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Environmental Responsibility and Policy in a Two-country Dynamic Input–Output Model

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Abstract *Increased spatial dependency of economic activities, as well as spatial differentiation of production and consumption, has implications for environmental policy. One of the issues that has gained importance is the responsibility for the emissions from products that cross national boundaries during the environmental policy's lifetime. This paper discusses the different ethical views of environmental responsibility. Furthermore, the policy measures that are associated with the different viewpoints are analyzed in a novel dynamic two-country two-sector dynamic input–output model. A numerical example is modeled to assess taxing schemes that are based on these ethical viewpoints. The results show that a tax on the 'embodied' environmental pressure, which is generally viewed as ethically preferable, is less effective that the current policy of taxing consumers of products. Our discussion however shows that these results are very dependent on the model structure and initial parameters that are used. Nevertheless, the model illustrates that policies that are based on ethically superior standpoints may have detrimental distortionary effects in the dynamic setting.*

Key Words: Dynamic input–output model, international trade, technological change, environmental responsibility

Introduction

Increased globalization of economic activities has expanded the spatial differentiation of production and consumption. This has important implications for environmental policy because environmentally damaging emissions may be generated during the extraction, production, transportation and consumption of products. Since each of these stages of

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the lifecycle of a product may occur in different countries, environmental policies that are based on national boundaries may have distortionary effects. As a result, environmental emissions may simply be shifted from one country to the other, which sometimes can lead to worse environmental conditions on the global scale.

An example is the Kyoto protocol on greenhouse gases. The protocol binds certain countries to reducing the emissions of carbon dioxide within their national boundaries. Although limited trade of CO_2 emission rights is allowed, the emission targets are restricted to national boundaries. However, policies to reduce national emissions, such as carbon taxes, can lead to higher imports and lower domestic production of energy intensive products. These asymmetric policy targets, which are set unilaterally by western countries, lead to relocation of production. National emissions targets may be met, but global reductions could potentially increase because of inferior technologies and energy efficiency.

When targets are set in environmental agreements they are based on a variety of factors. As a starting point, an ethical viewpoint on the environmental responsibility of countries is agreed. As we have already discussed, the Kyoto protocol is based on the responsibility for the emissions within the geographical area of a country. However, the resulting targets are also based on other issues such as economic, historical and political factors. In the case of the Kyoto protocol, targets were only set for the rich countries since these emitted most greenhouse gases in the past and are economically the strongest.

This paper investigates three ethical viewpoints (described in detail in the following section) on environmental responsibility in a dynamic setting. The following question is investigated. What are the environmental and economic effects of policies based on different ethical viewpoints of environmental responsibility on global and country levels? The three viewpoints are analyzed in a numerical example of a dynamic two-sector two-country input–output model that includes technological progress, technology spillovers, economic growth, trade and environmental emissions. The input–output framework is well-suited for these types of studies, since it can accommodate monetary as well as physical or other units simultaneously, which is essential for any environmental analysis. Most dynamic input–output models focus on the national scale or have assumed exogenous trade flows. In this paper, endogenous trade flows are used.

The structure of this paper is as follows. The next section reviews the different ethical positions of environmental responsibility. The section after provides an overview of the theoretical background of economic growth, technology, trade and their influence on environmental emissions. The fourth section covers the assumptions and equations that are used in the model. The results of the baseline and policy scenarios are presented in the fifth section and the sixth section concludes.

Environmental Responsibility

During the lifecycle of a product there are a number of distinct phases that may be distinguished. First, there is the production phase, which includes extraction, production and transportation of the product. This process requires raw materials, energy, intermediate inputs, labor and capital inputs. The production process generates unwanted outputs as well, in the form of waste emissions. The second phase, the final consumption phase, also leads to environmentally detrimental emissions because the goods are discarded after use or require polluting inputs such as fossil fuel during their use.

When the stages in a product lifecycle occur in different geographic areas, as is the case for many products in the world today, the wastes that are generated in these stages also occur in different places. Assuming that in the global setting, the nation-state is the entity that bears responsibility in these matters, the question arises of which of these waste flows each country is responsible for. This issue is not new. In fact the assessment of the environmental relationship between countries has a long history. The following paragraphs will discuss the literature in this field.

IO modeling has led to many papers that assess the ‘embodied’ environmental load in imports and exports. In the case of embodied studies that are based on IO models the direct and indirect emissions of trade are evaluated (Bullard and Herendeen, 1975; Miller and Blair, 1985). Related to these studies are calculations of the ‘environmental balance of trade’ in which the net effect of trade on embodied environmental flows is calculated.[1]

Many studies examine data for one year. Most studies find that the exports of first world countries are more pollution and energy intensive than the imports, making them net exporters of environmental problems (Antweiler, 1996; Lenzen, 1998; Murata *et al.*, 1998; de Haan 2002). Wyckoff and Roop (1994) and Subak (1995) show that the carbon and methane contents of imports of western countries are sizeable compared with domestic emissions. However, Machado *et al.* (2001) show that third world countries, such as Brazil, can also have exports that are more carbon and energy intensive than their imports. Statistics Sweden (2002) and Suh *et al.* (2002) show that Sweden and the United States are net importers for some environmental pressures and net exporters for others.

Other studies calculate the ‘embodied’ or ‘balance of trade’ for several years. These studies provide insight in the ‘pollution haven hypothesis’, which implies that reductions in environmental emissions in western countries have been compensated by increases in the emissions by the other countries. In other words emissions have simply shifted from rich to poor countries. The evidence is mixed. The results in Schaeffer and Leal de Sá (1996) and Kondo *et al.* (2000) suggest that this shift is taking place for Brazil and **Q1** Japan respectively. However, Jacobsen (2000) and Munksgaard and Pedersen (2001) show that the embodied energy and carbon of Danish net exports is increasing. Atkinson and Hamilton (2002) also find that the net consumption of global resources by the OECD decreased from 1980 to 1985 and then stabilized. Muradian *et al.* (2002) show mixed results with respect to the shift from rich to poor countries. They show that for Western Europe and Japan the balance of embodied emissions in trade exhibits an inverted U curve, i.e. from 1976 to 1990 the ratio of emissions in imports and exports increased while after that it decreased (thereby raising doubt over a shift in pollution towards the third world). The US however shows and N shaped curve where the balance deteriorates towards the end of the 1990s.

Some studies try to model the shifts of the environmental burdens under certain model conditions. Gale (1995) for example shows the effect of the tariff elimination on pollution if Mexico joined the NAFTA. Lee and Roland-Holst (1997) use a general equilibrium model to test the economic and environmental effects on the Indonesian and Japanese economies under different tax and trade abatement strategies. Gielen and Moriguchi (2002) find that carbon taxing regimes implemented for the iron and steel sector in Japan and Europe could lead to significant carbon leakage, i.e. domestic carbon intensive production would be replaced by imports. Felder and Rutherford (1993) use a dynamic general equilibrium model to assess the effects of unilateral cuts in CO_2 emissions.

An influential trend of the literature is the ‘ecological footprint’, which was introduced by Wackernagel and Rees (1996). In this method, the quantity of land that is required to compensate for environmental pressures is evaluated. Despite the drawbacks associated with this method (van den Bergh and Verbruggen, 1999), the footprint does include environmental pressures irrespective of the location that the pressures arise. See also Bicknell *et al.* (1998); Proops *et al.* (1999); and Hubacek and Giljum (2003).

Finally, there are a number of the studies that explicitly discuss environmental responsibility. Eder and Narodoslawsky (1999) identify six types of responsibility that are territorial, production/consumption and direct/indirect factors. Bastianoni *et al.* (2004) discuss six different ways of assigning greenhouse gas emissions. Bazin *et al.* (2004) discuss the link between taxation and environmental responsibility. Lenzen *et al.* (2004) perform an input–output study of embodied CO_2 emissions using a five-region input output model of Denmark, Germany, Norway, Sweden and the rest of the world. They show that that the insights for Denmark on the trade of embodied CO_2 are very different when embodied CO_2 from trade partners is included. Lenzen *et al.* (2004) argue that the level of aggregation is an important issue in determining responsibility for CO_2 emissions.

Overall, this incomplete literature review shows that the trade and responsibility effects have enjoyed considerable attention. This is not surprising since shifting environmental burdens could lead to improvements in national environmental performances while global sustainability is harmed. It is these shifting mechanisms that are under investigation in this paper.

In this article, other notions of environmental responsibility are explored, despite practical and political problems that could arise if policies were based on them. The three notions of environmental responsibility that we consider are the following. First, the ‘use’ notion, where a country is held responsible for the waste emissions within its borders. As described earlier, this seems to be the consensus view for international agreements such as the Kyoto protocol. All wastes and emissions from the extraction, production, transportation and consumption phase are assigned to the country in which these activities take place. A corresponding policy tool would be to tax all emissions within the borders of the country.

Second, the ‘make’ notion, where a country is responsible for the products that it produces. This implies that the producers of products are responsible for all wastes generated during the lifecycle of a product (including it being discarded). Important in this viewpoint is that this responsibility remains, irrespective of the country in which the emission occurs. An appropriate policy would be to tax the use of raw materials since all primary materials used in the production process must at some stage in the product lifecycle be discarded. Although this viewpoint satisfies the idea of producer responsibility, its political implications are extreme. For example, the OPEC countries would be held responsible for all fossil fuels that it produced, and would be required to tax their primary asset.

Third, the ‘embodied’ material notion, where a country is deemed responsible for the direct and indirect waste streams generated during the lifecycle of the final consumption package. In other words, all the waste streams that were associated with producing, transporting and discarding the good. This type of analysis has already been discussed in this section. A tax could be imposed on the direct and indirect material content of each good and service that is consumed.

Theoretical Background

In environmental economics, the impact of human society on the environment is encapsulated by the IPAT equation (Ehrlich and Holdren, 1971). This simple model relates the environmental impacts (I) to the population (P), affluence (A) and technology (T) used in society. The implication is that reductions in one or more of the three driving forces will have to contribute to reductions in environmental emissions. However, this model is a simplified descriptive view that includes only the rudimentary assumptions about technology and trade. Global emissions of environmentally damaging substances can be represented by the following equations (assuming no stock changes). The total emissions equal the emissions from the production process plus the emissions from final consumption. That is,

$$m = \Sigma_i x \times s_i \times e_i^{\text{prod}} + \Sigma_i y_i \times e_i^{\text{cons}} \tag{1}$$

with

$$s_i = \frac{x_i}{x} = \frac{z_i + y_i}{x},\ e_i^{\text{prod}} = \frac{m_i^{\text{prod}}}{x_i},\ \text{and}\ e_i^{\text{cons}} = \frac{m_i^{\text{cons}}}{y_i}$$

where $M =$ total emissions in the economy; $x =$ total output of the economy; $x_i =$ output of sector i; $y_i =$ final demand for the product from sector i; $m_i^{\text{prod}} =$ emissions of production sector i; $m_i^{\text{cons}} =$ emissions from the final consumption of the product from sector i; $z_i =$ share of sector i in the total economy; $e_i^{\text{prod}} =$ emissions of production sector i per unit of its output; $e_i^{\text{cons}} =$ emissions from the final consumption of one unit of the product from sector i; and $z_i =$ output of sector i for intermediate use.

Assume that amongst i products there are polluting and non-polluting products. The equation suggests that there are six possible ways of reducing emissions. (1) Reduce the size of the economy (x); (2) decrease the sector share (s_i) of products by reducing the intermediate use of polluting products (z_i); (3) Decrease the sector share (s_i) of products by reducing the final demand for polluting products (y_i); (4) Decrease the emissions per unit output of the producing sectors (e_i^{prod}); (5) Decrease the final demand for polluting products (y_i); and (6) Decrease the emissions per unit final demand (e_i^{cons}).

However, if national boundaries are introduced into this model, policymakers that negotiate on the basis of these borders have more options than in the one-world case. There are two policy variables in the above list that have international dimensions. Both components of the sector share of an economy, the production of intermediates and final products, may be satisfied through import substitution. Rather than producing intermediate goods that are highly polluting, these products could simply be imported. Similarly, products that are polluting in the production phase, could also be acquired from elsewhere. Note that in terms of emissions from consumption this substitution possibility is not present.

The potential effectiveness of trying to change each of these six driving forces is an open question. First, the absolute values that are involved are important. For example, a producing sector may be highly polluting, but if it is a marginal sector in the economy, reducing the emission coefficients will do very little to improve the environmental conditions. Secondly, many of the variables in equation (1) are interrelated. This means that if a policy is introduced that affects one of the variables, then other variables may change because of these relationships. For example, if the final demand for some product increases it also affects the intermediate demand and total output of the economy. These distortionary effects become even more important in a multicountry setting in which policy measures are implemented on the basis of national boundaries. In the next section, a model is presented that tries to clarify some of these distortionary pressures in a two-country setting. However, some of the theoretical relationships between the variables are discussed briefly in the following subsections.

Economic Growth

The first policy option is to alleviate the environmental pressure of the economy by reducing the size of the economy (x). Since governmental policies invariably strive towards increasing economic output, such a policy is not likely to become politically feasible. Policy measures are therefore more likely to be focused on the other variables than the economic volume. An unresolved issue is whether it is possible to reduce emissions adequately without reducing economic output.

Some authors assert the contrary: economic growth *leads* to environmental improvements. This claim is based on the empirical trends known as the 'Environmental Kuznets Curve' (EKC), which depicts an inverted U-shaped relationship between emissions and income per capita for selected emission types and countries (see for example Grossman and Krueger, 1995). The curve takes a black-box view of an economy, and there is no reason to assume that this pattern will repeat itself automatically for the developing world. They also note that the diminishing emissions in the developed world could be illustrating a trend in the developed world to substitute environmentally unfriendly domestic products for imports. Furthermore, there are also indications that the U-shaped relationship may not be robust over time for the western world. De Bruijn (2000) points to evidence for relinking of economic prosperity and emissions suggests a disconcerting N-shaped relationship.

Technology

Technology plays an important role in both economic growth and the environmental repercussions of economic activity. There is consensus amongst economic growth theories that technological development is the most important source of long-term economic growth (see for example Romer, 1996). From the environmental point of view, the use of inputs (z_i) and the emissions (e_i^{prod}) from the production process are also dictated by the technologies in place. Similarly, the emissions from the consumption phase (e_i^{cons} and y_i) are also dictated by their technological characteristics. However, there is no guarantee that technological developments that drive economic growth will be beneficial to the environment, or vice versa that technological developments that lead to greater environmental performance will benefit economic growth. A case in point is the industrial revolution, which brought economic prosperity, but also increased western societies' dependence on environmentally detrimental materials.

Technology, however, is a difficult concept to define. A company's 'technology' is the result of the chemical, mechanical, organizational characteristics of its production process, which manifests itself in the inputs required and the products and emission outputs. Technological change is often modeled by using expenditures on R&D as an indicator of the technological advances of a company. However, expenditures such as restructuring costs, which make the company more efficient, affect the technology as well.

An important aspect of technology is its characterization as a public good. Technological knowledge is non-rival (i.e. the use of technology by one producer does not preclude its use elsewhere). However, it is partially excludable, i.e. patent laws or secrecy allow a producer to use a technology exclusively for a period of time (Romer, 1990; Aghion and Howitt, 1992). This explains the incentives for firms to invest in R&D because it gives them the opportunity to reap monopolistic profits for a period of time.

Technology also has a positive externality in that it spreads in the economy. These spillovers can be domestic (to similar companies or companies with similar technologies) or international. The input–output literature has been used extensively to investigate productivity gains from R&D in different sectors. See, for example, the special issues of this journal (*Economic Systems Research*, 1997a, b) that dealt specifically with intersectoral R&D spillovers.

Sector Structure and Trade

The possibility of intercountry trade allows for import substitution. Traditional trade theories predict that countries will automatically specialize in the products for which it has a comparative advantage. In the case of environmental policy, the possibility of import substitution may actually have a detrimental effect. Simultaneously, intercountry trade is viewed as contributing to economic growth (Frankel and Romer, 1999). Recently, the influence of free trade on the environment has also been evaluated (Antweiler *et al.*, 2001). The international material-product chain (IMPC) is proposed in van Beukering *et al.* (2000). The IMPC indicates the extraction, use and production of materials and products in an international setting. The model presented here is an example of a simple IMPC model.

A Two-country Two-sector Input–Output Model

To illustrate the distortionary effects that unilateral policy measures may have in a multi-country setting, a model is presented in this section. Variables that correspond to volumes (such as mass, service units and number of discoveries) will be indicated by symbols with an overbar, while symbols for monetary variables, coefficients and prices do not carry an overbar. The model is called SIMBIOSES referring to Spatial Industrial Metabolism and Behavior of Input/Output Structures in an Economic System. An input–output framework model has been adopted because of the following advantages. First, it is an ideal framework in which technology, sector structure and trade can be integrated. The second advantage is that the input–output framework can accommodate monetary as well as physical units in a coherent manner. Since the distortionary pressures are complicated, the model is kept very simple: a two-sector two-country input–output model. With this model we can analyze the dynamic effects, distortions, in different countries and sectors, for various policies.

The traditional input–output model with constant technical coefficients is unsuitable for the aims of this paper. A dynamic input–output model is required in which the technical coefficients change as a result of technological improvements. The most successful models that use input–output information are computable general equilibrium (CGE) models.

However, CGE models generally evaluate static equilibria under a certain policy scenario. In this paper, a dynamic model is required. Furthermore, CGE models calculate optimum solutions by maximization or minimization. The model required here includes sub-optimal solutions because of the lack of information about future technological change.

The Leontief–Duchin–Szyld dynamic input–output models (Duchin and Szyld, 1985) view technological change as a result of new capital goods being introduced. The model suffers from stability and sensitivity problems (Fleissner, 1990). Databases about the input requirements of different capital goods are also required. Recently, the endogenous growth theory has been transferred to the input–output setting (Los, 2001). The article models labor productivity, which results in economic growth. The technical intermediate input requirements are, however, kept unchanged. The model presented in this paper does not include growth through the growth of capital like the Leontief–Duchin–Szyld dynamic input–output models. It is more in line with the endogenous growth model by Los (2001), but focuses on changes in intermediate inputs rather than on labor productivity.

The growth mechanism and change in technology are modeled in a novel way in the ensuing model. Nevertheless, a number of standard modeling practices from the growth literature are adopted. First, economic growth is generated by technological improvements. Second, as was discussed earlier, technology is modeled as a non-rival partially excludable good. This implies that for a period of time a firm can reap the benefits of a technology before the knowledge ‘spills over’ to other companies. In this model, this is implemented by assuming that companies keep their technology secret for one period. This implies that for one period a company can ask customers to pay the price of the previous period, while the actual cost price is lower, due to lower input requirements. These monopolistic profits are pocketed by the firm (this idea is based on the non-rival partly excludable characteristics as described in Romer, 1990, and Aghion and Howitt, 1992).

Technology is driven by R&D expenditures. Industries are assumed to invest in R&D and are rewarded by efficiency improvements in the inputs requirements. The potential for input efficiency improvements is determined by an exogenous technology function. R&D requires material, service and labor inputs, but this production mix does not benefit from technological improvements.

In this analysis the two countries, A and B, both have a material (M) and service sector (S) that produces a physical good and an intangible service respectively. The goods and services are identical, irrespective of the country that produces them. The materials sector converts raw materials into material goods with 100% efficiency, i.e. no waste emerges from this conversion process. Material and service products may be used as intermediate or final goods. Intermediate goods are used either in the production process (indicated as sub-sector P) or for R&D activities (indicated by R). Once a material good is consumed, either as an intermediate by a company or as a final good by consumers, it is discarded and becomes a waste emission. The model is asymmetrical with respect to the countries: country A is assumed to be a technology leader while country B is a laggard. The monetary framework of the model is shown in Table 1.

The monetary input–output table simply depicts the balance of payments for each sector of the economy, where the columns represent the costs and the rows represent the payments received by the sector. The material (M) and service (S) sectors output are capable of being exported or imported for final consumption but not as intermediate inputs, because it would complicate the model even further. Labor (L) and raw materials

Table 1. Monetary input–output table

		Country *A*					Country *B*					
		M		*S*		*Y*	*M*		*S*			
		P	*R*	*P*	*R*		*P*	*R*	*P*	*R*	*Y*	*X*
Country *A*	*M*	z^A_{MM}	f^A_{MM}	z^A_{MS}	f^A_{MS}	y^{AA}_M					y^{AB}_M	x^A_M
	S	z^A_{SM}	f^A_{SM}	z^A_{SS}	f^A_{SS}	y^{AA}_S					y^{AB}_S	x^A_S
	L	z^A_{LM}	f^A_{LM}	z^A_{LS}	f^A_{LS}							
	G											
Country *B*	*M*					y^{BA}_M	z^B_{MM}	f^B_{MM}	z^B_{MS}	f^B_{MS}	y^{BB}_M	x^B_M
	S					y^{BA}_S	z^B_{SM}	f^B_{SM}	z^B_{SS}	f^B_{SS}	y^{BB}_S	x^B_S
	L						z^B_{LM}	f^B_{LM}	z^B_{LS}	f^B_{LS}		
	G											
Profit		m^A_M		m^A_S			m^B_M		m^B_S			
Gross output		x^A_M		x^A_S			x^B_M		x^B_S			

Notes: z^U_{ij} = inputs in monetary terms from sector i (= M, S, L) in country U (= A, B) to sector j; f^U_{ij} = inputs in monetary terms from sector i (= M, S, L) in country U for R&D in sector j; y^{UV}_i = final demand in monetary terms for products from sector i (= M, S) in country U by consumers in country V; x^U_i = output in monetary terms of sector i in country U; m^U_i = profits in monetary terms of sector i in country U.

(G) are assumed to be immobile. The monetary balance equations are obtained from the equality between the row totals and the column sums in Table 1.

As Table 2 shows, underlying the value table are volume and price components.[2] This table registers output flows of sector M in mass units while sector S is measured in service units. The volume measures are represented by variable names with a bar. Since the model is dealing with homogeneous products and no price discrimination is assumed, the base price of the goods and services is the same for all users. However, the price can differ for each user because of the possibility of taxation. The price p is therefore the net price composed of the base price plus tax. Note that the mass of material products is balanced by the use of raw materials from nature and intermediate products. It is assumed that the entire mass of raw materials is converted to products (i.e. no waste is generated during the production process).

Now that the model framework is clear, the equations used in the model are discussed. The model has a sequentially dynamic structure. The basic model structure is: (1) wages and profits (monopoly rents) are earned by the laborer-owners of industries in period $t-1$; (2) a portion of the wages is invested in R&D while the rest is used for consumption; (3) the R&D leads to discoveries; (4) discoveries improve the efficiency at which inputs are used, the improvement is certain but the magnitude is unknown; (5) the demand for goods and services (from R&D, intermediate goods and final consumption) are provided at the prices of period t but at a production price that is lower because of input efficiency improvements; (6) wages (from R&D and production) and monopoly rents are earned.

The model starts by assuming that a certain income w (consisting of the wages for production workers and R&D workers as well as monopoly profits) was earned in period $t-1$. This income is spent in period t. A portion (θ) of the wage income is reserved for R&D purposes while the rest $(1-\theta)$ is used to purchase goods

Table 2. Input–output table in volume and price components

		Country A					Country B					
		M		S			M		S			
		P	R	P	R	Y	P	R	P	R	Y	X
Country A	M	$\bar{z}^A_{MM} \cdot p^A_M$	$\bar{f}^A_{MM} \cdot p^A_M$	$\bar{z}^A_{MS} \cdot p^A_M$	$\bar{f}^A_{MS} \cdot p^A_M$	$\bar{y}^{AA}_M \cdot p^A_M$					$\bar{y}^{AB}_M \cdot p^A_M$	$\bar{x}^A_M \cdot p^A_M$
	S	$\bar{z}^A_{SM} \cdot p^A_S$	$\bar{f}^A_{SM} \cdot p^A_S$	$\bar{z}^A_{SS} \cdot p^A_S$	$\bar{f}^A_{SS} \cdot p^A_S$	$\bar{y}^{AA}_S \cdot p^A_S$					$\bar{y}^{AB}_S \cdot p^A_S$	$\bar{x}^A_S \cdot p^A_S$
	L	$\bar{z}^A_{LM} \cdot p^A_L$	$\bar{f}^A_{LM} \cdot p^A_L$	$\bar{z}^A_{LS} \cdot p^A_L$	$\bar{f}^A_{LS} \cdot p^A_L$							
	G	$\bar{z}^A_{GM}$										
Country B	M					$\bar{y}^{BA}_M \cdot p^B_M$	$\bar{z}^B_{MM} \cdot p^B_M$	$\bar{f}^B_{MM} \cdot p^B_M$	$\bar{z}^B_{MM} \cdot p^B_M$	$\bar{f}^B_{MS} \cdot p^B_M$	$\bar{y}^{BB}_M \cdot p^B_M$	$\bar{x}^B_M \cdot p^B_M$
	S					$\bar{y}^{BA}_S \cdot p^B_S$	$\bar{z}^B_{SM} \cdot p^B_S$	$\bar{f}^B_{SM} \cdot p^B_S$	$\bar{z}^B_{SM} \cdot p^B_S$	$\bar{f}^B_{SS} \cdot p^B_S$	$\bar{y}^{BB}_S \cdot p^B_S$	$\bar{x}^B_S \cdot p^B_S$
	L						$\bar{z}^B_{LM} \cdot p^B_L$	$\bar{f}^B_{LM} \cdot p^B_L$	$\bar{z}^B_{LM} \cdot p^B_L$	$\bar{f}^B_{LS} \cdot p^B_L$		
	G						$\bar{z}^B_{GM}$					

Note: a bar is used to indicate the inputs, final demands and outputs in volume terms; p_i^U gives the base price of materials, services, labor ($i = M, S, L$) for sector i in country U. Note that raw materials (G) have a value in this table but they do not appear in the monetary Table 1. This is because these are natural resources that only obtain value once they are extracted. The column therefore includes different units and cannot be added up. If one deleted all the prices and the non-mass values one would obtain a physical input–output table.

and services. Equations (2) and (3) show the demand for goods in country A. For $i = M,\ S$

$$y_i^{AA}(t) = \begin{cases} \rho_i \cdot \sum_{j=M,S}[1 - \theta_j^A(t)]w_j^A(t-1)\cdot \\ \quad \exp[-[\mu_i[p_i^{AA}(t) - p_i^{BA}(t)]]^{\phi}] & \text{if } p_i^{AA}(t) > p_i^{BA}(t) \\ \rho_i \cdot \sum_{j=M,S}[1 - \theta_j^A(t)]w_j^A(t-1) & \text{if } p_i^{AA}(t) \leq p_i^{BA}(t) \end{cases} \tag{2}$$

$$y_i^{BA}(t) = \begin{cases} \rho_i \cdot \sum_{j=M,S}[1 - \theta_j^A(t)]w_j^A(t-1)\cdot \\ \quad \exp[-[\mu_i[p_i^{AA}(t) - p_i^{BA}(t)]]^{\phi}] & \text{if } p_i^{AA}(t) > p_i^{BA}(t) \\ 0 & \text{if } p_i^{AA}(t) \leq p_i^{BA}(t) \end{cases} \tag{3}$$

where $\Sigma_{i=M,S}\rho_i = 1$; and y_i^{UV} denoting the final demand (in monetary terms) for the product of sector i in country $U(= A,\ B)$ by consumers in country V; w_j^U the income in sector j in country U; p_i^{UV} the price of the final product from sector i in country U as paid by consumers in country V; ρ_i the share of disposable income spent on good i; θ_j^A the fixed proportion of wages in sector j in country A that is used for R&D; and parameters μ_i and ϕ, which reflect the sensitivity of the consumers to price differences between imported and domestic final products. The equivalent equations for y_i^{BB} and y_i^{AB} are obtained by replacing A with B and B with A in equations (2) and (3).

The equations have three separate parts. The parameter ρ_i identifies the portion of the income that is reserved for consumption of material goods or services. The second part calculates the total amount of income that is spent on consumption rather than R&D. The parameter $1 - \theta$ (i.e. the fraction reserved for consumption) is multiplied by the total income. The last part of this equation shows what portion of the material goods or services come from each country. Since the products from both countries are identical, this is purely a question of price competition.

The price competition is best explained graphically (see Figure 1). The exponential function $\exp[-(p^B - p^A)^2]$, for example, simply implies that a larger difference in prices between countries, leads to a larger trade flow. The function therefore dictates that if the price difference is very small the amount of domestic goods consumed is very high and the amount imported small. This type of relationship is consistent with the idea that the import share increases exponentially as the price difference increases but that there is a point of inflection where the increases in import share start to slow

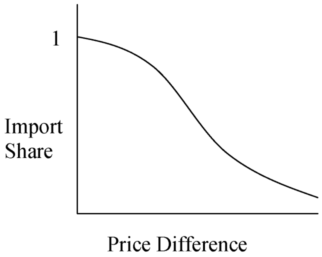

Figure 1. Function $\exp[-(p^B - p^A)^2]$

down due to structural reasons (for a similar rule for imports, see Los and Verspagen, 2000).

Country A is richer than country B and invests a larger and constant share of the wages in R&D. Country B is assumed to adjust its fraction according to its relative wealth at that moment. It is assumed that as the wages of country B converge to the level of country A, also the percentage spent on R&D converges. That is, for $j = M, S$

$$\theta_j^B(t) = \frac{w_j^B(t-1)}{w_j^A(t-1)} \cdot \theta_j^A \tag{4}$$

Investments in R&D in country A are assumed to be a fixed constant of the income. This follows Los (2001) and insights from the innovation literature. Freeman and Soete (1997) point out that producers use simple rules of thumb when it comes to making investment decisions. The money reserved for R&D is spent on generating 'discoveries' in the area of material, service or labor productivity.

A second source of R&D euros is from government subsidies. The total amount of these subsidies is equal to the taxes raised in period $t-1$. The total amount of money that is reserved for R&D is used to fund the production of discoveries. The R&D process requires materials, services and labor inputs to produce discoveries and innovations (say patents) as output. The number of discoveries from R&D by producers and by the government is therefore:

$$\bar{d}_{ij}^{U(PROD)}(t) = \frac{r_{ij}^{U(PROD)}(t)}{\sum_{i=M,S,L} c_i^U(t) \cdot p_i^U(t)} \quad \text{and} \quad \bar{d}_{ij}^{U(GOV)}(t) = \frac{r_{ij}^{U(GOV)}(t)}{\sum_{i=M,S,L} c_i^U(t) \cdot p_i^U(t)} \tag{5}$$

for $i = M, S, L$; $j = M, S$; and $U = A, B$; with $\bar{d}_{ij}^{U(GOV)}$ discoveries financed by government R&D assistance of sector i in country U towards improving the efficiency of the use of input j and, similarly, $\bar{d}_{ij}^{U(PROD)}$ for discoveries from R&D financed by sector i; $r_{ij}^{U(GOV)}$ R&D assistance by the government to sector i in country U towards improving the efficiency of the use of input j and, similarly, $r_{ij}^{U(PROD)}$ the R&D expenditure by producers in sector i in country U for that purpose; c_i^U the input requirements for a discovery; and p_i^U the base price of materials, services and labor ($i = M, S, L$) for sector i in country U.

However, the producers and governments have decisions to make about the allocation of R&D funds. In this decision both the producers and government exhibit optimizing behavior but have no foresight. All R&D decisions are therefore based on present information.

The producer minimizes the expected input costs for the next period. This is done on the basis of information about the present period. A producer knows the last efficiency gain per unit R&D for each input ($\Delta k_{ij}^U / \Delta \bar{d}_{ij}^U$), where k_{ij}^U is the hybrid-unit technical coefficient, i.e. the physical amount of input i required per unit physical output of sector j in country U. The producer also knows the average price that was paid for these inputs and the share of the intermediate costs that this inputs required, that is $p_i^U(t) \cdot r_{ij}^{U(PROD)}(t) / \Sigma_{l=M,S,L} c_l^U(t) \cdot p_l^U(t)$. Based on this information and the fixed R&D budget, the producer will optimize the amount of R&D that is used for research into material, service and labor efficiency. The producer minimizes the expected cost reductions by selecting where to make discoveries. For $j = M, S$ and $U = A, B$, we have

$$\operatorname*{Min}_{r_{ij}^{U(PROD)}} \left\{ \sum_{i=M,S,L} \frac{\Delta k_{ij}^{U}}{\Delta \bar{d}_{ij}^{U}} \cdot \frac{r_{ij}^{U(PROD)}(t)}{\sum\limits_{l=M,S,L} c_{l}^{U}(t) \cdot p_{l}^{U}(t)} \cdot p_{i}^{U}(t) \right\} \tag{6}$$

with

$$\sum_{i=M,S,L} r_{ij}^{U(PROD)}(t) = \theta_{j}^{U}(t) \cdot w_{j}^{U}(t-1)$$

The government has a different objective function. Since material products are the only goods that are directly detrimental to the environment, it is only interested in improving the material input efficiency of these sectors. It therefore looks for the optimal spread of its R&D resources (which is equal to the tax revenue) amongst the two sectors. The way the taxes are raised will be discussed in the next section when the scenarios are introduced. The objective function of the government is to minimize the expected material use. That is

$$\operatorname*{Min}_{r_{Mj}^{U(GOV)}} \left\{ \sum_{j=M,S} \frac{\Delta k_{Mj}^{U}}{\Delta \bar{d}_{Mj}^{U}} \cdot \frac{r_{Mj}^{U(GOV)}(t)}{\sum\limits_{l=M,S,L} c_{l}^{U}(t) \cdot p_{l}^{U}(t)} \cdot \bar{x}_{j}^{U}(t-1) \right\} \tag{7}$$

with

$$\sum_{j=M,S} r_{Mj}^{U(GOV)}(t) = TR^{U}(t-1)$$

with $TR^{U}(t)$ the tax revenue in country U, and $\bar{x}_{i}^{U}$ the physical output of sector i in country U (in tons). Note that it is assumed that no strategic shifting of R&D euros occur by the producer in anticipation of government subsidies. The overall effect of R&D budgets and the discoveries that these entail, is that it reduces the technical coefficients k of both countries, i.e. the material, service and labor requirements per unit output reduces. This technological progress follows a ‘learning by doing’ path. The technical coefficients converge to a minimum potential coefficient α. The rate at which the value k converges to this value is dependent on the cumulative amount of discoveries.

In graphical terms, these developments are depicted by Figure 2. The figure depicts the stylized stages of technological progress presented in Grübler *et al.* (1999). This shows that the rate of technological progress may be split into different parts, each with differing rates of developments.

This technology cycle needs some clarification. Each input has potential for being used more efficiently, contingent on R&D being carried out to develop more discoveries. The marginal effect of each new discovery differs (although the model could easily be run with

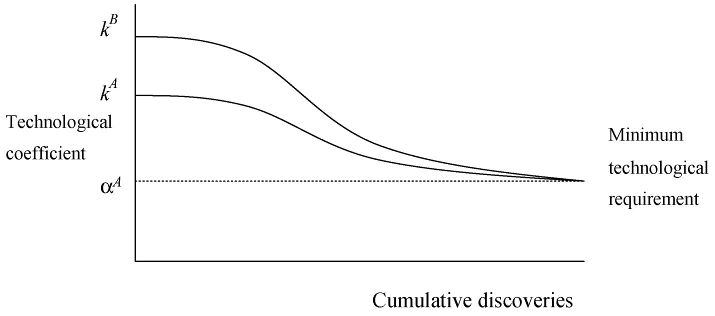

Figure 2. Technology cycles and spillovers from country *A* to *B*

other functional forms). The shape of the curves is not known to the producers or the government (no foresight) but they do know the efficiency improvement of the last euro of R&D, i.e. the gradient of the curve.

Figure 2 is represented by equations (8) and (9). Country *A* converges towards the minimum level α while country *B*, the technology laggard, catches up with the input coefficients of country *A*. The figure represents the classic maturation cycle of a technology, after which it will be replaced by other technologies. For $i = M, S, L$, and $j = M, S$

$$\begin{aligned} k_{ij}^{A}(t) = {} & \alpha_{ij}^{A} + [k_{ij}^{A}(0) - \alpha_{ij}^{A}]\cdot \\ & \times \exp\left(-\left[\beta\cdot\sum_{v=0}^{t}\left[\bar{d}_{ij}^{A(PROD)}(v) + \bar{d}_{ij}^{A(GOV)}(v)\right]\right]^{2}\right) \end{aligned} \tag{8}$$

$$\begin{aligned} k_{ij}^{B}(t) = {} & k_{ij}^{A}(t-1) + [k_{ij}^{B}(t-1) - k_{ij}^{A}(t-1)]\cdot \\ & \times \exp\left(-\left[\gamma\cdot\sum_{v=0}^{t}\left[\bar{d}_{ij}^{B(PROD)}(v) + \bar{d}_{ij}^{B(GOV)}(v)\right]\right]^{2}\right) \end{aligned} \tag{9}$$

with α_{ij}^{A} the coefficient that sets the limit of minimum possible technical coefficient of an input, β the coefficient that sets the effectiveness of the R&D, and γ the coefficient that sets the speed at which country *B* converges with the technical coefficients of country *A*. Now that the technological and demand components are known for period *t*, the physical output $\bar{x}_i^U$ in period *t* can now be calculated through the static hybrid-unit input–output model. That is, for $i, j = M, S$, and $U = A, B$

$$\bar{x}_i^U(t) = \sum_{j=M,S} h_{ij}^{UV}(t)\cdot\left(\sum_{l=M,S}\bar{f}_{jl}^{U}(t) + \sum_{V=A,B}\bar{y}_j^{UV}(t)\right) \tag{10}$$

where $h_{ij}^{UV}(t)$ are coefficients of the interregional hybrid Leontief inverse. This inverse is obtained as $\mathbf{H}(t) = [\mathbf{I} - \mathbf{K}(t)]^{-1}$, with $\mathbf{H}(t)$ the matrix with elements $h_{ij}^{UV}(t)$, $\mathbf{K}(t)$ the matrix with elements $k_{ij}^{UV}(t)$ and $\mathbf{I}$ the identity matrix. Further note that for $i, j = M, S$, and $U = A,B$

$$\bar{f}_{ij}^{U}(t) = c_i(t) \cdot \sum_{i=M,\,S,\,L} \left[\bar{d}_{ij}^{U(PROD)}(t) + \bar{d}_{ij}^{U(GOV)}(t)\right] \tag{11}$$

In equation (10), the input–output hybrid-unit model is used to find the physical outputs that are to be expected in period t. It is called the hybrid-unit model because it can facilitate different units (in this case mass and service units). The hybrid-unit model is superior to the standard input–output model since volumes are better descriptors of the technological requirements. Furthermore, these coefficients are not dependent on price changes (Miller and Blair, 1985).

The monopolistic profits are calculated by subtracting the input costs and R&D costs from the total output. The reason that these monopolies exist is because technology is partially excludable. That is, through patent or secrecy, transfers may be blocked or diminished (as described in Romer, 1990). It is assumed that the period for which these profits are earned is one period in the model. For $i = M, S$, and $U = A, B$ the monopolistic profits $m_i^U(t)$ are obtained as

$$m_i^U(t) = x_i^U(t) - \sum_{j=M,S,L} z_{ji}^U(t) - \sum_{j=M,S,L} f_{ji}^U(t) \tag{12}$$

The sum of the producer's wages, R&D wages and monopolistic profits signify the income $w_i^U(t)$ of the sector. For $i = M, S$, and $U = A, B$, it is determined by

$$w_i^U(t) = z_{Li}^U(t) + f_{Li}^U(t) + m_i^U(t) \tag{13}$$

Finally, the prices of the model are calculated using the price input–output model. The price of labor is dependent on the tension on the labor market, i.e. if the labor requirements were high in the previous period the price of labor would grow accordingly. For $U = A, B$, we have

$$p_L^U(t+1) = \omega^U \cdot \sum_{j=M,S} \left[\bar{z}_{Lj}^U(t) + \bar{f}_{Lj}^U(t)\right] \tag{14}$$

where ω^U is a coefficient for labor price which converts the quantity of labor into a monetary value. The price input–output model calculates the prices of material goods and services. That is, for $i = M, S$, and $U = A, B$

$$p_i^U(t+1) = \sum_{v=A,B} \sum_{j=M,S} h_{ji}^{VU}(t) \cdot k_{Li}^U(t) \cdot p_L^U(t+1) \tag{15}$$

In our scenarios, the base price p may be increased by inclusion of a certain tax. The taxation schemes are based on the different viewpoints of environmental responsibility that were described in the second section. The tax and subsidy schemes are different for each of the scenarios and are summarized in Table 3. As noted earlier, it is assumed

Table 3. Scenario specific taxing and subsidy equations

Scenario (Environmental viewpoint)	Tax	Tax revenue (= subsidy)
No taxing (Default)	$p_M^A = p_M^{AA} = p_M^{AB}$	No taxes
1 Tax on material products (make)	$p_M^{AA} = p_M^{AB} = p_M^A + \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{i=M,S} \bar{z}_{Mi}^{AU} + \sum_{U=A,B} \bar{y}_M^{AU} \right)$
2 Tax on consumption of material products (use)	$p_M^{AA} = p_{YM}^{AB} = p_M^A + \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{i=M,S} \bar{z}_{Mi}^{UA} + \sum_{U=A,B} \bar{y}_M^{UA} \right)$
3 Tax on direct and indirect final material consumption (embodied)	$p_M^{AA} = p_M^A + \left(\sum_{U=A,B} h_{Mi}^{UA} \cdot \right) \tau$ $p_M^{BA} = p_M^B + \left(\sum_{U=A,B} h_{Mi}^{UB} \cdot \right) \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{V=A,B} \sum_{i=M,S} \left(h_{Mi}^{VU} \cdot \bar{f}_i^{UA} \right) \right)$

that only the leader country *A* initiates a tax scheme and redistributes the taxes as material efficiency subsidies in either sector in country *A*. The base price is always given a single superscript letter, while the actual price (i.e. base price plus tax) is given a two-letter superscript because it may vary across countries.

Results

We performed an exploratory analysis with SIMBIOSES for the analysis of the conditions as presented in Table 3. The model is implemented for two hypothetical countries since real-world data would be distorted by interactions among more than two countries. We aim to provide a purely theoretical exercise to illustrate the dynamics of the SIMBIOSES model, and to show possible effects of shifting the environmental responsibility by different tax regimes. The parameter values and initial variable values are given in the appendix. The tax policy is assumed to be at a fixed level during the whole period. This seems to be quite unrealistic but it enables us to derive a clear signal of a certain tax policy. Since prices decrease due to technological progress, the relative tax as a fraction of the gross price increases in time.

Figures 3(a) and 3(b) show the development of GDP in both countries. Clearly, the unilateral implementation of policies in country *A* results in increasing wealth in country *B*. Although the results for country *B* are fairly similar the implementation of the use tax leads to the highest level of economic growth, while the default scenario is the least beneficial for country *B*. The results for country *A* show that all tax regimes lead to lower growth than the default scenario. The embodied tax, however, leads to the highest GDP per capita, while the make tax scenario is significantly lower. Notice that the tax regime leads to a temporary reduction of economic output in the first years of the simulation. This is because, initially, the investment in R&D leads to minor improvements in the efficiency as depicted by Figure 2. However, as the cumulated amount of R&D spent on technological innovations increases, the marginal technological change increases. This leads to the acceleration of economic growth after the initial drop in wealth.

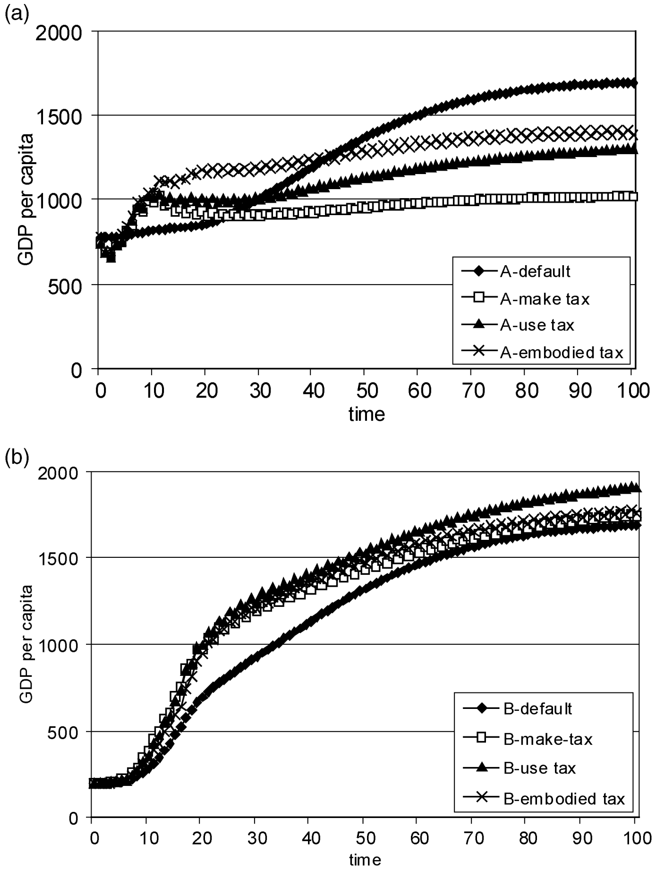

Figure 3. (a) GDP per capita in country *A*; (b) GDP per capita in country *B*

If the results are looked at from a global perspective, as is shown in Figure 4, the make tax scenario leads to the least attractive final GDP level. Nevertheless, the default scenario actually performs worse initially, but recovers through a similar level to the other three scenarios. But as Figure 3 shows, tax policies lead to a shift in the distribution of wealth due to increased catching up of country *B*.

The environmental consequences of these economic growth scenarios are shown in Figure 5. The results suggest that economic growth and environmental pollution are highly correlated in this model. There is definitely no question of decoupling of economic and environmental indicators. The make tax seems to lead to the largest reduction of emissions, but this is mainly due to the decreased economic output.

A more appropriate way would be to balance the consequences for economic development and environmental impact. Therefore, we map the discounted GDP (2%) to the overall pollution over the hundred time periods. Figure 6 shows the global results, while Figure 7 shows the results for countries *A* and *B*.

From a global perspective the embodied tax and use tax lead to the best results in terms of economic growth. It is interesting that the default scenario performs worse in economic terms as well as environmental performance. The make tax does the best environmentally,

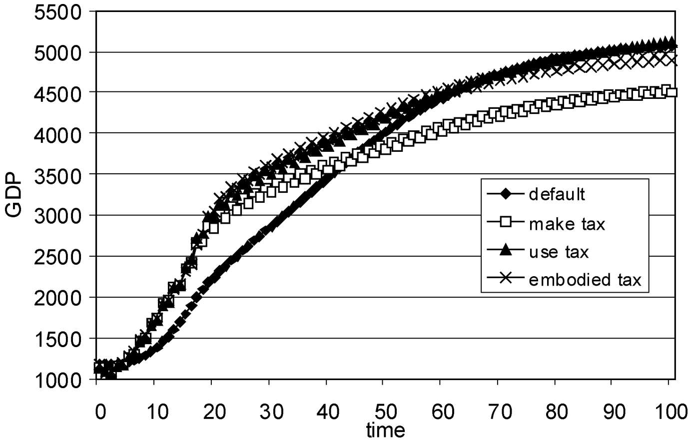

Figure 4. Global GDP

but at great expense to economic prosperity. The reason for the worse performance of the default scenario is that the investment decisions are sub-optimal. Figure 6 shows that the investments in R&D in the default scenario are smaller than the other scenarios which leads to lower economic growth than all other options. The taxing system has therefore improved the economic system as well as environmental system. However, the fact that the taxing policy has improved the optimality of the R&D decisions should be considered a fluke of the model. Governments cannot implement R&D policies that second-guess the R&D decisions made by producers. Nevertheless, it remains an intriguing result: shifting and increasing of R&D expenditures through taxing *could* potentially increase economic growth. The basic reasoning is as follows: the scenario that leads to quick R&D expenditures will lead to quicker economic growth and more efficient use of materials faster.

The individual results for country *A* show that economic performance is fairly similar for all four scenarios, while the environmental performance differs profoundly. The default scenario is highly polluting while the make tax is the least detrimental to the

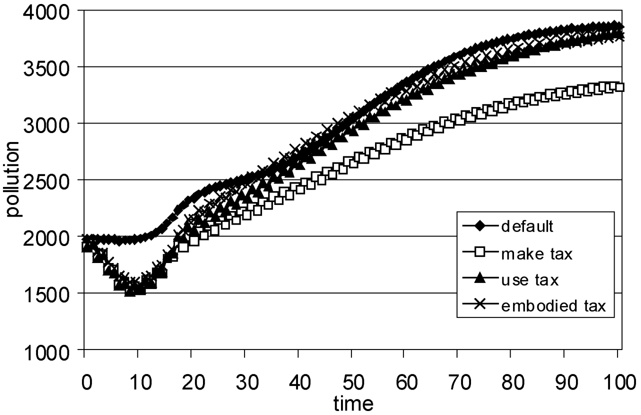

Figure 5. Global pollution

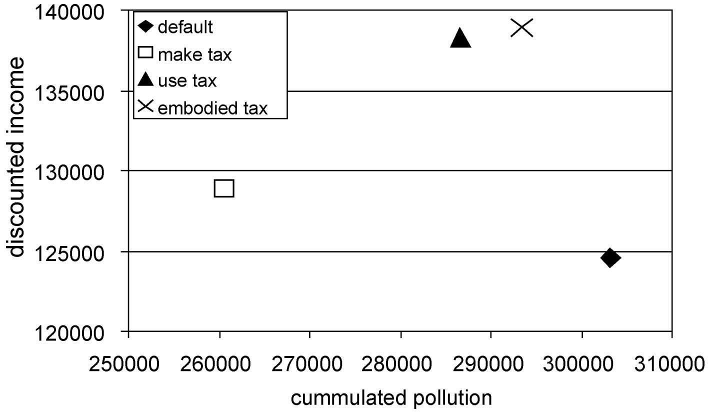

Figure 6. Global discounted GDP versus pollution

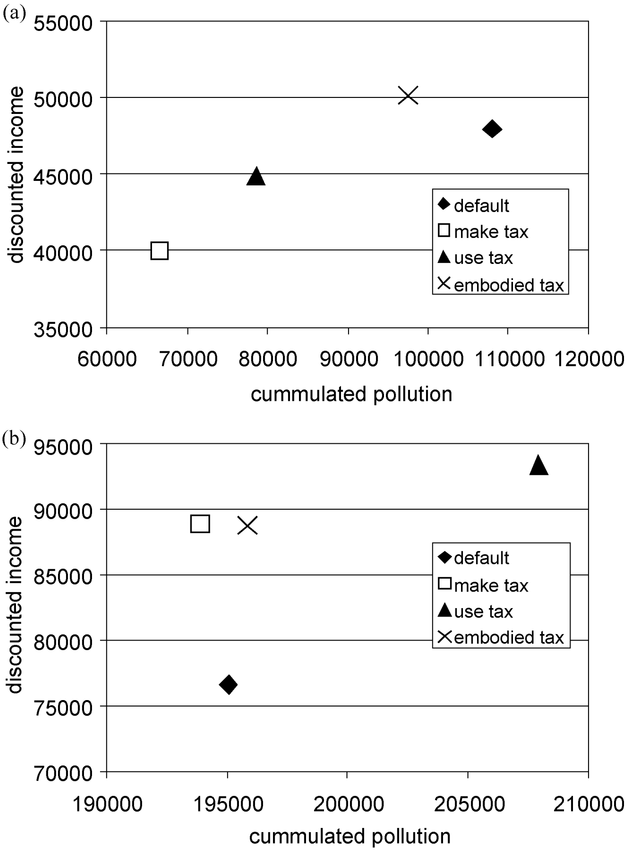

Figure 7. (a) Discounted GDP versus pollution in country *A*; (b) Discounted GDP versus pollution in country *B*

environment. The results for country *B* are more interesting. The default scenario leads to low environmental pressure, but also to a low economic growth. Any tax regime that is implemented in country *A* is beneficial to the economic wealth of country *B*. However, the results show that adopting the use tax would have significant detrimental effects on the environment, although it also leads to higher prosperity. This illustrates the notion of ‘carbon leakage’ whereby production of an environmentally unfriendly product shifts to another country.

The implications of the results are that country *A* should implement the make tax if its only objective is to reduce environmental pressure in country *A*. Figure 6 shows that this automatically also diminishes the global environmental pressures. However, if it believes that the economic sacrifices of this scenario are too large, it could adopt the use tax. However, Figure 7(b) illustrates that this leads to a massive shift towards pollution in the country *B*.

The more complex embodied tax regime might include some notion of fairness since it takes into account when and where products are processed in the international product cycle, in order to determine an environment tax. However, it is not effective from an environmental perspective as can be interpreted from Figures 6 and 7. Due to the political difficulty to implement a make tax, the only alternative in this numerical example seems to be the current compromise, a use tax.

Discussion and Conclusions

This paper aimed at two goals. First, to discuss the ethical positions of environmental responsibility. The resulting policy measures, based on these viewpoints are derived. Second, to contribute to the development of dynamic input–output modeling, by proposing a new two-country model. The model should be able to analyze technological development, economic growth, trade and environmental emissions in a two-country model.

With regard to environmental responsibility, the model shows the policy scenarios derived from the ethical positions. The results for the numerical example that has been chosen should simply be considered an illustration of the growth mechanism. Nevertheless, some interesting conclusions may be drawn. First, a lack of foresight implies that R&D expenditures by producers may be sub-optimal. Accepting this reasoning leaves open the possibility that taxing could actually enhance economic growth, as the numerical example shows. Second, the ‘ethically’ preferred taxing regime does not necessarily lead to the best environmental results in a dynamic setting.

With regard to the development of the sequential dynamic input–output model of two countries, the model has included bounded rationality foresight restrictions. Furthermore, the instability problems of capital goods dynamic input–output models have been avoided. The addition of trade in a dynamic input–output model has lead to new instabilities. Nevertheless, based on the preliminary results of the numerical example, the development of dynamic multi-region models is a necessity for analyzing environmental policies. This paper provides a (first) step in this direction.

Acknowledgements

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Notes

[1] Interesting methodological issues in this field have been raised. For example, Battjes *et al.* (1998) criticize the assumption that imports use the same production technology as domestic products; Jacobsen (2000) discusses aggregation in embodied emission calculations; and Kainuma *et al.* (2000) focus on embodied CO_2 calculations using a CGE and an IO model.

[2] A special case of this volume input–output table is the so-called physical input–output table (PIOT) which has been constructed for, amongst others, the Netherlands, Germany, Denmark and Italy (Konijn *et al.*, 1995, 1997; Stahmer *et al.*, 1997; Pedersen, 1999; Nebbia, 1999). See Hoekstra (2005) or Hoekstra and van den Bergh (2005) for an overview. PIOTs deal with transactions in the economy that have a mass component. Clearly this development is important for environmental analysis because the mass balance principles dictate that all raw material extraction and emissions by the producers are recorded.

References

Aghion, P. and Howitt, P. (1992) A model of growth through creative destruction, *Econometrica*, 60, pp. 323–351.

Antweiler, W. (1996) The pollution terms of trade, *Economic Systems Research*, 8, pp. 361–365.

Antweiler, W., Copeland, B.R. and Taylor, M.S. (2001) Is free trade good for the environment?, *American Economic Review*, 91, pp. 877–908.

Atkinson, G. and Hamilton, K. (2002) International trade and the 'ecological balance of payments', *Resources Policy*, 28, pp. 27–37.

Bastianoni, S., Pulselli, F.M. and Tiezzi, E. (2004) The problem of assigning responsibility for greenhouse gas emissions, *Ecological Economics*, 49, pp. 253–257.

Battjes, J.J., Noorman, K.J. and Biesiot, W. (1998) Assessing the energy intensities of imports, *Energy Economics*, 20, pp. 67–83.

Bazin, D., Ballet, J. and Touahri, D. (2004) Environmental responsibility versus taxation, *Ecological Economics*, 49, pp. 129–134.

van den Bergh, J.C.J.M. and Verbruggen, H. (1999) Spatial sustainability, trade and indicators:an evaluation of the 'ecological footprint', *Ecological Economics*, 29, pp. 61–72.

van Beukering, P.J.H., van den Bergh, J.C.J.M., Janssen, M.A. and Verbruggen, H. (2000) International material–product chains: an alternative perspective on international trade and trade theories, *Discussion paper* TI2000-034/3, Tinbergen Institute, Amsterdam.

Bicknell, K.B., Ball, R.J., Cullen, R. and Bigsby, H.R. (1998) New methodology for the ecological footprint with an application to the New Zealand economy, *Ecological Economics*, 27, pp. 149–160.

Bullard III, C.W. and Herendeen, R.A. (1975) The energy cost of goods and services, *Energy Policy*, 1, pp. 268–277.

de Bruijn, S. M. (2000) *Economic Growth and the Environment: An Empirical Analysis*(Dordrecht: Kluwer Academic Publishers).

Duchin, F. and Szyld, D.B. (1985) A dynamic input–output model with assured positive outcome, *Metroeconomica*, 37, pp. 269–282.

Economic Systems Research (1997a) Special Issue: Intersectoral R&D Spillovers, Volume 9, Number 1, pp. 3–142.

Economic Systems Research (1997b) Special Issue: Invention Input–output Analysis, Volume 9, Number 2, pp. 147–230.

Eder, P. and Narodoslawsky, M. (1999) What pressures are a region's industries responsible for? A method of analysis with descriptive indices and input–output models, *Ecological Economics*, 29, pp. 359–374.

Ehrlich, P.R. and Holdren, J.P. (1971) Impact of population growth, *Science*, 171, pp. 1212–1217.

Felder, S. and Rutherford, T.F. (1993) Unilateral CO_2 reductions and carbon leakage: The consequences of international trade in oil and basic materials, *Journal of Environmental Economics and Management*, 25, pp. 162–176.

Fleissner, P. (1990) Dynamic Leontief models on the test bed, *Structural Change and Economic Dynamics*, 1, pp. 321–357.

Frankel, J.A. and Romer, D. (1999) Does trade cause growth?, *American Economic Review*, 89, pp. 379–399.

Freeman, C. and Soete, L. (1997) *The Economics of Industrial Innovation*, 3rd edn (London: Pinter).

Gale, L.R. (1995) Trade liberalization and pollution: an input–output study of carbon dioxide emissions in Mexico, *Economic Systems Research*, 7, pp. 309–320.

Gielen, D. and Moriguchi, Y. (2002) CO_2 in the iron and steel industry: an analysis of Japanese emission reduction potentials, *Energy Policy*, 30, pp. 849–863.

Grossman, G.M. and Krueger, A.B. (1995) Economic growth and the environment, *Quarterly Journal of Economics*, 110, pp. 353–377.

Grübler, A., Nakicenovic, N. and Victor, D.G. (1999) Dynamics of energy technologies and global change, *Energy Policy*, 27, pp. 247–280.

de Haan, M. (2002) Disclosing international trade dependencies in environmental pressure indicators: the domestic consumption perspective. Paper presented at the *14th International Conference on Input–Output Techniques*, Montreal.

Hoekstra, R. (2005) *Economic Growth, Material Flows and the Environment: New Applications of Structural Decomposition Analysis and Physical Input–Output Tables* (Cheltenham, UK: Edward Elgar).

Hoekstra, R. and van den Bergh, J.C.J.M. (2005) Constructing physical input–output tables for environmental modeling and accounting: framework and illustrations, *Ecological Economics* (forthcoming).

Hubacek, K. and Giljum, S. (2003) Applying physical input–output analysis to estimate land appropriation (ecological footprints) of international trade activities, *Ecological Economics*, 44, pp. 137–151.

Jacobsen, H.K. (2000) Energy demand, structural change and trade: a decomposition analysis of the Danish manufacturing industry, *Economic Systems Research*, 12, pp. 319–343.

Kainuma, M., Matsuoka, Y. and Morita, T. (2000) Estimation of embodied CO_2 emissions by general equilibrium model, *European Journal of Operational Research*, 122, pp. 392–404.

Kondo, Y., Moriguchi, Y. and Shimizu, H. (1998) CO_2 emissions in Japan: influences of imports and exports, *Applied Energy*, 59, pp. 163–174.

Konijn, P.J.A., de Boer, S. and van Dalen, J. (1995) *Material Flows and Input–Output Analysis: Methodological Description and Empirical Results. Sector National Accounts* (Voorburg: Statistics Netherlands).

Konijn, P.J.A., de Boer, S. and van Dalen, J. (1997) Input–output analysis of material flows with application to iron, steel and zinc, *Structural Change and Economic Dynamics*, 8, pp. 129–153.

Lee, H. and Roland-Holst, D. (1997) The environmental and welfare implications of trade and tax policy, *Journal of Development Economics*, 52, pp. 65–82.

Lenzen, M. (1998) Primary energy and greenhouse gases embodied in Australian final consumption: an input–output analysis, *Energy Policy*, 26, pp. 495–506.

Lenzen, M., Pade, L.L. and Munksgaard, J. (2004) CO_2 Multipliers in multi-region input–output models, *Economic Systems Research*, 16, pp. 391–412.

Los, B. (2001) Endogenous growth and structural change in a dynamic IO model, *Economic Systems Research*, 13, pp. 3–34.

Los, B. and Verspagen, B. (2000) Shifting consumption patterns: a neglected determinant of growth performance? Working paper, Department of Economics, University of Groningen, the Netherlands.

Machado, G., Schaeffer, R. and Worrell, E. (2001) Energy and carbon embodied in the international trade of Brazil: an input–output analysis, *Ecological Economics*, 39, pp. 409–424.

Miller, R.E. and Blair, P.D. (1985) *Input–Output Analysis: Foundations and Extensions*(Englewood-Cliffs, NJ: Prentice-Hall).

Munksgaard, J. and Pedersen, K.A. (2001) CO_2 accounts for open economies: producer and consumer responsibility?, *Energy Policy*, 29, pp. 327–334.

Muradian, R., O'Connor, M. and Martinez–Allier, J. (2002) Embodied pollution in trade: estimating the 'environmental load displacement' of industrialized countries, *Ecological Economics*, 41, pp. 51–67.

Murata, A., Kato, K. and Kurokawa, K. (1998) An estimation of environmental impact of the trade of industrial products: a case of Japan, *International Journal of Global Energy Issues*, 11, pp. 123–140.

Nebbia, G. (1999) *Contabilià monetaria e contabilità ambientale* (Bari: Università di Bari).

Pedersen, O.G. (1999) *Physical Input–Output Tables for Denmark. Products and Materials 1990, Air Emissions 1990–92* (Copenhagen, Statistics Denmark).

Proops, J.L.R., Atkinson, G., von Schlotheim, B.F. and Simon, S. (1999) International trade international trade and the sustainability footprint: a practical criterion for its assessment, *Ecological Economics*, 28, pp. 75–97.

Romer, D. (1996) *Advanced Macroeconomics* (New York: McGraw-Hill).

Romer, P. (1990) Endogeneous technological change, *Journal of Political Economy*, 98, pp. 71–102.

Schaeffer, R. and Leal de Sá, A. (1996) The embodiment of carbon associated with Brazilian imports and exports, *Energy Conversion Management*, 37, pp. 955–960.

Stahmer, C., Kuhn, M. and Braun, N. (1997) *Physical Input–Output Tables for Germany, 1990* (Wiesbaden: German Federal Statistical Office).

Statistics Sweden (2002) *Environmental Impact of Swedish Trade*, Rapport 2002:2 (Stockholm: Statistics Sweden).

Subak, S. (1995) Methane embodied in the international trade of commodities, *Global Environmental Change*, 5, pp. 433–446.

Suh, S., Huppes, G. and Udo de Haes, H. (2002) Environmental impacts of domestic and imported commodities in the U.S. economy. Paper presented at the *14th International Conference on Input–Output Techniques*, Montreal.

Wackernagel, M. and Rees, R. (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth* (Gabriola Island: New Society).

World Resource Institute (2000) *Weight of Nations: Material Outflows from Industrial Economies* (Washington, DC: World Resource Institute). **Q2**

Wyckoff, A.W. and Roop, J.M. (1994) The embodiment of carbon in imports of manufactured products: implications for international greenhouse gas emissions, *Energy Policy*, 22, pp. 187–194.

Appendix: Initial Values Used in the Model

		Country *A*					Country *B*						
		M		*S*			*M*		*S*		*Y*		
		P	*R*	*P*	*R*	*Y*	*P*	*R*	*P*	*R*	*Y*	*X*	Units
							Value Table						
Country *A*	*M*	450	0	150	0	400					0	1000	Euros
	S	150	0	450	0	400					0	1000	Euros
	L	400	0	400	0							800	Euros
Country *B*	*M*					0	600	0	200	0	200	1000	Euros
	S					0	200	0	600	0	200	1000	Euros
	L						200	0	200	0		400	Euros
Profit	0	0	0	0		0	0	0	0			0	Euros
Gross Output	1000	0	1000	0	800	1000	0	1000	0	400	5200		
							Table in Hybrid Units						
Country *A*	M	450	0	150	0	400					0	1000	tons
	S	15	0	45	0	40					0	100	service units
	G	1000	0	0	0	0						1000	tons
Country *B*	M					0	600	0	200	0	200	1000	tons
	S					0	20	0	60	0	20	100	service units
	G						1000	0	0	0	0	1000	tons

Price		Units
M	1	Euro/ton
S	10	Euro/service unit

Parameters					
ρ_i	0.5	$i = M, S$	α_{MM}^V	0.2	$V = A, B$
μ_M	1.5		α_{MS}^V	0.6	$V = A, B$
μ_S	0.0625		α_{SM}^V	0.01	$V = A, B$
ϕ	1.5		α_{SS}^V	0.4	$V = \mathrm{A}, B$
θ_j^A	0.03	$j = M, S$	α_{LM}^V	0.1	$V = A, B$
c_M^V	0.1	$V = A, B$	α_{LS}^V	1	$V = A, B$
c_S^V	0.01	$V = A, B$	ω^A	0.005	
c_L^V	0.1	$V = A, B$	ω^B	0.0025	
β	0.0025		τ	0.05	
γ	0.01				