Environment and Economic Growth: Is Technical Change the Key to Decoupling?

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Summary

The relationship between economic growth and pollution is very complex, depending upon a host of different factors. Thus the study of this phenomenon represents a challenging endeavor. While most economics papers begin with theory and support that theory with econometric evidence, the literature on Environmental Kuznets Curves has proceeded in the opposite direction: first developing an empirical observation about the world, and then attempting to supply appropriate theories. A number of papers have aimed at providing the theoretical underpinnings to the Environmental Kuznets Curve. Prominent here is the class of optimal growth models. These are usually studied from the point of view of the analytical conditions that must hold in order to obtain an inverted-U functional relationship between pollution and growth. These models are however seldom confronted with the data. In this paper we take one popular optimal growth model designed for climate change policy analysis and carry out a few simulation exercises with the purpose of characterizing the relationship between economic growth and emissions. In particular, we try to assess the relative contribution of the ingredients of the well-known decomposition of the environment-growth relationship put forth by Grossman (1995): according to it, the presumed inverted-U pattern results from the joint effect of scale, composition, and technology components. We do this focusing on the developed regions of the world and on a global pollutant, CO2 emissions.

Keywords: Climate Policy, Environmental Modeling, Integrated Assessment, Technical Change

JEL: H0, H2, H3

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1. Introduction

The relationship between economic development and environmental quality is the subject of a long-standing debate. Precisely thirty years ago a number of respected scholars, mostly social and physical scientists, attracted the public attention to the growing concern that the economic expansion of the world economy will cause irreparable damage to our planet. That concern stems from two rather intuitive concepts: first, more output requires more inputs so that the earth's natural resources (including exhaustible energy sources) will be quickly depleted; second, more output causes more emissions and waste: the earth could soon exceed the carrying capacity of the biosphere. In the famous volume *The Limits to Growth* (Meadows, Meadows, Randers, and Behrens, 1972), the members of the Club of Rome ventilated the necessity that, in order to save the environment and even the economic activity from itself, economic growth cease and the world make a transition to a steady-state economy (see Ekins, 2000, for a more thorough discussion of this position).

In the last decade the economists' view about the relationship between economic growth and environmental quality has prevailed: increase in the former does not necessarily mean deterioration of the latter; in current jargon, a de-coupling or de-linking is possible, at least after certain levels of income. This is the basic tenet at the heart of the so-called Environmental Kuznets Curve (EKC henceforth), the empirical reduced-form relationship that has been widely investigated in the last ten years.[1]

A spat of initial influential studies, Grossman and Krueger (1993, 1995), Shafik and Bandyopadhyay (1992), Panayotou (1993), Shafik (1994), Selden and Song (1994) identified, mostly in the case of local air and water pollutants, a bell shaped curve for the pollution-GDP curve. This behavior implies that, starting from low per capita income levels, per capita emissions or concentrations tend to increase but at a slower pace. After a certain level of income (which typically differs across pollutants) – the "turning point" – emissions or concentrations start to decline as income further increases. It must be said that in the case of global pollutants like CO_2 the evidence is less clear-cut.

Although appealing to many – policy makers, politicians, scholars, sectors of the public opinion – the main problem with the EKC is its reduced form nature. Being based on no firm theoretical basis, the EKC is ill-suited for drawing policy implications. The inverted-U relationship between economic growth and the environment cannot be simply exported to different institutional contexts, to different countries with different degrees of economic development, not even to different pollutants.

The consideration just made represents the motivation underlying the crop of recent papers aiming at the study of the EKC relationship from a theoretical viewpoint. What these studies basically do is to lay out a theoretical model and derive the implied relationship linking GDP growth to pollution. On this basis they then study the analytical conditions on key model parameters that ensure an inverted-U shape.

Various types of theoretical models can be employed for such endeavor, from very simple to quite complex ones. However, it appears that, given the phenomenon under scrutiny, growth models – specifically, optimal growth models – are the natural candidate for the purpose. While there is no lack of growth models with pollution designed for this task in the literature,

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[1] Many empirical investigations on the EKC have been conducted, as well as a limited number of theoretical studies attempting a rationalization of the inverted-U pattern. By now also an increasing number of survey papers have appeared, including a companion paper to the present one (Galeotti, 2002).

surprisingly no one has been confronted with actual data.[2] At the same time, the literature dealing with climate change has proposed a number of models which can be simulated in order to gain insights on the problem and its economic implications, but no one appears to have been put to study explicitly the environment–development nexus from the EKC perspective.

This is the tack of the present chapter. We first consider the conceptual basis offered for econometrically estimated EKCs. A fundamental and well-known decomposition attributes the resulting inverted-U pattern to the joint working of a scale, a technical, and a composition effect. We present this in Section 2. In Section 3 we provide a short overview of theoretical work on EKCs. We next describe one of the most popular models for climate change analysis. There we emphasize the importance of technical change. In Section 5 we simulate such model to assess its properties in terms of the growth-environment relationship. Moreover, we focus in particular on CO_2 and on developed countries. Concluding comments close the paper.

2. Conceptual Aspects of the Environmental Kuznets Curve

Far from being provided with theoretical underpinnings, the inverted-U Environmental Kuznets Curve has been rationalized with reference to a few alternative, possibly competing explanations. These are the so-called "stage of growth" hypothesis, the role of technical progress, and the role of environmental quality being a luxury good for individuals (see Galeotti, 2002).

The conceptual basis of the EKC has been identified in three effects jointly at work. Grossman (1995) first proposed to distinguish three main channels through which economic growth affects the environment. Firstly, there is a *scale effect*: a larger scale of economic activity leads per se to increased environmental degradation. This occurs because increasing output requires that more inputs and thus more natural resources are used up in the production process. In addition, more output also implies increased wastes and emissions as by-product of the economic activity, which contributes to worsen the environmental quality. If the scale effect has negative implications for the environment, a positive impact is associated with a *composition effect*: as income grows, the structure of the economy changes, with a gradually increasing share of cleaner activities in GDP. Finally, technological progress often occurs with economic growth since a wealthier country can afford to spend more on research and development. This generally leads to the substitution of obsolete and dirty technologies with cleaner ones, which also improves the quality of the environment. This is known as the *technique effect* of growth on the environment. Technical change is not however per se always environment-friendly, as it can lead to the emergence of new sectors and industries with new kinds and degrees of pollution problems, like the generation of new harmful pollutants.

An inverted-U relationship between environmental degradation and per capita income suggests that the negative impact on the environment of the scale effect tends to prevail in the initial stages of growth, but that it will eventually be outweighed by the positive impact of the composition and technique effects that tend to lower the emission level.

The above considerations can be also put in a more formal way. Following Panayotou (2000), emissions (E) in period t in a country are given by the following identity:

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[2] An exception is given by Ansuategi and Escapa (2002), who use a numerically calibrated overlapping generations model of climate-economy interactions for EKC analysis.

$$\begin{aligned} E_t &= \sum_{j=1}^{n} Y_t \left(\frac{E_{jt}}{Y_{jt}}\right)\left(\frac{Y_{jt}}{Y_t}\right) \\ &= \sum_{j=1}^{n} Y_t \cdot I_{jt} \cdot S_{jt} \end{aligned} \qquad j=1,2,\ldots,n \tag{1}$$

where Y_t is GDP, E_{jt} is emissions from sector j and Y_{jt} is sectoral GDP or value added. The ratio $I_{jt}=E_{jt} / Y_{jt}$ is j-th sector emission intensity and $S_{jt}=Y_{jt} / Y_t$ is the share of j-th sector GDP in total economy GDP. Differentiating equation (1) with respect to time and dividing the derivatives by E_t, we obtain Grossman (1995)'s decomposition equation:

$$\frac{\dot{E}_t}{E_t} = \frac{\dot{Y}_t}{Y_t} + \sum_{j=1}^{n} e_{jt} \frac{\dot{S}_{jt}}{S_{jt}} + \sum_{j=1}^{n} e_{jt} \frac{\dot{I}_{jt}}{I_{jt}} \tag{2}$$

where e_{jt} is j-th sector share of emissions in total emissions (i.e. $e_{jt} = E_{jt} / E_t$) and where a dot over a variable denotes time differentiation. The first term on the right-hand side of (2) reflects the "scale effect", the second term the "composition effect" effect and the third term the "technological change effect." A discrete approximation of the Grossman decomposition equation was tested by de Bruyn (1997) for commercial SO_2 emissions during 1980-90 for West Germany and the Netherlands. The author found that technological change explained most of the reduction in those emissions, while structural change had little effect. This should not be surprising since both these countries are developed economies having undergone most of these structural changes prior to 1980. In contrast, there has been considerable technical change during the period especially in the form of policy-induced installation of end-of-the pipe abatement technology and more modest progress in terms of fuel substitution and use of more energy efficient technologies.

3. Theoretical Work on the Environmental Kuznets Curve

As noted by Panayotou (2000) and Levinson (2001), the EKC literature consists of two distinct but related areas of research: an empirical strand – the majority - of mostly ad hoc specifications and estimation of a reduced form equation relating an environmental indicator to income per capita and a theoretical strand of models of the interaction between environmental degradation and economic growth. The latter includes optimal growth, endogenous growth and overlapping generations models. As documented in the previous section, the empirical models are built on heuristic theory or resort to ex post theoretical justifications of their findings rather than ex ante formal derivations from optimizing behavior or other theoretical constructs. At the same time, with a few exceptions, the results of theoretical models have not been subjected to rigorous empirical testing, but they are broadly consistent with the findings of the empirical literature.

Panayotou (2000) gives a succinct overview of the theoretical contributions to the study of the interplay between environment and economic growth. According to the author they can be divided into four major categories: (i) optimal growth models; (ii) models in which the environment (rather than pollution) is a factor of production, (iii) endogenous growth models; and (iv) other macroeconomic models of growth and the environment. In particular:

- *Optimal growth models* build on the Ramsey-Koopmans-Cass framework. These are dynamic optimization models in which the utility maximization problem of the infinitely lived consumer is solved using the techniques of optimal control theory. Either the stock or

the flow of pollution is an argument of both the production function and the utility function of the representative consumer. Most of these models support the Environmental Kuznets Curve that has been found empirically. Examples of this group are Tahvonen and Kuuluvainen (1994), Selden and Song (1995), and Stokey (1998).
- *Models of the environment as a factor of production* include not only pollution as an argument of production and utility functions, but the environment itself. This may be interpreted as the stock of natural capital that the economy is endowed with or as the aggregate level of environmental quality. In these models property rights are decisive in determining whether environmental degradation eventually declines with growth. Examples of this group are Lopez (1994) and Chichilinsky (1994).
- *Endogenous growth models* relax the neoclassical specification of the production function assumed in the optimal growth models. Production functions in these models are of the Romer's type, that is they are characterized by increasing returns to scale and spillover effects. Tightening pollution standards with economic growth is optimal in these models. Examples of this group are Lighthard and van der Ploeg (1994), Bovenberg and Smulders (1995, 1996), and Stokey (1998).
- *Other macroeconomic models* include Diamond-type overlapping generation models. These models add support to the results of the optimal growth models and suggest that their results may be arrived at in other contexts as well. Examples are John and Pecchenino (1994) and Jones and Manuelli (2000). In this residual category we can also include simple static models like the one outlined by Stokey (1998) and the Robinson Crusoe – static, one good, one person, one period – model of Andreoni and Levinson (2001).

Much like econometrically estimated reduced form EKCs lack a firm theoretical basis, the above theoretical models have not been, to our knowledge, confronted with the data. It is therefore difficult to discern among competing classes of theoretical models and select the most realistic ones. Models of optimal growth are however prominent in a related area of environmental economics: the study of the impacts of climate change and of the corresponding mitigation policies. This field has seen its relevance increase after the discussion on global warming and the proposed international agreements (most notably the Kyoto Protocol) designed to cope with it. Models in this area are typically simulated over a number of future periods on the basis of actual data for a specific year and of parameters that are calibrated to existing estimates. Climate models usually deal with greenhouse gasses, chiefly carbon dioxide, a global pollutant. We know that in this case inverted-U EKCs are more difficult to identify. The reason lies in the global nature of such pollutant, which involves cross-border externalities, so that no one country has sufficient incentive to regulate emissions. The free rider problem may simply be more troublesome with carbon than any other pollutant. The evidence is however mixed (see Schmalensee, Stoker, and Judson, 1998; Galeotti and Lanza, 2002).

It is of interest to analyze what climate change optimal growth models imply for the relationship between growth and the environment. In particular, it would be interesting to try to assess the relative role of individual effects, scale and technology, identified by Grossman (1995). These simulated models are among the few tools that lend themselves to such a purpose. We therefore turn to consider one of the most popular climate models.

4. A Popular Optimal Growth Model for the Study of Climate Change

Nordhaus's RICE is a well-known regional dynamic general equilibrium model for the study of the economic aspects of climate change (Nordhaus and Yang, 1996). It is basically a single sector optimal growth model suitably extended to incorporate the interactions between economic activities and climate. There is one such model for each of the six macro regions into which the world is divided: USA, Japan, Europe, Former Soviet Union (FSU), China, and Rest of the World.

Within each region a central planner chooses the optimal paths of fixed investment and of rate of pollution abatement that maximize the present value of per capita consumption. The value added created via production (net of climate change) is used for investment and consumption and is produced according to a constant returns Cobb-Douglas technology, which combines the inputs from capital and labor with the level of technology. Population (taken to be equal to full employment) and technology levels grow over time in an exogenous fashion, whereas capital accumulation is governed by the optimal rate of investment.

As for climate, CO_2 emissions are generated by output production. More specifically, emissions are equal to unabated output times a carbon intensity parameter that changes exogenously over a given time path. Emissions cumulate into carbon concentration which in turn produce an increase in temperature. The climate feeds back into the economy through a wedge between output produced and output available for consumption and investment: the damage function depends upon the temperature of the planet.

While very popular, the RICE model – like many other such tools – is characterized by a process of technical change that is exogenous to the model itself. This is not very convenient in general, and is not useful for the scope of the present paper.[3]

In previous work we modified and extended the RICE model so as to allow for both endogenous and induced technical change (Buonanno, Carraro, Castelnuovo, and Galeotti, 2000, 2001; Buonanno, Carraro, and Galeotti, 2003). In particular, in that model – termed ETC-RICE – it was assumed that R&D investment accumulates into a stock of knowledge that affects both the production technology (endogenous technical change) and the emission-output ratio (induced technical change) (see also Nordhaus, 2002). Thus, the idea is that more knowledge will help firms increase their productivity and reduce their negative impact on the environment. In this modified version, the central planner in each country chooses also the optimal R&D effort that, in turn, increases the stock of technological knowledge. The amount of R&D is therefore a policy variable envisaged by the model.

More recently, Castelnuovo, Galeotti, Gambarelli, and Vergalli (2002) proposed an alternative formulation of the same model that allows for an alternative source of technical change, Learning by Doing (LbD). In particular, it is supposed that the accumulation of knowledge occurs not as a result of deliberate (R&D) efforts, but as a side effect of conventional economic activity. In this extension of the RICE model, the authors model LdB in a simple way, by assuming that learning occurs as a side effect of the accumulation of new physical capital. This entails a production function that exhibits increasing returns to capital. In order to maintain the analogy with the R&D-based version of the model we also allow for the emission-output ratio to depend upon cumulated capacity, i.e. the sum of past physical investment efforts. It should be apparent that these model specifications make explicit reference to the recently developed theory of endogenous growth that emphasizes the role of knowledge, of physical and human capital, R&D activities, and LbD.

4.1 Essential Elements of the Model: "Red Technical Change"

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[3] Among others, see Löschel (2001) for a survey of the role of technological change in economic models of environmental policy.

To start with, we consider the specification of the model which only allows for endogenous technical change, i.e. the case in which knowledge affects only factor productivity. We will refer to this case as “*red technical change*”. In the case in which innovation is brought about by R&D spending, it is assumed that the stock of knowledge is a factor of production, which enters a country production technology along with physical capital and labor. Knowledge therefore enhances the rate of productivity. The RICE production function is as follows:

$$Q(n,t) = A(n,t) K_R(n,t)^{\beta_n^R} \left[L(n,t)^{\gamma} K_F(n,t)^{1-\gamma} \right] \tag{1a}$$

where Q is output (gross of climate change effects), A the exogenously given level of technology and K_R, L and K_F are respectively the inputs from knowledge capital, labor and physical capital (n and t index time and country respectively), γ and β^R are parameters. The stock of knowledge accumulates as follows:

$$K_R(n,t+1) = R\,\&\,D(n,t) + (1-\delta_R) K_R(n,t) \tag{2}$$

where $R\&D$ are expenditures in Research and Development and δ_R is the rate of knowledge depreciation. Finally, $R\&D$ spending is included in the fundamental identity of sources and uses:

$$Y(n,t) = C(n,t) + I(n,t) + R\,\&\,D(n,t) \tag{3a}$$

where C is consumption, I gross fixed capital formation and Y is output net of climate change effects, in accordance with the following expression:

$$Y(n,t) = \Omega(n,t) Q(n,t) \tag{4}$$

with Ω being an output scaling factor that captures emissions controls and damages from climate change via increases in temperature.[4]

In the case of Learning by Doing equation (1a) has to be modified in a manner that enables a rise in productivity due to physical capital (installed capacity), without the contribution of K_R in the production function. It is possible to formalise this idea by simply modifying the Cobb-Douglas coefficients, so that returns to scale result to be increasing, given the augmented capital-output elasticity. Thus, equation (1a) is modified as follows:

$$Q(n,t) = A(n,t) \left[L(n,t)^{1-\gamma} K_F(n,t)^{\gamma} \right] K_F^{\beta^L} = A(n,t) \left[L(n,t)^{1-\gamma} K_F(n,t)^{\gamma+\beta^L} \right] \tag{1b}$$

where β^L can be referred to as the learning-by-doing coefficient. With LbD equation (2) is missing in this version of the model and equation (3a) reverts back to its original formulation in the RICE model:

$$Y(n,t) = C(n,t) + I(n,t) \tag{3b}$$

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[4] The precise formulation of the damage function is reported in the appendix. One could suitably modify this function in order for the model to reproduce a bell-shaped EKC. We do not do this, as we modify Nordhaus’ original model version only in those respects that are crucial for rationalizing the EKC, that is technical change and regulation.

This implies that, under the LbD approach, knowledge creation does not place any claim on resources, *ceteris paribus.*

4.2 Essential Elements of the Model: "Green Technical Change"

As said above, besides affecting factor productivity, knowledge influences also the emissions-output ratio. We refer to this case as "*green technical change*". Following the R&D approach, it is assumed that the stock of knowledge, besides being a factor of production, also serves the purpose of reducing, *ceteris paribus,* the level of carbon emissions. Thus, R&D efforts prompt both environmental and non-environmental technical progress. More precisely, consider the RICE emissions-output relationship, whose original version is as follows:

$$E(n,t) = [1-\mu(n,t)]\sigma(n,t)Q(n,t), \qquad 0 \le \mu(n,t) \le 1 \tag{5}$$

where μ is the domestic abatement rate and σ is the exogenously given emissions-output ratio. Accounting for induced technical change, (5) is modified as follows:

$$E(n,t) = \left[\sigma_n + \chi_n^R \exp\left(-\alpha_n^R K_R(n,t)\right)\right][1-\mu(n,t)]Q(n,t) \tag{5a}$$

where α_n^R is the region-specific elasticity through which knowledge reduces the emission-output ratio, χ_n^R is a scaling coefficient, and σ_n is the value to which the emission-output ratio tends asymptotically as the stock of knowledge increases without limit. In this formulation, R&D contributes to output productivity on the one hand, and affects the emissions-output ratio, and therefore the overall level of pollution emissions, on the other hand.[5]

With a LbD-based knowledge accumulation, equation (5a) is simply replaced by the following:

$$E(n,t) = \left[\sigma_n + \chi_n^L \exp\left(-\alpha_n^L K_F(n,t)\right)\right][1-\mu(n,t)]Q(n,t) \tag{5b}$$

where we substitute knowledge capital with physical capital. Hence, physical capital covers the role that knowledge capital has in the R&D approach, i.e. K_F contributes to output productivity on the one hand, and affects the emissions-output ratio, and therefore the overall level of pollution emissions, on the other hand.

4.3 Essential Elements of the Model: Regulation via Emission Trading

The model provides for two forms of environmental regulation for each region. One is the rate of pollution abatement, which is however one of the choice variables of the model and as such difficult to switch on and off without fundamentally altering the working of the model. The other possibility is the imposition of an exogenous ceiling to emissions. However, this case would not be very informative because, as a country grows, it sooner or later reaches the limit after which income may increase but emissions do not. The shape of the income-pollution relationship would not be interesting to study. As an alternative, we can think of imposing an upper limit to *world* emissions that cannot be overcome, and assigning region-specific limits which however may or may not be exceeded by interregional trade of rights to emit. This type

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[5] Of course R&D efforts may or may not be successful in producing a commercially viable innovation. No account is taken in this model of the uncertainty surrounding that process. Sensitivity analysis with respect to the relevant parameters ought to be carried out, but this is beyond the scope of the present paper.

of regulation is precisely what is implied by the Kyoto Protocol when use is made of international emission trading, its main flexibility mechanism. In this way, we can switch on and off the possibility of trading.

Going back to the model specification, when considering emission trading, two additional equations have to be included. The first one accounts for the new burden that emissions permits represent in the fundamental sources and uses identity. Hence, equations (3a) and (3b) have to be respectively replaced by the following:

$$Y(n,t) = C(n,t) + I(n,t) + R\&D(n,t) + p(t)NIP(n,t) \tag{6a}$$

$$Y(n,t) = C(n,t) + I(n,t) + p(t)NIP(n,t) \tag{6b}$$

In addition, equation (7) states that the Kyoto limits can be relaxed in the case of emission trading:

$$E(n,t) \leq Kyoto(n) + NIP(n,t) \tag{7}$$

The variable *NIP* represents the net demand for permits, while *Kyoto* is the emission target set in the Kyoto Protocol for each one of the signatory countries and the BAU (Business As Usual) levels for the non-signatory ones. According to (6a) and (6b), resources produced by the economy must be devoted, in addition to consumption, investment and, in (6a), research and development, to net purchases of emission permits. Equation (7) states that a region's emissions may exceed the limit set in Kyoto if permits are bought, and vice versa in the case of sales of permits. Note that *p(t)* is the price of a unit of tradable emission permits expressed in terms of the *numeraire* output price. Moreover, there is an additional policy variable to be considered in this case, which is net demand for permits *NI*P.

Under the possibility of emission trading, the sequence whereby a Nash equilibrium is reached can be described as follows. Each region maximises its utility subject to the individual resource and capital constraints, now including the Kyoto constraint, and the climate module for a given emission (i.e. abatement) strategy of all the other players and a given price of permits *p(t)* (in the first round this is set at an arbitrary level). When all regions have made their optimal choices, the overall net demand for permits is computed at that given price. If the sum of net demands in each period is approximately zero, a Nash equilibrium is obtained; otherwise the price is revised as a function of the market disequilibrium and each region's decision process starts again.[6]

5. Simulating the Environment-Growth Relationship

In this section we are interested in understanding the EKC implications of the climate model described above. In addition, the ability of controlling the model structure allows us to isolate individual effects, to turn on and off some relevant feature of the model, and carry out the associated simulations. In this way we can run some counterfactual exercises in order to assess the relevance of some of the factors determining the shape of the EKC.

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[6] The appendix reports the remaining equations that make up the full model.

We carry out the present exercise for the case of carbon dioxide. This is the greenhouse pollutant entertained by the RICE model. Both early and recent studies find that emissions of global pollutants - such as carbon dioxide (CO_2) - either monotonically increase with income or start declining at income levels well beyond the observed range. The inability of finding a bell shaped relationship lies in the global nature of such pollutant, which involves cross-border externalities, so that no one country has sufficient incentive to regulate emissions. The free rider problem may simply be more troublesome with carbon than with any other pollutant.

In the present case we limit our attention to the developed regions of the world considered in the RICE model, and precisely USA, Japan, and Europe. In addition, we present results also for another region, the Former Soviet Union (Russia and Eastern European countries), on the grounds that countries in this group belong to the so-called Annex B countries of the Kyoto Protocol. The reason why we concentrate on developed countries is because Grossman's decomposition of the EKC applies primarily to the developed world. In this part of the world we can reasonably presume that scale, technology, and composition effects have played, partly if not fully, their role.

The simulation period runs from 2000 to 2100. In order to analyze aspects of the EKC curve in developed countries, consider the following four effects determining the curve:

- a "*green technology effect*", which ceteris paribus ought to decrease pollution;
- a "*scale effect*", which ceteris paribus leads to an increase in emissions;
- a "*composition effect*", which should produce a decrease in pollution;
- a *"regulation effect"*, which should contain emissions.

In RICE the consumer has access to only a single produced good. Therefore the model is not suited for assessing the role of the composition effect. We can however run counterfactual simulations in which we suppress the role of environment-friendly "green" technical progress in all countries in every period and analyze scenarios in which regulation in the form of a ceiling to emissions is imposed together with the possibility of emission trading.[7]

The scenarios we consider are presented in Table 1.

Table 1: Alternative Scenarios for EKC Analysis

Scenario	Environment-friendly Technical Change	Regulation
No green technical progress No regulation	$\sigma_n = 1; \chi_n = 0$	Business-As-Usual (BAU) scenario
Green technical progress No regulation	R&D-based: model equation (5a) LbD-based: model equation (5b)	BAU scenario
No green technical progress Regulation	$\sigma_n = 1; \chi_n = 0$	Kyoto forever Annex B Trading
Green technical progress	R&D-based: model equation (5a)	Kyoto forever

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[7] The role of Grossman's effect is also investigated within the context of a computable general equilibrium model for Norway by Bruvoll, Fæhn, and Strøm (2002).

Regulation	LbD-based: model equation (5b)	Annex B Trading

The next four graphs present the results of the simulations for the scenarios outlined above separately for the four regions we consider. We present evidence for the income vs. emissions per capita.[8]

Figure 1 considers the evolution of the world regions as described by the model when there is no upper limit to emissions and no endogenous "green" technical change operates in order to reduce the rate at which the unabated portion of output translates into emissions (equation (5) above). We have already noted that a single good model like the present one cannot properly account for the "stages of growth" explanations of bell-shaped EKC: the transition to different economic phases characterized by a different composition of output. Moreover, "red" technical change is active: R&D is undertaken or experience is built up in order to enhance the rate of output productivity which – *ceteris paribus* – produces harmful emissions. The results are in line with expectations: in the absence of green technical progress and regulation the environment-income relationship is monotonically increasing. Note that the world regions undertake some pollution abatement, but the incentives to do it in substantial amounts – absent any limitations to emissions generation – are extremely small. Note that our simulation show essentially no differences across the forms of green technical change (R&D vs LbD), and the steeper curve is that of the FSU followed by the USA, Europe and Japan.

How do the above results change when we allow for endogenous green technical change? Regions now undertake optimally R&D efforts both for productivity enhancement but also for emission reduction, in addition to pollution abatement. Alternatively, not only does the past fixed investment activity increases output capacity but also contributes to increase experience which translates into a higher fixed capital (marginal) productivity. Countries are still unconstrained in the amount of emissions they can discharge into the atmosphere. And it is this fact that explains the trend in Figure 2, where we allow for endogenous "green" technical change but do not impose emission limits. Though less steep, the EKCs portrayed are still positively sloped and linear, with the significant exception of the Former Soviet Union in which case a clear concave shape emerges. Again, there are no differences across R&D and LbD formulations, but the amount of emissions is now halved relative to that of the previous case.

The trend of the income-pollution relationship changes significantly when we allow for emission limits together with possibility of trading while switching off the source of environment-friendly technical change. Remarkably, Figure 3 shows that regulation turns the EKC relationship from positively to negatively sloped in the case of FSU and USA. While it is not easy to rationalize the decisively decreasing tendency of the FSU, the USA relationship after an initial reduction appears to stabilize. The emission-income line of Japan and Europe is instead still increasing but a slower pace than before. Finally, the level of emissions is lower than in the previous two cases.

The final experiment is when we simulate the model enacting the emission trading market under the Kyoto Protocol and activating the process of endogenous technical change. This is done in Figure 4. Emissions per unit of income are no longer increasing but stabilize in the case of Europe and Japan. The USA seems to converge to the same level of pollution of the previous two regions. The FSU shows a decreasing but concave trend, suggesting also in this case a stabilization in per capita emissions toward the end of the simulation period.

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[8] Income and output are expressed in trillions of 1990 U.S. dollars, population in millions, emissions and energy consumption in Giga tons of carbon.

Before closing this section two final remarks, that apply to all simulations presented above, are in order. They both can be traced to the structure of the climate model employed. Firstly, notice that the model does not suggest significant differences as to the emission-output relationship between a R&D and a LbD formulation of endogenous technical change. In terms of the amount of emissions, some quantitative difference shows up only in the last and the only realistic simulation. Secondly, in all simulations Japan appears to grow more than all other regions, including the USA. Realism aside, this is probably due to the fact the USA "pay a higher price" for polluting in terms of economic growth in the model used here.

6. Conclusions

The literature on the Environmental Kuznets Curve describing the relationship between income and environment has developed through empirical contributions rather than by theoretical advances. Several papers have often referred to Grossman (1995)'s decomposition of the environment-growth relationship that identifies a scale, a composition, and a technology effect to explain the inverted-U pattern. More recently, a number of papers have provided theoretical underpinnings to the Environmental Kuznets Curve. Prominent here is the class of optimal growth models. These are usually studied from the point of view of the analytical conditions that must hold in order to obtain an inverted-U functional relationship between pollution and growth. These models are however seldom confronted with the data.

Optimal growth models are a fundamental tool of analysis in a related area of environmental economics: the study of climate change impacts and mitigation policies. These models are routinely simulated on the basis of actual data and calibrated parameters for scenario analysis and policy experiments.

In this paper we have taken one popular climate model, based on Nordhaus's RICE model, crucially highlighting the role of endogenous technical change. We have used it to run a number of simulations relevant for the purpose of characterizing the relationship between economic growth and emissions. In particular, in the light of Grossman's decomposition, we have considered the relative role of scale, environment-friendly technology, and of environmental regulation on the income-emissions nexus, as well as GNP growth and carbon energy consumption. This is a novel exercise that adds to the understanding of the environment-income relationship, on the one hand, and to the comprehension of the structure and working of current climate change models, on the other.

On the whole, the RICE model does not produce an inverted-U relationship between per capita CO_2 pollution and income. It does however deliver a few useful messages. Firstly, emissions strongly increase when the world's regions are "unregulated" and technical change is productivity enhancing. Secondly, a positive effect of "green" technical change is discernible in the sense that changes in the emission intensity over time induce a reduction in the positive slope of the environment-income relationship, but not enough to turn it negative. Only when regulation in the form of emission limits together with the possibility of emission trading is introduced, do economic growth and harmful emissions tend to be decoupled. We believe this to be an important policy message.

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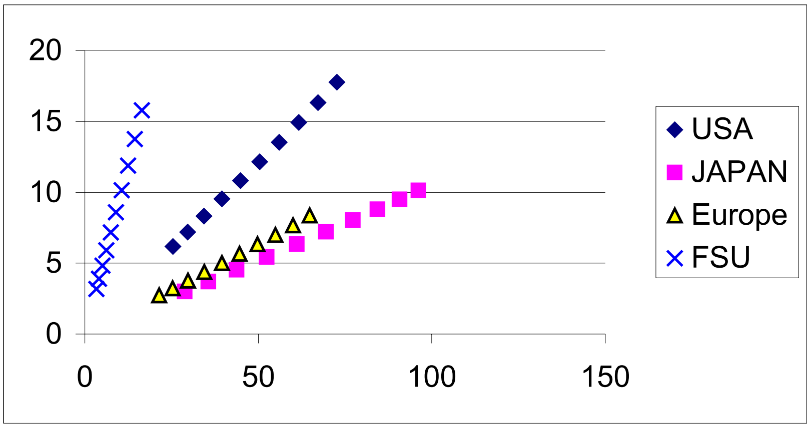
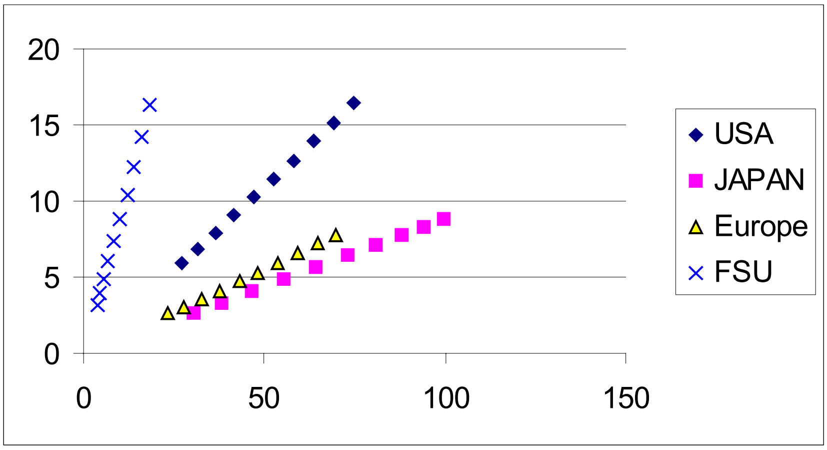
Figure 1: Model Simulations of Per Capita CO_2 Emissions vs Per Capita Income
The Case with No Green Technical Progress, No Regulation

(a) R&D-based Model Version



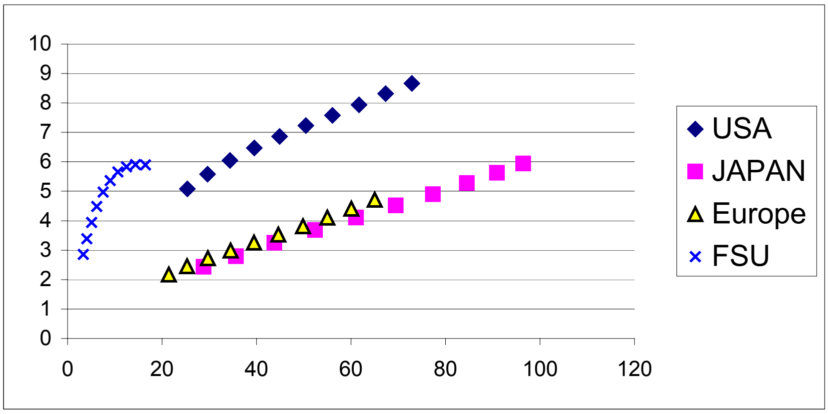
(b) LbD-based Model Version



Note to the Figures: Income is expressed in trillions of 1990 U.S. dollars, population in millions, emissions in Gigatons of carbon. Per capita emissions are measured on the vertical axis, income per capita on the horizontal axis.

Figure 2: Model Simulations of Per Capita CO_2 Emissions vs Per Capita Income
The Case with Green Technical Progress No Regulation

(a) R&D-based Model Version



(b) LbD-based Model Version

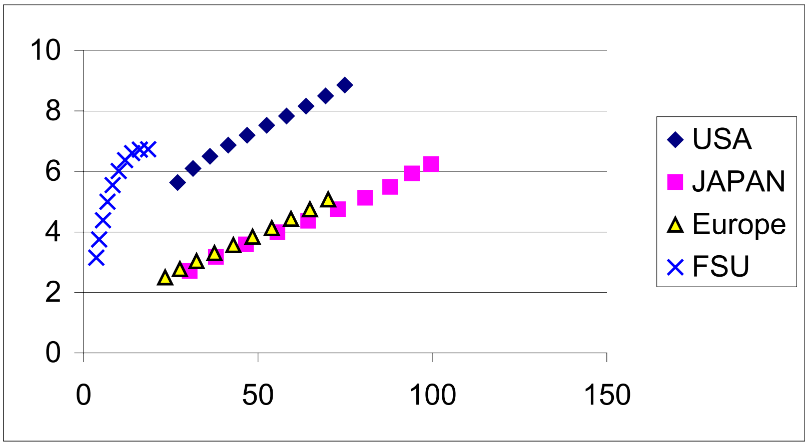
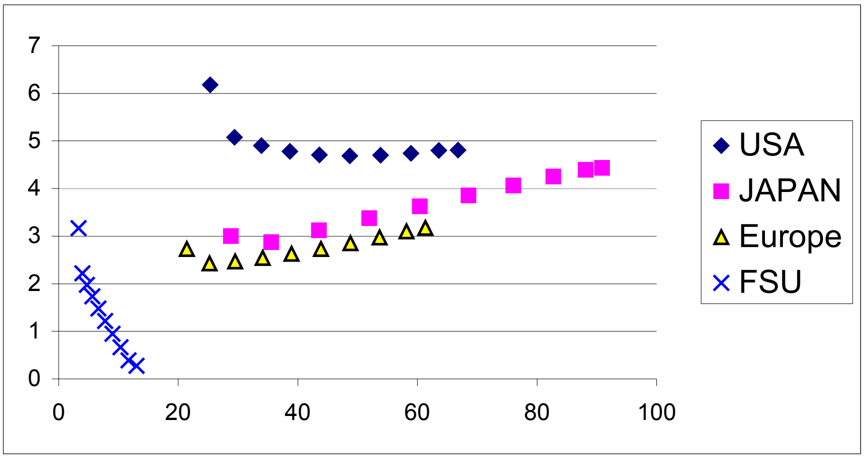


Figure 3: Model Simulations of Per Capita CO_2 Emissions vs Per Capita Income
The Case with Regulation, No Green Technical Progress

(a) R&D-based Model Version



(b) LbD-based Model Version

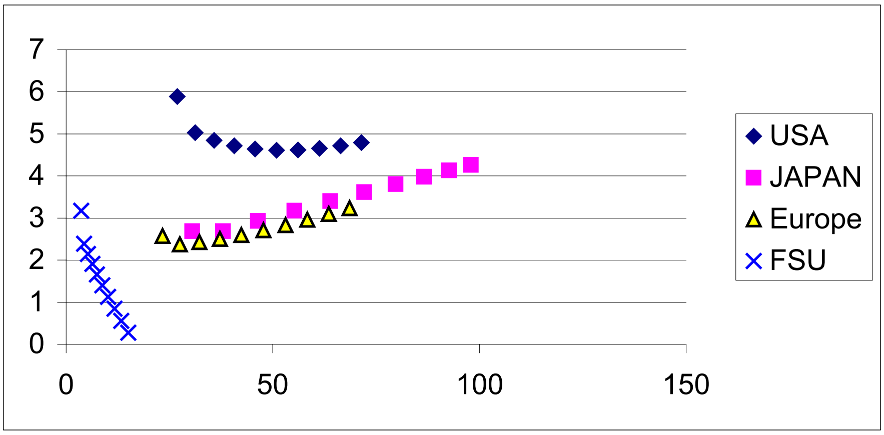
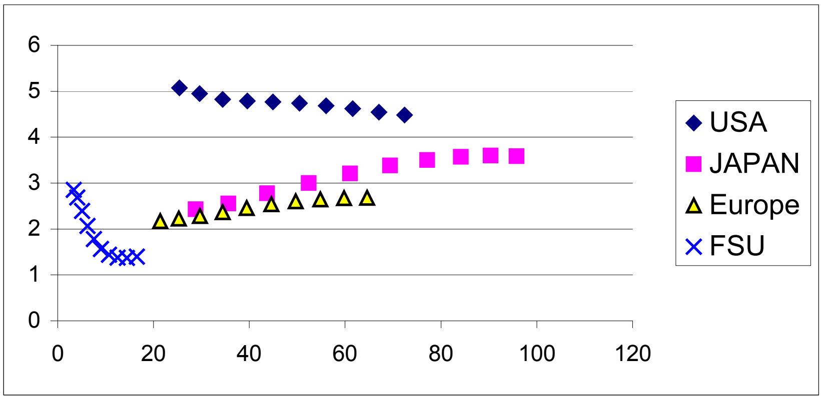
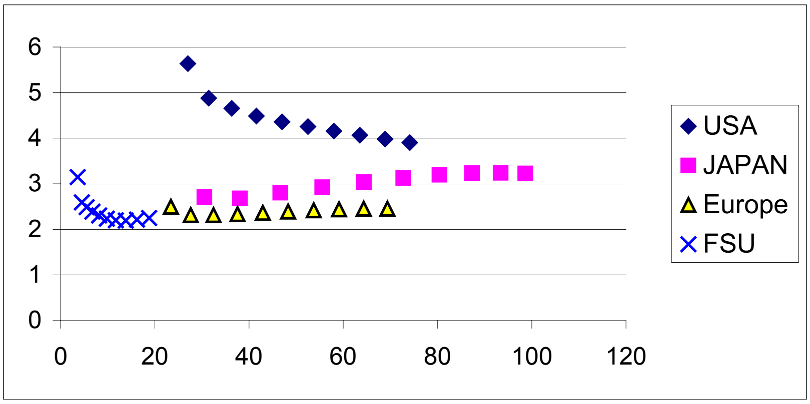


Figure 4: Model Simulations of Per Capita CO_2 Emissions vs Per Capita Income
The Case with Green Technical Progress and with Regulation

(a) R&D-based Model Version



(b) LbD-based Model Version



Appendix: The Remaining Elements of the Model

In this appendix we reproduce the remaining equations that make up the whole model. These equations are reported here for the sake of completeness and are the same as the ones found in the original RICE model.

In each region there is a social planner who maximizes the following utility function:

$$\max_{\{C(n,t)\}} \sum_{t=1}^{T} \beta^{t-1} L(n,t) \log[C(n,t)/L(n,t)] \tag{A.1}$$

where L represents the exogenously evolving population, C is the absolute level of consumption, and β is the discount factor. By assumption population equals the employed labor force. The discount factor is exogenously given. The budget constraint is given by an equation like (3) in the main text. Clearly, the capital stock evolves as follows:

$$K(n,t+1) = (1-\delta_K)K(n,t) + I(n,t) \tag{A.2}$$

where I is the level of Investments in physical capital and δ_K is the rate of depreciation of capital stock. The process is the same as that for *R&D*.

Turning to the climate module of the model, equation (4) in the main text shows the wedge existing between gross output Q and net output Y, justified by the negative effect exerted by the temperature level on the regions' utilities. Changes in temperature are generated by emissions through a few equations described hereafter.

First of all, the term $\Omega(n,t)$ in (4) is the just mentioned damage function with the following representation:

$$\Omega(n,t) = \frac{[1 - b_{1,n}\mu(n,t)^{b_2}]}{[1 + \theta_{1,n}\left(T(t)/2{,}5\right)^{\theta_2}]} \tag{A.3}$$

where μ is the domestic abatement rate controlled by each region, while T is the global temperature level, and b_1, b_2, θ_1, and θ_2 are parameters.

Equation (5) and variants describe how emissions are generated by production activity, and depend also on the domestic effort against pollution as well as the environmental technology that each region enjoys. Over time, emissions accumulate and form the carbon concentration stock M:

$$M(t+1) = \gamma \sum_n E(n,t) + (1-\delta_M)M(t) \tag{A.10}$$

where γ is the marginal atmospheric retention ratio of CO_2 emissions and δ_M is the rate of transfer of CO_2 from atmosphere to other reservoirs. The following step describes the relationship among the accumulation of greenhouse gases, the level of temperature, and climate change. The equations regulating the temperature level are:

$$T(t+1) = T(t) + \left\{\tau_1\left[F(t+1) - \lambda T(t)\right] - \tau_2\left[T(t) - T^*(t)\right]\right\}/\tau_3 \tag{A.11}$$

$$T^*(t+1) = T^*(t) + \left[T_1(t) - T_2(t)\right]/\tau_4 \tag{A.12}$$

$$F(t) = \eta \log[M(t)/M(0)]/\log(2) + O(t) \tag{A.13}$$

where T is atmospheric temperature relative to pre-industrial level, T^* is deep ocean temperature relative to pre-industrial level, F represents the radiative forcing from all greenhouse gas concentrations, τ_1, τ_2, τ_3, τ_4 are parameters of the climate equation, λ is the feedback parameter in climate model (inverse to temperature-sensitivity coefficient), η is a parameter enhancing the carbon concentration impact on the radiative forcing, and O is an exogenously given force.

Further information concerning the model structure, the calibration of parameters, and the simulation results under various policy regimes is found in Buonanno, Carraro, Castelnuovo, and Galeotti (2000, 2001), Buonanno, Carraro, and Galeotti (2001), and Castelnuovo and Galeotti (2002).

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