Structural Change, Economic Growth and the Environmental Kuznets Curve
A Theoretical Perspective

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Abstract
The question of whether economic growth will ultimately resolve environmental problems has recently been discussed in a mainly empirical literature. One of the mechanisms that can explain the finding of an inverted U-shaped relationship between income and emissions relies on the changes in the sectoral composition of economies associated with economic growth. This paper develops a multi-sector general-equilibrium model to study the dynamic relationships between technological progress, economic development, the sectoral composition of economies and emissions. In the model, structural change is the outcome of a complex interplay between factors of demand and supply, and results from both differences in technological progress on a sectoral level and from differences in income elasticities of demand for different goods. We will derive under what conditions such changes can give rise to a hump-shaped relationship between per capita income and emissions.

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1. Introduction

The past decades have witnessed historically unprecedented growth rates, drastic changes in the sectoral composition of economies (usually referred to as de-industrialization), and drastic increases in pollution. The latter development has resulted in a growing concern that expansion of the world economy at rates experienced in the last decades will cause irreparable damage to the environment. It is therefore not surprising that considerable research effort has been devoted to the question of whether growth and a 'sufficiently clean' environment can go hand in hand, or whether there are limits to growth. This research has been focused on the question of whether an inverted U-shaped relationship exists between several sources of pollution and economic development.[2] Such a relationship, which is a special form of a more general Income-Emission-Relationship (IER), is often being labeled an Environmental Kuznets curve (EKC), after Kuznets (1955) who found empirical evidence for an inverted U-shaped relationship between per capita income and income inequality.

Several reasons have been put forward as to why such a relationship might exist and why the positive link between output and pollution may be broken at a certain level of income. First, technological innovations that may potentially be related to per capita income can result in more output being produced with less pollution. Secondly, shifts in patterns of demand (often referred to as structural change or in more popular terms as 'de-industrialization') associated with rising per capita income may result in consumption and production becoming less pollution intensive.[3] Finally, richer people may be more aware of environmental problems and take increased care for the

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2 In contrast with the literature on the EKC which mainly focuses on the development of emissions during the process of development of economies over time, there is a literature which more explicitly deals with the question whether long-run (environmentally) sustainable growth is feasible and optimal (see, for example, Bovenberg and Smulders, 1995, and Aghion and Howitt, 1998). Although related to the topic of this paper, we leave this issue of optimality and feasibility of sustainable growth aside and focus on the changes and development of emissions over time that occur as countries growth rich.

3 There is an extensive literature discussing the relationship between structural change and economic growth, both theoretically and empirically (for example, Van Ark, 1996, Baumol, 1967, Baumol, Blackman and Wolff, 1989, Echevarria, 1997, Kongsamut, Rebelo and Xie, 1997, Maddison, 1991 and 1995, Pasinetti, 1981, Rowthorn and Ramaswamy, 1997, and Saeger, 1997). We refer to de Groot (1998) for an overview of this literature. Non-unitary income elasticities of demand for goods produced in different sectors and differentiated rates of technological progress on a sectoral level are shown to be crucial driving forces behind the observed patterns of sectoral change.

environment, which may result in technological innovations, shifts in patterns of demand, and policy reactions aimed at increased environmental conservation (see, for example, Selden and Song, 1995, and Stokey, 1998, for theoretical models in which socially optimal environmental regulations become stricter when per capita income increases, potentially giving rise to improved environmental quality).[4]

The relationship between economic growth and pollution has been studied intensively in the empirical literature (see a special issue of Ecological Economics (1998) for an overview and a discussion of existing insights). This literature is far from conclusive on the shape of the IER and the driving forces behind it.[5] Although some papers point at the existence of an EKC for some pollutants (for example, Grossman and Krueger, 1992, Panayotou, 1993, Selden and Song, 1994, and Shafik and Bandyopadhyay, 1992), no evidence exists on an EKC for all pollutants or types of environmental problems. An important criticism one can raise against the studies mentioned before is that they yield little insight into the mechanisms that cause pollution to fall after some level of per capita income has been surpassed. At best, time trends have been taken into account in these studies to test for developments unrelated to per capita income. This trend may reflect technological progress resulting in lower energy intensities (as is often suggested in the papers), but it may as well indicate, for example, rising prices of energy relative to prices of other inputs resulting in substitution away from energy (see Agras and Chapman, 1999, for a recent regression analysis emphasizing the relevance of energy prices for explaining the shape of the IER).

To open the black box, a two step procedure could be employed in which in the first step structural equations are modeled and estimated relating environmental regulations, technology, and industrial composition to GDP. In the next step, the level of pollution can then be modeled as being related to regulations, technology and industrial composition (cf. Grossman and Krueger, 1995). The problem with such an approach is that it is very data demanding. Another way to gain insights into the

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4 An alternative way to get rid of pollution-intensive production is to replace it to foreign (poorer) countries. A problem with this argument is that this replacement cannot continue indefinitely. At some point in time, all countries have become so rich that no country is anymore more willing to absorb the pollution intensive production. In other words, replacement cannot be the explanation why, in the long run, pollution would decrease with income.

5 An indepth discussion of the estimation techniques to be used is beyond the scope of this paper. Nevertheless, it is important to note that there is controversy over this. No agreement has for example been reached on the usefulness of pooled-cross section estimates (e.g., de Bruyn, van den Bergh and Opschoor, 1998, Dijkgraaf and Vollebergh, 1998) and the type of conditioning variables one should take into account.

relevance of the various potential mechanisms yielding an 'Income Emission Relationship' (further denoted IER) is the use of decomposition techniques (e.g., De Bruyn, 1997, Selden et al., 1996, and Sun, 1998). These techniques decompose changes in pollution or energy use into a scale effect (resulting from increased activity), an intensity effect (resulting from energy efficiency increasing technological change), and a structure effect (resulting from the changing sectoral composition of the economy). They thereby give some descriptive idea of the quantitative importance of the factors that may give rise to an IER. Still another way of testing for an IER that yields some insights in driving forces behind the IER uses regression analysis, but distinguishes between total pollution, pollution intensity (capturing the intensity effect), and polluting activity (capturing the scale effect) as the dependent variables. This approach is used by de Bruyn, van den Bergh and Opschoor (1998), and Hilton and Levinson (1998). Given this state of affairs which can predominantly be characterized as 'testing without theorizing', it is surprising that so little effort has been devoted to theoretically model the relationship between per capita income and pollution. For some notable exceptions in which one-sector macro-models are developed, we refer to Copeland and Taylor (1994), Lopez (1994), Selden and Song (1995), and Stokey (1998).

In this paper, we will develop a theoretical multi-sector general-equilibrium model that allows us to study the relationship between economic development and pollution. In particular, the model allows us to study the interaction between pollution, changes in the sectoral composition of economies, and technological change. We refer to, for example, Schipper and Meyers (1992) for a convincing and pervasive empirical illustration of how important sectoral des-aggregation is for really understanding developments of aggregate emissions or energy use. Recently, Duchin (1998) has emphasized the importance of explicitly considering demand factors when she stated that 'most environmental degradation can be traced to the behavior of consumers either directly, through activities like the disposal of garbage or the use of cars, or indirectly through the production of activities undertaken to satisfy them'. A sound theoretical study of the relationship between income and emissions thus requires the simultaneous consideration of factors of demand (that is, consumer preferences) and supply (that is technology and technological progress).[6] The model in this paper provides us with a framework that can be used as a theoretically consistent background when thinking about the relationship between economic development and pollution. An important characteristic of the model presented here that distinguishes it from existing models is that the model allows us to simultaneously study the effects of technological progress and changes in the structure of demand on the development of the sectoral structure and pollution.

We will proceed as follows. In section 2, we will develop and describe a simple model that allows us to simultaneously study economic growth, structural change, and the development of emissions. In section 3, we will illustrate the mechanisms that give rise to a relationship between economic development, sectoral structure in terms of labor and output and emissions in a simplified and analytically tractable two-sector version of the model. In section 4, we generalize the model of section 3 to a three-sector version of the model. By simulating the model, we will show how the shape of the IER depends on (i) the development of the price of emissions relative to other inputs (which may be influenced by for example tax measures), (ii) technological progress, and (iii) changes in consumption patterns driven by non-unitary income elasticities of demand and relative price changes due to differentiated sectoral technological progress. The question how this shape is affected by different elasticities of substitution between consumption goods and inputs in the production process will be addressed as well. Section 5 contains an evaluation and a conclusion, and discusses potential future research, both theoretical and empirical.

2. A simple model

In this section, we develop a model of a closed economy that consists of *S* sectors producing final consumption goods. For simplicity, we assume perfect competition in all sectors. Production takes place with labor and emissions. Emissions are modeled as an input in the production process, and can either be interpreted as an externality from

[6] Trade and patterns of specialization may drive a wedge between consumption and production patterns, but in my opinion this factor is unlikely to be crucial in answering the question whether an EKC can occur since the process of replacing dirty production to poorer regions cannot continue indefinitely (of course certainly not on a world wide scale). Related to the question whether trade is influencing the IER and domestic pollution is the question whether trade causes sectoral shifts and rising income inequality. Interestingly, this last question has been addressed in the debate on the causes and consequences of de-industrialization in the US by Rowthorn and Ramaswamy, 1998. They conclude that trade is unlikely to have played a decisive role in explaining shifts in the sectoral composition and increased income inequality in the US economy.

production or as a by-product of energy use. Labor (L) is homogeneous and fully employed. We normalize the amount of labor at 100 so that we can conceive sectoral employment shares as shares in total employment.[7] Emissions and labor are modeled as relatively bad substitutes in the production process of final consumption goods, which is the empirically relevant case (see, for example, Kemfert, 1998). Consumer preferences are such that goods from all sectors are consumed. Income elasticities of demand may differ for goods from different sectors. Emission and labor productivity in the production sectors grow at constant and exogenous growth rates, but are allowed to differ between sectors. In this section, we will describe the model and characterize its solution.[8]

2.1 Preferences

Consumers derive utility from the consumption of goods produced in the S final goods sectors of the economy. Preferences of a representative consumer are specified as

$$U = \left[\sum_{i=1}^{S} a_i (C_i - \overline{C}_i)^r \right]^{\frac{1}{r}} \quad \text{where} \quad r < 1, r \neq 0, \sum_{i=1}^{S} a_i = 1. \qquad (1)$$

U is the utility index, C_i the consumed amount of goods from sector i, $\overline{C}_i$ is the subsistence requirement of consumption, and a_i is a distribution parameter (where it leads to no confusion, we have dropped time indices in the paper). In the absence of subsistence requirements, the elasticity of substitution between goods from different sectors is equal to $1/(1-\rho)$. The budget constraint corresponding to this problem is

$$\sum_{i=1}^{S} C_i P_{Ci} \leq Y, \qquad (2)$$

7 We could extend the model by allowing for population growth. However, since most of the discussion on the EKC focuses on the relationship between per capita emissions and per capita GDP and since the allocation of labor and the rates of technological progress are scale insensitive, this extension does not add to the analysis. This would change once we would allow for, for example, the endogenous determination of growth by modeling the rate of technological progress as a function of the scale of operation (which is standard in most models of endogenous growth). We refer to de Groot (1998) for such an analysis and their consequences.

8 This model can be seen as an extended version of de Groot (1998) in which production takes place with only labor.

where P_{Ci} is the price of a good produced in sector i, and Y is nominal disposable income (which is equal to wage income in the economy). We assume that $\sum \overline{C}_i P_{Ci} \leq Y$ so nominal disposable income is sufficient to fulfill subsistence requirements. Three remarks with respect to the choice of the utility function deserve attention. Firstly, the introduction of subsistence requirements in the utility function is an easy way of allowing for non-unitary income elasticities of demand that can differ between sectors. The sector with the largest (smallest) subsistence requirement can be shown to have the lowest (highest) income elasticity of demand (see Appendix A).[9] Secondly, there is no need to assume $\overline{C}_i$ to be non-negative on theoretical grounds, but it gives these values a simple interpretation as subsistence requirements (e.g., Deaton and Muellbauer, 1980). Finally, in the special case in which $\rho \to 0$, the utility function boils down to a Stone-Geary utility function.[10]

Formulating the Lagrangian corresponding to optimization problem (1) and performing standard optimization yields the demand for goods from sector i as a function of prices and demand of goods from sector j (see Appendix A)

$$C_i = \overline{C}_i + \left(C_j - \overline{C}_j\right)\left(\frac{a_j P_{Ci}}{a_i P_{Cj}}\right)^{\frac{1}{r-1}} \tag{3}$$

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9 The subsistence requirements will mainly be associated with requirements for goods of different sectors like the agricultural, manufacturing and service sector, with agricultural goods typically being characterized by the large subsistence requirements. The framework that we present here could be extended by, for example, endogenizing the subsistence-requirements or modeling the state of the environment as an amenity in the utility function. In the spirit of the literature of the EKC, it is easily imagined that pollution extensive goods have a higher income-elasticity than otherwise similar pollution intensive goods.

10 To be more precise, evaluating equation (1) at $\rho \to 0$ by taking logs on both sides and applying l'Hôpital's rule reveals that the optimisation problem in the case where $\rho \to 0$ boils down to

$$\max_{C_i} C = \prod_{i=1}^{S} \left(C_i - \overline{C}_i\right)^{a_i} \text{ s.t.} \sum_{i=1}^{S} C_i P_{Ci} \leq Y$$

With no subsistence requirements, a Stone-Geary utility function becomes a standard Cobb-Douglas utility function (and of course so does a CES-utility function when $\rho \to 0$). We refer to Klump and Preissler (1997) for an extensive discussion on the characteristics of various forms of CES-functions that are used in the literature.

Substituting this expression into equation (2) and rewriting yields the demand for goods from sector *i* as

$$C_i = \overline{C}_i + \left(\frac{P_{Ci}}{a_i}\right)^{\frac{1}{r-1}} \frac{\left[Y - \sum_{j=1}^{S} P_{Cj}\overline{C}_j\right]}{\sum_{j=1}^{S} P_{Cj}\left(\frac{P_{Cj}}{a_j}\right)^{\frac{1}{r-1}}}. \tag{3a}$$

This reveals that consumers demand their subsistence requirement plus a weighted average of their disposable income that is left after the subsistence requirements for all goods have been fulfilled. The weights are determined by relative prices and possibilities of substitution.

2.2 Production

Producers of consumption goods operate under perfect competition and produce with a constant returns to scale technology, using labor (L_i) and emissions (E_i). There is exogenously given labor-augmenting and emission-saving technological progress. The levels of labor and emission productivity are denoted by h_{Li} and h_{Ei}, respectively. The production function which belongs to the family of CES-functions looks like

$$Q_i = \left[b_{Li}(h_{Li} L_i)^s + b_{Ei}(h_{Ei} E_i)^s\right]^{1/s} \tag{4}$$

where Q_i is the produced amount of good i, and b_{Li} and b_{Ei} are share parameters. The elasticity of substitution between labor and energy is equal to $1/(1-\sigma)$ which is smaller than one provided that $\sigma \leq 0$, as we will assume throughout the paper. The factors $h_L L$ and $h_E E$ can be seen as the total amount of labor and emission services used in the production process (in efficiency units). The introduction of two technology parameters allows for biased technological progress, that is differences in the growth rate of labor and emission productivity (see for example Den Butter and Hofkes, 1998, for a discussion of the importance of considering biased technological progress).[11] Among others, biased technological progress implies that the input-mix at given relative prices may change over time which can be relevant from an empirical point of view. Profit maximization (or cost minimization) under perfect competition yields the sectoral

[11] There is no biased technological progress if we assume that at all times in all sectors, $h_{Ei}=h_{Li}=h_i$. In that case, we can write the production function as $Q_i = h_i\ [\ b_{Li}L_i^{\ s} + b_{Ei}E_i^{\ s}\ ]^{1/\sigma}$.

emissions as a function of technology levels, input prices, and labor demand (see Appendix B)

$$E_i = L_i \left[\frac{b_{Ei} P_L h_{Ei}^s}{b_{Li} P_E h_{Li}^s} \right]^{\frac{1}{1-s}} \tag{5}$$

According to this expression, the input of emissions relative to labor in sector *i* increases if the price of labor relative to the price of emissions increases, or if the technological progress is biased towards labor (under the assumption that σ<0). The response to these relative changes is larger, the better the substitution possibilities between emissions and labor are. Using this expression, we can write the produced amount of goods as a function of sectoral labor inputs

$$Q_i = L_i \left(\frac{P_L}{b_{Li} h_{Li}^s} \right)^{\frac{1}{1-s}} \left[b_{Li}^{\frac{1}{1-s}} \left(\frac{P_L}{h_{Li}} \right)^{\frac{-s}{1-s}} + b_{Ei}^{\frac{1}{1-s}} \left(\frac{P_E}{h_{Ei}} \right)^{\frac{-s}{1-s}} \right]^{\frac{1}{s}} \tag{6}$$

We assume that the price of emissions is exogenously given.[12] Since we assume perfect competition and zero profits in equilibrium, output prices will equal equal average (and marginal) costs

$$P_{Ci} = \left[b_{Li}^{\frac{1}{1-s}} \left(\frac{P_L}{h_{Li}} \right)^{\frac{-s}{1-s}} + b_{Ei}^{\frac{1}{1-s}} \left(\frac{P_E}{h_{Ei}} \right)^{\frac{-s}{1-s}} \right]^{\frac{s-1}{s}} . \tag{7}$$

So the price of final goods is equal to a weighted average of the input-prices (in efficiency- units). From this point onwards we take the wage rate as numeraire (P_L=1). The productivity of labor and emissions increase according to

$$\frac{dh_{Li}}{dt} = h_{Li} g_{Li} \quad \text{and} \quad \frac{dh_{Ei}}{dt} = h_{Ei} g_{Ei} , \tag{8}$$

12 Depending on the interpretation of emissions, we can conceive P_E as a tax on emissions or as the price of energy which is determined on the world market. What we are ultimately interested in is how pollution or emissions will change as a result of productivity growth, structural change, and the development of the price of energy *relative* to wages. In future work, we will further elaborate on the determination of the price of emissions/energy, but this is beyond the scope of the current paper.

where g_{Li} and g_{Ei} are the exogenously given growth rates of labor and emission productivity, respectively.

2.3 Equilibrium and solution to the model

The model is completed by the imposition of labor-market clearing according to which

$$L = \sum_{i=1}^{S} L_i, \tag{9}$$

where L is the exogenously given labor supply, and the imposition of goods-market equilibrium according to which

$$Q_i = C_i. \tag{10}$$

Total emissions per period (E) are the sum of sectoral emissions so they equal

$$E \equiv \sum_{i=1}^{S} E_i \tag{11}$$

In order to consider the state of the environment (further labeled as R), we assume that the state of the environment develops according to

$$\frac{dR}{dt} = g_R R - x E, \tag{12}$$

where g_R is the regenerative capacity of the environment and ξ measures the extent in which emissions result in environmental damage. This change may also be interpreted as the net decrease in the concentration of Greenhouse Gases. Despite its simplicity, we think that this model captures the essence of the relationship between economic development, structural change, technological progress, and pollution.

We are now ready to derive the solution of the dynamically recursive model.[13] Starting from an exogenously determined relative price for the inputs in the production process, initial values for labor and emission productivity, and taking the wage rate as the numeraire of the model, we find the prices of consumption goods produced in the

[13] The model is equivalent to de Groot (1998) under the assumption that production takes place without emissions, i.e., b_{Ei}=0 and b_{Li}=1.

final goods sectors. Combining equations (5), (6) and (10), we can write consumption of goods from sector *i* as a function of labor. Combination of this expression with equation (3) and substitution in the labor market constraint (equation 9) yields the sectoral employment shares. In the following sections, we will derive these solutions in more detail. The dynamics of the model are easily found by using equation (8).

3. An analytical analysis of a two-sector version of the model

This section will be devoted to an analysis of the characteristics of the model, and in particular to a description of the mechanisms that shape the Income-Emission-Relationship. In order to retain an analytically tractable solution, some restrictions have to be imposed. First, we only consider a two-sector version of the model. Within this version, we start with an analysis of the special case in which emissions are a pure externality from production and are not being priced (i.e., $\sigma \rightarrow -\infty$ and P_E=0). The production function then simplifies to a Leontief production function, i.e.

$$Q_i = \min\left[h_{Li} L_i , h_{Ei} E_i\right] \tag{4a}$$

In this special case, emissions are directly tied to produced (and consumed) quantities of the final consumption good according to

$$E_i = \frac{Q_i}{h_{Ei}} = \frac{C_i}{h_{Ei}} = \frac{h_{Li} L_i}{h_{Ei}} \tag{5a}$$

where $1/h_{Ei}$ measures the emission intensity of output. Total emissions increase due to an increased volume of production resulting from labor-augmenting technological progress (at a given sectoral allocation of labor and emission intensity), they decrease due to a decreased emission intensity (at given sectoral allocation of labor and labor productivity), and due to a shift of the sectoral allocation of labor toward less emission-intensive activities (at given labor and emission productivity levels).

Modeling consumer preferences according to a Stone-Geary utility function ($\rho \rightarrow 0$) and using the production function (equation (4a)), the prices of final consumption goods (equation (7)) and goods- and labor-market equilibrium (equations (9) and (10)), the sectoral allocation of labor is straightforwardly derived as (see also Appendix C)

$$L_1 = a_1 L - \frac{a_1 \overline{C_2}}{h_{L2}} + \frac{(1-a_1)\overline{C_1}}{h_{L1}} \quad \text{and} \quad L_2 = (1-a_1)L + \frac{a_1 \overline{C_2}}{h_{L2}} - \frac{(1-a_1)\overline{C_1}}{h_{L1}}$$

These expressions reveal that the allocation of labor over time can develop in a non-monotonous way (see de Groot, 1998, for a more extensive discussion on the determination and development of the allocation of labor). Labor shares of the two sectors will converge to a_1L and $(1\text{-}a_1)L$, respectively. The transition to this equilibrium allocation will depend on the initial situation. If sector 1 is characterized by relatively high subsistence requirements and a fast growth rate of labor productivity relative to sector 1, sector 1 will initially be relatively large, it will subsequently shrink, reach a minimum size which is below its equilibrium size and then continue to expand until it has reached its equilibrium size.[14]

Using equations (5a), (11) and the previously derived sectoral allocation of labor, total emissions are derived as

$$E = \frac{a_1 h_{L1} L}{h_{E1}} + \frac{(1-a_1)h_{L2} L}{h_{E2}} + \frac{a_1 \overline{C_2}}{h_{E2}}\left[1 - \frac{h_{E2} h_{L1}}{h_{E1} h_{L2}}\right] + \frac{(1-a_1)\overline{C_1}}{h_{E1}}\left[1 - \frac{h_{E1} h_{L2}}{h_{E2} h_{L1}}\right] \tag{11a}$$

The first two effects reflect increases in emissions due to increased volumes of production of goods and can be labeled as structural effects; in the presence of productivity growth, emissions tend to increase. This tendency may be (partly) offset by increases in the emission productivity (i.e., decreases in the emission-output ratio). In the special case in which there is no bias in technological progress, an increased volume of production will not result in additional emissions as emission-saving technological progress is exactly sufficient to compensate for the increased volume of output. Note that in another special case in which there is no emission-saving technological progress, total emissions will unambiguously increase in a growing economy. Hence, emission-saving technological progress is crucial to achieve reductions in emissions in a growing economy. The third and the fourth term in equation (11a) capture changes in emissions associated with structural change and can be labeled as transitional effects. The sign of these effects crucially depends on the emission-labor intensities. Let us consider the situation in which the emission-labor input ratio is relatively large in sector 1 (i.e., $E_1/L_1 = h_{L1}/h_{E1} > h_{L2}/h_{E2} = E_2/L_2$). The third

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[14] This holds if $(1-a_1)\overline{C_1} h_2(0) > a_1 \overline{C_2} h_1(0)$, where $h_i(0)$ denotes labor productivity in sector i at time t=0.

term in equation (11a) is then negative and the fourth term is positive. Assuming as before that subsistence requirements as well as (non-biased) technological progress is relatively large in sector 1, total emissions will initially decline, reach a minimum, and then increase to their equilibrium level. This development of emissions is fully associated with changes in the sectoral composition resulting from non-unitary income elasticities of demand, and is explained since large productivity growth in sector 1 results in a fast decline of sector 1 which is emission-intensive. This very simple example already illustrates that emissions can follow complex, non-monotonous developments in the presence of non-unitary income elasticities of demand, different rates of sectoral technological progress and different sectoral emission intensities.

Let us now turn to a discussion of the characteristics of the two-sector version of the model in the case in which the substitution elasticity between labor and emissions is unity (so the production function is of the Cobb-Douglas type). For notational convenience, we define b_{Ei} as 1-b_{Li}. Again under the assumption of a Stone-Geary utility function, sectoral employment shares are derived as (see Appendix C)

$$L_1 = \frac{b_{L1}a_1 L + b_{L1}b_{L2}\left[(1-a_1)\overline{C}_1 P_{C1} - a_1\overline{C}_2 P_{C2}\right]}{(1-a_1)b_{L2} + a_1 b_{L1}} \text{ where } P_{Ci} = \left(\frac{1}{b_{Li}h_{Li}}\right)^{b_{Li}}\left(\frac{P_E}{(1-b_{Li})h_{Ei}}\right)^{1-b_{Li}}$$

The development of the employment share of the first sector thus depends on the term in square brackets. As in the previous case, the development of the labor share may be non-monotonous. More precisely, the combination of high subsistence requirements with fast productivity growth in a particular sector resulting in strongly decreasing prices tends to give rise to initially declining and later on increasing employment shares of that particular sector. In addition to the previous analysis, employment shares are also affected by the development of emission prices and emission-saving technological progress as they influence the (relative) price of final goods and thereby patterns of demand. More specifically, if the in a price- increase of the final good of that sector), the employment share of this sector will increase energy price in efficiency units in a particular sector increases relatively strongly (resulting.

Using equations (5a), (11) and the previously derived sectoral allocation of labor, total emissions, total emissions are derived as

$$E = \frac{L[a_1(1-b_{L1}) + (1-a_1)(1-b_{L2})] + P_{C1}\overline{C}_1(1-a_1)[b_{L2}(1-b_{L1}) - b_{L1}(1-b_{L2})]}{P_E[a_1 b_{L1} + (1-a_1)b_{L2}]} +$$

$$\frac{-P_{C2}\overline{C}_2 a_1[b_{L2}(1-b_{L1}) - b_{L1}(1-b_{L2})]}{P_E[a_1 b_{L1} + (1-a_1)b_{L2}]}$$

Emissions can thus basically be split into two parts. The first part in square brackets can be labeled structural and only declines if the relative price of energy increases, resulting in firms substituting away from emissions in their production process. The second part can be labeled transitional and it will vanish over time as productivity increases and prices of end-products decline. During the transition, the change of the transitional part of emissions depends on (i) relative emission-labor intensities, (ii) subsistence requirements, (iii) relative price changes of consumption goods, and (iv) relative changes of input prices. In the special case of equal relative outlays on emissions and labor ($b_{L1} = b_{L2}$) the transitional part will be absent. Next, consider the case in which $b_{L1} < b_{L2}$, implying that sector one is relatively emission intensive. Assuming that, as before, sector 1 is characterized by high subsistence requirements and fast (non-biased) productivity growth, emissions initially decline, they reach a minimum, and then start to increase again until they reach their equilibrium value.

We can of course further extend the number of cases to be considered, but this is beyond the scope of this section. We have seen that (i) differences in the rates of technological progress and (ii) non-unitary income elasticities of demand are sufficient to explain non-monotonous developments of sectoral labor shares and total emissions. Furthermore, we showed how these developments can be explained as the complex outcome of an interaction between demand factors (that is, preferences) and supply factors (that is, characteristics of the production process captured by emission intensities, substitution possibilities and rates of technological progress). In the next section, we will proceed with a numerical simulation of a three-sector version of the model.

4. Simulations with a three-sector version of the model

In this section, we will proceed with the discussion of a three-sector version of the model. We will consider the development of emissions and the sectoral allocation of labor over time. This analysis reveals how the IER will be shaped as the outcome of the interplay of factors of demand and supply that were discussed in the previous section. Special attention will be devoted to the question how the shape of the IER is affected by different substitution elasticities between final consumption goods and inputs in the production process. Furthermore, we discuss the consequences of biases in the rate of technological progress on the shape of the IER. Changes in emissions will be decomposed into a volumetric part associated with macroeconomic growth, a technological part associated with changes in the emission-intensity of output (due to either technological progress or substitution between emissions and the other factor of production), and a compositional part associated with changes in the sectoral composition of demand.

We divide the economy into three sectors. The first (say agricultural) sector is characterized by large subsistence requirements (i.e. a low income elasticity of demand) and strong labor-augmenting technological progress. It takes an intermediate position in terms of its emission intensity of production. The third (say service) sector has exactly opposite characteristics, namely small subsistence requirements and limited labor-augmenting technological progress. It is characterized by the lowest emission intensity of production. The second (manufacturing) sector takes an intermediate position with respect to subsistence requirements and productivity growth, while its emission intensity is largest. Goods produced in the three sectors are taken to be relatively bad substitutes. Also, emissions and labor are bad substitutes in the production of final consumption goods. This characterization of sectors captures some crucial elements of sectoral characteristics and matches rather well with empirical evidence. As we will show, it enables us to mimic the development of sectoral structures that is so characteristics for all economies (see also de Groot, 1998, for an analysis of the sectoral composition of economies in the context of the de-industrialization debate).

The model is as described in section 2. We repeat that we can interpret E as energy-inputs in the production process or as emissions resulting from the production of final goods. We assume the (relative) price of this input as exogenously determined. This price can be interpreted in several ways. It can be seen as an energy price which is determined exogenously on the world market, or as a tax on emissions levied in a lump-sum manner by the government and redistributed to the consumers. For an analytical expression of the sectoral allocation of labor, we refer to Appendix C. Here, we will restrict our attention to the presentation of some simulation results.

In order to illustrate the relevance of factors underlying changes in total emissions, we will engage in a decomposition analysis. Starting from equation (11) we can derive that

$$E = C \sum_{i=0}^{S} \frac{E_i}{L_i} \frac{L_i}{C_i} \frac{C_i}{C}$$

Where C is real total output at constant prices ($C_1 + C_2 + C_3$). We further label the emission-labor ratio (E_i/L_i) by p, the inverse of labor productivity (L_i/C_i) by l, and the share in total (real) output (C_i/C) by s. By straightforward taking time derivatives, the growth rate of emissions can be written as

$$\hat{E} = \underbrace{\hat{C}}_{\text{volume}} + \underbrace{\sum e_i \hat{p}_i + \sum e_i \hat{l}_i}_{\text{technology}} + \underbrace{\sum e_i \hat{s}_i}_{\text{composition}} \quad \text{where} \quad e_i = \frac{E_i}{E}$$

A hat indicates a percentage change in time (i.e. $\hat{x} = (dx/dt)/x$). The change in emissions is thus equal to the growth rate in output corrected for changes in the emission-labor ratio, changes in labor productivity and changes in the sectoral composition of output (weighted with the sectoral share in total emissions). Taken together, changes in the emission-labor ratio and changes in labor productivity may be seen as technological (supply-side related) effects, while changes in the sectoral composition are driven by the demand-side of the model (i.e., preferences).

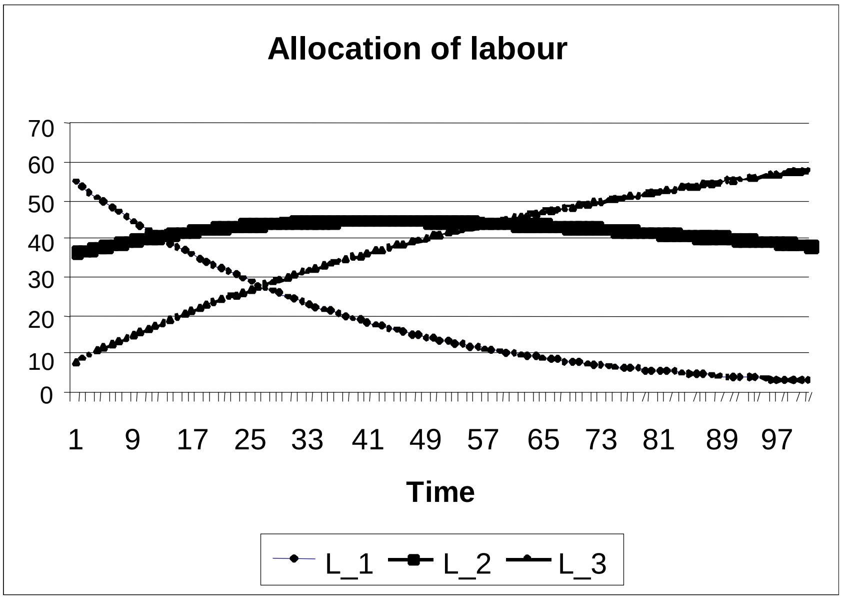
Let us now proceed with the numerical simulation of the model. In the first numerical example that we consider, we assume the absence of biased technological progress.[15] The results of this example are illustrated in Figure 1 and Table 1.[16] The development of the allocation of labor roughly mimics the typical development of the sectoral structures of economies. The labor share of the agricultural sector continuously declines. This is caused by the high rate of technological progress in combination with the low income elasticity of demand (due to the high subsistence requirements). The relatively high growth rate in the agricultural sector leads to a decline in the price of agricultural goods relative to manufacturing and service goods. Given the bad substitutability between agricultural and other goods, the falling relative prices lead to a less than proportionate increase in the demand relative demand for agricultural goods (that is, the share of nominal income spent on agricultural goods declines due to the change in relative prices). The share of agricultural employment consequently declines. A second factor that causes the decline in agricultural employment is related to the high subsistence requirements for goods from this sector, resulting in a low income elasticity of demand and a declining share of income being spent on agricultural goods as time proceeds. The labor share of the service sector shows an exactly opposite pattern. The development of the labor share of the manufacturing sector shows a hump-shaped pattern. Its initial increase is caused by the strong release of labor from the agricultural sector which more than offsets the decline due to the lower (relative) amount of labor required to produce the goods (given the relatively high labor-augmenting technological progress and the relatively bad substitutability between manufacturing and service goods). After some time, the latter effect of less labor being needed to produce the manufacturing goods will start to dominate and the

15 The analysis is based on g_{L1}=0.04, g_{L2}=0.01, g_{L3}=0.0025, g_{Ei}= g_{Li}, b_{L1}=1-b_{E1}=0.9, b_{L2}=1-b_{E2}=0.6, b_{L3}=1-b_{E3}=0.95, a_1=0.1, a_2=0.4, a_3=0.5, $\overline{C}_1$=50, $\overline{C}_2$=30, $\overline{C}_3$=0, $h_{iL}(0)$=1, $h_{1E}(0)$=100, $h_{2E}(0)$=10/6, $h_{3E}(0)$=400, r =-5, P_E=1, σ=-4.

16 On the horizontal axis is time and not (per capita) real income. In all cases we consider, real income continuously grows over time. Hence, the pictures of emissions as a function of (per capita) real income reveal precisely the same pattern.

manufacturing labor share will decline. The development of emissions shows a hump-shaped development and closely mimics the development of the employment share of the manufacturing sector. This is easily seen by considering equation (5). In the absence of biased technological progress, the change in emissions is driven by the change in employment shares, weighted with emission-intensities. As the manufacturing sector is characterized by the largest emission-intensity, total emissions will roughly mimic the development of the manufacturing employment share. By taking a closer look at Table 1, several things stand out. First, the macroeconomic growth rate slows down due to the shift towards less technologically progressive activities (i.e. from agricultural to manufacturing to services). Secondly, the technological effect is confined to a productivity effect; with constant relative input prices and no biased technological progress, the emission-labor intensity will remain constant. The productivity effect remains as improved technologies imply that equal production volumes can be made with less emissions. The decline in the productivity effect is caused by the shift over time towards more emission-extensive goods. Finally, there is a role for structural change which becomes more prominent the better final goods are substitutes. Relative price changes associated with increased productivity then result in stronger changes in consumption patterns.

Figure 1. Non-biased technological progress



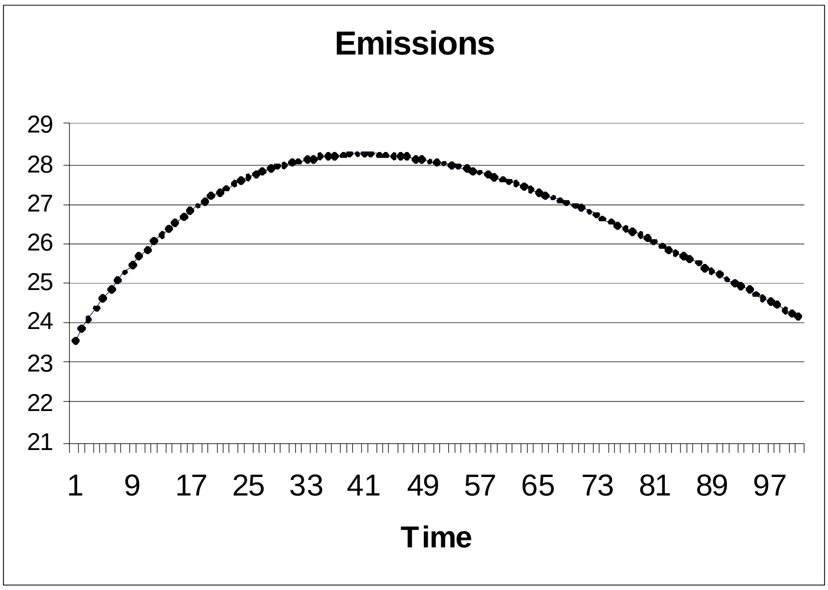


Table 1. Decomposition of emission growth (in annual percentage changes)

Period	1	10	50	100
BASE-LINE (see footnote 15 for parameters)				
Emissions	+1.16	+0.73	-0.12	-0.41
Macro-growth (real)	+2.53	+2.01	+1.03	0.75
Substitution	0	0	0	0
Productivity	-1.10	-1.07	-1.01	-0.99
Structural Change	-0.25	-0.19	-0.14	-0.16
RELATIVELY GOOD SUBSTITUTABILITY BETWEEN FINAL GOODS (?=-2)				
Emissions	+1.10	+0.66	-0.12	-0.34
Macro-growth (real)	+2.50	+1.97	+1.15	+1.05
Substitution	0	0	0	0

Productivity	-1.10	-1.06	-1.01	-0.99
Structural Change	-0.27	-0.22	-0.24	-0.39

Let us next consider the case in which emission-augmenting technological progress is absent.[17] So technological progress is biased and purely labor-augmenting. The results are illustrated in Figure 2 and Table 2. The development of the allocation of labor is roughly similar to the one described in the previous example (and for similar reasons). Emissions however will unambiguously increase over time. This is caused by the fact that production (and consumption) of the goods produced in the three sectors of the economy continuously increases over time. With constant emission intensities, emissions will continuously increase. This increase initially takes place relatively fast as the macroeconomic growth rate is large due to the strong emphasis in consumption on goods that are produced with high growth in labor productivity. The increase levels of after some time once production shifts from manufacturing towards the emission-extensive service sector. By taking a closer look at Table 2, we see that in contrast with Table 1, substitution plays a role. In the absence of emission-saving technological progress and under bad substitutability between labor and emissions, emission-labor intensities will increase, having a 'positive' effect on the growth of emissions. This effect is smaller, the better the inputs in the production process form substitutes (see Table 2). This example illustrates that without changes in the emission intensity, there is no possibility of a decline in emissions as countries grow richer (driven by for example changes in the sectoral composition of economies). This result underlines the importance of understanding technological progress and the potential bias in technological progress. By taking a closer look at Table 2, we see that in contrast with Table 1, substitution plays a role.

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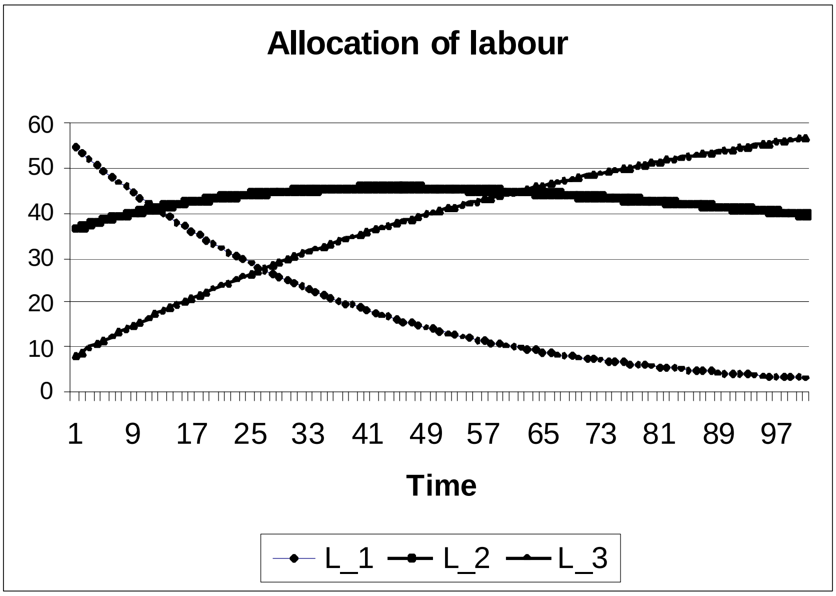
17 The analysis is based on g_{L1}=0.04, g_{L2}=0.01, g_{L3}=0.0025, g_{Ei}=0, b_{L1}=1-b_{E1}=0.9, b_{L2}=1-b_{E2}=0.6, b_{L3}=1-b_{E3}=0.95, a_1=0.1, a_2=0.4, a_3=0.5, $\overline{C}_1$=50, $\overline{C}_2$=30, $\overline{C}_3$=0, h_{iL}(0)=1, h_{1E}(0)=100, h_{2E}(0)=10/6, h_{3E}(0)=400, r =-5, P_E=1, σ=-4.

Figure 2. Biased Technological progress



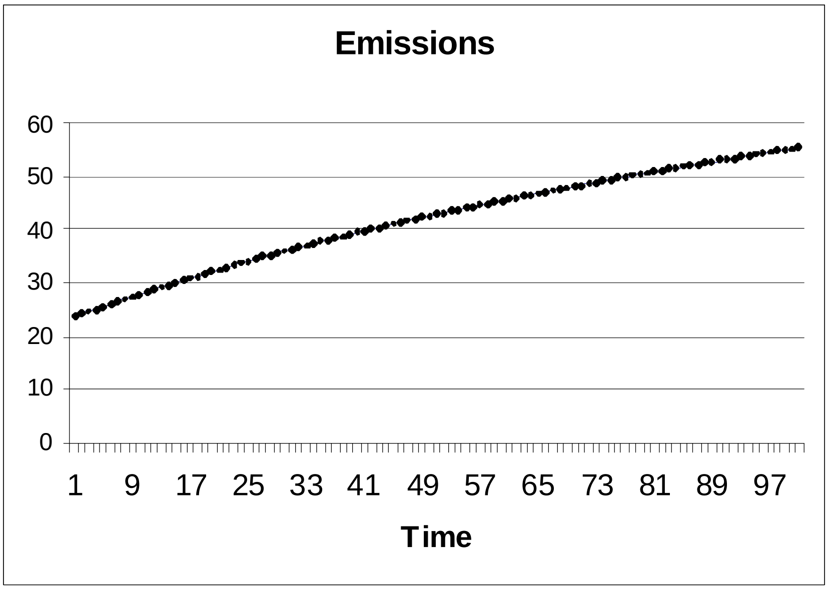
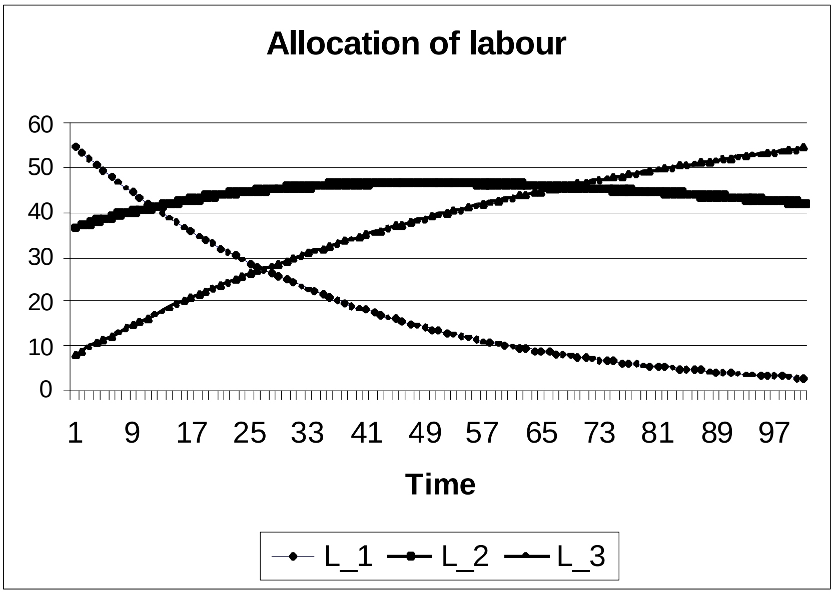


Table 2. Decomposition of emission growth (in annual percentage changes)

Period	1	10	50	100
BIASED TECHNOLOGICAL PROGRESS				
Emissions	+2.09	+1.62	+0.70	+0.41
Macro-growth (real)	+2.50	+1.97	+0.99	+0.65
Substitution	+0.89	+0.88	+0.86	+0.85
Productivity	-1.02	-1.01	-0.97	-0.93
Structural Change	-0.26	-0.21	-0.16	-0.15
RELATIVELY GOOD SUBSTITUTABILITY BETWEEN INPUTS (?=-2)				
Emissions	+1.92	+1.47	+0.60	+0.32
Macro-growth (real)	+2.44	+1.93	+0.96	+0.65
Substitution	+0.76	+0.75	+0.72	+0.70
Productivity	-1.01	-0.98	-0.91	-0.86
Structural Change	-0.25	-0.20	-0.16	-0.15

Our next step is to look at the effects of changes in the energy price relative to wages (in the case of non-biased technological progress). Let us, therefore, assume that energy prices rise with 2.5% per period. The results are depicted in Figure 3 and Table 3. Two effects are noteworthy. First, the decline in energy-use/emissions sets in much earlier and emission growth is much slower. This is due to the substitution away from the more expensive input. The effect is stronger the larger the substitution elasticity between energy and labor (see also Table 3). Secondly, the allocation of labor is affected by the increase in energy prices. The shift towards labor is strongest in the sector making intensive use of this factor (the manufacturing sector). We thus see a relatively slowly declining share of employment in the manufacturing sector. We would like to emphasize that provided that substitution possibilities between emissions and labor inputs are sufficiently large, continuously increasing prices of emissions may cause the de-linking of growth and emissions, even in the absence of energy-saving technological progress. We refer here to Agras and Chapman (1999) for a recent empirical analysis which basically arrives at the conclusion that once energy-prices are included in the regression analysis, the hump-shaped relationship between emissions and per capita income ceases to apply. The decline in emissions experienced in the eighties can according to them be traced back to increased oil prices. This also empirically illustrates the relevance of changing energy-prices.

Figure 3. Growth in energy-price



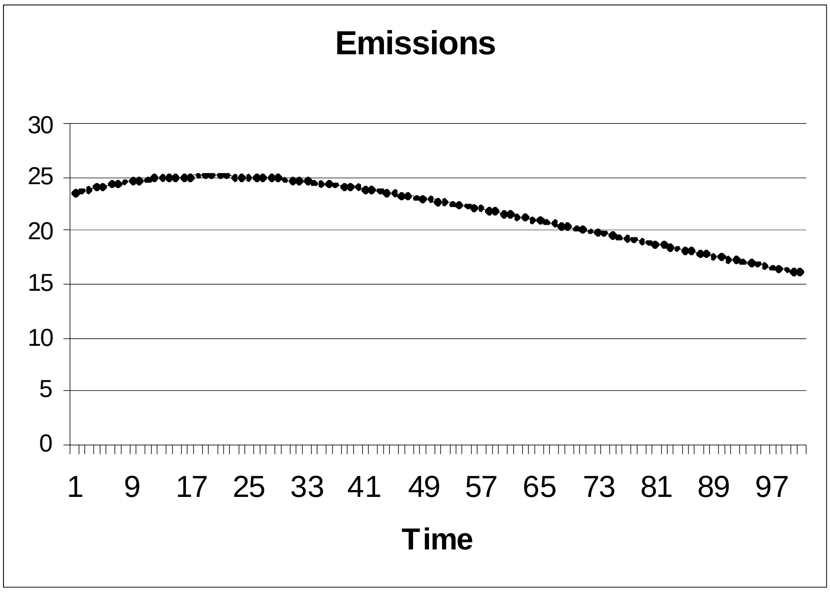


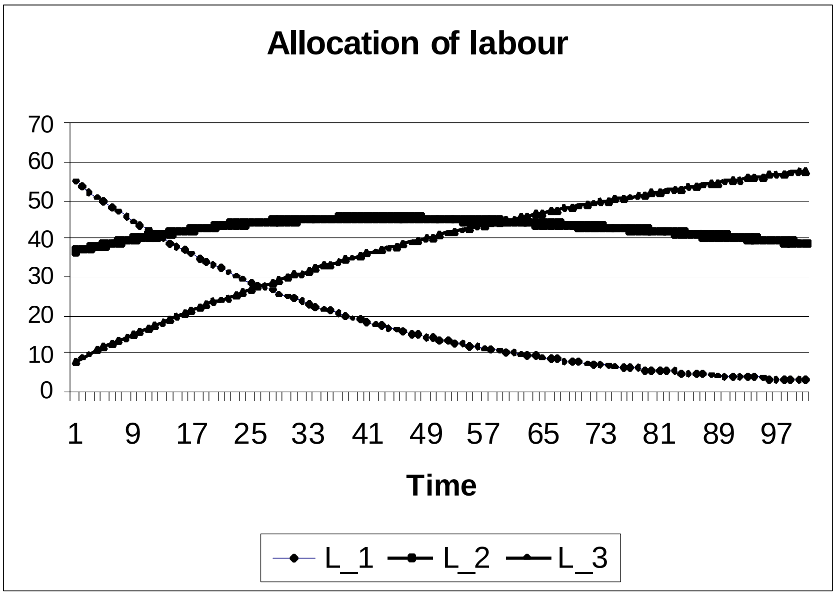
Table 3. Decomposition of emission growth (in annual percentage changes)

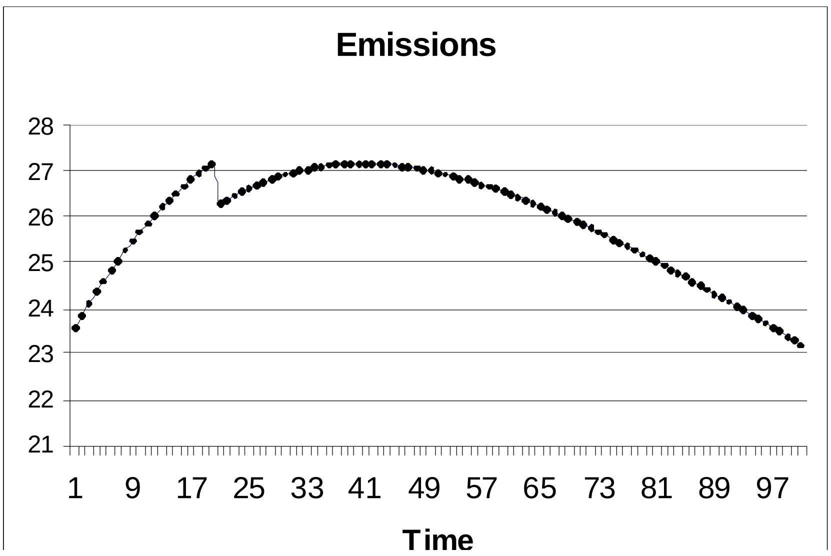
Period	1	10	50	100
2.5 % ANNUAL INCREASE IN RELATIVE PRICE OF EMISSIONS				
Emissions	+0.75	+0.31	-0.53	-0.80
Macro-growth (real)	+2.46	+1.92	+0.92	+0.62
Substitution	-0.49	-0.49	-0.49	-0.49
Productivity	-0.91	-0.86	-0.71	-0.59
Structural Change	-0.26	-0.23	-0.25	-0.33
RELATIVELY GOOD SUBSTITUTABILITY BETWEEN INPUTS (?=-2)				
Emissions	+0.43	+0.02	-0.76	-0.96
Macro-growth (real)	+2.38	+1.84	+0.84	+0.53
Substitution	-0.82	-0.82	-0.82	-0.82
Productivity	-0.83	-0.73	-0.54	-0.37

Structural Change	-0.26	-0.22	-0.23	-0.30

Finally, let us consider the case in which at some point in time an energy tax is imposed resulting in a once and for all increase in energy prices. Suppose, for example, that after 20 periods, the energy price once and for all increases with a percentage equal to the energy tax. The results for energy use will be clear after the discussion of the effects of an increase in energy-prices and are depicted in Figure 4; emissions will decline upon introduction of the energy-tax and continue to follow a similar path of development as before (due to the structural change), but at a lower level. This example reveals that the empirical finding of a temporary decline in emissions may be caused by the introduction of stricter environmental regulation. If the strictness is not increased over time, the path of emissions shows a similar development as compared to the no-policy case, but at a lower level. This analysis also reveals that the empirical finding of an N-shaped development of emissions may be caused by a once and for all increase in the strictness of environmental regulation (see Figure 4 left to the top of emissions). These policy measures can give some relief to environmental problems and will reduce the level of emissions (which is of course relevant for environmental quality), but they are unlikely to affect the direction of change of emissions. For this, technological progress has to be affected by the policy measures.

Figure 4. Introduction of tax on energy





5. Conclusion and evaluation

In this paper, we developed a theoretical multi-sector model that allowed us to simultaneously study the development of the sectoral composition of economies in terms of labor and output, and total (and sectoral) emissions in the economy. The model yields insights into the factors determining the shape of Income Emission Relationships. Total emissions are, ceteris paribus, negatively influenced by (i) decreased production, (ii) increased relative prices of emissions / energy, (iii) biased technological progress augmenting emissions in efficiency units, and (iv) shifts in the demand for goods toward less emission intensive goods. The paper deviates from and contributes to the existing theoretical literature in that it explicitly considers the potential of structural change as an explanatory factor for the occurrence of an EKC by developing a multi-sector model in which the sectoral composition of the economy is endogenously determined. It revealed that although changes in the sectoral composition may give some relief and may explain temporary declines in emissions, they are insufficient to persistently delink (real) income and emissions. For this, emission-saving measures either resulting from continuously increasing prices of emissions or emission saving technological progress are crucial. Future policies should hence focus on technological innovation, especially with respect to emission-saving technologies.

Of course, the theoretical model of this paper could be extended in several ways. Each extension would make the model more realistic, but at the expense of increased complexity and loss of insight in the mechanisms yielding a relationship between pollution and economic development. We will discuss here some interesting extentions that are beyond the scope of the current paper. First, we could endogenize the rates of (biased) technological progress. Secondly, we could explictly introduce an energy sector that provides the sectors producing consumption goods with intermediate inputs. Such an extension would allow for the endogenous determination of the price of energy and also the effects of resource depletion, etc. Thirdly, we could allow for trade in the model. This would allow us to consider the consequences of patterns of specialization that may drive a wedge between consumed and produced quantities for the shape of the ‘Income-Emission-Relationship’. Finally, we could further dig into the determination and consequences of various policy measures for the shape of the relatinship between emissions and per capita income. Although all these extentions are interesting in their own right, we think that they would not dramatically alter the mechanisms that result in a relation between pollution and economic development. Neither do we think that the patterns of development would essentially be altered by these extensions.

In most of the empirical research on the Environmental Kuznets Curve, most of the factors that were shown to be crucial in determining the shape of the Income-Emission Relationship have been left implicit. What is mostly studied is the relationship between some proxy for the state of the environment and (per capita) income. At best, a time trend has been included that is often found to be significant. A significant time trend is then often interpreted as technological progress. But as the analysis in this paper has revealed, it might as well be due to for example rising relative prices of emissions (or energy). Also stricter regulations of increased energy taxes may result in significant time trends. Further research will therefore be aimed at gathering empirical evidence at the lowest possible level of sectoral des-aggregation on the basis of which we will calibrate the model. Information is needed on substitution elasticities between goods from different sectors as well as between inputs in the production process, the development of sectoral employment and output shares, the development of sectoral emission intensities, and the development of ratios of energy to other inputs. This calibration of the model aimed at the replication of these patterns will yield empirical insight into the relevance of the factors identified in this paper that shape the IER.

Appendix A. Consumer behavior

The Lagrangian corresponding to the optimization problem of the representative consumer who maximizes his or her utility (equation (1)) subject to the budget constraint (equation (2)) reads as

$$\Lambda = \left[\sum_{i=1}^{S} a_i \left(C_i - \overline{C}_i \right)^r \right]^{1/r} + l \left(Y - \sum_{i=1}^{S} C_i P_{Ci} \right). \tag{A.1}$$

Taking derivatives results in

$$\frac{\partial \Lambda}{\partial C_i} = \frac{1}{r} \left[\sum_{i=1}^{S} a_i \left(C_i - \overline{C}_i \right)^r \right]^{\frac{1}{r}-1} r\, a_i \left(C_i - \overline{C}_i \right)^{r-1} - l\, P_{Ci} = 0 \quad \forall i = 1,\dots,S. \tag{A.2}$$

We can thus derive that

$$\frac{a_1 (C_1 - \overline{C}_1)^{r-1}}{P_{C1}} = \dots = \frac{a_i (C_i - \overline{C}_i)^{r-1}}{P_{Ci}} = \dots = \frac{a_S (C_S - \overline{C}_S)^{r-1}}{P_{CS}}. \tag{A.3}$$

Rewriting yields expenditures on good *j*

$$C_j P_{Cj} = P_{Cj} \overline{C}_j + P_{Cj} \left(\frac{P_{Cj}}{a_j} \right)^{\frac{1}{r-1}} \left(\frac{P_{Ci}}{a_i} \right)^{\frac{-1}{r-1}} \left(C_i - \overline{C}_i \right). \tag{A.4}$$

Substituting this expression into the budget constraint and rewriting yields Marshallian demand for good *i*

$$P_{Ci} C_i = P_{Ci} \overline{C}_i + P_{Ci} \left(\frac{P_{Ci}}{a_i} \right)^{\frac{1}{r-1}} \frac{\left[Y - \sum_{j=1}^{S} P_{Cj} \overline{C}_j \right]}{\sum_{j=1}^{S} P_{Cj} \left(\frac{P_{Cj}}{a_j} \right)^{\frac{1}{r-1}}}, \tag{A.5}$$

so that demand for goods from sector *i* can be written as

$$C_i = \overline{C}_i + \left(\frac{P_{Ci}}{a_i}\right)^{\frac{1}{r-1}} \frac{\left[Y - \sum_{j=1}^{S} P_{Cj}\overline{C}_j\right]}{\sum_{j=1}^{S} P_{Cj}\left(\frac{P_{Cj}}{a_j}\right)^{\frac{1}{r-1}}}. \tag{A.6}$$

The income elasticity of demand can be derived as

$$\frac{\partial C_i}{\partial Y}\frac{Y}{C_i} = \frac{Y}{\overline{C}_i \sum_{j=1}^{S} P_{Cj}\left(\frac{P_{Cj}}{P_{Ci}}\frac{a_i}{a_j}\right)^{\frac{1}{r-1}} + \left[Y - \sum_{j=1}^{S} P_{Cj}\overline{C}_j\right]}. \tag{A.7}$$

This expression reveals how sectoral demand changes if nominal income Y increases with one percent, keeping everything else constant. If there are no subsistence requirements, income elasticities are equal to one. The income elasticity of good *i* is larger when its subsistence requirement is smaller. A larger subsistence requirement of good *j* lowers the income elasticity of good *i*.

Appendix B. Producer behavior

The producer's maximization problem is

$$\max_{L_i, E_i} \pi = C_i P_{Ci} - P_L L_i - P_E E_i \tag{B.1}$$

The first-order conditions corresponding to this problem are

$$\frac{\partial \pi}{\partial L_i} = P_{Ci} \frac{1}{\sigma} [.]^{\frac{1}{\sigma}-1} \sigma \beta_{Li} \left(\eta_{Li} L_i\right)^{\sigma-1} \eta_{Li} - P_L = 0 \tag{B.2}$$

and

$$\frac{\partial \pi}{\partial E_i} = P_{Ci} \frac{1}{\sigma} [.]^{\frac{1}{\sigma}-1} \sigma \beta_{Ei} \left(\eta_{Ei} E_i\right)^{\sigma-1} \eta_{Ei} - P_E = 0 \tag{B.3}$$

Dividing these two first-order conditions yields equation (5) in the main text. Employing the zero-profit condition yields the price of the consumption good produced in sector *i*

$$P_{Ci} = \frac{P_L L_i + P_E E_i}{C_i} \tag{B.4}$$

Substitution of the equations (4), (5) and (11) yields P_{ci} as a function of prices and parameters of the model, as given in equation (7) in the main text.

Appendix C. Solution of the model

By combining equations (3), (6) and (12), we can derive that

$$L_i = \frac{\overline{C}_i}{B_i} + \left(B_j L_j - \overline{C}_j\right)\left(\frac{a_j P_{Ci}}{a_i P_{Cj}}\right)^{\frac{1}{r-1}} \text{ where } B_i = \left[b_{Li} h_{Li}^{s} + b_{Ei} h_{Ei}^{s} \left[\frac{b_{Ei} P_L h_{Ei}^{s}}{b_{Li} P_E h_{Li}^{s}}\right]^{\frac{s}{1-s}} \right]^{\frac{1}{s}} \quad \text{(C.1)}$$

Substituting this expression into the labor-market constraint and rewriting, we can derive the sectoral allocation of labor as

$$L_j = \frac{\overline{C}_j}{B_j} + \frac{L - \sum_{i=1}^{S} \frac{\overline{C}_i}{B_i}}{B_j \left(\frac{a_j}{P_{Cj}}\right)^{\frac{1}{r-1}} \sum_{i=1}^{S} \frac{1}{B_i} \left(\frac{P_{Ci}}{a_i}\right)^{\frac{1}{r-1}}} \quad \text{(C.2)}$$

showing that the sectoral allocation of labor equals the amount of labor required to produce subsistence requirement plus a weighted average of the amount of labor that is left after subsistence requirements of all goods have been produced.

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