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Into the black box of environmental Kuznets curves: Optimal growth and material resource use in two trading countries

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Abstract. Most important environmental problems can be related to materials flows through the economy. Regional and national economies use materials that are either extracted domestically or imported from other regions. Therefore, an analysis of optimal patterns of combined economic development and materials use requires that both trade and environmental aspects are taken into account. A model is presented here that optimises long-term welfare for two regions that trade in virgin and recycled materials as well as consumer goods. The regions differ in one respect, namely with regard to domestic availability of a material resource. Analysis of the model shows, among other things, that the relationship between production and virgin material use can follow an Environmental Kuznets curves or an N-shaped curve. The latter points at “re-linking” of income growth and material resource use. Although trade of material resources and goods increases the carrying capacity of both regions, and in turn their levels of welfare, it can not prevent the re-linking phenomenon.

JEL classification: Q30, Q32, R13

1. Introduction

An economic system consumes material inputs, processes them into usable forms, and generates waste. The total of physical processes that convert raw materials into finished products and waste shows a similarity with metabolism in organisms, and therefore has been referred to as “industrial metabolism” (Ayres and Simones 1994). The extraction, use and disposal of materials cause much environmental pressure, such as polluting emissions to water, air and

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soil, and land use and cover changes at or around extraction sites. From an economic perspective, optimal development should balance the economic (net) benefits and environmental costs of material use.

The concept of industrial metabolism suggests to analyse material flows from an integrated perspective, taking into account system-wide or rebound effects of economic activities as well as problem shifting phenomena that arise due to environmental policies. An example of the rebound effect is that when cars become more fuel efficient, consumers tend to buy larger cars and travel more kilometres. As a result, the net energy savings will be smaller than expected on the basis of purely technological considerations. An example of problem shifting is that reducing waste in one part of the economy-environment system can lead to more emissions in another part of the system. Well-known are end-of-pipe measures, which reduce pollution to water and air, but generate highly polluted waste that is either burned or dumped in landfills.

In addition, the notion of industrial metabolism suggests that a trade-off is necessary between energy and material use. For example, incineration of waste paper is in some cases more desirable from an environmental perspective than recycling. Leach et al. (1997) studied the options for waste paper treatment in the UK, taking into account the various energy uses. New paper is produced mostly in Sweden and uses renewable energy sources in the pulp phase. Recycling in the UK requires fossil energy. Burning waste paper, on the other hand, will generate energy. A simple social evaluation of these options is not easy, especially because prices do not reflect externalities generated by certain types of energy use, notably combustion of fossil fuels.

Due to environmental regulation, production and recycling can shift to other regions. The reduction of energy related emissions in OECD countries and the increase of these in non-OECD countries is partly due to migration of energy-intensive industries from OECD to non-OECD countries (Suri and Chapman 1998). With the phenomenon of globalisation and the associated increase of international trade, factor mobility and foreign investments, the spatial dimension is becoming increasingly important in studies of the relationship between economic growth, materials use and energy intensity (van Beukering et al. 2000).

The analysis presented here therefore aims to extend the traditional theoretical analysis of growth and material use to a multiregional context. It offers a first formal treatment of the spatial dimension of industrial metabolism, linking economic growth, materials use and international or interregional trade. This continues earlier conceptual work (Janssen and van den Bergh 1999). A two-region model is developed that describes primary (raw) materials, secondary (recovered) materials and materials incorporated in products. The regions differ only in the carrying capacity determined by the regional renewable material resource. This difference gives rise to interregional material flows, which consist of primary materials, secondary materials, and materials in products.

One of the current puzzles in the literature on the relation between economic growth and environmental pressure is whether a “de-linking” of income growth and environmental pressure is possible beyond a certain level of economic welfare, usually measured by GDP or GDP per capita. As will be discussed in Sect. 2 below, there is no univocal evidence for the de-linking or “Environmental Kuznets curve” hypothesis (as coined by Panayotou 1993).

Up till now, the literature has used extremely compact, reduced form or “black box” models, without deriving these from explicitly structural models. The model presented here is aimed at opening the black box, by specifying activities in each region and interactions among regions, all of which influence income growth, trade and material use characteristics. Thus, we are able to analyse the relationship between optimal growth, economic activities and environmental pressure in a way that generates a richer palette of explanations and interpretations of de-linking.

The organisation of this paper is as follows. Section 2 discusses theories and concepts relating to economic growth, trade and development, with the aim to link the Environmental Kuznets debate to considerations of trade and globalisation. In Sect. 3 a general model of the physical dimension of a two-region economy is formulated. Section 4 presents numerical optimisation results for a number of scenarios. Section 5 concludes.

2. Economic growth, trade and the environment

During the 1990s, the old ‘growth debate’ has been revived around the relationship between economic growth and material use. This has generated new concepts, such as decoupling, dematerialisation, Factor 4 and the “Environmental Kuznets Curve” (EKC). The EKC hypothesis reflects a relationship between environmental pressure and income per capita that consists of three phases: (1) initially, per capita income growth goes along with a progressively increasing environmental pressure; (2) further income growth is associated with an increase, at a decreasing rate, of environmental pressure, until at a threshold income level it reaches a maximum; (3) income growth beyond this threshold goes along with a reduction in environmental pressure.

Explanations for these phases are based on supply and demand side factors. At the supply side, technological progress aimed at resource-saving or abatement of emissions is induced by higher levels of production, and therefore income. At the demand side, higher income cause individuals to attach a higher value to environmental quality. This has two consequences. First, it may induce them to spend a higher proportion of their income on less environmentally-damaging consumption, such as cleaner products and services. In addition, it may stimulate them to support stringent environmental policies, through political elections and referenda.

The EKC hypothesis has generated its own body of empirical research. Well-known early studies are Lucas et al. (1992), Selden and Song (1994), and Grossman and Krueger (1995). A recent, critical overview is de Bruyn and Heintz (1999). The main implication of the EKC is that growth by itself would be able to solve environmental problems. This is regarded as an interesting addition to the traditional view that considered economic growth and environmental protection as antitheses. It should be noted that the EKC describes but does not explain the three phases. Or, better, it offers room for different interpretations such as those noted above. It therefore can be considered as a sort of “black box model”, with little explanatory value. This is reflected by the fact that the standard specification is a polynomial of order 2 or 3 that focuses on income as an explanatory variable. Moreover, the empirical support for the EKC hypothesis is very doubtful, because it is based

on environmental indicators that are partial, from both environmental and spatial perspectives. In relation to the spatial perspective adopted hereafter, it is worthwhile to mention that part of the reduction of environmental pressure at high incomes can be explained by the relocation of polluting production activities to less wealthy regions (Suri and Chapman 1998).

De Bruyn and Opschoor (1997) question the inverted-U-shaped relationship between environmental pressure and income, and propose an N-shaped relationship, reflecting a re-linking of economic growth and environmental pressure. The idea behind this is that during times of radical changes in technology and institutions, the relationship between environmental pressure and income may be altered significantly, due to substitution, new production methods, new products, and new waste treatment and recycling techniques. However, once the easy options of substitution and technological improvement have been exhausted, re-linking occurs.

An increase in trade is often claimed to directly contribute to an increase in environmental pressure, because it is associated with more transport, more – or opening up new – resource extraction in certain regions, and more pollution around the world. On the other hand, trade is often regarded to contribute to international competition, which in turn can lead to improved economic and environmental performance of various economic activities.

A novel way of analysing the impact of increasing trade flows on the environment is to view trading partners as an interconnected material product chain (Beukering et al. 2000). A material-product chain is defined as a set of linked flows of materials and products so as to fulfill a certain service (Opschoor 1994). Globalisation of the product chain will lead to an optimal allocation in terms of production costs of various segments over a larger region. Beukering et al. explain the various flows of international material-product chain using different theories of trade. The Heckscher-Ohlin theorem can be used to explain trade between different sectors in the product chain as a result of relative factor endowments. Other theories can provide explanations on intra-sectoral trade. For example, Fujita et al. (1999) claim that centripetal (network effects) and centrifugal (e.g., congestion) forces are the main sources of international allocation. Centripetal forces promote economic clusters, while centrifugal forces leads to a spatial allocation of economic clusters.

Trade theories have also dealt with the impact of technology. It can cause both desirable and undesirable effects on the environmental pressure of economies (Grübler 1998). An example of a technology-oriented trade theory is Vernon (1966). He argues that new products are first produced in the most advanced economies. Subsequently, demand spreads internationally, leading to trade, which ultimately stimulates importing countries to start their own production. A similar pattern is predicted by the demand oriented trade theory of Linder (1961). He argues that the demand for the most advanced products is generated in high-income countries, and that low-income countries accept lower quality substitutes. This can explain the relatively large use of recycled products in developing countries compared with developed countries (Beukering and Bouman 2001).

An analysis of the international material-product chain requires a dynamic trade model that incorporates technological change next to supply and demand elements. Adding a physical dimension to the description of the economic system will subsequently give rise to a model suitable to study

spatial and international patterns of material flows. Such a model is described in the next section.

3. A two-region model of industrial metabolism

The model describes an economic system consisting of two regions, as schematically illustrated by Fig. 1. In line with the discussion in the previous section, a chain of activities is considered. Materials are extracted from a renewable resource. We do not include non-renewable resources separately, but can mimic a non-renewable resource by assuming a zero renewal rate. New or virgin materials can, together with recycled materials, be used to produce consumer goods. Note that perfect recycling is not possible as a consequence of the Second Law of Thermodynamics, according to which even perfectly efficiently running systems need inputs of energy to compensate for the increase in entropy. Consumption of consumer goods generate utility. These goods depreciate and the resulting waste material can be either recycled or dumped into the environment. Such waste reduces the carrying capacity of the renewable resources. Trade between the regions consists of consumer goods, and primary and secondary materials. Trade is balanced in monetary terms, while it is bounded by certain mass balance conditions. The overall social objective is to maximise the sum of discounted utility of consumption in each region. This can be realised by appropriate choices of investments in capital stocks of material extraction, production of consumer goods, and recycling. In other words, it takes time to change the economic structure in a desired direction due to investments and capital accumulation. In view of the foregoing, the model is formulated as a dynamic optimisation model that combines and extends the standard economic growth model with material cycles and trading regions. The model includes some elements that

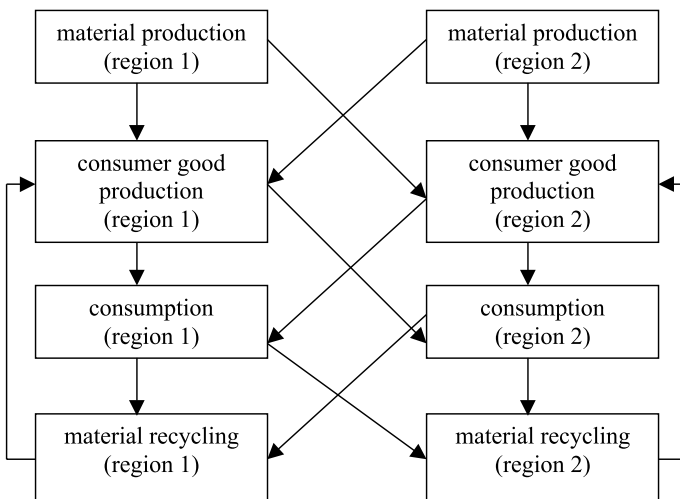


Fig. 1. Trade flows and the international material-product chain (based on van Beukering et al. 2000)

are common in integrated models used to study policies for climate change mitigation (Nordhaus 1994; Nordhaus and Yang 1995), spatial economic models of sustainability (van den Bergh and Nijkamp 1995), and economic models of materials flows (van den Bergh and Nijkamp 1994; Kandelaars 1999). The novelty of the model is the integration of material flows in a two-regional product chain with economic production, consumption and trade relationships. The model is presented in detail below. The Annex provides a complete list of explanations of variable and parameter symbols, as well as of used parameter values.

3.1. Objective function

The investment decisions are assumed to maximize the discounted sum of the general level of utility of consumption. The objective is:¹

$$\max \sum_{r=1,2} \int_0^{t_h} \frac{C_r^\eta}{(1+\rho)^t} dt \quad (1)$$

The objective function is the usual net present value function, which in this case equals the sum of utilities of consumption discounted by ρ , over the relevant time horizon (from 0 till t_h) and regions (1 and 2). The yearly level of utility in region r is specified as C_r^η , where C_r denotes the level of consumption of goods in region r , and the parameter η the degree of nonlinear influence of the consumer good on the utility level.

3.2. Consumption

The amount of consumer goods C_r in the economy changes due to the addition of new consumption goods, $C_{\eta,r}$, and the depreciation of discarded consumer goods. The stock of consumer goods aggregated durable and nondurable goods into one variable. The depreciation rate of consumer goods, $\delta_{c,r}$, is assumed to be a certain percentage per annum, reflecting an average lifetime of consumer goods equal to $1/\delta_{c,r}$ years.

$$\frac{\partial C_r}{\partial t} = C_{\eta,r} - \delta_{c,r} \cdot C_r \quad (2)$$

The amount of new consumer goods $C_{\eta,r}$ is the sum of domestically produced goods, $C_{P,r}$, and imported goods, $C_{M,r}$, minus exported consumer goods, $C_{X,r}$. Imports and exports satisfy a trade balance condition.

$$C_{\eta,r} = C_{P,r} + C_{M,r} - C_{X,r} \quad (3)$$

3.3. Production of consumer goods

The production of consumer goods $Y_{C,r}$ is given by a standard constant-returns-to-scale Cobb-Douglas production function using as production factors capital $K_{C,r}$ and materials M_r . The production function contains

¹ We omit time subscripts to economize on notation.

parameters for the scale of technology $a_{C,r}$ technological change, $\tau_{C,r}$, and elasticity of output with respect to the inputs, $\gamma_{C,r}$. Variable time is denoted by t .

$$Y_{C,r} = \left(\frac{a_{C,r}}{\tau_{C,r}^t} \right) \cdot K_{C,r}^{\gamma_{C,r}} \cdot M_r^{1-\gamma_{C,r}} \quad (4)$$

The capital stock used in the production of consumer goods includes represents machines and buildings. It depends on yearly investments, $I_{C,r}$, and a capital depreciation rate $\delta_{k,c,r}$

$$\frac{\partial K_{C,r}}{\partial t} = I_{C,r} - \delta_{k,c,r} \cdot K_{C,r} \quad (5)$$

3.4. Extraction of materials

The extraction of materials, $M_{E,r}$, depends on the use of capital in this sector, $K_{E,r}$. The dynamics of the capital stock follows the same logic as Eq. (5), and is therefore not given here. Production depends, in addition, on parameters representing the level of technology, $a_{E,r}$, technological change, $\tau_{E,r}$, elasticity $\gamma_{E,r}$, and a depletion factor $\pi_{E,r}$.

$$M_{E,r} = \left(\frac{\pi_{E,r} \cdot a_{E,r}}{\tau_{E,r}^t} \right) \cdot K_{E,r}^{\gamma_{E,r}} \quad (6)$$

The depletion factor, formulated in Eq. (7), captures the fact that more capital is needed to extract the same amount of material as the size of the material resource decreases. This is based on the assumption that the highest quality of the resource is depleted first. When there is no depletion $\pi_{E,r}$ takes its maximum value, which equals one.

$$\pi_{E,r} = \left(\frac{M_r}{M_r(0)} \right)^{\rho_{\pi,r}} \quad (7)$$

Here $\rho_{\pi,r}$ represent the sensitivity of the rate at which the depletion factor declines when the resource declines.

The price of virgin materials can be defined as proportional to the ratio of capital inputs to output:

$$p_{E,r} = \alpha_{E,r} \cdot \frac{K_{E,r}}{M_{E,r}} \quad (8)$$

Here $\alpha_{E,r}$ is an annuity factor, which is defined as

$$\alpha_{E,r} = \frac{i}{(1 - (1 + i))^{(-1/\delta_{E,r})}} \quad (9)$$

where i is the interest rate, and $1/\delta_{E,r}$ the capital life time.

3.5. Recycling

The physical amount of recycling, $M_{R,r}$, is a function of capital $K_{R,r}$, and parameters for the level of technology, $a_{R,r}$, technological change, $\tau_{R,r}$, elasticity $\gamma_{R,r}$, and a recycling factor, $\pi_{R,r}$. The dynamic specification of the capital stock for recycling materials, $K_{R,r}$, is analogous to Eq. (5) and not shown here.

$$M_{R,r} = \left(\frac{\pi_{R,r} \cdot a_{R,r}}{\tau_{R,r}^t} \right) \cdot K_{R,r}^{\gamma_{R,r}} \quad (10)$$

The scaling factor for recycling $\pi_{R,r}$ captures that a higher rate of recycling efforts is limited by the requirement for an associated higher level of capital inputs; for example, using more energy to extract a lower concentration of materials. The variable $x_{R,r}$ is a decision variable representing the level of recycling.

$$\pi_{R,r} = (1 - x_{R,r})^2 \quad (11)$$

The determination of the price of recycled materials $p_{R,r}$ is analogous to Eqs. (8) and (9), and therefore omitted here.

3.6. Allocation of total output

Each region obtains income from production in three sectors. This is either invested, $I_{I,r}$ ($i = C, M, R$), or spent on consumer goods, $C_{n,r}$.

$$Y_{C,r} + M_{E,r} + M_{R,r} = I_{C,r} + I_{E,r} + I_{R,r} + C_{n,r} \quad (12)$$

3.7. Material stocks and flows

The physical dimension of the economic system consists of material stocks and flows between these, as shown in Fig. 2. To limit model complexity, the attention is focused on the material content of consumer goods, and exclude material content of capital goods. The extraction of new materials ($M_{E,r}$) equals net demand for materials from both regions. Furthermore, we assume that a fraction, $w_{E,r}$, of material use is lost as waste during the production process. Materials can be recycled or end up in the environment. Note that this implicitly assumes that recyclable and virgin materials are perfect substitutes. Relaxing this assumption would require distinguishing between different productivity rates - or even roles in the production process - of different material stocks, virgin and non-virgin, which in turn would result in a much more complex model.

A renewable material resource is formulated, following a logistic formulation.² The renewal rate is equal to λ_r and the maximum resource size is equal to the carrying capacity $Z_{M,r}$. The resource declines due to extraction of materials, $M_{E,r}$.

$$\frac{\partial M_r}{\partial t} = \lambda_r \cdot M_r \cdot \left(1 - \frac{M_r}{Z_{M,r}}\right) - M_{E,r} \quad (13)$$

The amount of materials incorporated in consumer goods is denoted by $M_{C,r}$. It increases through the use of materials in production of new consumer goods, and declines through the depreciation of the stock of consumer goods. The parameter φ transforms the amount of consumer goods into materials. The parameter $\delta_{c,r}$ is the depreciation rate (see Eq. (2)).

² The standard logistic equation is formulated as $dX/dt = \lambda * X * (1 - X/Z)$, with λ the growth rate, X the stock size and Z the carrying capacity.

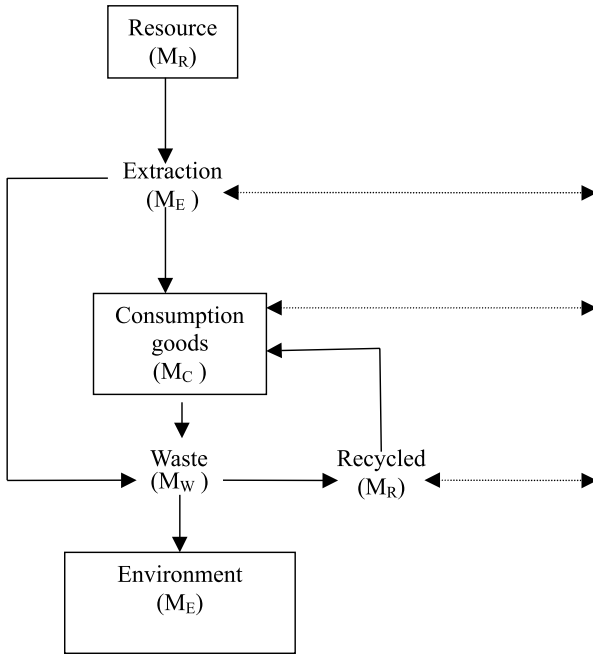


Fig. 2. Material stocks and flows within one region. Note: Dashed lines represent interregional flows

$$\frac{\partial M_{C,r}}{\partial t} = \varphi \cdot C_{n,r} - \delta_{c,r} \cdot M_{C,r} \tag{14}$$

The total amount of waste that is yearly produced, $M_{W,r}$, is equal to the depreciation of consumer goods plus the waste generated by the production of primary and secondary materials, with $w_{E,r}$ and $w_{R,r}$ denoting loss rates of primary and secondary materials.

$$M_{W,r} = \delta_{c,r} \cdot M_{C,r} + \sum_{r=1,2} (w_{E,r} \cdot M_{E,r} + w_{R,r} \cdot M_{R,r}) \tag{15}$$

A share $x_{R,r}$ of material waste is recycled, resulting in a yearly amount of recycled material $M_{R,r}$.

$$M_{R,r} = x_{R,r} \cdot M_{W,r} \tag{16}$$

The remainder accumulates in the environment, denoted by the stock $E_{M,r}$.

$$\frac{\partial E_{M,r}}{\partial t} = (1 - x_{R,r}) \cdot M_{W,r} \tag{17}$$

3.8. Trade balance

Trade balance is assumed, meaning that import and export are equal in monetary terms. Trade can involve consumer goods, and primary and secondary materials. The allocation of imports and exports follows from the optimisation objective. Trade is subject to the following trade balance

equation, which states that the values of imports of regions 1 and 2 are equal (van den Bergh and Nijkamp 1995).

$$C_{M,1} + p_{E,2} \cdot M_{E,1,2} + p_{R,2} \cdot M_{R,1,2} = C_{M,2} + p_{E,1} \cdot M_{E,2,1} + p_{R,1} \cdot M_{R,2,1} \quad (18)$$

Here, the value of imports is equal to the sum of the values of imported consumer goods, virgin materials and secondary materials. $M_{E,i,j}$ and $M_{R,i,j}$ denote the extracted virgin materials and the recycled materials that originate from region i and are used in region j . Certain material balance conditions hold as well all, namely: all extracted or recycled material are being used in some region, or $M_{i,j,1} + M_{i,j,2}$ equals $M_{i,j}$ for $i=E,R$, and $j=1,2$.

3.9. Environmental feedback

Environmental degradation caused by the accumulation of materials in the environment is assumed to negatively affect the carrying capacity of the resources, $Z_{M,r}$. Different types of environmental feedbacks can be considered. Here local and global feedbacks are distinguished, where the first one only includes damage caused by pollution generated in the own region, while the latter also includes damage from transboundary pollution (van den Bergh and Nijkamp 1995). Given a pollution damage coefficient κ_r , the change in carrying capacity can be formulated for the case with local feedback as:

$$Z_{M,r}(t) = \left(e^{-\sum_{j=0}^t \kappa_r \cdot E_{M,r}(j)} \right)^2 \quad (19)$$

and for the case with global feedback as:

$$Z_{M,r}(t) = \left(e^{-\sum_{r=1,2} \sum_{j=0}^t \kappa_r \cdot E_{M,r}(j)} \right)^2 \quad (20)$$

3.10. Decision variables

The optimisation exercise is based on choosing values over time for three decision variables for each region, i.e. six decision variables in total. The decisions on how much to invest in the various capital stocks are formulated by:

$$I_{C,r}(t) = x_{C,r} \cdot Y_{C,r}(t) \quad (21)$$

$$I_{E,r}(t) = x_{E,r} \cdot M_{E,r}(t) \quad (22)$$

Here $x_{C,r}$ and $X_{R,r}$, denote the proportion of sectoral output invested in production of consumer goods, and material extraction, respectively. The other decision variable, the rate of recycling $X_{R,r}$, is already incorporated in Eq. (9).

This completes the model specification.

4. Optimisation results

This section presents results from numerical optimisation exercises performed with the model. The numerical values of parameters and initial conditions (see Annex) are identical for the two regions, except with regard to the carrying capacity of the material resource. The symmetry of the regions allows to focus on the core issue, namely the interaction between growth, trade and materials flows among regions with different material resource capacities. In region 1 the carrying capacity of the material resource is set at a higher level than in region 2.

The presence of six decision variables gives rise to a complex numerical optimization problem. The levels of the decision variables are assumed not to be time-varying, but are fixed over the whole time period.

We will examine the implications of particular assumptions about trade, technological development, resource dynamics and sensitivity of the resource for environmental pollution. The results are compared with those obtained for a reference scenario. For reasons of limited space, we only show graphs for the reference scenario; more detailed information, including sensitivity analysis can be found in Janssen and van den Bergh (2000). The reference scenario is constructed in such a way that the global economy, i.e., the two regions jointly, yields a long term growth rate over a period of 100 years that equals 3%. The parameter values for the reference case are given in the Annex. These are not based on a particular empirical case but in line with values commonly used in economic models. Although the results are depicted for 100 years, the time horizon of optimisation is set at 200 years to avoid end-of-time-horizon effects. This is a common procedure in numerical dynamic optimisation studies (see Nordhaus 1994).

We consider five alternative cases or scenarios:

1. *No trade*. The regions cannot trade.
2. *Technology of material production*. Technological development reduces the cost of extraction and recycling ($\tau_R = 0.99$; $\tau_E = 0.99$).
3. *Non-renewable resource*. The growth rate of the resource is set at zero in each region ($\lambda_r = 0$).
4. *Local feedback*. Materials accumulated in the environment of a region reduce the carrying capacity of the respective material resource ($\kappa_r = 0.001$).
5. *Global feedback*. Materials accumulated in the global environment reduce the carrying capacity of the material resources in both regions ($\kappa_r = 0.001$).

4.1. Reference case

Maximising the sum of discounted utility of consumption implies that each region specialises in one specific economic activity in the product chain. The economic output of the resource rich region, region 1, is dominated by the extraction of materials, whereas the economic output of the resource poor region, region 2, is mainly determined by the production of consumer goods and material recycling (Figs. 3 and 4). The rate of economic growth is lower in region 1 than in the region 2, although the discounted utility of consumption is somewhat higher in region 1 than in region 2. This follows from the relatively high re-investment fraction of economic output in region 2.

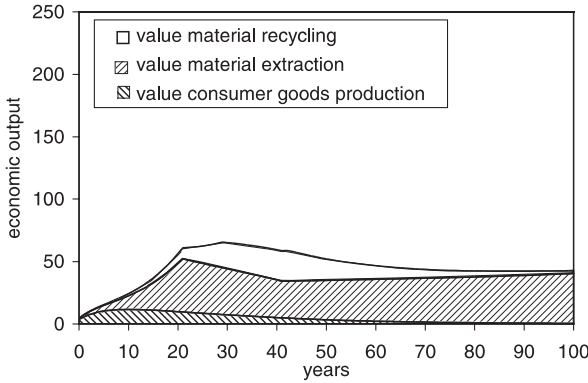


Fig. 3. Sources of economic output in region 1 under the reference case scenario

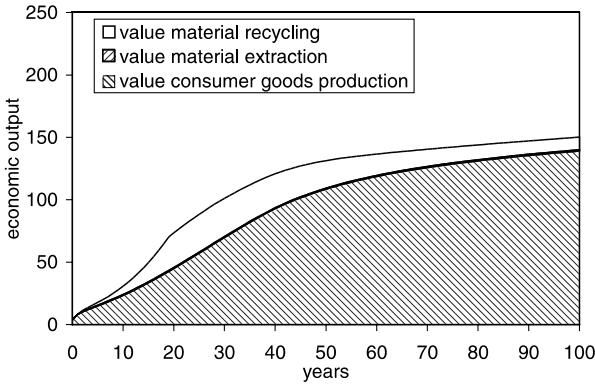


Fig. 4. Sources of economic output in region 2 under the reference case scenario

Production of consumer goods is more capital intensive than material extraction or recycling.

In relation to these results, note that there is some empirical evidence that economies with relatively large natural resources exports have relatively low growth rates. Sachs and Warner (1995) found that economies with a high ratio of natural resource exports to GDP in 1971 (the base year in their analysis) tended to have low growth rates during the subsequent period 1971–1989. Similar results were obtained by Gylfason et al. (1999). Economic explanations of such findings are the Dutch Disease – the resource sector drawing capital and labor away from manufacturing and agricultural sectors, thus raising their production costs – and rent seeking – notably, investment influenced by powerful groups (Torvik 2002; Ross 1999; Gylfason 2001). In our model, the low rate of economic growth is best explained by the Dutch Disease phenomenon, since the elasticity of inputs to production are higher for consumer goods than for the production of primary and secondary materials (see Eqs. (4), (6), (10)).

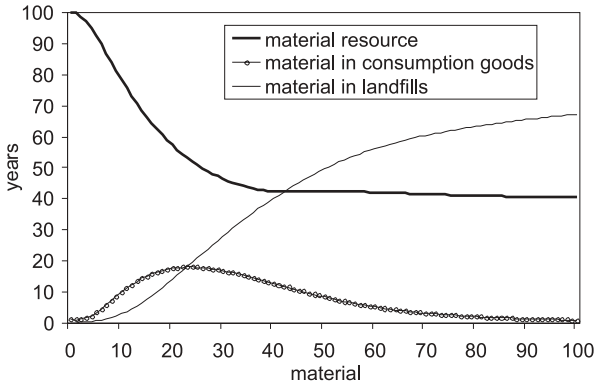


Fig. 5. Material stocks in region 1 under the reference case scenario

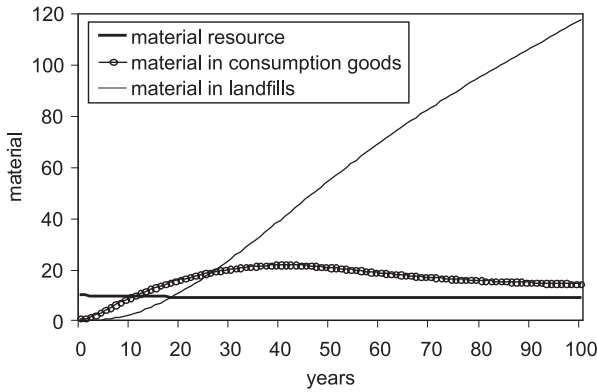


Fig. 6. Material stocks in region 2 under the reference case scenario

Resource depletion occurs mostly in region 1 (Figs. 5 and 6). The extracted material from the resource in region 1 is to a large extent exported to region 2, which focuses on the production of consumer goods. The stock of materials encapsulated in consumer goods initially increases, due to increased consumption. After 30 years, the stock starts to decline due to dematerialization, which is stimulated by the depletion of the material resources. Materials accumulate in the environment of both regions, although at a faster rate in region 2.

Material inputs in production of consumer goods originate from resource extraction and recycling. Nevertheless, region 1, which has a lower long run consumption level than region 2, only uses recycled material during the second half of the period considered.

The amount of new materials for production of consumer goods is chosen as an indicator of environmental pressure of economic activities. Note that pressure means here depletion of the material resource. The relation between this indicator and economic output is depicted for each region as well as for the total of regions in Figs. 7–9. Figures 7 and 9 show curves that are similar

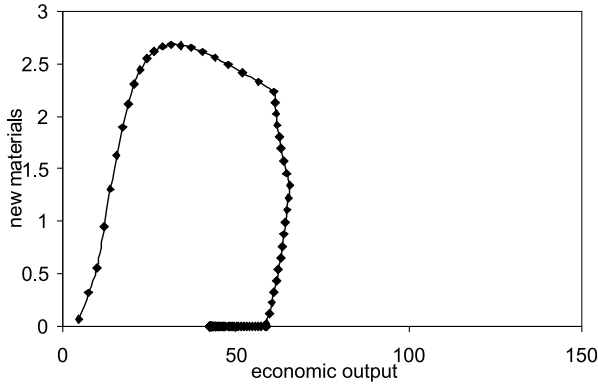


Fig. 7. Relation between inputs from new materials and economic output in region 1 under the reference case scenario

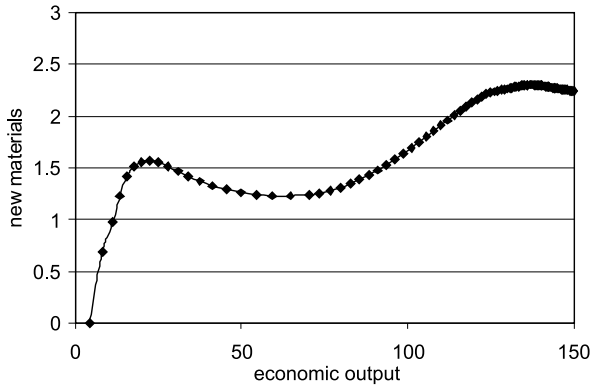


Fig. 8. Relation between inputs from new materials and economic output in region 2 under the reference case scenario

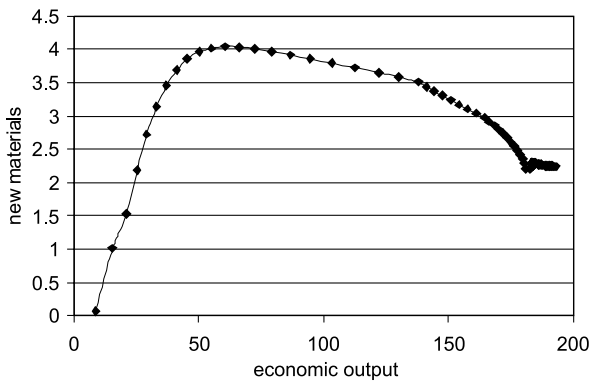


Fig. 9. Relation between inputs from new materials and economic output in both regions under the reference case scenario

to the Environmental Kuznets or inverted-U curve, as discussed in Sect. 2. Figure 8 resembles an N-shaped curve, as hypothesized by de Bruyn and Opschoor (1997). The latter reflects that initially a de-linking between income growth and absolute resource use occurs, but once technological gains are exhausted, re-linking occurs.

The difference between the inverted-U curve for region 1 (Fig. 7) and the N-shaped curve for region 2 (Fig. 8) can be explained as follows. Initially, region 1 consumes a large amount of new materials before it turns to recycled materials, and then stops using new material inputs. Region 2 requires an increasing amount of material input due to the relatively high rate of economic growth. This demand can not be supplied by recycled materials at low costs. Consequently, the amount of inputs of new materials increases. The N-shaped curve for this region is indirectly related to the initially large domestic consumption of virgin materials in region 1, because this reduces the availability of virgin materials for export from region 1 to region 2. The subsequent shift to recycling in region 1 reduces its demand for virgin materials, which allows an increase in the export of virgin materials to region 2. This illustrates the intricate link between spatial interactions, in this case trade, and the relationship between environmental pressure and economic growth.

4.2. No trade

If the regions are not allowed to trade, each has a lower rate of growth. The discounted sum of utility of consumption is about 27% lower than the reference case in both regions (see Table 1). Region 2 is constrained by a lack of resources, which are needed to reach the rate of economic growth obtained under the reference case. It cannot benefit from the export of materials from region 1 to 2. Likewise, the consumption level in region 2 grows at a lower rate compared to the reference case. The EKC stabilises at a lower level and then turns to form an N-shaped curve. This is caused by the scarcity of virgin material relative to secondary material. After a fast growth of virgin material use, depreciation of consumer goods results in a large supply of secondary materials, reducing the demand for virgin materials during a short period.

Table 1. The discounted sum of utility of consumption in both regions ($U(C_i)$) in absolute and relative terms, for the six experiments

Scenario	Total discounted utility region 1		Total discounted utility region 2	
	Absolute level	% Change relative to Reference	Absolute level	% Change relative to Reference
Reference	413.0	0	394.1	0
No trade	300.2	-27.3	286.0	-27.4
Technology of material production	425.3	+ 3.0	469.2	+ 19.1
Nonrenewable Resource	291.0	-29.5	294.3	-25.3
Local feedback	381.6	-7.6	329.6	-16.4
Global feedback	369.3	-10.6	334.7	-15.1

Subsequently, consumption of virgin materials increases again, but at a slower rate. It is clear from this case that trade increases the carrying capacities and the long term and maximum growth rates of both regions.

4.3. Technology of material production

Here the amount of capital needed to extract and recycle materials decreases at an exogenous rate. Because of the improved options to use the available virgin and secondary material resources, the discounted utility of consumption increases in both regions as compared with the reference case (Table 1). The increase in region 2 is higher because it has fewer resources. The EKC found is very similar to the one under the reference case. The increased welfare is mainly due to increased possibilities to recycle materials. Improved technology of extraction leads to earlier scarcity of resources, which does not necessarily increase welfare.

4.4. Non-renewable resource

In the reference case, each resource has a growth rate of 10%. Here we set the growth rate at zero, so that the resource becomes non-renewable. This constraint has a severe impact on both regions. The discounted sum of utility falls by 30% in the resource rich Region 1 and 25% in Region 2, as compared with the reference case. The levels of consumer goods peak halfway the 100 year period, and decline afterwards. The EKC peaks at a high level at a low economic development during the first half of the period, and economic development growth levels off during the second part of the 100-year period.

4.5. Local feedback

The accumulation of materials in the environment leads to a reduction in the carrying capacity of the own resource. An increased amount of materials is recycled, to avoid its accumulation in the environment. The amount of new materials extracted peaks at a lower level. As a result, the rate of economic growth levels off. The consumption of goods increases at a low rate in region 1, while in region 2 the amount of consumer goods decreases during the second half of the 100-year period. Explanations for this phenomena are a reduction of materials extraction, leading to a lower level of trade, and a reduction of economic growth. The resource poor region suffers the most from the reduced availability of virgin resources.

4.6. Global feedback

Global feedback means that waste generated in one region affects the resource in the other region. This imposes an extra constraint on the optimisation exercise. It leads to a lower optimal use of new materials compared with the local feedback situation. Moreover, the economic output falls at the end of the time horizon. The utility of consumption decreases compared with the local feedback case (Table 1). Similar to the local feedback case, the resource-poor region suffers the most from the global feedback.

5. Conclusions

A model was presented that allows to study hypothesised EKC and N-shaped relationships between economic growth and environmental pressure by taking account of materials flows and trade. For this purpose, the model describes product chains in two trading economies. Materials are extracted from a renewable resource, used as inputs for the production of consumer goods, and recovered and recycled. Through trade, the regions can increase their carrying capacity and in turn their maximum and sustainable growth rates. When the regions differ with regard to the carrying capacity of the resource, welfare optimisation requires that regions specialise. The region with the largest carrying capacity will specialise in resource extraction, while the other region will specialise in the production of consumer goods.

Numerical optimisation experiments show that both regions are sensitive to alternative assumptions regarding technological change in extraction and recycling, as well as regarding resource dynamics. All experiments generate global relationships between environmental pressure and income that support the re-linking hypothesis of de Bruyn and Opschoor (1997), except when environmental feedback stimulates a collapse of the economies. N-shaped relationships between environmental pressure and income can be explained by exhaustion of easy technological solutions to environmental and resource problems. Moreover, the results shows that the existence of an N-shaped curve is consistent with theoretical insights on trade of materials between countries, and substitution between virgin and secondary materials, driven by relative scarcity.

The model is an abstract and simplified description of two economies, their internal activities, their physical dimensions, and their interactions. Since the inclusion of physical relationships in spatially explicit economic models is rare, the main innovation has been to integrate these elements into a single, internally consistent model. The analysis has been performed using parameter values in realistic ranges. The main conclusion is that it is unlikely that de-linking of environmental pressure and economic growth is possible over a longer period of time.

Evidently, the current model is not appropriate to address all issues relevant to re- and de-linking. Simplifying assumptions were needed to employ numerical dynamic optimization to solve the model. Possible extensions are the inclusion of endogenous technological change – both learning-by-doing and learning-by-using –, more complex sectoral interactions, accounting for materials in capital goods, substitution in consumption between services and material products, relocation of firms, and spatial clusters of economic activities driven by agglomeration effects.

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Appendix

List of Variables

r denotes region ($r = 1, 2$)

Stocks (between brackets are initial values)

- C_r = level of consumption goods (200,300)
- $K_{C,r}$ = level of capital goods in production of consumption goods (40,40)
- $K_{R,r}$ = level of capital goods in recycling of materials (100,10)
- $K_{E,r}$ = level of capital goods in extraction of materials (2, 0.05)
- M_r = material contained in the resource (100,10)
- $M_{C,r}$ = material contained in consumption goods (1,5)
- $E_{M,r}$ = waste material accumulated in the environment (0,0)

Flows

- $C_{n,r}$ = new consumption goods
- $C_{P,r}$ = production of consumption goods
- $C_{M,r}$ = import of consumption goods
- $C_{X,r}$ = export of consumption goods
- $Y_{C,r}$ = output of consumer goods production
- $M_{E,r}$ = extracted virgin materials
- $M_{R,r}$ = recycled materials
- $M_{E,i,j}$ = virgin materials extracted in region i and used in region j
- $M_{R,i,j}$ = recycled materials recovered in region i and used in region j .
- $I_{C,r}$ = capital investment in production consumer goods
- $I_{E,r}$ = capital investment in extraction
- $I_{R,r}$ = capital investment in material recycling
- $P_{E,r}$ = price of extracted virgin materials
- $P_{R,r}$ = price of recycled materials
- $\pi_{E,r}$ = resource depletion scaling factor
- $\pi_{R,r}$ = recycling scaling factor
- $\alpha_{E,r}$ = annuity factor extraction virgin materials
- $\alpha_{R,r}$ = annuity factor recycled materials

Parameters (between brackets are the parameter values in the reference case)

- η = elasticity consumption (0.5)
- ρ = discount rate (0.03)
- $\delta_{C,r}$ = depreciation rate of consumer goods (0.2)
- $\delta_{M,r}$ = depreciation rate of capital goods (0.04)
- $\delta_{kc,r}$ = depreciation rate of capital goods in consumer goods production (0.04)
- $\delta_{km,r}$ = depreciation rate of capital goods in material extraction (0.04)
- $\delta_{kr,r}$ = depreciation rate of capital goods in recycling materials (0.1)
- $a_{C,r}$ = technology level in production consumer goods (2)
- $a_{E,r}$ = technology level in extraction (1)
- $a_{R,r}$ = technology level in recycling (10)
- $\gamma_{C,r}$ = elasticity of output production consumer goods (0.6)
- $\gamma_{E,r}$ = elasticity of output extraction (0.6)
- $\gamma_{R,r}$ = elasticity of output recycling (0.6)
- $\tau_{C,r}$ = technology improvement production consumer goods (1)
- $\tau_{E,r}$ = technology improvement extraction (0.995)
- $\tau_{R,r}$ = technology improvement recycling materials (0.995)
- $p_{\pi,r}$ = exponent of depletion function (0.25)
- i = interest rate (0.03)

$w_{E,r}$ = loss rate materials, extraction virgin materials (0.1)

$w_{R,r}$ = loss rate materials, recycling materials (0.1)

λ_r = intrinsic growth rate of material resource (0.1,0.1)

$Z_{M,r}$ = carrying capacity of the material resource (100,10)

κ_r = impact coefficient material resource (0)

φ = transformation parameter (1)

Decision variables

$x_{E,r}$ = rate of investments in material extraction

$x_{C,r}$ = rate of investments in producing consumer goods

$x_{R,r}$ = % of recovering waste materials