coordinate their policies, a unilateral green policy in one country may not necessarily reduce the present value of total damage costs. If policy parameters are different, then in general the two switching times are different. Then a policy change that leads to a narrowing of the gap between these two switching times will lead to a green paradox outcome. To illustrate, consider the polar case where the demand for energy is completely inelastic (i.e., the demand curve is vertical). Suppose D units of energy are demanded in each country per unit of time. Assume that country 1 has a higher carbon tax rate. Then consumer price in market 1 will reach the price b at an earlier time than that in market 2. Now suppose country 2 (the low tax country) increases its carbon tax rate marginally. Then the date of resource depletion will be brought closer to the present. This will increase the present value of the future damage cost, a green paradox result. [13]

This result can be generalized to the case of demand function that is less than completely inelastic. To summarize, if the demand for energy is sufficiently price-inelastic, the total climate costs will increase if the carbon tax is marginally increased in the country that initially has the lowest tax.

The change in *world welfare* is in general not the same as the change in total *climate costs.* This is because a carbon tax in an economy creates a distortion if the climate effects are absent. If the countries have different carbon tax rates, the marginal distortions are not equalized, which is itself a source of inefficiency. However, it remains true that if the marginal climate cost is high enough, the secondary effects of a tax change on distortions are dominated by the climate effect. Then, if the demand for energy is sufficiently price-inelastic, world

[13] The proof of this result is straightforward. We have two equations $DT_1 + DT_2 = X_0$, and

$$T_1 - T_2 = \frac{1}{r}\ln\left[\frac{b-\theta_1}{b-\theta_2}\right]$$

Since θ_1 is greater than θ_2, T_1 is smaller than T_2. We can see that a marginal increase in θ_2 (such that the new θ_2 is still lower than θ_1) will decrease T_2, i.e., the exhaustion date is brought closer to the present.

welfare will decrease if the carbon tax is marginally increased in the country that initially has the lowest tax.

Let us now turn to the analysis of the effect of technological progress. What happens if due to exogenous technical progress, the cost of the substitute falls? If the two countries are identical, the date of exhaustion will be brought closer to the present, and we obtain a weak green paradox result.[14] Now consider the situation where the countries have different carbon tax rates. Let θ_1 be greater than θ_2, which implies that T_1 is smaller than T_2. Then a fall in b may cause T_2 to increase or decrease. In the special case of completely inelastic energy demand, it can be shown that T_2 increases and T_1 decreases when b falls. In this polar case, total climate costs falls if the present value of the social cost of carbon is declining over time. More generally, as long as the demand is sufficiently inelastic, a fall in b can increase T_2 if θ_1 is greater than θ_2. The fall in b then has two opposing effects on emissions (a) it reduces the resource rent, leading to lower prices, increasing early emissions (a weak green paradox), and (b) it increases T_2, leading to more emissions in the final stage, and as a consequence, because total emissions are fixed due to the assumption that the fixed stock of exhaustible resources is eventually used up, the emissions in the medium run decrease. In this case, the effect on total climate costs is ambiguous.

Finally, we consider the impacts of a subsidy on the consumption of the substitute. Assume that in country i a *per unit* subsidy σ_i is introduced and is expected to remain constant forever.[15] If both countries increase the per unit subsidy by the same amount, the effect on climate costs are the same as that created by a fall in the production cost of the substitute. Consider then the case of an increase in subsidy for consumption of the renewable substitute in only one country. Suppose σ_2 is greater than σ_1 and the carbon tax rates are the same in both countries. Then T_1 is smaller than T_2. Consider a marginal increase in σ_1. The price of oil will fall, increasing near-term emissions in both countries, a weak green paradox result. But T_2 will increase, lengthening the life of the exhaustible resource stock. Therefore late emissions increase. It follows that medium-term emissions decrease. Assume the marginal damage cost is constant over time, which implies that the present value social cost of carbon is falling over time. Then because of the net change in emissions is non-monotone over time, it is not clear what will happen to the total costs of climate change when there is a marginal increase in σ_1. Let

[14]If the present value of the social cost of carbon is falling over time, this results in an increase of total climate costs. Concerning social welfare, the positive effect of cost reduction on welfare may well be outweighed by the negative effect of higher climate costs.

[15]There is of course a credibility problem here. Once the fossil fuel stock has been exhausted, the governments no longer have an incentive to subsidize the renewable energy. For simplicity, let us abstract from this problem.

us turn to the effect of a marginal increase in σ_2. Then the resource exhaustion time T_2 will fall, and extraction increases at all time $t \leq T_2$. It follows that in this case the result is unambiguous: A marginal increase in the subsidy rate in the country with the lowest subsidy rate will increase total climate costs.

Can a green paradox outcome arise if the perfect substitute is available in only one country, and if the marginal production cost of the substitute increases with the output level? This question is taken up in Grafton et al. (2012), using a continuous-time infinite-horizon model. There are two countries, called North and South. Both countries need energy to produce the final consumption goods. One unit of energy is obtained from one unit of oil, or one unit of a clean substitute. Oil producers sell oil to both North and South, at the same price. In North, a clean substitute is produced at increasing marginal cost. There is an ad valorem rate of subsidy on the production of the clean energy. The clean energy cannot be exported to South. The authors ask the following question: does an increase in the ad valorem rate of subsidy bring the exhaustion date of the exhaustible resource closer to the present, thus increasing the present value of total climate costs? The model distinguishes two phases. In Phase 1, both countries use oil, and the clean energy is produced in North. In Phase 2, North relies completely on the clean energy, and South is the only user of oil. The authors show that an increase in the subsidy for clean energy in North will shorten Phase 1 and lengthen Phase 2. The effect on the exhaustion time is ambiguous. In their model, a green paradox outcome is possible if a given increase in the subsidy rate expands output when the price of energy is high by much more than when the price of energy is low. The intuition is that, in such a case, oil producers, anticipating greater competition from the clean energy sector later stages, switch more oil extractions to the earlier stages. More oil will be used earlier on rather than later on. Short term pollution increases.

Carbon leakage in a three-country, two-period general equilibrium model with caps on pollution permits

While Hoel (2011) and Grafton et al. (2012) have obtained interesting results on unilateral changes in climate policies, their models are partial equilibrium in nature: there is a numeraire good in the background, and utility is linear in that good. One may wonder to what extent this quasi-linearity is responsible for the green paradox outcome. The answer is that quasi-linearity is a simplifying assumption, not a crucial assumption. To show this, let us turn to a general equilibrium model that does not rely on this quasi-linear property.

Eichner and Pethig (2011) formulate a model that emphasizes parameters such as the inter-temporal elasticity of substitution (IES). They point out that the relatively modest leakage rates reported in static models were due to the neglect of inter-temporal responses. They develop a simple two-period model. They interpret period 1 as the medium term and period 2 as the very long term. There are three countries: a fossil-fuel exporting country, called country F, an abating country, called country A, and a non-abating country, called country N. Let us call the fossil fuel "oil" for short. Unlike to model of Hoel (2011) and Grafton et al. (2012), there is no renewable substitute for oil. Countries A and N use oil to produce the consumption goods. There are no other factors of production. The abating country is interpreted as the coalition of countries that have made a commitment to cap their emissions. There is no capital accumulation, and no extraction cost. The stock of fossil fuels is exogenously given. [16]

The assumption of zero extraction cost is favorable to carbon leakage because it makes oil suppliers highly willing to shift extraction from one period to another.

In this model, governments neither play Nash nor cooperate. [17] In fact, governments play no role at all in country N and country F, and the government of country A is not maximizing anything: it simply tightens an emissions cap. [18]

The authors simply ask: how much carbon leaks into the non-abating country when the abating country tightens its emissions cap in one of the periods. Consumers have identical preferences, represented by a utility function that displays constant elasticity of substitution between period 1 consumption and period 2 consumption. There is no uncertainty of any kind. Agents maximize intertemporal utility subject to an intertemporal budget constraint, as in the standard Arrow-Debreu general equilibrium model.

The elasticity of inter-temporal substitution (IES) is denoted by σ, which can take any positive value. As σ tends to 1, this utility function tends to the Cobb-Douglas function. The limiting case where σ tends to infinity implies that consumptions in the two periods are perfect substitutes (the indifference curves are then linear). The other polar case where σ tends to zero implies that indifference curves are L-shaped (Leontief utility function).

The authors consider the climate impact of alternative policies for country A: it can tighten its period 1 cap, or its period 2 cap.

The authors state that the market rate of interest is assumed to be zero (p. 771). Upon reflection, this is actually just a normalisation: all prices used by the authors can be interpreted as present value prices. Thus an interest rate (in terms of the consumption good) can be introduced into the model. It is equal to the marginal rate of substitution of period-two consumption for period-one consumption, minus 1. (See the Appendix for technical details.) This interest rate is endogenous: it changes when policy parameters change. For example, a tightening of period-one cap on emissions would tend to result in a fall in period-one output. Fuel uses will be increased in period two, because the total stock must be exhausted over

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[16] Berg, Kverndokk, and Rosendahl (2002) take up the case where oil explorations depend on the existence of climate treaties.

[17] Due to this assumption, the authors can assert that emission taxes and quotas are equivalent. This equivalence breaks down when countries play game and exert their market power. See e.g. Kiyono and Ishikawa (2011).

[18] For a survey of models where countries play dynamic emission games, see Long (2010), which draws on the theoretical tools expounded in Dockner et al. (2000).

the two periods. To induce consumers to reduce period-one consumption and increase period-two consumption, the rate of interest would rise.

The authors found that if the non-abating country tightens the cap in period one (while there is no cap in period two) some carbon leakage will occur, i.e. total emissions in period 1 do not fall as much as the decrease in the cap, and the rate of leakage may exceed 100% (i.e., total emissions in period 1 rise, a green paradox outcome). [19]

The intuition behind this green paradox result is not hard to grasp. A tightening of period 1 cap tends to induce an increase in the interest rate to shift consumption to period 2. The period 1 price of oil falls. This induces the non-abating country to increase its period 1 demand for oil. Thus a leakage occurs. Leakage rates in excess of 100% constitute a green paradox: the non-abating country's increased demand for oil in period 1 is greater than the reduction in the period 1 cap imposed in the abating country. This would happen if the willingness to substitute period 2 consumption for period 1 consumption is weak. In the extreme case of a Leontief utility function (i.e., zero intertemporal substitutability) a green paradox outcome is inevitable. [20] Assuming there is only a cap in period 1, the authors show that if the IES is below a threshold level, then tightening period 1 cap will lead to a green paradox outcome. This threshold level is higher (i.e. a green paradox outcome is more likely) if the absolute value of the price elasticity demand for fossil fuel is greater, or the first period world output of the final good is the smaller, or the implicit permit price in country A is higher, or first period emissions of the non-abating country are higher. This result turns out to be essentially unchanged if there is also a cap in period 2.

Can a tightening of the cap in period 2 lead to more emissions in period 1? The authors find that this will happen if and only if the price of fossil fuel in period 1 falls in response to such a tightening. It can be shown that such a price fall cannot occur in the case of a Leontief utility function.

Our explicit treatment of interest rate in the model of Eichner and Pethig (2011) shows that the interest rate effect is a powerful channel for the green paradox. In fact, this channel has been identified in Long and Stähler (2012a). They consider a two-period general equilibrium model of a closed economy with a fixed stock of exhaustible resources and show how a permanent fall (that occurs in period 1) in

[19] This is their Proposition 1. Note that tightening of period 1 cap in the abating country is equivalent to an increase in period 1 emission permits in that country. By assumption, there is no international permit market.

[20] It is interesting to note that both in Hoel (2011) and in Eichner and Pethig (2011), the lack of substitutability favors a green-paradox outcome. However there are important differences here. In Hoel (2011), an increase in the carbon tax of the low tax country results in a green-paradox. In contrast, in Eichner and Pethig (2011), it is the tightening of the cap in the more environmentally conscious country that results in a green paradox. The two models are quite different. Hoel (2011) relies on the assumption of constant cost of producing the perfect substitute.

the cost of a substitute in both periods generates inter-temporal reallocation of consumption in favor of period 2, where the share of the substitute in the energy sector is large. (They assume that oil extraction in period two is more costly than in period 1 because of the depletion effect.) This reallocation of consumption may require an increase in the interest rate. The rise in the rate of interest tends to shift resource extraction toward period 1, thus increasing damages in period 1, and possibly increasing the present-value of the stream of damages. This is a green paradox outcome. Long and Stähler (2012a) support their theoretical results with numerical simulations.

The interest rate channel suggests a possible green paradox that could arise from a Green New Deal. [21] Suppose the governments of the world embark on a program of substantial public borrowing to finance colossal R&D projects in alternative energy. This can raise the interest rate, bringing the bulk of extraction closer to the present, worsening short-term pollution.

Green paradox under border-tax adjustments with dynamic supply responses

The dynamic models surveyed above do not take into account the possible use of border tax adjustment as an additional policy instrument available to a country that imposes a tax on domestic carbon emissions. Long and Stähler (2012b) take up this issue. They modify the closed-economy model of Long and Stähler (2012b) and propose a two-period, two-country model where the equilibrium interest rate is endogenously determined in the world market, allowing for borrowing and lending between countries, as well as trade flows in oil and final goods. They show that, under certain conditions, border tax adjustments that are introduced in period 1, to be applied for both periods, can raise the interest rate and consequently increase fossil fuels extraction in period 1 and reduce fossil fuels extraction in period 2, a weak green paradox result. If the BTA is introduced in the second period, the standard green paradox follows through the announcement effect. What is interesting in their paper is that the BTA is introduced in the first period, and the green paradox is generated through the interest rate channel.

In their model, a composite good is produced using energy and capital. Energy can be obtained from fossil fuels or from a perfect substitute that is produced under constant cost, using the composite good. The fossil fuels are available only in the less developed country (called the foreign country, or F), and must be extracted using capital. Marginal extraction cost in period t increases with period t extraction. Furthermore, a higher extraction level in period 1 shifts the period 2 marginal extraction cost curve upwards. The perfect substitute can be produced in both the home country (H) and the foreign country. The authors first consider an integrated world equilibrium, and demonstrate a weak green paradox result: they show that a technological improvement in the production of the perfect substitute

[21] I thank a referee for suggesting both the term Green New Deal, and the paradox of the Green New Deal.

can have two effects: it lowers the price of fossil fuels and raises the interest rate.[22] This rise in interest rate results in more extraction in period 1.

Next, they consider trade. In the laissez-faire scenario, fossil fuels are exported from F to H. In H, firms that use fossil fuels are called "brown firms", and those that use the perfect substitute are called "green firms." Firms are indifferent between being brown and being green. Now, suppose the government of H introduces a carbon tax that must be paid by domestic firms that use fossil fuels. In this model, such a tax by itself has no effect on world production and consumption: the brown domestic firms simply re-locate themselves to F. Therefore, in this setting, the carbon tax (on production) has no impact on prices of goods and of factors of production. In particular, the price of fossil fuels remains the same as in the business-as-usual scenario. Extraction levels are not affected.

Let H introduce border tax adjustments, such that brown capitalists who repatriate their dividends to H must pay a tax that reflects the carbon content of their repatriated dividends. This is effectively a carbon tax on consumption. This tax is designed so that in H the consumer price of the brown consumption good is equal to that of the green consumption good. As a result, the price of the brown consumption good in F falls by the amount of the tax. This induces a fall in the price of fossil fuels, to the advantage of H. This fall has a similar impact on the interest rate as the technological improvement that lowers the price of fossil fuels in the close-economy model of Long and Stähler (2012b): the rate of interest may rise, to shift consumption toward the future. If the increase in the rate of interest is large enough, extraction will be shifted to period 1, which is a weak green paradox result.

Concluding Remarks

We reviewed the various channels that can give rise to green paradox outcome in a world where countries do not coordinate their environmental policies. We found that in static frameworks, carbon leakage can arise, and the leakage rate may exceed 100%, even though most static simulations revealed much lower leakage rates. The static models however ignore dynamic supply responses by owners of fossil fuel stocks, and the estimated leakage rates may display a downward bias. In dynamic models, two more channels are identified. First, extractions can be shifted from the future to the present, even if the interest rate is constant. This can happen when countries adopt different levels of carbon tax. Second, the rate of interest rate can change when the tax rates change. This favors more current extraction. The dynamic models however tend to be very simple in structure because the Ockham's razor principle has been used. Many real world complexities have been left out in order to focus on the main mechanisms behind the green paradox in a world with heterogeneous countries.

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[22] The increase in the interest rate is a consequence of a wealth effect. The world as a whole becomes wealthier because of the technological improvement, which has greater impact in period 2 because share of oil in the energy sector is smaller in period 2 than in period 1. For a numerical example of the increase in interest rate in response to a permanent technological improvement, see Long and Stähler (2012a).

What lessons do we learn from the carbon leakage literature? First, if a large part of the world chooses to free ride, unilateral efforts to reduce domestic emissions can be ineffectual. Second, the wide range of estimates of carbon leakages obtained from a variety of static CGE models suggests that climate policy making not only suffers from uncertainty about climate sensitivity, but also from uncertainty about production structure and market responses. Third, while dynamic formulation is essential to capture the inter-temporal supply responses of owners of fossil fuel resources, the existing dynamic models of world trade with exhaustible resources are in a very early stage of development.

The main challenge is to construct dynamic computable general equilibrium models with both trade and resource extractions by forward looking agents in order to provide better estimates of the extent of carbon leakages and to guide policies. Also, other real world features such as imperfect substitutability between fossil fuels and clean energy should be taken into account. [23]

APPENDIX: Introducing the interest rate into the model of Eichner and Pethig (2011).

The (present-value) price of the consumption good in period t is p_{xt}, and it is assumed that p_{x1} is unity. The (present-value) price of fossil fuel in period t is denoted by p_{et}. Let us denote the consumption rate of interest by r such that $1+r=1/p_{x2}$. Then a fall in p_{x2} is interpreted as a rise in the rate of interest r. Let us define the price of oil in period t in terms of period t consumption good as follows:

$$q_{et} = p_{et} / p_{xt}$$

The Hotelling rule requires that the oil price rises at the rate of interest,

$$q_{e2} = (1+r)q_{e1}$$

This equation is equivalent to the constancy of the present-value price of oil. The oil exporting country, country F, is indifferent as to how much oil is produced in period 1 and period 2, as long as the sum of production equals to the total oil stock.

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[23] For a model with imperfect substitution, see Long (2012). Fischer and Salant (2012) have simulated green paradox results in a dynamic model with partial equilibrium features. Another aspect that we did not cover is the heterogeneity of resource intensities, see Pittel and Bretschger (2011).

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