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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 implication for environmental policy. One of the issues that has gained importance is the responsibility for the emissions from products that cross national boundaries during its life cycle. This paper discusses the different ethical views of environmental responsibility. Furthermore, the policy measures that are associated with the different viewpoints on environmentally responsibility are analyzed in a novel dynamic two-country two-sector dynamic input-output model. A numerical example is used to illustrate that an ethically preferable tax, which takes account of environmental damages throughout the lifecycle of the product, is less effective that the current policy of taxing consumers of products. Therefore, we might conclude that policies that are based on ethically superior standpoints may have detrimental distortionary effects in the dynamic setting.

Keywords: Dynamic input-output model, International trade, Technological change, Environmental responsibility, Environmental policy, Ethics

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1. 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 the life cycle of a product may occur in different countries, environmental policies that are based on national boundaries may have distortionary effects. This paper develops a novel dynamic input-output model that may provide the theoretical structure for dynamic analysis of environmental taxing on the national and global environmental performance.

For example, some policy measures that target domestic emissions penalize companies that export their produce to other countries, while ignoring the emissions generated during the production of the imports. 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 exports of energy intensive products. This is known as "carbon leakage". Gielen and Moriguchi (2002), for example, find that carbon taxing regimes implemented for the iron and steel sector in Japan and Europe could lead to significant carbon leakage. Machado, et al. (2001) found that Brazilian exports are becoming increasingly more energy intensive than its imports. This effects implies that the asymmetric policy targets 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.

This paper illustrates the problems associated with structural changes, and the effects that policy measures may play in shifting the burden of environmental emissions between countries. This paper furthermore explores the different policies that arise from different ethical viewpoints of the environmental responsibility that nation states hold. These issues are analyzed in 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 to these type of studies, since it is capable of modeling technology, sector structure and trade simultaneously. It also has the added benefit that it can accommodate monetary as well as physical units, which are essential for any environmental analysis. The following questions are investigated:

- how do tax regimes, based on different viewpoints of environmental responsibility, lead to differences in economic growth and environmental performance?
- how do the dynamics technology, policy and trade pan affect economic and environmental performance in a hypothetical two country dynamic model? What

implications are there for the economic and environmental criteria, both on the national and global scale?

The second contribution of this paper is to contribute to the development of dynamic input-output models. Due to the long-term dynamics of materials flows within an economic system, static models are only of limited use. Furthermore, in an increasing globalized economic system, the spatial dimension requires explicit attention as well. The few dynamic input-output models that exist have focused on the national scale or have assumed exogenous trade flows. In this paper, endogenous trade flows are introduced in a dynamic input-output model.

The structure of this paper is as follows. First, Section2 reviews the different ethical positions of environmental responsibility. Next, Section 3 provides an overview of the theoretical background of economic growth, technology, trade and their influence on environmental emissions. Section 4 covers the assumptions and equations that are used in the model. The results of the baseline and policy scenarios are presented in Section 5. Section 6 concludes.

2. 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.

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 which of these waste flows each country is responsible for. The current state of affairs suggests that the consensus view is that each country is responsible for the emissions that occur within its borders (such as the Kyoto protocol). Due to the distortionary nature of some of the policies based on this notion, one might wonder about its “fairness” and effectiveness. Indicators such as “ecological footprints” and “hidden flows” have been constructed to include emissions that have occurred in the early life cycle of a product, irrespective of the country (Wackernagel and Rees, 1996; WRI, 2000).

It is important to realize that this consensus view may have been reached because other notions of environmental responsibility were beyond the possibilities of the political process. It is therefore possible that superior (from an environmental and economic point of view) notions of environment responsibility were not considered because they were politically infeasible.

In this article other notions of environmental responsibility are explored, despite practical and political problems that could arise if policies were based on them. Below, the three notions of environmental responsibility are described:

- "Use – A country is held responsible for the waste emissions within its borders". As described earlier, this seems to be the consensus view. 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.
- "Make – 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.
- "Embodied material - 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. Calculating the embodied direct and indirect inputs has a long history in input-output analysis (Bullard III and Herendeen, 1975). Wyckoff and Roop (1994) used the method to suggest that Kyoto type agreements can cause import substitution. The method also assigns environmental responsibility to service sectors because they create indirect waste streams. A tax could be imposed on the direct and indirect material content of each good and service that is consumed.

3. Theoretical background

In environmental economics the impact of human society on the environment is encapsulates 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 1 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):

Emissions = Emissions from production process + Emissions from final consumption

$$M = \sum_i X \cdot S_i \cdot E_i^{prod} + \sum_i Y_i \cdot E_i^{cons}$$
Where
$$S_i = \frac{X_i}{X} = \frac{Z_i + Y_i}{X}$$
$$E_i^{prod} = \frac{M_i^{prod}}{X_i} \qquad (1)$$
$$E_i^{cons} = \frac{M_i^{cons}}{Y_i}$$

M - Total emissions in economy
X - Total economic output of the economy
S_i - Share of sector in total economy
E_i^{prod} - Emission coefficient of the production sector *i*
Y_i - Final demand for products from sector *i*
E_i^{cons} - Emission coefficient of the final consumption of product from sector *i*
Z_i - Intermediate demand for products from sector *i*
M_i^{prod} - Emissions of the production sector *i*
M_i^{cons} - Emissions from the final consumption of product from sector *i*
X_i - Output of sector *i*

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)
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. Firstly, 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 2 are interrelated. This means that if policy is introduced which affects one of the variables, then other variables may change because of these relationships. For example, if the final demand for 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 Section 3 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 paragraphs.

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, 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 curves take 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 by 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) point to evidence for relinking of economic prosperity and emissions suggests a disconcerting N-shaped relationship.

Technology

Technology plays a very 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. 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 (Aghion and Howitt, 1992; Romer, 1990). 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 *Economic Systems Research (Vol 9, No. , 1997)* 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 is proposed in 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.

3. A 2-country 2-sector input-output model

To illustrate the distortionary effects that unilateral policy measures may have in a multicountry setting a model is presented in this section. The model is called SIMBIOSES refering to Spatial Industrial Metabolism and Behaviour of Input/Output Structures in an Economic System. An input-output framework model has been adopted because of the following advantages. Firstly, it is an ideal framework in which technology, sector structure and trade can be integrated. The second advantage is that the input-output framework accommodates monetary as well as physical units in a very coherent manner. Since the distortionary pressures are complicated, the model is kept very simple: a 2 sector 2 country input-output model.

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 general equilibrium models. However, CGE models generally evaluate static equilibria under 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, "new" 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 the endogenous growth model by Los (2001) but focuses on changes in intermediate inputs rather than 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. Firstly, economic growth is generated by technological improvements. The second assumption, as was discussed in Section 2, 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 Aghion and Howitt (1992) and Romer (1990).

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. 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.

Table 1. Monetary value input-output table

		Country A			Country B			
		M	**S**	**Y**	**M**	**S**	**Y**	**X**
Country A	**M**	z_{MM}^{AA}	z_{MS}^{AA}	y_M^{AA}			y_M^{AB}	x_M^A
	S	z_{SM}^{AA}	z_{SS}^{AA}	y_S^{AA}			y_S^{AB}	x_S^A
	Labor	z_{LM}^{A}	z_{LS}^{A}					
	Raw Materials	z_{GM}^{A}						
Country B	**M**			y_M^{BA}	z_{MM}^{BB}	z_{MS}^{BB}	y_M^{BB}	x_M^B
	S			y_S^{BA}	z_{SM}^{BB}	z_{SS}^{BB}	y_S^{BB}	x_S^B
	Labor				z_{LM}^{B}	z_{LM}^{B}		
	Raw Materials				z_{GM}^{B}			

The physical volume equivalents of these monetary values are represented by bold variables. 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 (G) are assumed to be immobile. All notation is listed in appendix 1.

Underlying the value table are volume and price components.[2] Sector M is in physical units while sector S has' service units'. Since the model is dealing with homogenous products and no price discrimination is assumed, the base price of the goods and services are equal 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.

The relationship between the price, volume and the value are given by the following equations.

$$
\begin{aligned}
&\text{for } i = M, S, L \text{ and } j = M, S \text{ and } U, V = A, B \\
&z_{ij}^{U}[t] = \mathbf{z}_{\mathbf{ij}}^{\mathbf{U}}[\mathbf{t}] \cdot p_i^{U}[t] \\
&y_i^{UV}[t] = \mathbf{y}_{\mathbf{i}}^{\mathbf{UV}}[\mathbf{t}] \cdot p_{Yi}^{UV}[t] \\
&z_{Li}^{U}[t] = \mathbf{z}_{\mathbf{Li}}^{\mathbf{U}}[\mathbf{t}] \cdot p_{Li}^{U}[t] \\
&z_{Gi}^{U}[t] = \mathbf{z}_{\mathbf{Gi}}^{\mathbf{U}}[\mathbf{t}] \cdot p_{Gi}^{U}[t] \\
&f_{ij}^{U}[t] = \mathbf{f}_{\mathbf{ij}}^{\mathbf{U}}[\mathbf{t}] \cdot p_{Fi}^{U}[t]
\end{aligned}
\qquad (2)
$$

[2] A special case of this volume input-output table is the so-called physical input-output table (PIOT) which has been constructed for the Netherlands, Germany, Denmark and Italy ((Gravgard-Pedersen, 1999; Konijn et al., 1995; Konijn et al., 1997; Nebbia, 1999; Stahmer et al., 1997). 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.

The monetary balance equation sets of the row totals equal to the column sum of table 1.

$$\text{for } i = M, S \;\; U = A, B$$
$$x_i^U[t] = \sum_j z_{ij}^U[t] + \sum_V y_i^{VU}[t] = \sum_j z_{ji}^U[t] + z_{Li}^U[t] + z_{Gi}^U[t] \tag{3}$$

The material sector M is dictated by the mass balance principle.

$$\text{for } i = M, S \;\; U = A, B$$
$$\mathbf{x_i^U[t]} = \sum_j \mathbf{z_{ij}^U[t]} + \sum_V \mathbf{y_{ij}^{VU}[t]} = \sum_j \mathbf{z_{ji}^U[t]} + \mathbf{z_{Gi}^U[t]} \tag{4}$$

The mass of the material products is balanced by the use of raw materials Z_R from nature and intermediates products. It is assumed that the entire mass of raw materials Z_R is converted to products (i.e. no waste is generated during the production process).

Now that the model framework is defined, 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 a 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 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 of the wage (*θ*) income is reserved for R&D purposes while the rest is used to purchase goods and services (1-*θ*). Equation 5AA and 5BA shows the demand for goods in country A.

$$\text{for } \mathrm{i} = \mathrm{M}, \mathrm{S}$$
$$\begin{aligned} y_i^{AA}[t] &= \rho_i \cdot \sum_{j=M,S} \left(1-\theta_j^A[t]\right) \cdot w_j^A[t-1] \cdot \exp\left(-\left(\mu_i \cdot \left(p_{Yi}^{AA}[t] - p_{Yi}^{BA}[t]\right)\right)^{\phi}\right) \;\; \text{if } p_{Yi}^{AA}[t] > p_{Yi}^{BA}[t] \\ y_i^{AA}[t] &= \rho_i \cdot \sum_{j=M,S} \left(1-\theta_j^A[t]\right) \cdot w_j^A[t-1] \quad \text{if } p_{Yi}^{AA}[t] \le p_{Yi}^{BA}[t] \end{aligned} \tag{5AA}$$

$$\text{for } i = M,S$$

$$y_i^{BA}[t] = \rho_i \cdot \sum_{j=M,S} \left(1-\theta_j^A[t]\right)\cdot w_j^A[t-1]\cdot\left(1-\exp\left(-\left(\mu_i\cdot\left(p_i^{AA}[t]-p_i^{BA}[t]\right)\right)^{\phi}\right)\right) \text{ if } p_{Yi}^{AA}[t] > p_{Yi}^{BA}[t] \quad \text{(5BA)}$$
$$y_i^{BA}[t] = 0 \quad \text{if } p_{Yi}^{AA}[t] \le p_{Yi}^{BA}[t]$$

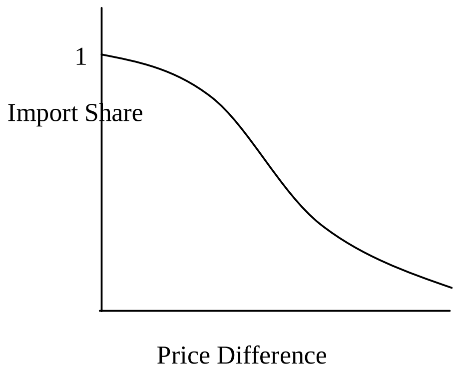
$$\text{where } \sum_{i=M,S} \rho_i = 1$$

For y_i^{BB} and y_i^{AB} replace A with B and B with A in equations (5AA) and (5BA)

The equations have three separate parts. The parameter ρ identifies what portion of the income that is reserved for consumption of material goods or services. The second part calculates the total amounts of the income that is spent on consumption rather than R&D. The parameter 1-θ, 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 a purely a question of price competition.

The price competition is best explained graphically (see figure 1). The exponential function $\exp(-(p^B - p^A)^2$ of equation (5) simply implies that a larger difference in prices between countries, leads to a large 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 starts to slow due to structural reasons (for a similar rule for import see Los and Verspagen, 2000).

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



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, so too does the percentage spent on R&D converge (see equation 6).

for $j = M, S$

$$\theta_j^B[t] = \frac{w_j^B[t-1]}{w_j^A[t-1]} \cdot \theta_j^A \tag{6}$$

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) that 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 as output. The quantity of discoveries from producers R&D and government R&D is therefore:

for $i = M,S,L$ and $j = M,S$ and $U = A,B$

$$\begin{aligned} \mathbf{d}_{\mathbf{ij}}^{\mathbf{U(PROD)}}[\mathbf{t}] &= \frac{r_{ij}^{U(PROD)}[t]}{\sum_{i=M,S,L} c_i^U[t] \cdot p_{Fi}^U[t]} \\ \mathbf{d}_{\mathbf{ij}}^{\mathbf{U(GOV)}}[\mathbf{t}] &= \frac{r_{ij}^{U(GOV)}[t]}{\sum_{i=M,S,L} c_i^U[t] \cdot p_{Fi}^U[t]} \end{aligned} \tag{7}$$

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 (*dk*/*d*d term).
- The producer also knows the average price that was paid for these inputs and the share of the intermediate costs that this inputs required (p*s/s term).

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. In summary the producer optimization is:

The producer minimizes the expected cost reductions by selecting where to make discoveries

for $j = M,S$ and $U = A,B$

$$\underset{r_{ij}^{U(PROD)}}{Min} \left\{ \sum_{i=M,S,L} \frac{\Delta \mathbf{k}_{\mathbf{ij}}^{\mathbf{U}}}{\Delta \mathbf{d}_{\mathbf{ij}}^{\mathbf{U}}} \cdot \frac{r_{ij}^{U(PROD)}[t]}{\sum_{i=M,S,L} c_i^U[t] \cdot p_{Fi}^U[t]} \cdot p_i^U[t] \right\} \tag{8}$$

$$\sum_{i=M,S,L} r_{ij}^{U(PROD)}[t] = \theta_j^U[t] \cdot w_j^U[t-1]$$

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 the sectors. It therefore looks for the optimal spread of its R&D resources (which is equal to the tax revenue) amongst the 2 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:

The government minimizes the expected material use

for $j = M,S$ and $U = A,B$

$$\underset{r_{Mj}^{U(GOV)}}{Min} \left\{ \sum_{j=M,S} \frac{\Delta \mathbf{k}_{\mathbf{Mj}}^{\mathbf{U}}}{\Delta \mathbf{d}_{\mathbf{Mj}}^{\mathbf{U}}} \cdot \frac{r_{Mj}^{U(GOV)}[t]}{\sum_{i=M,S,L} c_i^U[t] \cdot p_{Fi}^U[t]} \cdot \mathbf{x}_{\mathbf{j}}^{\mathbf{U}}[\mathbf{t-1}] \right\} \tag{9}$$

$$\sum_{j=M,S} r_{Mj}^{U(GOV)}[t] = \text{Tax revenue}^{\text{U}}\,[t-1]$$

Note that it is assumed that no strategic shifting of R&D Euro's 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 Grubler, 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 other functional forms). The shape of the curves are not known to the either the producers or 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. Technology Cycles and Spillovers from country A to B

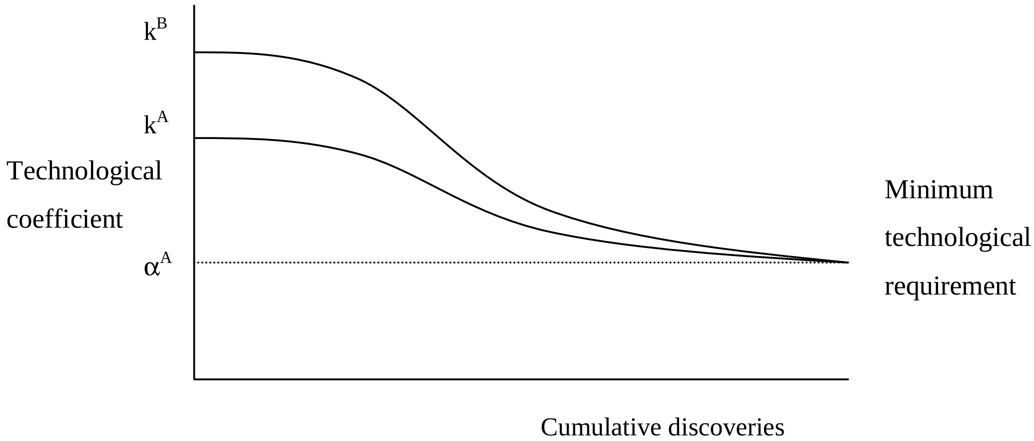


Figure 2 is represented by the following equations 10A and 10B. Country A converges towards the minimum level α while country B, the technology laggard catches up with the input coefficients of country A. The figure represents the classic maturation cycle of a technology, after which it will be replaced by other technologies.

for $i = M, S, L$ and $\mathrm{j} = M, S$ and $V = A,B$

$$\mathbf{k}_{\mathbf{ij}}^{\mathbf{A}}[\mathbf{t}] = \alpha_{ij}^{A} + \left(\mathbf{k}_{\mathbf{ij}}^{\mathbf{A}}[\mathbf{0}] - \alpha_{ij}^{A}\right) \cdot \exp\left(-\left(\beta \cdot \sum_{t'=0}^{t}\left(\mathbf{d}_{\mathbf{ij}}^{\mathbf{A(PROD)}}[\mathbf{t}] + \mathbf{d}_{\mathbf{ij}}^{\mathbf{A(GOV)}}[\mathbf{t}]\right)\right)^{2}\right) \tag{10A}$$

$$\mathbf{k}_{\mathbf{ij}}^{\mathbf{B}}[\mathbf{t}] = \mathbf{k}_{\mathbf{ij}}^{\mathbf{A}}[\mathbf{t-1}] + \left(\mathbf{k}_{\mathbf{ij}}^{\mathbf{B}}[\mathbf{t-1}] - \mathbf{k}_{\mathbf{ij}}^{\mathbf{A}}[\mathbf{t-1}]\right) \cdot \exp\left(-\left(\gamma \cdot \sum_{t'=0}^{t}\left(\mathbf{d}_{\mathbf{ij}}^{\mathbf{B(PROD)}}[\mathbf{t}] + \mathbf{d}_{\mathbf{ij}}^{\mathbf{B(GOV)}}[\mathbf{t}]\right)\right)^{2}\right) \tag{10B}$$

Now that the technological and demand components are known for period t, the physical output q in period t can now be calculated (where $h_{ij}^{UV}[t] = (I - k_{ij}^{UV}[t])^{-1}$) through the static hybrid-unit input-output model:

for $U = A,B$ and $i = M, S$ and $j = M, S$

$$\mathrm{x}_{\mathbf{i}}^{\mathbf{U}}[\mathbf{t}] = \sum_{j=M,S} \mathbf{h}_{\mathbf{ij}}^{\mathbf{UV}}[\mathbf{t}] \cdot \left(\sum_{i=M,S} \mathbf{f}_{\mathbf{ji}}^{\mathbf{U}}[\mathbf{t}] + \sum_{V=A,B} \mathbf{y}_{\mathbf{j}}^{\mathbf{UV}}[\mathbf{t}]\right) \tag{11}$$

Where

for $U = A,B$ and $i = M, S, L$ and $j = M, S$

$$\mathbf{f}_{\mathbf{ij}}^{\mathbf{U}}[\mathbf{t}] = \mathbf{c}_{\mathbf{i}}[\mathbf{t}] \cdot \sum_{i=M,S,L} \left(\mathbf{d}_{\mathbf{ij}}^{\mathbf{U(PROD)}}[\mathbf{t}] + \mathbf{d}_{\mathbf{ij}}^{\mathbf{U(GOV)}}[\mathbf{t}] \right) \qquad (12)$$

In equation 11 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 the physical units are a better descriptor of the technological requirements since 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 i.e. through patent or secrecy transfer 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 $U = A,B$ and $i = M, S$

$$m_i^U[t] = x_i^U[t] - \sum_{j=M,S,L,G} z_{ji}^U[t] - \sum_{j=M,S,L} f_{ji}^U[t] \qquad (9)$$

The sum of the producers wages, R&D wages and monopolistic profits signify the income of the sector.

for $i = M, S$ and $U = A,B$

$$w_i^U[t] = z_{Li}^U[t] + f_{Li}^U[t] + m_i^U[t] \qquad (10)$$

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

$$\mathrm{p}_{\mathrm{L}}^{\mathrm{U}}[\mathrm{t}+1] = \omega^{\mathrm{U}} \cdot \sum_{\mathrm{j=M,S}} \left(\mathbf{z}_{\mathbf{Lj}}^{\mathbf{U}}[\mathbf{t}] + \mathbf{f}_{\mathbf{Lj}}^{\mathbf{U}}[\mathbf{t}] \right) \qquad (11)$$

The price input-output model calculates the prices of material goods and services.

for $U = A,B$ and $i = M, S$

$$p_i^U[t+1] = \sum_{V=A,B} \sum_{j=M,S} \mathbf{h}_{\mathbf{ji}}^{\mathbf{VU}}[\mathbf{t}] \cdot \mathbf{k}_{\mathbf{Li}}^{\mathbf{U}}[\mathbf{t}] \cdot p_L^U[t+1] \qquad (12)$$

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 section 2. The tax and subsidy schemes are different for each of the scenarios and are summarized in table 2. As noted earlier, it is assumed 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.

Table 2. Scenario specific taxing and subsidy equations

Scenario (Environmental viewpoint)	**Tax**	**Tax revenue (=subsidy)**
No taxing (Default)	$p_i^U = p_i^{UU} = p_i^{UV} = p_{Yi}^{UU} = p_{Yi}^{UV}$	No taxes
1 Tax on material products (make)	$p_M^{AA} = p_M^{AB} = p_M^A + \tau$ $p_{YM}^{AA} = p_{YM}^{AB} = p_M^A + \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{i=M,S} z_{Mi}^{AU} + \sum_{U=A,B} y_M^{AU} \right)$
2 Tax on consumption of material products (use)	$p_M^{AA} = p_{YM}^{AA} = p_M^A + \tau$ $p_M^{BA} = p_{YM}^{BA} = p_M^B + \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{i=M,S} z_{Mi}^{UA} + \sum_{U=A,B} y_M^{UA} \right)$
3 Tax on direct and indirect final material consumption (embodied)	$p_{YM}^{AA} = p_{YM}^A + \left(\sum_{U=A,B} h_{Mi}^{UA} \right) \cdot \tau$ $p_{Yi}^{BA} = p_{Yi}^B + \left(\sum_{U=A,B} h_{Mi}^{UB} \right) \cdot \tau$	$\tau \cdot \left(\sum_{U=A,B} \sum_{V=A,B} \sum_{i=M,S} \left(h_{Mi}^{VU} \cdot f_i^{UA} \right) \right)$

5. Results

We performed an exploratory analysis with SIMBIOSES for the analysis of the conditions as presented in Table 2. The model is implemented for 2 hypothetical countries since real world data would be distorted by interactions among more than 2 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 appendix 2. The tax policy is assumed to be at a fixed level during the whole period. This seems to be quite unrealistic but it enable 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.

Figure 3A and 3B 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 lead 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 improvement. This lead to the acceleration of economic growth after the initial drop in wealth.

Figure 3A. GDP per capita in country A

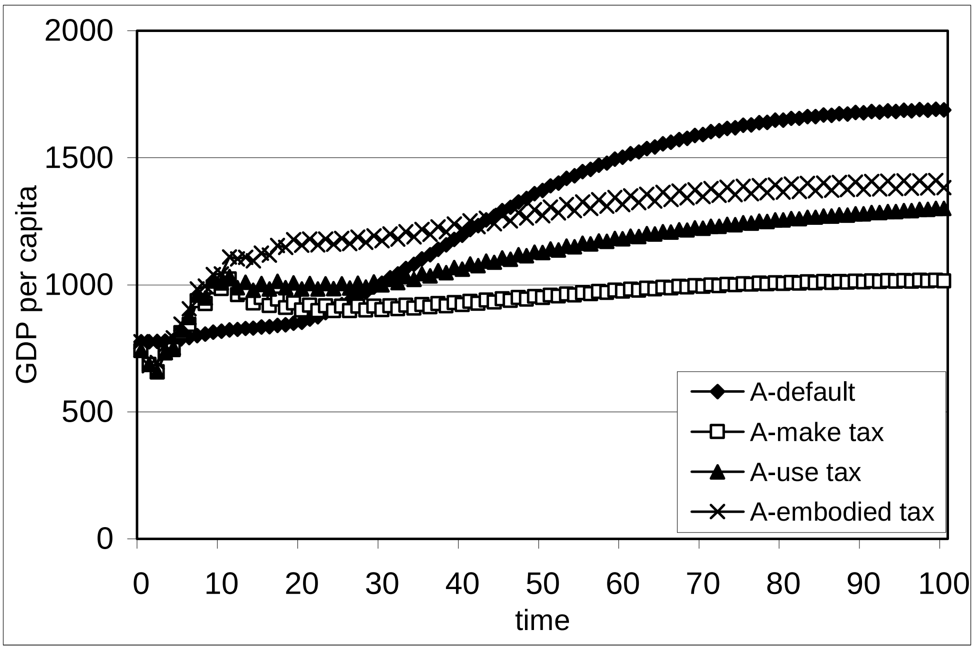
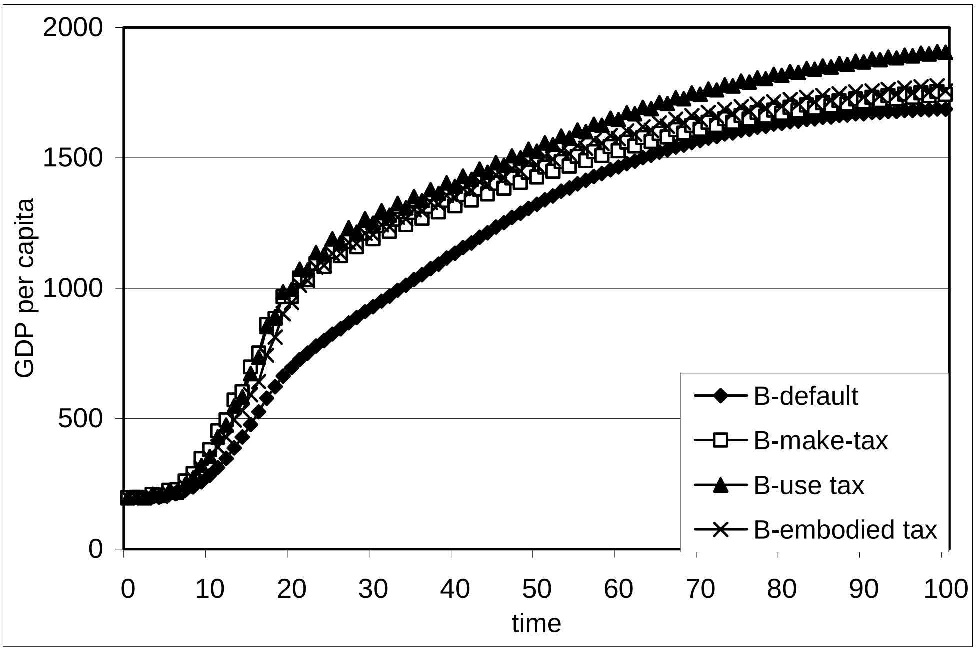
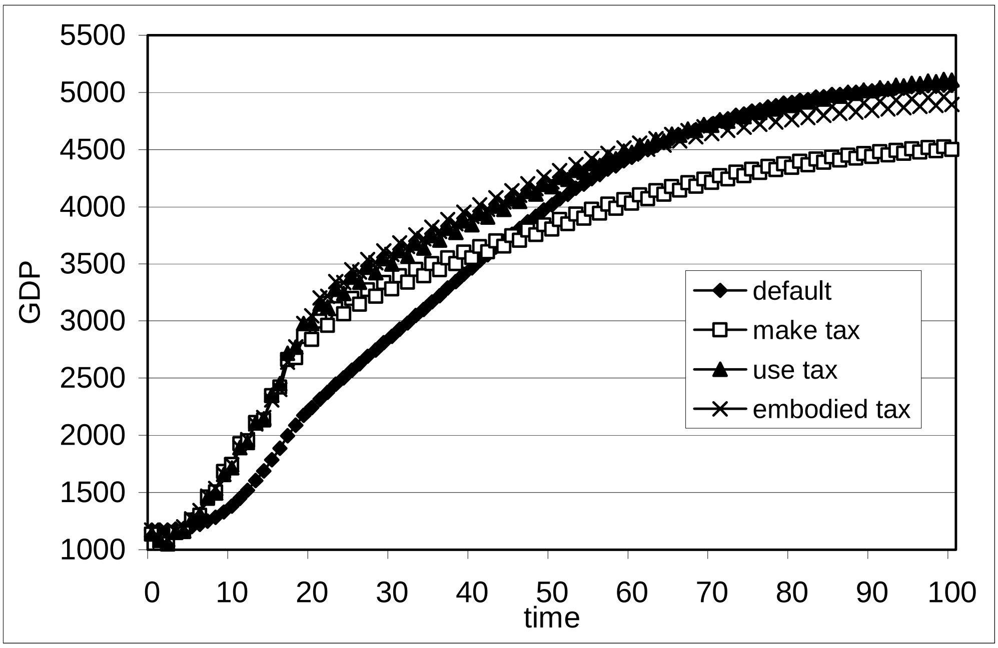


Figure 3B. GDP per capita in country B



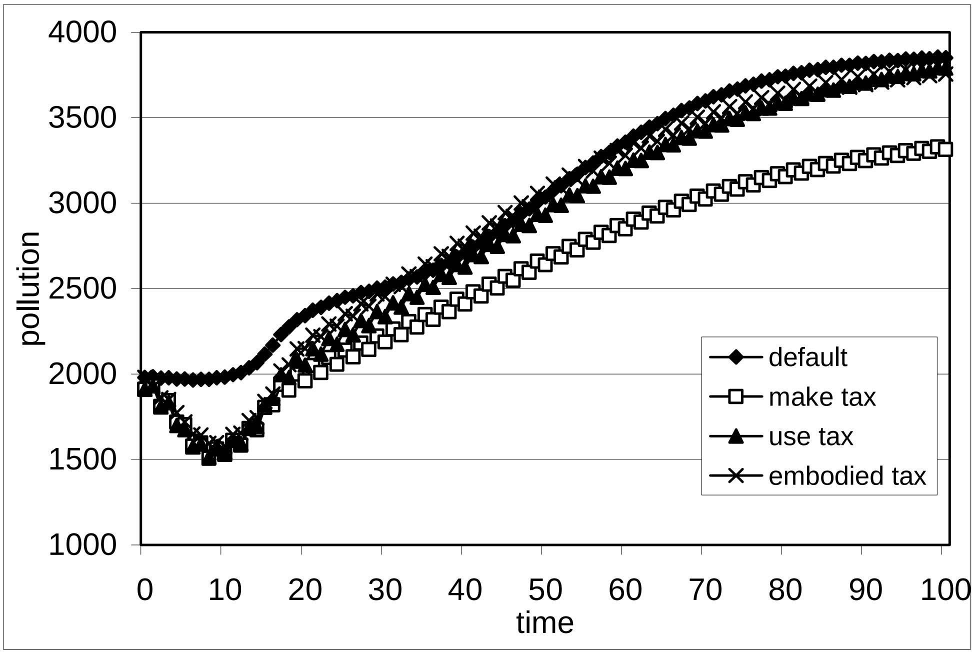
If the results are looked at from a global perspective, as is shown in figure 4, the make tax scenario leads to the least attractive final GDP level. Nevertheless, the default scenario actually performs worse initially, but recovers through a similar level as the other three us scenarios. But as Figure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

Figure 4.Global GDP



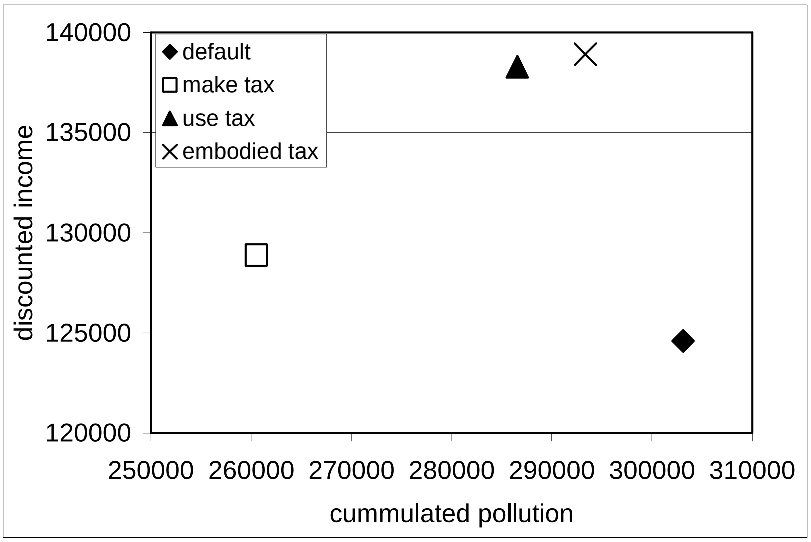
The environmental consequences of these economic growth scenarios are shown in Figure 5. The results suggest that economic growth and environmental pollution are highly correlated in this model. There is definitely no question of decoupling of economic and environmental indicators. The make tax seems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

Figure 5. Global pollution



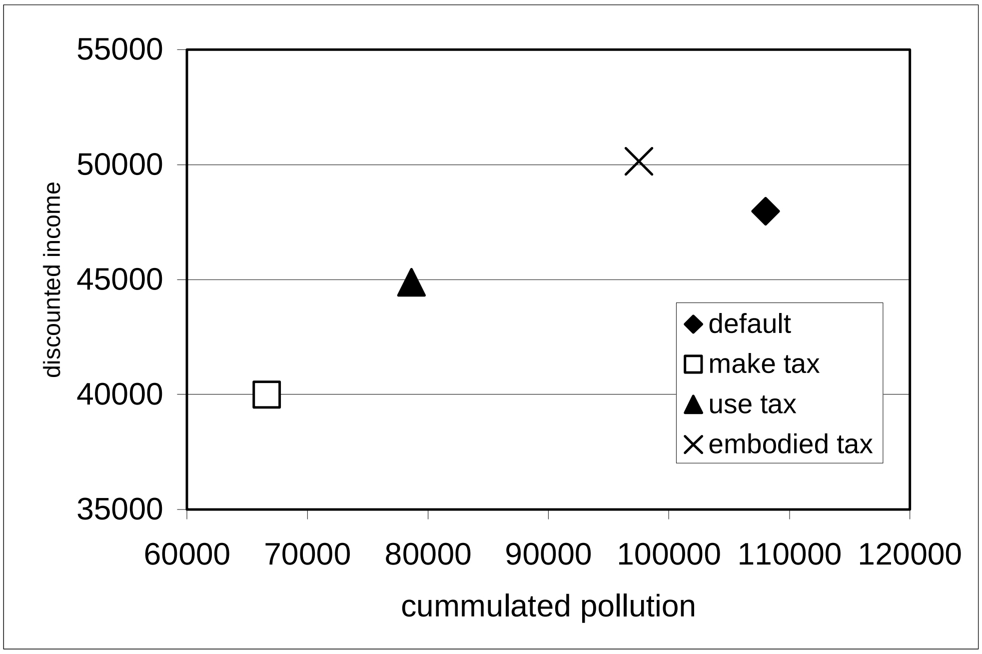
A more appropriate way would be to balance the consequences for economic development and environmental impact. Therefore, we map the discounted GDP (2%) to the overall pollution over the hundred time periods. Figure 6 shows the global results, while Figures 7 and 8 show the results for countries A and B respectively.

Figure 6. Global discounted GDP versus pollution



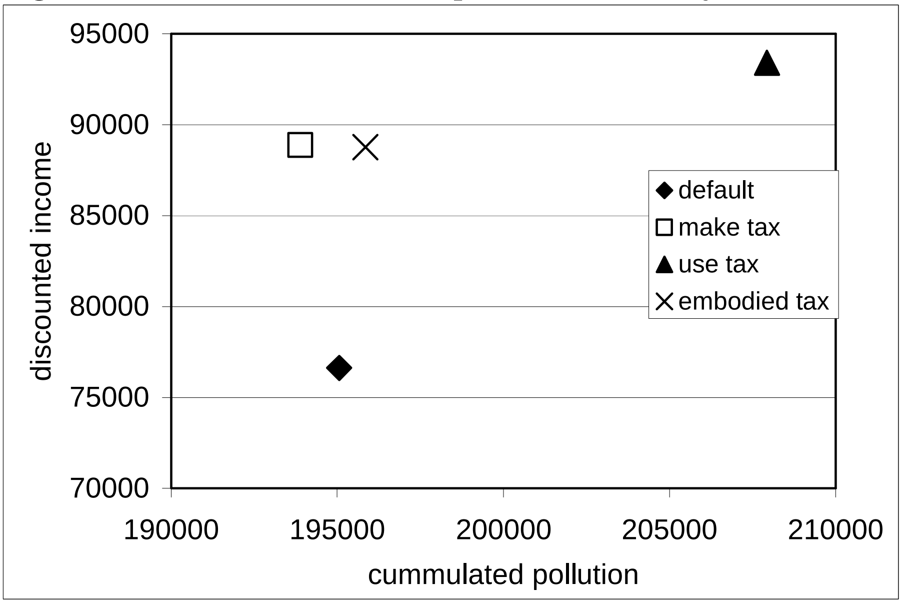
From a global perspective the embodied tax and use tax lead to the best results in terms of economic growth. Interesting is that the default scenario performs worse in terms economic as well as environmental performance. The make tax does the best environmentally, but at great expense to economic prosperity. 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 al 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 quicker economic growth and more efficient use of materials faster.

Figure 7. Discounted GDP versus pollution in country A



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 environment.

Figure 8. Discounted GDP versus pollution in country B



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 is 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. Figure 7 illustrates however 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 6-8. 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.

6. 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:

- 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.
- The "ethical" 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 into this direction.

Appendix 1: List of variables

c_i^U - Input requirements for discovery

$d_{ij}^{A(GOV)}$ - Discoveries financed by government R&D assistance of sector i in country A towards improving the efficiency of use of input j (Euro)

$d_{ij}^{A(PROD)}$ - Discoveries financed by sector i R&D in country A towards improving the efficiency of use of input j (Euro)

f_i^U - Monetary value of inputs required by R&D sector to produce discoveries (bold=volume measure)

h_{ij}^{UV} - Hybrid-unit Leontief inverse $h_{ij}^{UV}[t] = (I - k_{ij}^{UV}[t])^{-1}$

k_{ij}^{V} - Hybrid-unit technical coefficient, the physical amount of input i required per unit physical output of sector j in country V

p_i^U - Base price of product from sector i in country U

p_{ij}^U - Price of materials, sectors, labor and raw materials (i=M,S,L,G) for sector i in country U

p_{Yi}^{UV} - Price of final product from sector i in country U paid by consumers in country V

r_{ij}^A - Total R&D effort in sector i in country A towards improving the efficiency of use of input j (Euro)

$r_{ij}^{A(GOV)}$ - R&D assistance by government of sector i in country A towards improving the efficiency of use of input j (Euro)

$r_{ij}^{A(PROD)}$ - R&D effort by sector i in country A towards improving the efficiency of use of input j (Euro)

x_i^U - Monetary output of sector i in country U (bold=volume measure)

y_i^{UV} - Monetary quantity of final demand for products from sector i in country U by consumers in country V (bold=volume measure)

z_{ij}^U - Inputs in monetary terms from sector i (i=M,S,L,G) in country U to sector j (Euro) (bold=volume measure)

θ_i^A - Fixed proportion of wages in sector i of country A used for research and development

α - Coefficient that sets the limit of minimum possible technical coefficient of an input.

β - Coefficient that sets the effectiveness of the R&D

γ - Coefficient that sets the speed at which country B converges with the technical coefficients of country A

τ - Tax rate per ton of material

μ - Coefficient for the sensitivity of the consumers to the inputs prices

ρ_i - share of disposable income spent on good i

Appendix 2: Initial values used in model

Value Table

	Ma	Sa	Mb	Sb	Ya	Yb	X	
Ma	450	150	0	0	400	0	1000	Euros
Sa	150	450	0	0	400	0	1000	Euros
Mb	0	0	600	200	0	200	1000	Euros
Sb	0	0	200	600	0	200	1000	Euros
La	400	400					800	Euros
Lb			200	200			400	Euros
	1000	1000	1000	1000	800	400	5200	

Prices

Ma	1	Euro/ton
Sa	10	Euro/Service Unit
Mb	1	Euro/ton
Sb	10	Euro/Service Unit
Raw M	0	

Volume

	Ma	Sa	Mb	Sb	Ya	Yb		
Ma	450	150	0	0	400	0	1000	tons
Sa	15	45	0	0	40	0	100	units
Mb	0	0	600	200	0	200	1000	tons
Sb	0	0	20	60	0	20	100	units
Raw M	1000		1000					

Parameters

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

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