The environmental Kuznets curve reexamined for CO_2 emissions in Canadian manufacturing industries

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Abstract

Recent studies of the environmental Kuznets curve raise questions regarding the relationship between environmental indicators and GDP and the fundamental reasons that explain this relationship. In response, this thesis presents one-sector and two-sector models to analyze the alternative causal relationships between an environmental indicator and GDP at different stages of economic development. These models analyze how economic scale, technology, preferences, and economic structure influence the causality and shape of the relationship. These theoretical studies are followed by two empirical studies. The first tests the causal relationship between CO_2 emissions and GDP in Canadian manufacturing industries. The second explores several factors as the fundamental causes that influence the CO_2 emissions in the same industries. Factors, such as economic scale, preferences, technological progress, structural change, and energy input, are found to be crucial in the determination of CO_2 emissions. The empirical results are positive, but there are data limitations. The empirical studies can be re-evaluated as more data becomes available.

Résumé

Des études récentes de la courbe Kuznets en économie environnementale soulèvent des questions concernant (1) la relation entre les indicateurs environnementals et le produit domestique brut (PDB) et (2) les raisons de base qui expliquent cette relation. Cette these développe des modèles économiques de un-secteur et de deux-secteur afin d'analyser les hypothèses alternatives sur le lien entre un indicateur environnemental et le PDB à différents stages de développement économique. Ces modèles déterminent comment l'échelle économique, la technologie, les préférences et la structure économique influencent la causalité et la forme de la courbe. Deux études empiriques portent sur ces études théoriques. La première examine la relation causale entre les émissions de CO2 et le PDB pour certaines industries de fabrication canadiennes. La deuxième cherche à découvrir les causes qui déterminent les emissions de CO2 aux mèmes industries. L'échelle économique, les préférences, le progrès technologique, le changement structural et les intrans d'énergie sont des déterminants cruciaux des émissions de CO2. Les résultats empiriques sont significants, mais il y a des limitations au niveau des donnés. Ces résultats doivent être ré-évalués quand il y aura plus de donnés.

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Chapter 1: Introduction

1.1 Background

There was a major slowdown in productivity growth[1] in Canada and the United States that began in the early 1970's. Multifactor productivity growth rates in the period of 1973-1992 were low and negative in some years.

Table 1.1 Growth in multifactor productivity (annual averages, in percent)

	1961 - 73	1973 - 81	1981 - 92	1961 - 92
Canada	2.69	0.24	0.58	1.31
Goods [1]	3.59	0.02	1.15	1.80
Services [2]	2.50	0.86	-0.03	1.18
United States	1.00	0.01	0.93	0.72
Goods	1.42	-1.21	2.13	0.99
Services	0.80	0.37	0.10	0.44

Sources: Statistics Canada; United States, Department of Commerce, Bureau of Economic Analysis.
[1] Agriculture and related industries; fishing and trapping; logging and forestry; mining, quarrying, and oil wells; manufacturing; construction; and other utilities.
[2] Transportation and storage; communication; wholesale trade; retail trade; finance, insurance, and real estate; and community, business, and personal services.

There has been some debate regarding the causes of the slowdown in productivity and growth. A variety of causes have been proposed. In the 1970's and 1980's, economists, such as Daly and Cobb (1989), suggested that there were limits of growth. Environmental constraints and corresponding environmental regulations have been suggested as contributing factors. Considerable empirical work has attempted to estimate the

[1] The definition of productivity here is given by Baldwin et. al. (2001). Productivity is a measure of productive capacity or efficiency of an economy. It can be defined in terms of a level---how much output is produced per unit of input---or in terms of growth rate---the increase rate of growth per worker.

Productivity can be measured as the increase in output relative to the increase in a single input like labour (growth in labour productivity) or the increase in output relative to the increase in a bundle of inputs like labour and capital (growth in multifactor productivity). The latter measures the residual increase not due to either labour or capital input.

productivity effect of environmental regulation. Owing to the use of different methodologies, time periods, and data, the results of these estimates have varied widely. One of the more detailed analyses of the impact of various factors (including environmental regulation) on productivity growth can be found in the work of Denison (1978, 1979a and 1979b). He argued that the productivity slowdown comes from the diversion of primary inputs from production to pollution abatement. He estimated that the slowdown of productivity growth resulting from pollution abatement expenditures was 22% annually from 1973-1975 and 8% from 1975-1978. Christainsen and Haveman (1981), however, criticized this explanation. They stated that environmental regulation affects productivity growth, not only by diverting resources from primary production but also by affecting the efficiency of firms' resource allocation decisions. There may also be an effect on the allocation of research and development (R&D) expenditures between primary production and abatement (Christainsen and Heveman, 1981, pp.383). Based on aggregate level data, Christainsen and Heveman (1981, pp.388) suggested that not more than 15%, and more likely between 8-12%, of the slowdown in productivity growth could be attributed to environmental regulation in the United States.

However, since the early nineties productivity growth has recovered. In the mean time, some economists observed the phenomenon of increasing and then decreasing levels of some pollutants with respect to per capita GDP. The restrictions of the environment and the relationship between the environment and the economy began to interest more economists. The earliest empirical work to analyze this relationship were the World Development Report 1992, a background paper for the 1992 World Development Report by Shafik and Bandyopadyay (1992), and a working paper by Grossman and Krueger (1991)[2]. They proposed an inverse U-shaped Curve to describe the relationship between some pollutant levels and per capita national income across countries. Since it is similar to the relationship between inequality and income described by Kuznets (1955), this curve has become known as the Environmental Kuznets Curve (EKC). The same idea is embodied in both models, that an externality or distortion caused by economic growth increases in the early stage of development and then decreases in the high-income stage. A wave of testing this EKC relationship in the early 1990's provided a large amount of evidence for the EKC for different pollutants (also see Selden and Song 1994, Panayotou 1993, and Holtz-Eakin and Selden 1995). Their research suggested that the environmental problems would be eventually solved by economic development.

There has been considerable effort to try to explain this phenomenon. It has been hypothesized that in the early stage of economic development, the resource and environmental carrying capacity are large enough to support subsistence economic activity. The pollution level either does not grow or grows very slowly. As economic development accelerates with the intensification of agriculture and resource extraction, and with the take off of industrialization, the rates of resource depletion begin to exceed the rates of resource regeneration, and waste generation increases beyond the capacity of the environment to absorb it. At higher levels of development, structural change towards services and information-intensive industries, together with increased environmental awareness and preferences for environment-favouring goods, enforcement of

[2] This was the first Environmental Kuznets Curve (EKC) study. The paper was later published as Grossman and Krueger (1993).

environmental regulations, higher environmental expenditures, and innovation of environment-favouring technology in production all result in a gradual decline of environmental degradation.

Theoretical models have been developed in order to provide a rational basis to explain the EKC. There are the general equilibrium model by Lopez (1994), an overlapping generation model by John and Pecchenino (1994), and a neo-classical growth model by Stokey (1998). The main points considered in these models include (1) how to incorporate pollution, (2) the substitution between conventional factors and pollution in production, (3) the income elasticity of consumption goods and pollution, and (4) who pays for the environment. Although different models have different implications, they all support that the EKC exists under some conditions.

As theoretical models developed, empirical studies progressed, as well. More factors were introduced to account for the EKC. A recent empirical study by Dinda, Coondoo, and Pal (2000) explained the pollution-income relationship using three factors: technology, sectoral composition and growth rate. They refuted the idea that the relationship between environmental quality and per capita income is uniform across countries. As an alternative, they proposed a model based on national economic characteristics.

However, Pasche (2002) pointed out that the EKC could be only a short run phenomenon. In the long run, there is a limit to how much technological progress and structural change can reduce pollution. In this case, the environment-economy relationship will be N shaped instead of an inverted U. Coondoo and Dinda (2002) also cast doubt on the unidirectional causality of income causing environmental changes and not vice versa. They asserted that the nature and direction of causality might vary from one country to the other. Coondoo and Dinda (2002) studied income-CO_2 emission causality based on a Granger causality test using cross-country panel data for 88 countries from 1960 to 1990. Their results indicated three different types of causality relationships holding for different country groups. These new findings challenge the previous models.

1.2 Problem statement

In the early work on the EKC, researchers simply regressed environment indicators on quadratic or cubic per capita GDP using cross-country data and obtained an inverted U-shaped curve. Based on the results of these simple studies, they stated that environmental problems would be eventually solved by economic development itself; there was no need to worry about the environment and no need to be bothered by environmental policy-making. However, the EKC relationship came from the assumption of unidirectional causality of income causing environmental changes. Stern (2002. p. 201) cast doubt on this. "Emissions per capita of sulfur have decreased in recent decades in wealthy countries. However, there is some evidence that this is a time-related effect rather than an income related effect (Stern and Common, 2001). Also, even if increases in income in the currently rich countries actually reduce emissions in those countries, this may be achieved through moving emissions-generating activities to other countries (Stern et at, 1996)". Coondoo and Dinda (2002) studied income-CO_2 emission causality, and their results indicate three different types of causality relationship holding for different country groups. This leaves open the question of why there might be different causal relationships at different stages of economic development.

To address this question theoretically, one sector and two sector models are proposed, followed by an empirical test of the causal relationship between CO_2 emissions and GDP at the level of specific industries in Canada. Similar results to Coondoo and Dinda (2002) are obtained: that is, for different industries the causal relationships are different. But, for most industries, there is no causal relationship in either direction.

If GDP is not a sufficient explanation for the evolution of a pollutant, the factors that determine GDP, should be studied. As an economy develops, not only does GDP increase, but there are also changes in economic structure, technology, preferences and environmental policy. What is the real mechanism between the economy and the environment? Dinda, Coondoo, and Pal (2000) explained the pollution-income relationship using three factors: technology, sectoral composition and growth rate. Stern (2002) attributed the changes in the emission of anthropogenic pollutants to changes in input mix, output mix, scale, and the state of technological progress.

All the previous empirical studies used national or city level data. No work has tried to explain the economy-environment mechanism from a micro foundation. Here the economy-environment mechanism is explored by treating each manufacturing industry as an individual economic agent. The hypothesis is that CO_2 emissions are determined by economic scale, preferences, economic structure, technology, and energy input.

1.3 Structure of the thesis

The thesis is organized as follows. Chapter 2 presents a review of the literature associated with the EKC. Five issues in the literature are presented. In section 2.1 intuitive explanations for the emergence of the EKC are presented. Reasons are attributed to production technology, consumers' preferences, environmental regulation and economic structure. In section 2.2 theoretical models that derive the conditions for the existence of an inverted U-shaped EKC are explored. In section 2.3 theoretical models stressing the effect of technology and economic structure on pollution are analyzed. In section 2.4 empirical results and research methods on the EKC are reviewed. In section 2.5 additional problems related to the EKC study are presented.

In chapter 3, two models are presented that are used to explain the possibility of different causal relationships between pollution and economic development at different stages of development. Different shapes are demonstrated for the relationship between an environmental indicator and income to show how the time path of the relationship can vary. The effect of scale, technology, preferences, and structural change in the determination of the relationship between an environment indicator and income are also studied.

In chapter 4, two empirical studies are presented. In section 4.1 the causal relationships between CO_2 emissions and GDP are tested using industry level data for Canada. In section 4.2 several factors are combined in an empirical model of CO_2 emissions to test the hypothesis of a micro-foundation for CO_2 emissions, using industrial level data for Canadian manufacturing industries. This model explores the importance of economic scale, preferences, structural change, technology, and energy input on the evolution of CO_2 emissions.

The final chapter presents a summary of findings and a discussion of the limitations of the thesis.

Chapter 2: literature review

The purpose of this chapter is to review the literature that is connected with analyzing and testing the relationship between environmental quality and economic growth. First, an intuitive explanation for the emergence of EKC is given. Second, some theoretical models are presented, which derive the conditions for the existence of an inverted U-shaped EKC. Third, theoretical models stressing the effect of technology and economic structure on pollution are analyzed. The fourth section reviews some empirical results and research methods on the EKC.

2.1 Intuitive Explanations of the EKC

Economists have tried to explain the phenomenon of first increasing pollution then decreasing pollution as income increases from different perspectives: production technology, consumers' preferences, environmental regulation and economic structure. This section provides a summary of their ideas.

One method of explanation is to decompose the effect of economic growth on pollution into scale, technology and composition effects. This borrows from the analyses of the relationship between trade and the environment (Grossman and Krueger 1993). Antweiler, Copeland, and Taylor (1998) define the scale effect as the negative environmental effect of increases in income that comes from scaling up[3] economic activity. The technology effect is the positive environmental consequence of increases in

[3] Scaling up activity occurs when all factors of production are increased by the same proportion.

income that call for cleaner technology in production and abatement technology in reducing pollution; how goods are produced. The composition effect of increases in income concerns changes in economic structure; what goods are produced. It has been hypothesized that increased income will change the composition of goods demanded and produced from clean to dirty in the early stage of economic development, and then from dirty to clean after the economy has developed to a high enough level. Industrial structure changes correspondently. At a low level of income, the negative scale effect and negative composition effect are dominant resulting in increased pollution with the growth of income. At higher levels of income, the positive technology effect and composition effects are dominant which cause pollution levels to decrease. Therefore, an inversed U-shaped EKC could be expected.

From the aspect of production technology, some have suggested that some environmental constraints will become non-binding with the growth of the economy. Stokey (1998), for example, suggested that economic growth would make cleaner technologies feasible. She assumed there is a threshold level of economic activity. Below it, only the dirtiest technology can be used and above it cleaner technology can be used. Before the threshold level of economic activity is reached, pollution increases linearly with economic growth. After the threshold is passed, cleaner technologies decrease pollution with the growth of income. The resulting pollution-income path is therefore like an inverse V-shaped EKC, with a sharp peak at the point where a continuum of cleaner technologies becomes available.

From the aspect of individual preferences, Jaeger (1998) assumes that at a low level of economic development with a low level of pollution, consumers are satiated with the air quality, and the marginal benefit of additional environmental quality is zero. Consequently, the environmental resource constraint is non-binding. With economic growth, represented by a growing population and polluting firms, the preference for environmental resources increases. Once the threshold of satiation of consumers' preferences is passed, poor air quality becomes increasingly intolerable and an increase in the quality of environment will increase the utility of consumers. So growth may be accompanied by improved environmental quality satisfying the needs of consumers. Like Stokey (1998), therefore, Jaeger's pollution-income relationship is an inverse-V-shaped. A similar explanation can be found in the work of Bradford at el (2000). As a country gets richer, there are at least two preference effects on pollution. First, the pure income effect will induce more consumption of environmental quality as income increases. Second, the composition effect of economic growth might shift the consumption bundle in the direction of less pollution-intensive goods, such as digitally recorded entertainment (Bradford at el 2000). Therefore, the pollution-income time path is an inverse-U-shaped.

From the aspect of policy-making, Jones and Manuelli (2001), for example, addressed the question of how increased income results in improved environmental quality. They argued that advanced institutions are needed to appropriately incorporate externalities in order to control pollution. This is because a political and civil system in which individuals' demand for environmental quality can be expressed might be crucial for changes in environmental quality. These institutions are only well developed in developed economies.

There are also some comprehensive explanations, which try to incorporate changes in preferences of consumers, changes in technology, and changes in policy-making together. The story is as follows. As the economy grows, growing effluents from production will show growing evidence of harmful effects that will be recognized by people (perhaps first by natural scientists). This increases public concern for the environment. At the same time, as income increases, people are prepared to pay more for environment quality. These two conditions mean that the demand for environment quality exists and can be expressed. That will be reflected in the policy making and trigger more stringent environmental policies. The new environmental policies, which reflecting the demand of consumers, have feedback on production and induce producers to employ new technologies to change the composition of goods and bads (pollution). So the positive environmental effect of income growth, technology and composition effects are enforced by environmental policy and induced by consumers' demand (Smulders and Bretschger, 2000).

In summary, pollution tends to be related to both industrial production and consumers' consumption, and thus impact both the supply and demand sides of the economy. The marginal benefit of environmental regulation tends to balance the marginal non-environmental cost foregone. All these factors, technology, preferences and regulation will be present in the industrial structure of the economy, which determines the combination of goods that maximize consumers' utility.

2.2 Theoretical models of the EKC

This section reviews four theoretical models by Lopez (1994), Seldon and Song (1995), Bovenberg and Smulders (1995), and Stokey (1998). These models have derived the conditions supporting the emergence of the EKC in terms of the assumptions regarding consumption, production and how pollution costs are incorporated into production and consumer preferences.

Lopez (1994) stated that economic growth improves environmental quality if and only if producers internalize environmental stock feedback effects[4] on production. For environmental resources without stock feedback effects on production, economic growth causes degradation of environmental quality definitely if preferences are homothetic. In the non-homothetic case, the relationship between growth and pollution depends on the elasticity of substitution in production between conventional factors and pollution and on the relative degree of curvature of utility in income.

In this review, only the case where resources exhibit small stock productive effects is concerned. Lopez (1994) incorporated environmental factors into production and consumption using a static general equilibrium model in order to study a one-way

[4] Examples of environmental factors that have productive stock feedback effects are forests, fish stock, and agricultural soil quality. In these cases production can expand in the short run by more intense exploitation of the resource, but at the cost of a gradual reduction in the stock, which eventually may decrease productivity in the respective industries. An important example where the productive stock feedback effects are negligible is air quality. Expansion of industrial production may increase air pollution, but greater air pollution is unlikely to significantly affect industrial production. Moreover, at least on a local basis, the stock effect of air pollution is very short-lived. A reduction in emissions is likely to cause a fast recovery of air quality in the local (city) framework and thus the stock effect is quite negligible. (Lopez, 1994, pp. 165)

connection between growth and environmental degradation. He incorporated environmental quality as an additional factor into the neoclassical standard aggregate production function $f\ (K,\ L;\ \psi)$, where K is capital, L is labor and ψ is an index of technological progress. ψ represents the residual of output that is unaccounted for by K and L. The production technology exhibits constant returns to scale in the factors of production. The new model becomes $y = G\ (f\ (K,\ L;\ \psi),\ x;\ \tau)$, where y is output of industry, x is the environmental factor (pollution) used by industry, and τ is an index of technology indicating the marginal rate of substitution between the conventional factors f and the environmental factor x. He assumed weak separability between the environmental factor and conventional factors f, constant returns to scale and exogenous technical change and prices.

At the same time, pollution directly enters the utility function of consumers as a negative effect. The societal welfare function, $\mu(\cdot)$, is a function of total consumption of goods and of pollution x. Total expenditure on goods is assumed equal to the revenue, $R\ (p; f(K,\ L;\ \psi),\ x;\ \tau)$, where p is the price of output. The welfare function is increasing and concave in R and decreasing and concave in pollution x. The optimal welfare is defined by

$$\text{Max}\ \mu = \mu\,(\,R\ (p; f(K,\ L;\ \psi),\ x;\ \tau),\ x,\ p) \qquad (2.1)$$

Maximization of $\mu(\cdot)$ with respect to x yields the optimal level of the environmental factor (e.g. air emissions) under the assumption that the air quality externality is completely internalized.

Lopez supposed that the relationship between pollution and income is highly related with characteristics of the production and consumption functions. He analyzed, therefore, the effects of homothetic consumption and non-homothetic consumption, the elasticity of substitution in production between conventional factors and pollution and the relative degree of curvature of utility in income on the shape of the relationship between pollution and income.

In the case where preferences are homothetic and polluters pay the true social marginal cost of pollution, pollution is increasing with economic growth. Economic growth in the long run would be limited by the capacity to produce new technology that could improve the environment. Using the general equilibrium conditions and some calculus, he obtained that changes in environmental factors (pollution x) are related to inputs and production-pollution technologies,

$$\dot{x} = s_k \dot{K} + s_L \dot{L} + A + \eta , \tag{2.2}$$

where $\bullet$ indicates rate of growth, s_k is the share of capital and s_L is the share of labor in total revenue. A is a technology index representing the rate of a conventional factor productivity increase, $A = \dot{f} / f(K, L; \psi)$ (keeping K and L constant). Economic growth is usually accompanied with $A \geq 0$. η is a technology index representing the rate of environmental improvement. Let $x / f(K, L; \psi) = \phi$, then $\eta = \dot{\varphi} / \phi$. If $\eta < 0$, technical change improves the environment. Therefore, growth based on capital accumulation or increased employment necessarily causes increases in pollution if preferences are homothetic. If growth is based purely on technological change (A and η), the effect on pollution would be ambiguous depending on the difference between the strength of the effect of environmental improvement of technical change (η) and the effect of the increase in production of technical change (A)[5]. He concluded that environmental saving technical change is likely to be less than conventional factor saving technical change, i.e. $|A|>|\eta|$ (Lopez 1994 pp.169). This is due to the fact that pollution control occupies a small share of private cost and conventional factors, particularly labor, occupy a large share of the cost. In this case pollution increases monotonically with economic growth.

In the case where preferences are non-homothetic and polluters pay the true social marginal cost of pollution, the effect of economic growth on pollution is ambiguous. The effect of factor expansion on pollution depends on the elasticity of substitution in production between pollution and non-pollution inputs and the income elasticity of the utility function. A higher elasticity of substitution in production between conventional inputs and pollution implies that firms need to spend less on conventional inputs to reduce pollution in response to a higher pollution fee. Or just a small increase of the price of pollution will be enough to reduce pollution to a larger extent. Higher income elasticity means that consumers would give up a proportionally greater amount of additional income as they have more income in order to buy a better environment. The value of income elasticity is crucial for the relationship between pollution and income. If the income elasticity is sufficiently greater than one and the elasticity of substitution in

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[5] Usually, it is assumed that A, the increase in output from technology progress, does not influence pollution. The result here indicates that any effort that is oriented to increasing output will increase pollution. Only the effort that is oriented to decreasing pollution will actually decrease pollution.

production between conventional inputs and pollution is large enough, an inverted U-shaped relationship between income and pollution could be obtained.

Selden and Song (1995) used the neoclassical environmental growth model of Forster (1973) to examine the dynamic relationships among pollution, abatement effort, and income and how these determine the steady-state levels of capital, consumption, and environmental quality. In their model, the utility of the representative agent is $U_1(C)+U_2(x)$, where $U_1(C)$ is increasing at a decreasing rate in consumption, C, and $U_2(x)$ is decreasing at an increasingly negative rate in pollution x. Pollution is produced by a function which is additively separable in the capital stock, K, and expenditure on abatement, E, $x(K, E)$. The production function, $f(K)$, is increasing and concave in K. Capital depreciates at rate δ, net investment *is* $\dot{K} = f(K) - \delta K - C - E$, and the initial stock of capital is K_0.

The social planner's problem is to select trajectories for K, C, E, and x to maximize the present value of the stream of utility over an infinite time horizon, subject to the constraint on net investment.

$$\max_{\{C, K, E\}} \int_0^{\infty} e^{-\rho t} U(C, x(K, E))\, dt \, . \qquad (2.3)$$

$$\text{subject to } \dot{K} = f(K) - \delta K - C - E \text{ and } E \geq 0 \qquad (2.4)$$

By maximizing the current-value Hamiltonian,

$$\text{Max } U(C, x(K, E)) - \varphi(\dot{K} - f(K) + \delta K + C + E) \qquad (2.5)$$

The optimal trajectories, *(K(t), C(t), E(t), x(t)),* satisfy

$$\text{(a)}\quad \frac{\partial U}{\partial C} = \varphi \qquad (2.6)$$

$$\text{(b)}\quad \frac{\partial U}{\partial x} * \frac{\partial x}{\partial E} = \varphi \qquad (2.7)$$

$$\text{(c)}\quad \dot{\varphi} = \rho + \delta - \frac{\partial x / \partial K}{\partial x / \partial E} - f'(K) \qquad (2.8)$$

where ρ is time preference, and φ can be interpreted as the shadow value of capital. At interior solutions the marginal benefit from consumption and the marginal benefit from pollution abatement are both set equal to φ, which evolves at the rate equal to the sum of (i) the rate of time preference, (ii) the rate of depreciation of capital, (iii) the marginal abatement expenditure required to offset the pollution effects of an increase in the capital stock, and (iv) the marginal productivity of capital.

The solution to their model yields two important relationships: first is a J-shaped relationship between abatement effort and income. Pollution control expenditures are minimal below a critical level of income, but increase rapidly thereafter. Second is an inverted U-shaped relationship between pollution and income, whereby an initial increase in pollution is eventually offset by increased abatement effort as income increases.

Bovenberg and Smulders (1995) presented a two-sector endogenous growth model that incorporates pollution-abatement through technological change in order to study the relationship between economic growth and environmental quality. Their model examined the conditions for sustainable[6] and optimal growth and then determined the time paths for three types of assets: natural resources (these are treated as renewable resources here), physical capital, and knowledge. The accumulation of the stock of these three assets is affected by the endogenous flows of pollution, savings, and inputs into the R&D sector, respectively. Knowing the above information, the relationship between environmental quality and economic growth can be determined.

In this two-sector model, one sector produces a final good that can be either consumed or invested for future production. The second sector is the knowledge or environmental R&D sector. It generates knowledge about pollution-abatement technology. The environment is represented by the stock of natural capital, N, which includes, for example, clean soil, water and air. It provides the environment for economic activity and evolves according to the recovery capacity of nature and the damaging effects of pollution x, defined as the economy-wide level of pollution (in both the final good sector and environmental R&D sector).

$$\dot{N} \equiv \frac{dN}{dt} = E(N,x) \ , \ E_N > 0 \ and \ Ex < 0. \tag{2.9}$$

The final good, Y, is produced with three factors N, K and Z,

$$Y = Y\,(N, K_Y, Z_Y) \tag{2.10}$$

K_Y, represents physical and human capital used in the final good sector, and Z_Y, represents the input of 'harvested' natural resources or the flow of natural resources used in the final

[6] They define sustainable growth as the condition where consumption and man-made inputs (knowledge and physical capital) are growing, while the flow of pollution and the stock of natural capital remain unchanged. (Bovenberg and Smulders, 1995, pp.386)

good sector. This use of natural resources is considered to be pollution and is assumed to be necessary in production. While pollution Z_Y is a factor of production, it decreases the marginal productivity of K. Z_Y is produced according to

$$Z_Y = \nu \tau x \tag{2.11}$$

Where τ is an index of the available knowledge about pollution-abatement technology, $0<\tau<1$, where lower value of τ indicates higher level of abatement technology. τx represents the 'effective' level of pollution that affects economic activities, and ν is the share of effective pollution for which the final goods sector is responsible. The accumulation of pollution-abatement technology evolves at the rate:

$$\dot{\tau} = H(K_H, Z_H) \tag{2.12}$$

The inputs into the environmental R&D sector are physical capital K_H and effective pollution ($Z_H = (1-\nu)\tau x$).

Summing up, the model incorporates three kinds of capital: natural capital (N), 'physical' and human capital (K), and pollution-abatement knowledge capital (τ). Z and τ are accumulated according to equations (2.11) and (2.12), respectively, while the stock of economy-wide physical capital evolves according to the function:

$$\dot{K} = Y - C \tag{2.13}$$

where C is consumption, and $K = K_Y + K_H$.

On the consumer side, identical infinitely-lived individuals exhibit preferences over consumption goods, C, and environmental quality, N. A social planner maximizes intertemporal utility in equation (2.14) subject to the accumulation equations (2.9), (2.12), and (2.13) and the resource constrains $K = K_Y + K_H$ and $Z = Z_Y + Z_H$.

$$\max \int_0^{\infty} e^{-\rho t} U(C(t), N(t))\, dt \quad , \tag{2.14}$$

where ρ represents the rate of time preference.

The Hamiltonian for the maximization problem reads:

$$\begin{aligned} Max\ H = U(c, N) + \mu_1[Y(N, K_y, Z_y) - c] + \mu_2\, H(K_H, Z_H) + \mu_3\, E(N, x) \\ + \lambda_1[K - K_y - K_H] + \lambda_2[\tau x - Z_y - Z_H] \end{aligned} \tag{2.15}$$

In equation (2.15), μ_1, μ_2, and μ_3 denote the co-state variables associated with the accumulation of physical capital, knowledge capital, and natural capital, respectively, and where λ_1 and λ_2 are the Lagrange multipliers associated with the resource constraints for physical capital and effective pollution, respectively.

The solution yields the conditions under which sustainable growth is feasible and optimal. In such a solution, consumption, knowledge and physical capital are growing, while the flow of pollution and the stock of natural capital remain constant. This implies that the shadow price of natural resources, μ_3, rises over time, thereby encouraging substitution away from the use of environmental services toward consumption and the input of physical capital and knowledge. Environmental quality in the form of the stock of natural capital (N) can be maintained only when the reduction of consumption of environmental services resulting from this substitution effect equals the increase of consumption of environmental services resulting from the income effect that is due to the growth in productivity.

Stokey (1998) developed a static model in order to determine which restrictions on technology and preferences are consistent with the observed inverted U-shaped EKC. She, then followed with three growth models in which a social planner regulates pollution in order to achieve long run sustainable growth and optimal social welfare, and finally studied the issue of implementing these optima.

First, in the static model, she assumed that consumption goods and pollution are joint products of a production technology with constant returns to scale, and that reducing pollution occurs at the cost of foregone output. She used an index of technology τ, $\tau \in [0, 1]$, to relate potential output y with actual output c, $c = \tau y$. She assumed that all actual output c is consumed. Potential output is attained by using all productive resources in the most polluting way setting $\tau = 1$. As technology is changed to reduce pollution, actual output falls below potential (i.e. $\tau < 1$). Higher values for τ yield more goods but also more pollution. Let $x = y f(\tau)$ be the total pollution generated when potential output is y and the production technology τ is used. Thus, τ is also an index of the emission rate for production. For fixed potential output, pollution is an increasing and a strictly convex function of actual output, i.e. $f''(\tau) > 0$.

Preferences over the consumption good c and pollution x are separable:

$$U(c, x) = v(c) - n(x), \tag{2.16}$$

While v is strictly increasing and strictly concave, n is strictly increasing and strictly convex.

She assumed that there is direct regulation of emissions, in which the government imposes its choice of the appropriate technology on firms (τ). In response, competitive firms maximize profits given the constraint set by the government. Given potential output y, the government chooses the emission standard τ to maximize the utility of the representative consumer:

$$\max_{\tau \in [0, 1]} v(y\tau) - n(yf(\tau)) \tag{2.17}$$

For fixed potential output y, the optimal technology τ *(y) satisfies the condition that marginal benefit of pollution is larger than or equal to marginal cost of pollution,

$$v'(y\tau^*(y)) \geq n'(yf(\tau^*(y)))f'(\tau^*(y)), \text{ with equality if } \tau^*(y) < 1. \tag{2.18}$$

According to equation (2), she solved for the optimal technology τ *(y) for different potential y. The marginal benefit curve $v'(y\tau^*(y))$ is decreasing in τ for fixed y and shifts downward as y increases. The marginal cost curve $n'(yf(\tau^*(y)))f'(\tau^*(y)$ is increasing in τ for fixed y and shifts upward as y increases. Define $\hat{y}$ by

$$\frac{v'(\hat{y})}{n'(\hat{y})} \equiv f'(1) \tag{2.19}$$

For potential income below $\hat{y}$ the marginal benefit and marginal cost curves do not intersect. The solution is at the corner when $\tau = 1$, and the dirtiest technology is used. For potential income above $\hat{y}$ the solution in interior, and the emission standard τ becomes stricter as income rises. That is,

$$\tau^*(y) = 1, \text{ when } y \leq \hat{y}, \tag{2,20}$$

$$\tau^{*\prime}(y) < 0, \text{ when } y > \hat{y}. \tag{2.21}$$

Define the optimal total pollution as the pollution generated when the optimal technology is used:

$$x^*(y) \equiv yf(\tau^*(y)) \tag{2.22}$$

Clearly, total pollution increases with income below the critical income level $\hat{y}$. When the income level is above $\hat{y}$, she examined the special case of constant elasticity functions,

$$f(\tau) = \tau^{\beta,} \beta > 1, \tag{2.23}$$

$$v(c) = (c^{1-\sigma} - 1)/(1-\sigma), \sigma > 0, \tag{2.24}$$

$$n(x) = Bx^{\gamma}/\gamma, \gamma > 1, B > 0. \tag{2.25}$$

She obtained a result that total pollution decreases with income if $\sigma > 1$, increases with income if $\sigma < 1$, and is constant for $\sigma = 1$.

Therefore, for this special case, when $\sigma > 1$, an inverted U-shaped relationship between pollution and income is obtained. At incomes below the critical income level $\hat{y}$ there are no pollution controls and total pollution increases with income. At incomes above the critical income level $\hat{y}$ emission standards become increasingly stringent and the total level of pollution declines.

In the second part of the analysis the same preferences and technology are embedded in three growth models: a one sector endogenous growth model, *Ak* model in which potential output is a linear function of capital ($y = Ak$), and two versions of a one sector exogenous growth model ($y = A\ e^{gt}\ k^{a}$), in which g is a constant rate of technological change, $g>0$, a is capital share, ($0< a <1$), and t is time. In one of these exogenous growth models, pollution is treated as a flow and in the other as a stock[7]. In all three models the time path for total pollution displays the pattern suggested by the static model: if the elasticity of marginal utility with respect to income exceeds one, total pollution first rises with income, then peaks and gradually declines. In the endogenous growth model, sustained growth is not optimal in the presence of pollution. The intuition for this result is that as the capital stock grows society imposes ever stricter emission standards (τ decreases), reducing the rate of return on capital (A τ). When the rate of capital return gets low enough there is no incentive for further capital accumulation. In the exogenous growth model, however, the rate of return on capital is $(A\ e^{gt}\ \tau)^{1/a}$, in which e^{gt} increases over time while τ decreases with stricter emission standards. The result is there is not a steady state; instead there is a balanced growth path along which capital, output, and consumption grow at a common, constant rate, the emission standard becomes stricter at a constant rate, and the rate of return on capital remains constant, encouraging further accumulation. The tightening emission standard reduces the growth rate that would be higher in the absence of pollution, but the growth rate is still positive. Moreover, the

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[7] Pollutants that accumulate over time are stock pollutants whereas pollutants that quickly dissipate are flow pollutants. Greenhouse gases that have residence time in the atmosphere of decades are classic examples of stock pollutants, as are chlorofluorocarbons (CFCs) that deplete the stratospheric ozone layer. Suspended particulate matters emitted into the atmosphere are flow pollutants since they settle out within a matter of hours or days (Kolstad, 2000, pp.165).

long-run behavior of the system is the same for either a flow pollutant or a stock pollutant.

In the third part of the analysis, she analyses how government realizes the optima. The main conclusion is that tax and voucher schemes could implement the optima, but direct regulation, such as imposing an environmental standard, cannot achieve the optima.

She concluded that the inverted U-shaped EKC is a consequence of the elasticity parameter for consumption goods, σ, not for pollution, γ. Thus, if the assumed additive separability of preferences is approximately correct, all types of pollution should display the inverted U-shaped relationship with income. However, there could be differences in where the EKC peaks.

2.3 Models related to technology and economic structure[8]

This section presents theoretical models by Leontief (1970), de Groot (1999), and Pasche (2002), which analyzed how technology and economic structure affect the amount of pollution as income increases.

Leontief (1970) provided an early attempt to explain how pollution could be incorporated into a national input-output accounting model to show how pollution could be related to the structure of the economy. In his paper, he considered a simple economy consisting of

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[8] Economic structure is explained as input mix or output mix in different articles.

households and two production sectors, say agriculture and manufactures. Each of the two industries absorbs some of its annual output itself, supplies some to the other industry and delivers the rest to households. Pollution as a by-product of production is proportionally related to the output of each sector. He put these inter-sectoral flows in an input-output flow table (Table 1).

Table 2.1 Input-Output flows

Into From	Sector1 Agriculture	Sector 2 Manufactures	Final Demand Households	Total Output
Agriculture	25	20	55	100 bushels of wheat
Manufactures	14	6	30	50 yard of cloth
Air Pollution	50	10		60 grams of pollutant

The numbers entered in the first row are the amount of output from the agriculture sector that flows into the agriculture sector, the manufactures sector and households respectively and those shown in the second are the amount of output from the manufactures sector that flows into the agriculture sector, the manufactures sector and households respectively. The numbers entered in the third row are the quantities of pollution produced by the agriculture sector and manufactures sector respectively. For the agriculture sector, in order to produce 100 units of output, 25 units of wheat, and 14 units of cloth are needed and there are 50 units of pollution. Therefore, the input requirement coefficients in the agriculture sector are 0.25, 0.14 and 0.50 respectively per unit of output. The same calculation applies to the manufactures sector.

Table 2.2 Structural matrix of the economy

Into From	Sector1 Agriculture	Sector 2 Manufactures
Agriculture	0.25	0.40
Manufacture	0.14	0.12
Pollution	0.50	0.20

He combined these numbers into Table 2 and named it as the "structural matrix" of the economy since the input requirements of the two industries are represented by their specific technological structures. The numbers entered in the first column are the technical input coefficients and the technical pollution coefficient of the agriculture sector and those shown in the second are the technical input coefficients and the technical pollution coefficient of the manufactures sector. Therefore, in this simple economy, the technical structure of the economy can be represented as follows:

$$X_1-0.25X_1-0.40X_2=Y_1 \quad (2.26)$$
$$X_2-0.14X_1-0.12X_2=Y_2 \quad (2.27)$$
$$0.50X_1+0.20X_2=P \quad (2.28)$$

X_1 and X_2 are the unknown outputs of the agriculture and manufactures sectors respectively. Y_1 and Y_2 are the known demands of households. P is the amount of pollution. By solving this simple model, the amount of pollution can be determined, for predetermined consumer demands for agriculture and manufactures.

The implication of this model is that the technical structure of an economy and demands of consumers determine the amount of pollution. For each sector there are two types of technology: one is the conventional production technology represented by technical input coefficients; the other is the pollution technology represented by technical pollution coefficients. These both matter for the amount of pollution. In general equilibrium, the demand of households (Y_1, Y_2) induces how much food (X_1) and how much cloth (X_2) will be produced given the conventional production technology. This determines the amount of pollution given the pollution technology. But, when the demand of households is given, then a change of conventional production technology (technical input coefficient) will change the amount of pollution by changing the output mix (X_1/X_2) while a change of pollution technology (technical pollution coefficient) will change the amount of pollution directly given that the output mix is determined by demand and conventional production technology.

The purpose of the Leontief's (1970) method is to incorporate pollution as an additional production factor into a national accounting model. It is introduced here to show a clear picture of how economic structure (input mix or output mix) could affect the level of pollution.

de Groot (1999) developed a multi-sector general equilibrium model to study the interaction between pollution, changes in the sectoral composition of economies, and technological change. He set up the model with S sectors in a closed economy.

On the production side, two inputs, labour (L_i) and emissions (E_i, flow pollutant) produce consumption goods with a constant returns to scale technology. He assumes there are separate labour augmenting and emission-saving technologies, which grow at constant and exogenous growth rates. In other words, over time the technology evolves so that labour becomes more productive and pollution per unit of output is diminished. The levels of labour and emission productivity are denoted by τ_{Li} and τ_{Ei}. The introduction of two technology parameters allows for differences in the growth rate of labour and emission productivity, which implies that the input-mix, at constant relative prices, may change over time. The production function is

$$Q_i = [b_{Li}\,(\tau_{Li}\,L_i)^a + b_{Ei}\,(\tau_{Ei}E_i)^a]^{1/a} \tag{2.29}$$

Where Q_i is the produced amount of good i, and b_{Li} and b_{Ei} are share parameters. The elasticity of substitution between labour and resources is equal to $1/(1-a)<1$ with $a<0$.

Profit maximization (or cost minimization) under perfect competition yields the sectoral emissions as a function of the two technology parameters, input prices, and labour demand:

$$E_i = Li\left[\frac{b_{Ei}P_L\tau_{Ei}{}^a}{b_{Li}P_E\tau_{Li}{}^a}\right]^{1/1-a} \tag{2.30}$$

According to his results, in any sector, the input of emissions relative to labour increases if the price of labour relative to the price of emissions increases, or if technological progress is faster in labour productivity relative to that in emission productivity.

On the consumption side, preferences of a representative consumer are specified as a function of consumption of the good from sector i and of the subsistence requirement of that good:

$$U = \left[\sum_{i=1}^{S} a_i(C_i - \overline{C}_i)^{\sigma}\right]^{1/\sigma} \qquad where \quad \sigma < 1, \sigma \neq 0, \sum_{i=1}^{S} a_i = 1. \tag{2.31}$$

C_i is the consumed amount of goods from sector i, $\overline{C}_i$ is the subsistence requirement of consumption from sector i, and a_i is a distribution parameter. In the absence of subsistence requirements, the elasticity of substitution between goods from different sectors equal to $1/(1\text{-}\sigma)$. The budget constraint corresponding to this problem is

$$\sum_{i=1}^{S} C_i P_{C\ i} \leq Y \tag{2.32}$$

Consumers maximize utility subject to an income constraint and this yields the demand functions for consumption goods from each sector. Consumers' demand for good i equals their subsistence requirement for this good plus a weighted average of their disposable income that is left after the subsistence requirements for all goods have been fulfilled.

$$C_i = \overline{C}_i + \left(\frac{P_{Ci}}{a_i}\right)^{\frac{1}{\sigma-1}} \frac{\left[Y - \sum_{j=1}^{S} P_{Cj}\overline{C}_j\right]}{\sum_{j=1}^{S} P_{Cj}\left(\frac{P_{Cj}}{a_j}\right)^{\frac{1}{\sigma-1}}} \tag{2.33}$$

In a simple two-sector case, using market clearing conditions, he derived the optimal emissions. He assumed that labour and emissions are the only inputs in production; sector 1 is more pollution intensive than sector 2 and there is no population growth. The results for the optimal level of emissions are as follows

$$E = \frac{s_1 \tau_{L1} L}{\tau_{E1}} + \frac{(1-s_1)\tau_{L2} L}{\tau_{E2}} + \frac{s_1 \overline{C}_2}{\tau_{E2}}\left[1 - \frac{\tau_{E2}\tau_{L1}}{\tau_{E1}\tau_{L2}}\right] + \frac{(1-s_1)\overline{C}_1}{\tau_{E1}}\left[1 - \frac{\tau_{E1}\tau_{L2}}{\tau_{E2}\tau_{L1}}\right] \tag{2.34}$$

Where L is the total labour, and s_1 and $1\text{-}s_1$ are the labour share allocated to sector 1 and sector 2, respectively. The interpretations are as follows:

(i) In the first two terms, increases in labour productivity τ_{L1} and τ_{L2} tend to increase emissions, while increases in emission productivity τ_{E1} and τ_{E2} (i.e., decreases in the emission-output ratio) may partly offset the effect of increased productivity in good production. Emission-saving technological progress is crucial to achieve reductions in emissions in a growing economy.

(ii) The last two terms reflect the changes in emissions associated with structural change ($\overline{C}_i$ output mix and s_i labour share). The sign of these effects crucially depends on the emission-labour intensities ($E_1/L_1 = \tau_{L1}/\ \tau_{E1}$ and $E_2/L_2 = \tau_{L2}/\ \tau_{E2}$). If as assumed, $\tau_{L1}/\ \tau_{E1} > \tau_{L2}/\ \tau_{E2}$, then the third term is negative and the fourth term is positive. If as assumed subsistence requirements and technological progress are relatively large in sector 1, total emissions will initially decline, reach a minimum, and then increase to their equilibrium level. This development of emissions could be interpreted according to the following scenario. First, fast technological progress in sector 1 tends to substitute away some labour from sector 1 to sector 2. In this process emissions decrease. This progress in sector 1 means it is easier to provide good 1 and the price of good 1 may decrease. The demand for good 1 will increase because of the substitution and income effects. This will attract some labour back to sector 1. According to this first decline then increase feature of emissions from structure change, the author was able to conclude that although changes in the sectoral composition may give some relief and may explain temporary declines in emission level, they are insufficient to persistently reduce the emission output ratio. A significant time path of inversed U-shaped emission income relationship is more likely interpreted as technological progress, or due to rising relative prices of emissions (or energy).

In further studies, the author also found that relative price changes of consumption goods and relative changes of input prices (labour and emission prices, energy prices) also influence emissions.

Pasche (2002) argued that the origins of the EKC are the structural changes of the economy towards less pollution intensive industries and environment-saving technologies. The driving forces behind these two determinants are changes in preferences that favour environmental goods, and environmental regulations. He studied technical progress and structural change to determine to what extent these could support a path of sustainable growth in the economy. Sustainable growth is defined as a positive growth rate $\dot{Y} = w$ (w is constant) where the stock of pollution (stock pollutant) does not increase. In his paper, the carrying capacity of the ecosystem is introduced as the maximum pollution level P_m for sustainable growth and it is crucial to the analysis.

The author argued that, only in the short run, environmental technical progress or structural change could lead to positive growth with a constant or even decreasing level of pollution. This supports the empirical results for the EKC in the short run. In the long run, there are limits to sustainable growth. An evolutionary change of goods and production technology may shift the limits of growth and is hence a prerequisite for a long run EKC.

First, he rejected the possibility of sustainability based on solely environment-improving technical progress, where the process of technology production exhibits decreasing returns to scale. This is because a growing share of income has to be spent for continuing technical progress in order to compensate the pollution effects of growth. Hence, in the long run, either the environment is damaged and sustainability is violated, or the growth rate must decline to zero. He assumed emissions, E, to be proportional to output Y: $E = \tau Y$, $\tau > 0$, with parameter, τ, is a pollution technological factor (pollution technical standard). The pollution stock, P, accumulates through the flow of emissions, E, and decays at a rate δ, $\dot{P} = E - \delta P$, with $0 < \delta < 1$. With a continuously growing Y and therefore growing E the carrying capacity will be reached in finite time. Once P_m has been reached, any further sustainable growth requires $E \leq \delta P_m$. The sustainability condition becomes

$$\dot{E} = \dot{\tau} + \dot{Y} \leq 0 \qquad (2.35)$$

He assumed that part of income is spent on R&D in order to improve pollution-abatement technology. This causes the proportionality factor, τ, to decrease. Sustainability requires that $|\dot{\tau}| \geq |\dot{Y}|$. He also distinguished between past investments in environment-improving technology *I*, which is the capital stock in the environmental sector, and current environmental expenditures A. The pollution technical standard, τ, depends on current expenditures and the accumulated stock in environmental sector,

$$\tau = F(I, A, r) \qquad (2.36)$$

where *r* is an index reflecting the current *technological regime* in pollution technology production (Pasche, 2000, pp.384) including all technological possibilities and goods currently known, regardless of whether they are produced in a positive quantity or not. He assumed that the higher the technical standard already is, i.e. the lower τ, the more expensive it is to improve the products and processes. This means that the function *F (I, A, r)* exhibits decreasing returns to scale in the long run, since *r* represents a set of technologies and in the long run the most effective technology is adopted. (He acknowledged that it is possible one technology from the given set of technologies has increasing returns to scale, but it is unlikely that this is true for the set of technologies.) A technological regime is assumed to change discontinuously by innovations, rather than by gradual improvements of existing technologies.

He shows that differentiating equation (2.36) with respect to time t and using equation (2.35) yields:

$$\dot{Y} \leq -\dot{\tau} = -\varepsilon_I \dot{I} - \varepsilon_A \dot{A} \qquad (2.37)$$

with $\varepsilon_I = (\partial F / \partial I)(I / \tau) < 0$ as the technology-output elasticity of the environmental capital stock *I* and $\varepsilon_A = (\partial F / \partial A)(A / \tau) < 0$ as the technology-output elasticity of current environmental expenditures. Depending on these elasticities and the growth rates of *I* and *A*, it is possible that there is sustainable growth. For $\dot{Y} < -\dot{\tau}$, it is also possible that emissions decrease with growth, i.e. the EKC hypothesis is possible. However, under the assumption of decreasing returns to scale in the function *F*, i.e. $| \epsilon_I | + | \epsilon_A | < 1$, there are limits for the decrease in τ in the long run within a given technological regime r. Sustainable growth requires a growing share of income for current environment-related expenditures and investment in environment-improvement to decrease the pollution technical standard, τ, i.e. reduce pollution from production. Hence, the share of purely consumptive expenditures decreases overtime. In the short run, in the case of the first attempts to decrease τ, the returns to scale may increase. In the case where better technology is increasingly adopted (structural change within a sector) constant returns of scale could be expected as the technical structure within the sector becomes stable.

Second, he rejected the possibility of sustainability through change in the structure of output alone. The economy can grow, but if emissions are restricted to remain constant, then the growth potential of the economy is limited, even though structural change will allow growth to continue for some finite period of time. To demonstrate this he set up the model using two sectors. He assumed emissions, *E*, to be proportional to the output Y_1, and Y_2 respectively: $E = aY_1 + bY_2$, $a>b>0$, which means sector 1 is relatively pollution intensive. If sector 1 decreases as sector 2 increases, the total level of output can rise with constant or reduced emissions. If there is no technical progress, then structural change would have to ensure that $\Delta E = a\Delta Y_1 + b\Delta Y_2 \leq 0$, $\Delta Y_2 \leq -\frac{a}{b}\Delta Y_1$, holds true during the growth process. Since $-a/b < 0$, this means that one sector can only grow if the other sector cuts output.

In the (Y_1, Y_2) space in figure 1, equation $E = aY_1 + bY_2$ is a linear emission restriction and the other curves are production possibility frontiers, which describe how much Y_2 has to be given up in order to produce one more unit of Y_1. In the case of strictly concave production possibility frontiers, the optimal output with a predetermined emission level will be a corner solution, i.e. only one sector produces.

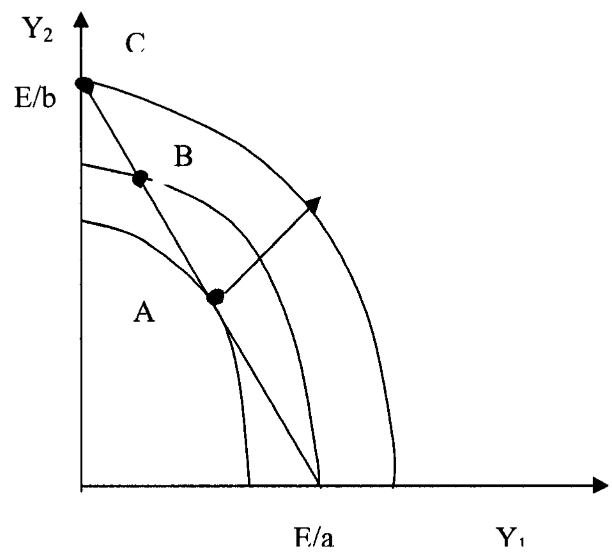

Fig. 2.1 Structure change with a linear emission restriction

Economic growth is a process that corresponds to an outward shift of the production possibility frontiers as shown in figure 2.1. Given the emission restriction line, economic growth follows a path from point A to point B, then to point C. In this process, the economic structure changes moving away from sector 1 to sector 2. Point C is the limit of long run growth. Only temporary growth with an accompanying structural change along the restriction line is possible.

In summary, he concluded that, only in the short run, environmental technical progress or structural change could lead to positive growth with a constant or even decreasing level of pollution. So, his model supports the existence of the EKC, at least in the short run. In the long run, the condition of a non-increasing emission level is violated by continued growth, and the EKC becomes N-shaped, as shown in figure 2.2. If the environmental constraint is binding the growth rate must converge to zero.

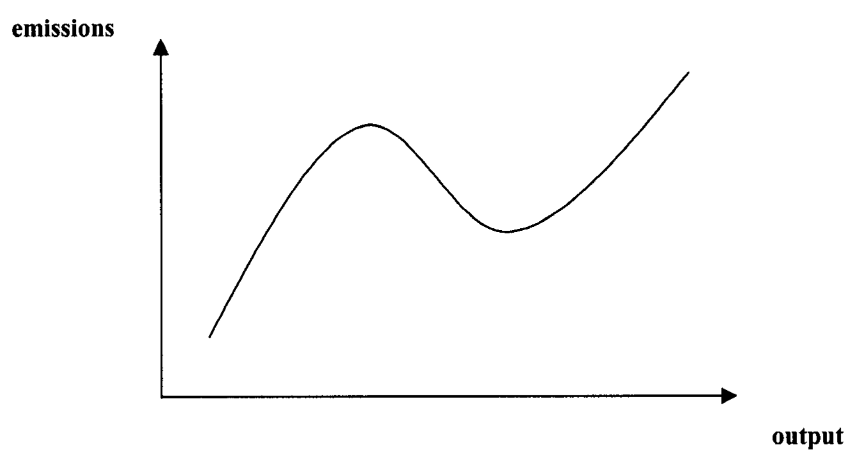

Fig. 2.2 An N-shaped Environmental Kuznets Curve

2.4 Empirical evidence for the EKC:

The empirical literature on the EKC has centered on two questions. First, does the Environmental Kuznets Curve actually exist and given it exists, where is the turning point? (Grossman and Krueger, 1993; Grossman and Krueger, 1995; Cole, Rayner, and

Bates, 1997; Holtz-Eakin and Selden, 1995) Second, what are the causes of the EKC? What particular variables contribute to explaining the income-pollution relationship? (Dinda, Coondoo, and Pal, 2000; Stern, 2002)

There are two approaches to estimate the relationship between per capita income and pollution levels. The first is to use reduced form equations, which relate the pollution level only to per capita income. The advantages of the reduced-form approach are that it directly gives the net effect of a nation's income on pollution and the data is easily collected. A limitation of the reduced-form approach is that it does not explain why the estimated relationship between pollution and per capita exists. Yet, this method can answer the first question of existence. The second approach is to model the theoretical structural equations relating environmental regulations, technology, and industrial composition to per capita income first, and then to estimate how the pollution level relates to environmental regulations, technology, and industrial composition. When econometric regression is used, it is called an econometric decomposition model. This method can provide an answer to the second question.

2.4.1 Existence of the EKC

Grossman and Krueger (1993) studied the relationship between economic growth and three types of air pollutant, sulfur dioxide, suspended particles and dark matter, in a cross-section of cities located in 42 countries in 1977, 1982 and 1988. The data came from the Global Environmental Monitoring System (GEMS)[9]. Using a simple regression analysis, the level of pollutant is explained as a function of per capita GDP in the country where the city is located, characteristics of the site and city, and a time trend. He found that for both (SO_2) and dark matter the concentrations increase with per capita GDP at low levels of national income, but decrease with per capita GDP at higher levels of income. The turning point comes somewhere between $4000 and $5000, measured in 1985 U.S. dollars. But the mass of suspended particles found in a given volume of air decreases monotonically with respect to per capita income.

Grossman and Krueger (1995) next examined the relationship between per capita income and four types of environmental indicators: urban air pollution, the state of oxygen regime in river basins, fecal contamination of river basins, and contamination of river basins by heavy metals. Using cross-country city level panel data from the Global Environmental Monitoring System in 1977, 1982 and 1988, they employed simple regression equations that relate the level of pollution in a country to a function of current and lagged income per capita in the country and to other covariates, such as dummy variables indicating the location of the monitoring station within the city (central city or suburban), the nature of the land use nearby the station (industrial, commercial, residential, or unknown), and population density of the city. The purpose of using these additional variables is to reduce the residual variance in the relationship between pollution and income and thus generate more precise estimates. They estimated the level

[9] Since 1976 the World Health Organization (WHO) has collaborated with the United Nations Environment Program in operating the Global Environmental Monitoring System (GEMS). The goal of this project has been to monitor closely the concentrations of several pollutants in a cross-section of urban areas using standardized methods of measurement.

of average income ("turning point"), above which environmental quality begins to improve. The "turning points" are found to vary for the different pollutants, but in almost every case these occur at a per capita income of less than US $8,000 (1985 dollars).

Cole, Rayner, and Bates (1997) tested the existence of EKC for different environmental indicators: total energy use, transport emissions of SO2, suspended particulate matter (spm), NO2, nitrates in water, traffic volumes, CFC emissions and methane using cross-country panel data. Their results suggested that an inverted U-shaped EKC only exists for local air pollutants, e.g. sulfur dioxide, spm, and carbon monoxide. In contrast, environmental indicators with a more global or indirect impacts, e.g. carbon dioxide, municipal waste, energy consumption and traffic volumes, either increase monotonically with income or have high turning points with large standard errors.

Dinda, Coondoo, and Pal (2000) re-examined the hypothesis of the EKC for two air pollutants, suspended particulate matter (spm) and SO_2. They used city-wise annual data on mean atmospheric concentration of spm and SO_2 for three periods (i.e. 1979-1982, 1983-1986 and 1987-1990) for 33 countries classified into low, middle and high income groups. The data were obtained from the World Development Report (World Bank, 1992). They used simple regression analysis and obtained results that do not uniformly support the EKC hypothesis. They obtained an inverse relationship between SO2 and PCGDP and a U-shaped relationship between spm and PCGDP, rather than an inverted U-shaped relationship, with an upward turn of the curve around a PCGDP level of US$ 12500 (in1985 prices).

2.4.2 Causes of the EKC

Several empirical studies have examined whether particular variables contribute to an explanation of the EKC. These including: the share of manufacturing in GDP, or changes in the output structure (Rock, 1996; Suri and Chapman, 1997), trade (Dieneke, et al, 1995; Suri and Chapman, 1997; Cole and Neumayer, 2002), energy prices (Unruh and Moomaw, 1996; de Bruyn et al., 1996), public R&D expenditures (Komen et al., 1997), and indicators of income inequality such as the Gini coefficient of income distribution (Torras and Boyce, 1996).

However, each of the above works only provides a partial explanation of the EKC. A more comprehensive analysis uses decomposition econometric models, which establish the theoretical model first, and then identify the factors that influence the level of emissions, i.e. decompose emissions into different explanatory variables. Dinda, Coondoo, and Pal (2000) empirically examined the hypothesis that pollution levels in an economy depend not only on the level of per capita GDP, but also on the sectoral composition of GDP, the technology used in production, and the time rate of growth of GDP, using the same data for spm and SO_2 as mentioned in 2.4.1. They defined the independent variables in their model as follows:

(i) The sectoral composition is represented as the ratio of industrial production to agricultural production. They supposed that a higher ratio of industrial production to agricultural production results in more pollution.

(ii) The technology used is represented by the capital-labour ratio. They supposed that the more capital-intensive the technology, the more likely it is to be more energy-intensive and hence more polluting. (However, coming to the effect of technology, it may be argued that between two countries with the same level of PCGDP, the one having a greater concern for pollution would have a higher capital-labour ratio, since a cleaner technology is likely more sophisticated, expensive and so capital intensive. So the effect of technology is ambiguous.)

(iii) Finally, the rate of growth of PCGDP may influence the pollution level since, *ceteris paribus*, a faster growth may commonly be achieved by exercising the option of using more polluting production practices.

The hypotheses they tested were: the marginal change in pollution level with respect to PCGDP is increasing in (i) the rate of growth of PCGDP, (ii) decreasing in time (iii) decreasing in the capital-labour ratio and (iv) decreasing in the industrial composition of GDP. To examine the possible partial effects the following model was specified:

$$y_{it} = \beta_0 + \beta_1 x_{it} + \gamma_1 p_1 + \gamma_2 p_2 + \delta_1 z_1 + \delta_2 z_2 + \eta_1 d_1 + \eta_2 d_2 + \theta_1 w_1 + \theta_2 w_2 + e_{it}$$

Where y_{it} is the pollution level of the pollutant being examined, x_{it} is PCGDP for i'th country in t'th period; p_1 and p_2 are dummy variables representing time period (i.e. $p_1 = 1$ for the period 1979-1982 and zero otherwise, $p_2 = 1$ for the period 1983-1986 and zero otherwise); d_1 is a dummy variable for capital intensity (i.e. $d_1 = 1$ for a country having capital-labour ratio greater than or equal to 1 and zero otherwise); d_2 is the dummy variable for the share of non-agricultural sector in GDP (i.e. $d_2 = 1$ for a country for which the non-agricultural sector accounts for 90% or more of GDP and zero otherwise); $z_j = x^*p_j$ $(j=1,2)$ are the income-time period interaction terms; $w_1 = x^*d_1$ is an income-capital intensity interaction term; $w_2 = x^*d_2$ is an income-share of non-agricultural sector interaction term; and e_{it} is the disturbance term.

Their results were that (i) the effect of capital intensity on pollution is negative, which suggested that more capital intensive technology is more environmental friendly; (ii) the effect of the sectoral composition on pollution is negative, which suggested that the more industrialized an economy is, the lower and flatter would be its pollution-PCGDP curve; (iii) the rate of growth is important in explaining observed pollution level of an economy, the faster the growth is, the more polluting is the economy.

Stern (2002) proposed specific categories for the causes of EKC. He proposed both proximate causes of EKC, changes in economic structure or output mix, input mix, and technology, as well as underlying causes such as environmental regulation, awareness, and education. He assumed that all these effects tend to counteract the gross impact of the scale effect. Increasing the *Scale* of production implies expanding production at given factor–input ratios, output mix, and state of technology. The scale effect is normally assumed to increase emissions proportionally so that a 1% increase in scale results in a 1% increase in emissions. In order to test the effects of these factors, he developed a non-linear emissions econometric decomposition model, which decomposes emissions into the proximate factors described above. He applied the model to a panel data set for sulfur emissions in 64 countries from 1973 to 1990. For the majority of countries, agriculture, industry, manufacturing, and services as a percentage of GDP from 1973 through 1989 are from UN National Accounts (United Nations, 1997). For a small number of countries in some years, data are from World Bank sources. For 1990, the World Development Report (World Bank, 1992) and other World Bank sources are used for most countries. For a few countries, whose data were missing for the year 1990 from both UN and World Bank sources, data are created by extrapolation. For the non-OECD countries energy use data is from Energy Statistics and Balances of Non-OECD Countries published by the International Energy Agency, (IEAa). For the OECD countries, the data are from Energy Balances of OECD Countries, published by the International Energy Agency, (IEAb).

Sulfur emissions data are obtained from A.S.L. and Associates (1997). GDP in real 1990 international dollars and population data come from the Penn World Table (Summers and Heston, 1991). (See Stern 2002 pp. 218 for more information)

The decomposed function is

$$S_{it} = f_i\,(y_{it}, x_{it}, A_{it}) \tag{2.38}$$

In country i in year t, S_{it} is the total emissions of sulfur, y_{it} is a vector of J types of outputs individually indexed by j, x is a vector of K types of inputs individually indexed by k, and A_{it} represents the state of technology. This technology index is not the conventional total factor productivity (TFP) index. Instead, it is an index of changes in sulfur emissions holding TFP and all other explanatory variables constant. He assumed that A_t is the same in all industries and all countries. He used a linear function of the inputs that is homogenous of degree one. This function form imposes the restriction that the elasticity of substitution between the different energy inputs in the production of sulfur emissions is infinite. This linear function is multiplied by a Cobb-Douglas function for the outputs. For the Cobb-Douglas form, homogeneity of degree zero implies that the coefficients of the outputs sum to zero. The model is specified to

$$S_{it} = \gamma_i A_t y_{Jit}^{(-\sum((j=1\ to\ J-1)\ a_j)} \prod_{j=1}^{J-1} y_{jit}^{a_j} (\sum_{k=1}^{K} \beta_k x_{xit}) \varepsilon_{it} \tag{2.39}$$

where a, β, γ and A are regression coefficients to be estimated and ϵ is disturbance term. In order to decompose the emissions to scale, technologies, output mix and input mix he did the following operations.

i) He divided all the output by aggregate output Y_{it} so that the output mix in the resulting decomposition is in terms of shares. Due to the zero degree homogeneity restriction this operation does not change the equality.

ii) He divided all the inputs by aggregate input X_{it} and multiplied the right hand side (RHS) of equation (1) by Xit.

iii) He also divided and multiplied the RHS by $TFP_{it} = Y_{it}/X_{it}$ and divide both sides by population, P_{it}.

These yields

$$\frac{S_{it}}{P_{it}} = \gamma_i \frac{Y_{it}}{P_{it}} \frac{A_t}{TFP_{it}} \left(\frac{y_{Jit}}{Y_{it}}\right)^{(-\sum((j=1 \text{ to } J-1)\, a_j)} \prod_{j=1}^{J-1} \left(\frac{y_{jit}}{Y_{it}}\right)^{a_j} \left(\sum_{k=1}^{K} \beta_k \frac{x_{xit}}{X_{it}}\right) \varepsilon_{it} \qquad (2.40)$$

Equation (2.40) decomposes emissions per capita into five components:

Y_{it}/P_{it}	Scale
A_t	Technology effects of emissions specific technical progress
$1/TFP_{it}$	Technology effects of overall technical progress
y_{jit}/Y_{it}	Output mix
x_{jit}/X_{it}	Input mix

In implementing the empirical study, first, he compared the decomposition model with the standard EKC model (the simple regression model with income determining emissions). He concluded that the decomposition model explains more of the variation in sulfur emissions per capita and has better statistical properties than the standard EKC model. Second, he found that there is no significant difference between the estimates of the parameters in the global decomposition model and models for OECD and non-OECD countries alone, which suggests that the model is basically well specified. Third, the model suggests that the role of output and input mix in changing global emissions is small, although they are statistically significant in the regression model. Increasing scale and countervailing clean technical progress are the most important factors driving changes in global sulfur emissions. The effects of input and output mix in individual countries vary widely. As a shortcoming, the model ignores non-energy inputs and the role of trade in generating emissions.

Coondoo and Dinda (2002) questioned the unidirectional causality of income leading to environmental change. They studied income-CO_2 emission causality based on a Granger causality test (GCT) using cross-country panel data on per capita income and the corresponding per capita CO_2 emission data for 88 countries from 1960 to 1990. The basic country-level time series data of PCGDP (in 1985 international prices) for the period 1950-1992 were taken from the PGDPCH series of the Penn World Table (Mark 5.6) available at http://www.nber.org/pwt5.6. The corresponding country-level annual time series data on PCCO2 (expressed in metric tonnes) for the period 1950-1996 were obtained from the Tables of National CO2 Emissions prepared by the Carbon Dioxide Information Analysis Center (CDIAC), Environmental Science Division, Oak Ridge National Laboratory (ORNL) of the USA.

GCT is a regression-based technique. For testing the null hypothesis that emissions x do not cause income y, the following autoregressive distributed lag regression equation is estimated:

$$y_t = \beta_0+\beta_1 y_{t-1}+\cdots+\beta_k y_{t-k}+\gamma_1 x_{t-1}+\cdots+\gamma_k x_{t-k}+\epsilon_t,\ t = 1,2,\ldots,T \qquad (2.41)$$

ϵ_t is the random disturbance term and $\beta_0, \beta_1, \ldots, \gamma_1, \gamma_2, \ldots$ are the regression parameters. If for this regression model H_0: $\gamma_1 = \gamma_2 = \cdots = \gamma_k = 0$ is rejected, it implies that emissions do cause income. Further, suppose the corresponding test of the null hypothesis that income causes emissions is rejected. Combining the two results, a unidirectional causality from emissions to income is obtained.

Their results indicate three different types of causality relationship holding for different country groups. For the developed country groups of North America and Western Europe (and also for Eastern Europe) the causality is from emissions to income. For the country groups of Central and South America, Oceania and Japan causality from income to emissions is obtained. Finally, for the country groups of Asia and Africa the causality is found to be bi-directional. The regression equations estimated as part of the GCT further suggest that for the country groups of North America and Western Europe the growth rate of per capita emissions has become stationary around a zero mean, and a shock in the growth rate of emissions tends to generate a corresponding shock in the growth rate of per capita income. If the emission rate is suddenly reduced, there will be a corresponding reduction in the income growth rate. The level of CO2 emissions of these countries is already very high accounting for 41.72% of the annual global emissions (Oak Ridge National Laboratory, CDIAC, 1998). In contrast, for the country groups of Central and South America, Oceania and Japan a shock in the income growth rate is likely to result in a corresponding shock in the growth rate of emissions. Finally, causality being bi-directional for the country groups of Asia and Africa, the income and the emission growth rates reinforce each other.

2.5 Further issues

Beyond the above introduction of studies on the EKC, there are still some other issues that deserve a mention. These are the difference between using time series data and cross-sectional data, the role of trade on EKC, and the difference between stock pollutant and flow pollutant.

2.5.1 Time series vs. cross-countries

One must be careful in interpreting the empirical results of EKC. Most empirical works use data for different countries for the same year. Most theoretical models interpret them as showing what will happen to environmental quality as income rises in a specific country over time. Unfortunately, we do not have a long enough time series of data to examine what happens to individual countries over time.

For different countries, it is probably justified to suppose that richer countries demand higher environmental quality while poor countries have a lower level of demand for environmental qualities. This is because it is generally accepted that environmental quality is a normal good and therefore the demand for it increases as income increases keeping other things constant. However, individual countries are very different from one another and there may be other factors that influence environmental quality. For instance, poor countries may tend to have very high population densities and rich countries may have low population densities. Low population density correlates with a high assimilative capacity of the environment, which is the environment's ability to naturally cleanse itself (Kolstad, 2000, pp. 248). Countries with high population density would have higher costs of providing environmental quality. This may enforce the income effect on demand for environmental quality from the supply side of environmental quality, i.e. environmental quality has higher potential price and lower demand in the poor countries. At the same time, it could be expected that, with the same income, one country may demand higher environmental quality just because the characteristics[10] of this country are combined with higher environmental assimilative capacity, and therefore, the price of the environmental quality is lower in this country.

Over time, for one country, environmental quality is determined by both supply and demand. The EKC is an equilibrium locus over time, where demand equals supply, but not only determined by income. The supply is determined by economic scale, technological progress and economic structure, while the demand of environmental quality can be highly related to income.

2.5.2 Trade and the EKC

Several of the EKC studies included trade variables, represented by an indicator of openness to trade. Whereas *ceteris paribus* openness might be expected to reduce environmental damage in both developing and developed countries (Grossman and

[10] Having lower density of population or natural characteristics, such as possessing more forests and being on the coast.

Krueger, 1991), trade itself may increase degradation of environmental quality in developing countries and reduce it in the developed countries. Kolstad (2000) used the Hecksher-Ohlin trade theory to interpret the effects of trade on the emissions in developing countries and developed countries. With a lower income level and therefore less demand for environmental quality, the value of environmental quality may be low in poor countries. A low price of environmental quality suggests that poor countries can provide relatively more environmental capacity and therefore they would specialize toward environment-intensive or "dirty" production, while the developed countries would specialize toward "clean" production. These specializations may explain part of the reduction in environmental degradation levels in the developed countries and increases in environmental degradation in lower income countries.

2.5.3 Stock pollutant vs. flow pollutant

Pollutants that accumulate over time are defined as stock pollutants whereas pollutants that quickly fade away are flow pollutants. Greenhouse gases that have residence time in the atmosphere of decades are classic examples of stock pollutants, as are chlorofluorocarbons (CFCs) that deplete the stratospheric ozone layer. Suspended particulate matters emitted into the atmosphere are flow pollutants since they settle out within a matter of hours or days (Kolstad, 2000, pp.165).

The decay of a flow pollutant is fast enough that the amount of it in the environment equals the amount emitted in the present period. So, the damage caused by a flow pollutant corresponds to the amount emitted. The decay of a stock pollutant is so slow that the pollutant emits faster than its decay, and therefore, the pollutant accumulates in the environment over time. The damage from stock pollutants comes from the stock of the pollutant, not just the amount emitted in the present period. Therefore, it is not possible to have much effect on the damage of a stock pollutant by adjusting emissions, at least in the short term. Further more, the damage of the emissions of a stock pollutant emitted in the present period will last for many periods. Compared to a flow pollutant, it is often the case that the cost of a stock pollutant is more difficult to internalize properly. This is so because the damage caused by this pollutant will be totally discovered only after many periods, and it is difficult to identify the damage caused by this pollutant over time.

Chapter 3: Economic models

3.1 A basic one-sector model

In this section the theoretical models presented by Stokey (1998) and Pasche (2002) are combined to explain the relationship between economic development and environmental quality. It is assumed that economic growth manifests itself in stages. In the same stage economic production adopts the same linear technology, while in different stages economic production adopts different technologies. The technology grows exogenously. This is different from Stockey's model, which stresses that the pollution level is determined by preferences and pollution technology changes continuously as the economy needs or prefers. The model developed here assumes that the production-pollution technology is exogenous. It acts as a changing constraint, interacting with preferences, to determine the relationship between pollution and income.

Figure 3.1 shows the pollution-income relationship in different stages of economic growth. The vertical axis P represents the amount of pollutant. The horizontal axis C or Y represents the consumption or income level (Assume all Y is consumed, i.e. Y=C and technology is exogenous). P_0 represents the environmental carrying capacity for the flow pollutant in question (for stock pollutant, P_0 is not a straight line, but it decreases as the pollutant accumulates). P_0 is an absolute binding constraint coming from the environment. OT_i represents production-pollution technology with $P_i = \beta i Y$, i.e. any output Y must be companied by an amount of $\beta i Y$ of the pollutant in stage i *(i=1,2,3,4,5, where i represents different stages of economic development)*. OT_1 represents the dirtiest production-pollution technology. OT_5 is the cleanest production-pollution technology, and it is assumed that the technology exogenously evolves from OT_1 to OT_5. It is assumed that OT_5 is an absolute binding condition on technology; further technical improvement is impossible. It is also assumed that there is one good, but this assumption does not influence the analysis since a bundle of goods can be aggregated into one good. Structural change of economy does not constitute a constraint for economic growth in the long run. Short run, structural change of the economy will be considered in the next section.

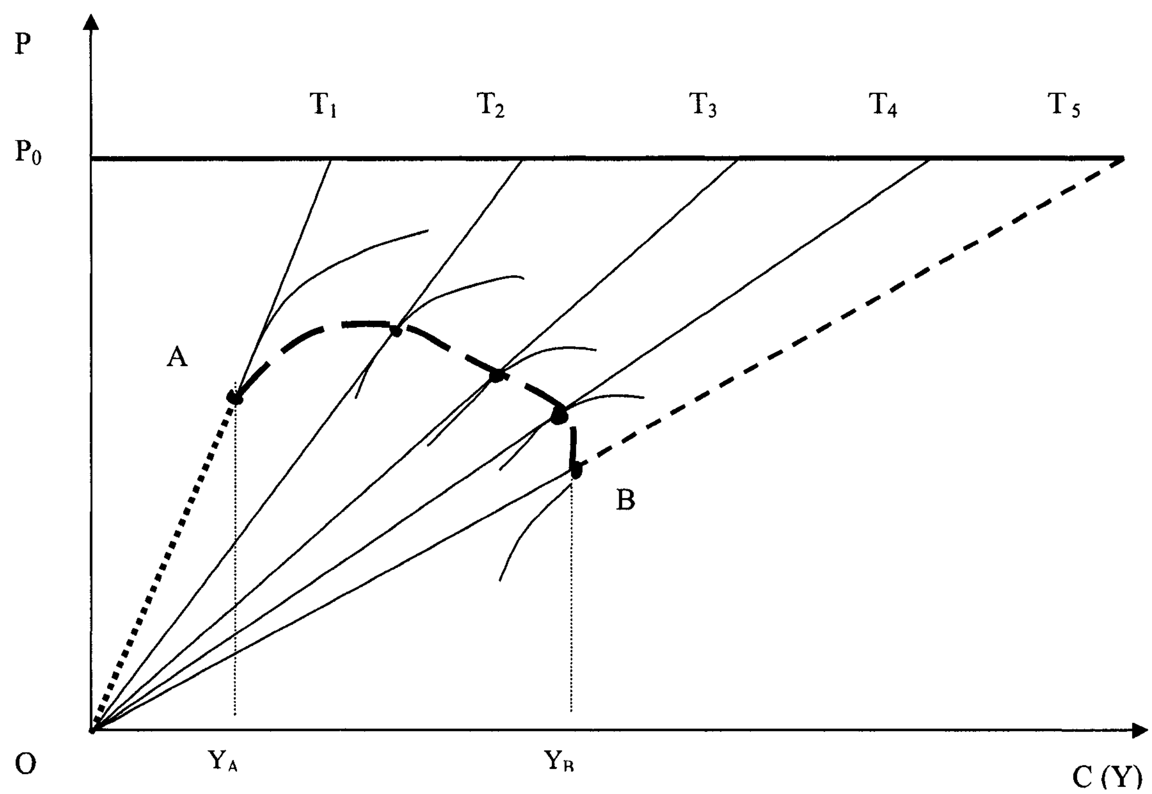

Fig. 3.1 An N-shaped pollution-income relationship

For convenience of analysis, three stages of development are defined, OA, AB and BT_5. First stage OA: Before point A, income level is low and pollution level is low. Consumers only care about their level of consumption. Pollution and income increase along line OA with the dirtiest technology OT_1. The income-pollution relationship shows purely causality from income to pollution.

Second stage AB: From point A, consumers begin to incorporate pollution into their utility function $U(C, P)$, $U_C > 0$, $U_P < 0$. Where consumers begin to incorporate pollution is related to the environmental carrying capacity for the pollutant in question. Given a production-pollution technology, consumers maximize their utility level by choosing C and P levels. If cleaner technology is easy to achieve, in other words, if from OT_1 to OT_5, the technology is flexible, the shape of AB is solely determined by the curvature of the utility function. How consumers incorporate the pollution into their utility function is related to the disutility (or damage) of the pollutant considered and the will of consumers to reduce the pollution (or environmental regulation). Both a monotonically decreasing (if the will to reduce the pollution is very strong) income-pollution relationship or an inverted U-shaped income-pollution relationship could be obtained. For an inverted U-shaped income-pollution relationship, the upward slopping segment represents the substitution effect is dominant. Consumers choose to increase consumption at the expense of environmental degradation. The downward slopping segment represents a dominant income effect. Consumers are willing to pay more for environmental improvement. The income-pollution relationship has dual causality. (The case for inflexible technology is analyzed later.)

Third stage BT_5: In this stage, there is no way to reduce pollution as the economy grows. Production grows along line OT_5, the cleanest production-pollution technology available. In this stage, it is assumed that society can choose a pollution level first, and then this level of pollution uniquely determines the level of economic development. In other words, the pollution level restricts economic growth. Along this segment, economic structure and consumers' preferences change with economic growth (See section 3.2).

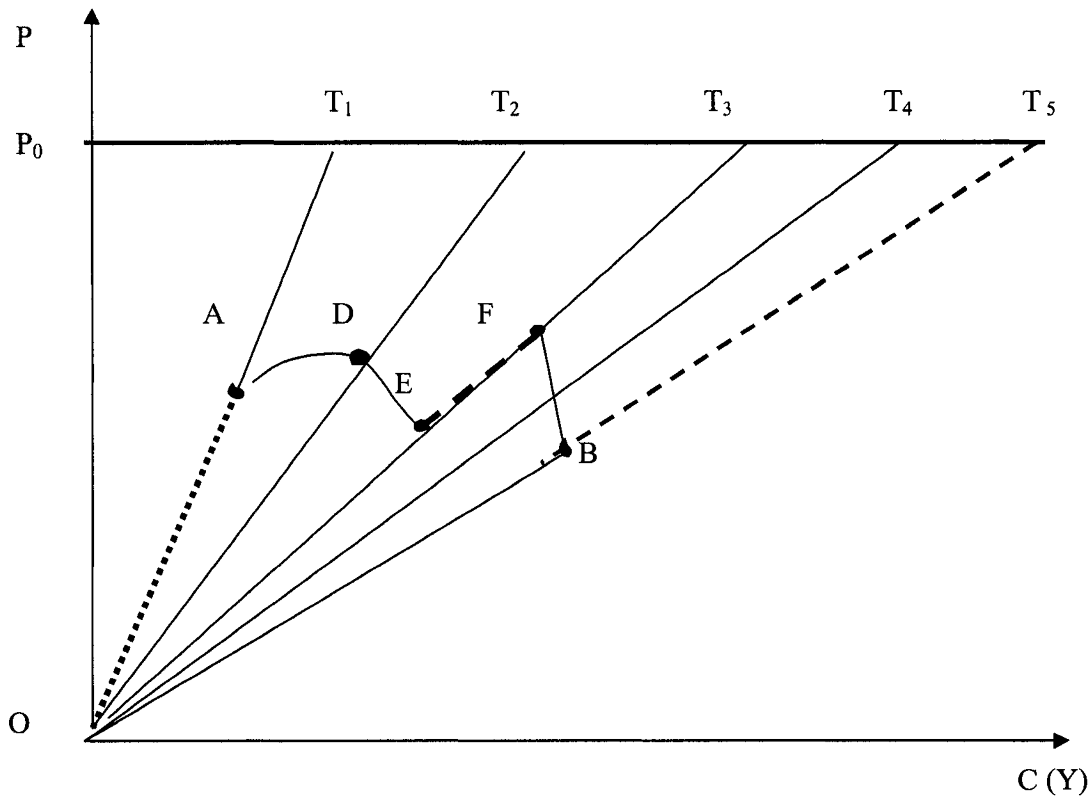

Fig. 3.2 Sub-stages of economic growth and income-pollution relationships

As a result, the income-pollution relationship is N – shaped. However, for the second stage, there are some sub-stages. Assume OT_3 represents the cleanest technology in the short run. In this period, OT_3 represents an "absolute" technological constraint and the economy develops along OT_3. The income-pollution relationship, therefore, is shown as the EF segment. At point F, a sudden release of technology constraint induces downward income-pollution relationship to point B. So, the shape of the income-pollution curve is highly related to the time period. ADE represents an inverted U-shaped income-pollution relationship, DEF represents a V shaped income-pollution relationship, and EFB represents an inverted V-shaped income-pollution relationship.

This result meshes the empirical results of different shapes of the income-pollution relationship for different pollutants. That is because the different characteristics of production-pollution technology constraints and environmental constraints for different pollutants in the same time period create different income-pollution relationships. This model also confirms the empirical results of Coondoo and Dinda (2002). The causality of income-pollution relationship could be expected to be different in developed and developing countries.

3.2 A two-sector model

In order to consider the effects of economic structural change on the income-pollution relationship, a two-sector model can be used. In this model, economic structure is defined in terms of the relative production levels of two outputs. This model can be used to show how changes in consumer preferences can induce a shift in economic structure as the economy grows. Sector 1 is relatively pollution intensive compared to sector 2. The emission level is a linear function of the output of the two sectors: $E = a\ Y_1 + b\ Y_2,\ a > b$

> 0, where parameters *a* and *b* represent production-pollution technology, and these are assumed to be constant during the period considered.

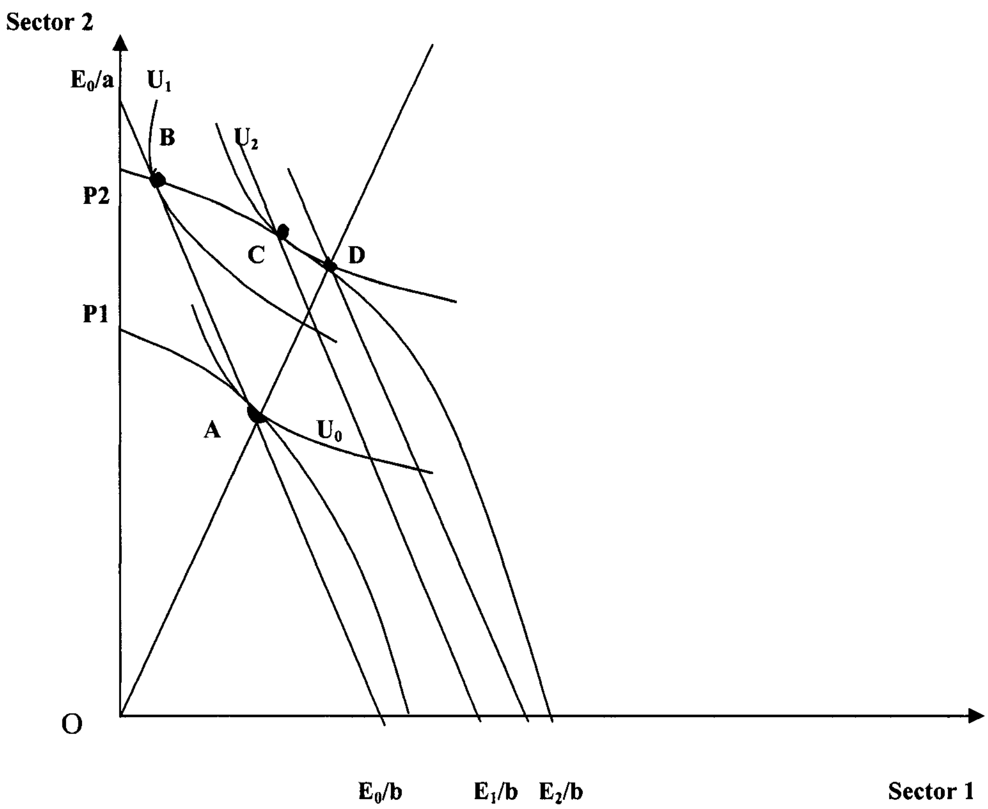

Fig. 3.3 The effect of structural change in the economy on emission level

When the economy is at level P_1 (P_1 is production possibility frontier, assumed to be strictly concave), the optimal production point is point A, where U_0 is tangent to P_1. The corresponding pollution level is E_0. Now suppose that the economy grows to production possibility frontier P_2. At the same time, there is a shift in consumer preferences. If the consumer's preferences do not change, the economy will produce at point D (It is due to the assumption that the curvatures of P_1 and P_2 are the same along OD line). Point D represents a production combination where the ratio of Y_1 and Y_2 does not change. The corresponding emission level is E_2. However, as the consumer's preferences change to

U_2, the optimal structure is defined at point C where U_2 is tangent to P_2 and the corresponding emission level is E_1. In this case, the change in preferences induces the change in economic structure from point D to C. This structural change in the economy causes a reduction of emissions from E_2 to E_1.

However, the effect of the structural change on pollution reduction is limited and it causes inefficiency in the economy. If the pollution level E_0 is aimed to be maintained, given the technology parameters a and b, economic growth could be realized only along a line AB. The economic structure changes correspondently. The highest production possibility frontier that could be reached is P_2 and the production point is B, where U_1 is tangent to emission constraint E_0. The structural change of the economy reduced the emission level from E_1 to E_0 at the expense of utility, which falls from U_2 to U_1. Another way to achieve point C with E_0 is to improve the production-pollution technology to a_n and b_n, satisfying $E_0/b_n=E_1/b$ and $E_0/a_n=E_1/a$.

This model can be used to explain the empirical results of Coondoo and Dinda (2002) that for the country groups of North America and Western Europe, the growth rate of emissions has become stationary around a zero mean, and a shock in the growth rate of emissions tends to generate a corresponding shock in the growth rate of income. Assume now that the technological parameters a and b represent the cleanest technology available for the developed countries, and E_0 is a level of pollution they do not want to exceed. Line AB then represents an absolute restriction for economic growth in this time period. The economy will choose a growth path along a line from A to B, accompanied by structural change. The growth rate of emissions is zero. Now, suppose there were technological change that would suddenly release the constraint of emissions, for example, a new technology a_n and b_n is available and it shifts the constraint to E_1/a and E_1/b, $E_1/a = E_0/a_n$ and $E_1/b = E_0/b_n$. The economy will jump to point C.

Chapter 4: Empirical results

One hypothesis of this thesis is that if a phenomenon exists at the macro-economic level, there should be a micro-foundation to explain it. With this in mind, industrial level data are used to test the relationship between pollution and economic development, where each of several industries are treated as individual economic units. The causal relationship between CO_2 emissions and GDP is tested at the industrial level in section 4.1. This is followed by a test of the effect of economic scale, preferences, economic structure, technology, and energy efficiency.

4.1 Causality tests

In this section, the causal relationship between GDP and CO_2 emissions is tested using the method proposed by Coondoo and Dinda (2002). However, the relationship is tested on a variety of manufacturing industries in Canada rather than for different countries.

4.1.1 Data[11]

Carbon Dioxide emission and real GDP data were obtained from the NAICS Carbon Dioxide Report by the Canadian Industrial End-use Energy Data and Analysis Centre. It is available from:

http://www.cieedac.sfu.ca/CIEEDACweb/mod.php?mod=pub&op=user&menu=1601

[11] The measurement of data can be found in the appendix 1.

The data ranges from 1990 to 2001 for 26 industries and more than 80 sub-industries in the Canadian manufacturing industry. 23 industries and sub-industries are selected. Most data are selected from industries whose NAICS end with three zeros. Some more narrowly defined sub-industries, whose NAICS end with two or one zero, are also used. The later is used to show the impact of using data of a more specific industry.

4.1.2 Regression model and results

Following Hamilton (1994), a Granger causality test is used (Granger, 1969). Our purpose is to test the causal relationship between two time-series variables x and y. If lagged values of a variable x have no explanatory power for any of the variables in a system, then x is viewed as weakly exogenous to the system (See Greene, 2000 p.657 and p.742). If variable x is weakly exogenous to the system, that means x does not cause any variable in the system.

Assume an autoregressive lag length $p = 1$ and estimate

$$x_t = c_1 + a_1 x_{t-1} + b_1 y_{t-1} + u_t \qquad (4.1)$$

by OLS. Conduct an $F(p, T\text{-}2p\text{-}1)$ test of the null hypothesis

$$H_0: \; b_1 = 0 \qquad (4.2)$$

If the null hypothesis cannot be rejected, there is evidence that a causal relationship from y to x may exist; otherwise, y does not cause x.

To calculate the sum of squared residuals from (4.1)

$$RSS_1 = \sum_{t=1}^{T} \hat{u}_t^{\,2} \tag{4.3}$$

and compare this with the sum of squared residuals of a uni-variable auto-regression for x_t

$$RSS_0 = \sum_{t=1}^{T} \hat{e}_t^{\,2} \tag{4.4}$$

Where $x_t = c_0 + a_0 x_{t-1} + e_t$ (4.5) is also estimated by OLS.

The test statistic is:

$$F \equiv \frac{(RSS_0 - RSS_1)/p}{RSS_1/(T-2p-1)} \tag{4.6}$$

If F is greater than the 5% critical value for an *F(p, T-2p-1)* distribution, then the null hypothesis that y does not cause x is rejected. With a lagged dependent variable in the regression, however, the test is valid only asymptotically (Hamilton, 1994).

Here the objective is to test the causality between CO_2 emissions and GDP at the level of the individual industries. The presumption for the EKC is that GDP causes CO_2, but not vice versa. As shown in chapter 3, at different stages of economic development, the relationship between CO_2 and GDP could be different. In the early stages of economic growth, there is a weak causal relationship or a one directional relationship with GDP causing CO_2. Later there is a restriction on CO_2 emissions and therefore CO_2 has feedback effects on GDP. However, if an innovation in technology takes place, and releases the restriction on CO_2 emissions, the causal relationship will be from GDP to CO_2. In the developed stage, the CO_2 emission restriction cannot be released. The causal relationship will be from CO_2 to GDP or bi-directional between CO_2 and GDP.

The model testing the causal relationship from GDP to CO2 is set up as follows:

$$CO2_t = c_1 + a_1 CO2_{t-1} + b_1 GDP_t + u_t \tag{4.7}$$

$$CO2_t = c_0 + a_0 CO2_{t-1} + e_t \tag{4.8}$$

With H_0: $b_1 = 0$, the test statistic is

$$F_{gc} \equiv \frac{(RSS_0 - RSS_1)/p}{RSS_1/(T-2p-1)} \tag{4.9}$$

Where $RSS_1 = \sum_{t=1}^{T} \hat{u}_t^{\,2}$ and $RSS_0 = \sum_{t=1}^{T} \hat{e}_t^{\,2}$. According to the data from 1990 to 2001, $T = 11$ while there is one restriction, so $p = 1$.

The model testing the causal relationship from CO_2 to GDP is set up as follows:

$$GDP_t = c_1 + a_1 GDP_{t-1} + b_1 CO2_{t-1} + u_t \tag{4.10}$$

$$GDP_t = c_0 + a_0 GDP_{t-1} + e_t \tag{4.11}$$

In equation (4.10) lagged CO_2 is used on the right hand side. That is because lagged CO_2 emissions are expected to have feedback effects on the current GDP if there is a causal relationship from CO_2 emissions to GDP.

With H_0: $b_1 = 0$, the test statistic is

$$F_{cg} \equiv \frac{(RSS_0 - RSS_1)/p}{RSS_1/(T-2p-1)} \tag{4.12}$$

Again, $RSS_1 = \sum_{t=1}^{T} \hat{u}_t^2$, $RSS_0 = \sum_{t=1}^{T} \hat{e}_t^2$, $T=11$, and $p = 1$.

Causality was tested for each industry and the results are reported in table 4.1. If F_{gc} is greater than the 5% critical value for an $F(p, T\text{-}2p\text{-}1)$ distribution, the null hypothesis that GDP does not cause CO_2 is rejected; that is, if F *is* sufficiently large, GDP does cause CO_2. The same is for the F_{cg} statistics. If F_{cg} is greater than the 5% critical value for an $F(p, T\text{-}2p\text{-}1)$ distribution, then the null hypothesis that CO_2 does not cause GDP is rejected; that is, if F *is* sufficiently large, CO_2 does cause GDP. At the 5% level, the critical value is $F(1, 8) = 5.32$.

From table 4.1 we see that for most industries there is no causality between GDP and CO_2 emissions in either direction if evaluated at a 5% level of significance. This casts some doubt on the effectiveness of using a simple regression of CO_2 emissions on GDP and therefore the simple uni-directional relationship with GDP causing CO_2 emissions. However, the time series is fairly short, so more data may have produced more significant results.

However, for three industries there is evidence that GDP causes CO_2 emissions: Petroleum and Coal Products Manufacturing (324000), Plastics and Rubber Products Manufacturing (326000) and Furniture and Related Product Manufacturing (337000).

And there are five industries for which CO_2 causes GDP: Wood Product Manufacturing (321000), Paper Manufacturing (322000), Non-Metallic Mineral Product Manufacturing (327000), Primary Metal Manufacturing, Non-Ferrous Metal (except Aluminium) Smelting & Refining (331410), and Fabricated Metal Product Manufacturing (332000).

Table 4.1 Causality tests between GDP and CO_2 emissions by industry

	NAICS	Industry	F_{gc}	F_{cg}
1	212000	Mining (excluding Oil and Gas)	0.018	1.964
2	212200	Metal Ore Mining	0.737	2.105
3	212210	Metal Ore Mining, Iron Ore Mining	0.535	0.069
4	311000	Food Manufacturing	3.271	1.326
5	312000	Beverage and Tobacco Product Manufacturing	0.655	0.766
6	313000	Textile Mills	0.367	0.859
7	314000	Textile Product Mills	3.704	2.255
8	315000	Clothing Manufacturing	4.407	3.226
9	316000	Leather and Allied Product Manufacturing	2.921	0.087
10	321000	Wood Product Manufacturing	0.154	5.485
11	322000	Paper Manufacturing	0.881	11.775
12	324000	Petroleum and Coal Products Manufacturing	6.123	0.973
13	325000	Chemical Manufacturing	0.339	0.489
14	326000	Plastics and Rubber Products Manufacturing	5.636	0.668
15	327000	Non-Metallic Mineral Product Manufacturing	2.646	5.627
16	331000	Primary Metal Manuf.	0.615	1.872
17	331410	Primary Metal Manuf., Non-Ferrous Metal (except Aluminium) Smelting & Refining	0.179	6.914
18	331500	Primary Metal Manuf., Foundries, Ferrous, Non-Ferrous	1.058	0.579
19	332000	Fabricated Metal Product Manufacturing	4.641	6.743
20	333000	Machinery Manufacturing	3.442	3.525
21	336000	Transportation Equipment Manufacturing	0.091	0.265
22	337000	Furniture and Related Product Manufacturing	7.079	1.721
23	339000	Miscellaneous Manufacturing	0.000	2.875

At the 10% level, the critical value is $F(1,8) = 3.46$. If the 10% level critical value is used, there would be three more industries pass the causality test from GDP to CO_2 emissions. The general results and implication would not be changed.

These results do not seem conclusive since there does not appear to be a pattern. One reason is that the time period could be too short. As seen in Chapter 3, the short run CO_2 and GDP relationship is highly related to which stage of economic development is being examined. Even so, these results support the hypothesis that there is no uniform causal relationship from GDP to CO_2 emissions for different industries. It could be due to the characteristics of the industries or the different levels of development of these industries. Therefore, the simple hypothesis of an inverted U-shaped EKC with GDP causing CO_2, as proposed in the early studies, is not supported, since there is no uniform causal relationship from GDP to CO_2 emissions. The discussion, therefore, should not be whether it is an inverted U-shaped, U-shaped, or other shape. With the presumption that the causality is uncertain, the next step is to explore the real factors behind GDP, which cause the change in CO_2 emissions.

4.2 The economy-environment mechanism

Several factors have been proposed that cause the changes in CO_2 emissions. In this section, these factors are tested using cross-industry data in Canada. As summarized in Chapter 2, there are several factors that might influence the amount of CO_2 emissions: economic scale, preferences, economic structure, technology, and energy input. Several indices are proposed that represent these effects to explain CO_2 emissions.

GDP is included as an explanatory variable, but it has an interpretation related to economic scale and preferences. GDP as an index includes, at least, two factors that could influence CO_2 emissions. The first is the scale effect. Higher GDP, ceteris paribus, represents larger economic scale and could induce more CO_2 emissions. A positive relationship between GDP and CO_2 emissions is expected. The second is an income effect or preference effect of GDP. GDP-squared is used to represent this. As income increases, the preference for a cleaner environment changes correspondingly. As GDP (i.e. income) increases, the industries have more money to invest in cleaner production technology, and they prefer cleaner production technology. It is assumed that the producers are the representative agents in the society, they are the producers of pollution and they are the consumers of the environment. Then the producers have responsibility, to some extent, for the environment. As their income increases, they would like to become more "generous" to the environment and expect to maintain higher environmental quality by their own actions and the actions of others. An example of this representative agents assumption involves citizens voluntarily recycle newspapers in Canada. They cannot benefit directly from their action. But they do benefit as a representative agent. It is also supposed that as income grows, preferences for a clean environment will grow faster, so that an increasing proportion of income will be spent on improving environmental quality. A negative relationship between GDP-squared and CO_2 emissions is expected. However, it is still a strong assumption that individual industry GDP-squared can be used to represent the preferences of society. However, it may be reasonable to suppose that the decisions of producers would reflect the preferences of society.

Structural change tends to decrease CO_2 emissions in the post industrialization stage, and this is expected to be the case in Canada from 1990 to 2001. Structural change is measured by the capital-labour ratio. A higher capital-labour ratio is hypothesized to be related to industries that are moving towards the use of high-value and information-intensive capital and hence are relatively clean industries. A negative relationship between the capital-labour ratio and CO_2 emissions is expected.

Improved technology is a factor that should lead towards an environmental improvement through cleaner production. So, a negative relationship between technology and CO_2 emissions is expected. However, there is no direct measure of technological progress so an index of progress is used, based on the Solow residual (Solow, 1957). By regressing[12] GDP on capital, labour, energy, material, and service inputs, a series of residuals are obtained. These residuals include information other than the inputs of capital, labour, energy, materials, and services that can explain the increase in GDP. It is usually interpreted as an index of technological progress.

The final factor is energy. The energy labour ratio is used and it is expected to have positive relationship with CO_2 emissions.

[12] In macroeconomic reports, total factor productivity (TFP) is not obtained by regression, but by subtracting some fixed proportions of the value of capital and labour inputs from the value of GDP, such as 0.36 times value of capital inputs and 0.64 times value of labour inputs.

4.2.1 Data

The data is a combination of two datasets. One is the productivity and input-output data, named KLEMS[13], obtained from the Micro-Economics Analysis Division of Statistics Canada. KLEMS contains data on Capital, Labour, Energy, Materials, Services and Output for 1961-1997. The other is the CO_2 emissions data, which were obtained from the Canadian Industrial Energy End-Use Data and Analysis Centre. The CO_2 emission data are available at: http://www.cieedac.sfu.ca/CIEEDACweb/index.php.

According to the Standard Industrial Classification (SIC)[14], these two data sets were combined to obtain data for 27 industries and sub-sectors of industries over the period from 1990 to 1997 with 189 observations. (In some cases there are missing observations for one or more variables. Those observations are deleted.) See appendix 2 for the industry detail.

4.2.2 Regression model and results

The empirical model is specified as follows:

$$CO2= \beta_0 + \beta_1 GDP+ \beta_2 GDP^2 + \beta_3 kl+ \beta_4 el+ \beta_5 tech+u \qquad (4.13)$$

13 The data set used in this study contains some series that are not generally released by Statistics Canada, because they are deemed to be of an unacceptable quality. The author bears sole responsibility for the results reported herein.

14 The North American Industry Classification System (NAICS) has replaced the Standard Industrial Classification system (SIC) as the standard for classifying industries in the updated dataset by Statistics Canada.

$\beta 0$ is the constant, kl is capital-labour ratio, el is energy-labour ratio, tech is a technology index, and u is an error term. Higher GDP represents larger scale and leads to more CO2 emissions, so $\beta 1$ is expected to be positive. GDP-squared represents the income or preference effect, and β_2 is expected to be negative. The capital-labour ratio is used to represent the environmental impacto of the technology of the industry. A higher capital-labour ratio means that cleaner technology is being used. Therefore, β_3 is expected to be negative. The energy-labour ratio should be directed related to CO_2 emissions. A higher energy-labour ratio causes more CO_2 emissions. Therefore, β_4 is expected to be positive. The technology factor should make the production more efficient, and hence cleaner. β_5 is expected to be negative.

Dinda, Coondoo, and Pal (2000) used the capital-labour ratio to represent technology. They supposed that the more capital-intensive the technology, the more likely it is to be more energy-intensive and hence more polluting. However, coming to the effect of technology, it may be argued that between two countries with the same level of PCGDP, the one having a greater concern for pollution would have a higher capital-labour ratio, since cleaner technology is likely more sophisticated, expensive and so capital intensive. So the effect of technology, represented by capital-labour ratio, is ambiguous. Here the capital-labour ratio is used to represent economic structure. This is a definition following Leontief (1970).

The energy-labour ratio is used for a similar reason as the capital-labour ratio. The relative use of energy would be a better index than an absolute use of energy to measure the efficiency of energy.

In order to use the technology factor, the Solow residual is obtained from the production function. The regression function is as follows:

$$GDP = \gamma_0 + \gamma_1 K + \gamma_2 L + \gamma_3 M + \gamma_4 S + \gamma_5 E + \epsilon \quad (4.14)$$

where K represents capital, L represents labour, M represents materials, S represents services, and E represents energy. The residual is used as the index of technology, denoted *tech*, which is the factor other than capital, labour, material, services, and energy that explains the level of output. The unit of GDP is millions of 1986 Canadian dollars, while the unit of inputs is thousands of 1992 Canadian dollars. The regression results are reported in table 4.2.

Table 4.2 Regression results: output as a function of inputs.

Source	SS	df	MS
Model	415215144	5	83043028.8
Residual	47588216.4	183	260044.898
Total	462803360	188	2461720.00

Number of obs =	189
F(5, 183) =	319.34
Prob > F =	0.0000
R-squared =	0.8972
Adj R-squared =	0.8944
Root MSE =	509.95

gdp	Coef.	Std. Err.	t	P>|t|
capital	.0003681	.000062	5.938	0.000
labor	.0010989	.0000578	18.995	0.000
energy	-.0001749	.0001414	-1.237	0.218
material	.0000799	.0000201	3.968	0.000
service	-.0006005	.000164	-3.661	0.000
_cons	395.6719	52.70503	7.507	0.000

This regression gives a R-squared 0.8972 and an F statistic with very small P-value. This means that, generally, this model fits well. The coefficients are significant with expected signs except for energy. The residuals from the regression in table 4.2 are used in the next regression, as a technology index, *tech*. The results are reported in Table 4.3.

Table 4.3 Regression results: determinants of CO_2 emissions.

Source	SS	df	MS
Model	1.5248e+09	5	304959653
Residual	1.1938e+09	183	6523761.73
Total	2.7186e+09	188	14460886.5

Number of obs = 189
F(5, 183) = 46.75
Prob > F = 0.0000
R-squared = 0.5609
Adj R-squared = 0.5489
Root MSE = 2554.2

co2emiss	Coef.	Std. Err.	t	P>|t|
gdp	2.463806	.3310863	7.442	0.000
gdp2	-.0002667	.0000523	-5.102	0.000
kl	-720.3972	294.5538	-2.446	0.015
el	9936.337	812.3727	12.231	0.000
tech	-2.565535	.4283698	-5.989	0.000
_cons	-2533.492	477.1405	-5.310	0.000

The F test is significant with a P value near zero. All the coefficients have the expected sign with very small P values. This suggests that statistically this model is well specified. This industrial level data is convenient to be used to test the effect of scale, preferences, structure, energy, and technology on CO_2 emissions. These factors explained about 55% of the variation of CO_2 emissions in this cross-section of Canadian industries.

In order to compare the effects of different explanatory variables, elasticities are calculated and reported in table 4.4. Elasticities for variable x are calculated by $\frac{\partial co2emiss}{\partial x} * \frac{\bar{x}}{\overline{co2emiss}}$. Variable x represents *gdp, gdp2, kl, el, and tech.* $\bar{x}$ is the mean of variable x. $\overline{co2emiss}$ is the mean of *co2emiss.* $\frac{\partial co2emiss}{\partial x}$ corresponds to the coefficients listed in table 4.3 for *gdp, gdp2, kl, el,* and *tech*, respectively. It may also be interesting to calculate the elasticity for GDP (including *gdp* and *gdp2*), that it (Coefficient of *gdp* +2*Coefficient of *gdp2** $\overline{gdp}$)* $\frac{\overline{gdp}}{\overline{co2emiss}}$.

Table 4.4 Elasticities of CO_2 emissions for different explanatory variables.

Variables	gdp	gdp2	GDP	kl	el
Elasticity	2.2591	-.7736	1.3729	-.2906	1.0871

Notice that the elasticity for variable *tech* is not calculated. That is because *tech* is represented by the residual, which has a mean of zero.

Another means that is able to compare the effect of different factors is to standardize the variables and re-run equation 4.2.1. The standardization procedure is to subtract the mean of each variable and divide it by its standard deviation. For example, the standardized variable X, denoted X_S, is obtained by $X_S = \frac{X - \overline{X}}{STD(X)}$. $\overline{X}$ is the mean of X. $STD(X)$ is the standard deviation of X. The regression results are reported in table 4.5.

Table 4.5 Regression results: standardized determinants of CO_2 emissions.

Source	SS	df	MS
Model	93.2976583	5	18.6595317
Residual	95.7023143	184	.520121274
Total	188.999973	189	.999999855

Number of obs = 189
F(5, 184) = 35.88
Prob > F = 0.0000
R-squared = 0.4936
Adj R-squared = 0.4799
Root MSE = .72119

sco2	Coef.	Std. Err.	t	P>|t|
sgdp	.8868612	.144853	6.122	0.000
sgdp2	-.6525451	.1451387	-4.496	0.000
skl	-.189057	.0556146	-3.399	0.001
sel	.5812907	.0553829	10.496	0.000
stech	-.145555	.0556125	-2.617	0.010

Notice that, the constant term dropped out after standardization. That is because by subtracting the mean from the dependant variable and explanatory variables, the information that could be explained by a constant is taken. This is according to the Frisch-Waugh-Lovell Theorem (See Davidson and MacKinnon, 2003, p. 63). The power of explanation fell to 48%, but the F statistic and coefficients remain highly significant. Now we can measure the scale, preference, structure, technology and energy effects separately and comparably. The coefficient estimated in the standardized regression now can be interpreted as the effect on CO_2 emissions of a one standard deviation change in the corresponding regressor. The effect on CO_2 is measured in deviations. The positive scale effect is the most important. For CO_2 emissions, the positive energy effect is also very important. The preference effect, represented by GDP-squared term, is the most important negative effect on CO_2 emissions. The effects of economic structure and technology are obvious but not as big as the other factors.

According to the regression results, a positive GDP term and a negative GDP-squared term are obtained. That is, the scale effect is positive, and the preference effect is negative. The relationship between CO_2 emissions and GDP is concave. But in the economic stage tested, the CO_2 emissions increase as GDP increases, since the elasticity of CO_2 emissions for GDP is 1.37. However, the preference coefficient is fixed in this model. Actually, it should change. Perhaps a varying parameter model can capture the effect of preferences better. It is possible that the coefficient of preferences increases as GDP increases and the negative effect of GDP exceed the positive effect of GDP.

The energy term has elasticity close to 1. For CO_2 emissions this result is reasonable since the amount of CO_2 emissions is directly related to the amount of energy used. Energy labour ratio is an important factor following GDP. Pursuing energy efficiency is a good political means to control CO_2 emissions.

The effects of structure and technology are apparent and negative. The input mix of capital and labour does have some effect on CO_2 emissions. And the technology does make the production cleaner if the Sollow residual used here can represent the technology.

At this industrial level, the effects of scale, preferences, structure, technology and energy are separated. The deviation in CO_2 emissions is a result of the "cooperation" of these factors. The early empirical study with only GDP and GDP-squared term as the explanatory variables and a pollutant as the dependent variable did not discover the true mechanism of how changes in income influence the deviations in pollution. Preferences, structure and technology factors are not only influenced by changes in income, but also by factors that are exogenously determined. Income alone cannot explain the evolution in pollution completely.

Chapter 5: Conclusion

There has been considerable theoretical and empirical research directed at understanding the relationship between the environment and economic growth. What is becoming evident is that the relationship is more complex then originally thought. The early 1990's empirical work that tested for the EKC relationship would be valid only if it is reasonable to presume unidirectional causality between GDP and CO2 emissions with GDP causing CO2 emissions. Stern (2002) cast doubt on this, as did the results of Coondoo and Dinda (2002) who studied income-CO_2 emission causality based on a Granger causality test. Their results indicate three different types of causality relationship holding for different country groups. This leaves open the question of whether there are different causal relationships at different economic stages and why.

To help answer the question whether or not, a one-sector model and a two-sector model were presented. The models stressed the technological constraints in the process of economic development, which interact with preferences to generate the curve. The causality relationship between GDP and pollution was shown not to be unidirectional. Causality is determined by the stage of economic development, and the corresponding constraints to development and environmental capacity. The effect of structural change in an economy on the relationship between GDP and pollution is also analyzed. Using the models developed in this thesis, the empirical phenomena studied by Coondoo and Dinda (2002) can be explained. To answer the question why, the theoretical models analyzed the reasons such as economic scale, technological progress, preferences, economic structure, and environmental capacity in the determination of the GDP and pollution relationship. This provides a microeconomic foundation for the relationship.

The theoretical analyses were followed by two empirical studies in order to test the micro foundation of the EKC relationship. Industrial level data from Canadian manufacturing industries were used and each manufacturing industry was taken as an individual economic agent. This was different from all previous empirical studies, which used national or city level data. The first study tested the causal relationship between GDP and CO_2 emissions. Using a Granger causality test, the results did not provide evidence to support the hypothesis of a unidirectional causal relationship. In only 3 of 23 industries was there evidence supporting causality from GDP to CO2 emissions. In only 5 industries was there evidence supporting causality from CO2 emissions to GDP. However, some regularity for the causal relationship was found. There were many limitations of this test. First, the data spanned a relatively short period from 1990 to 2001. Second, because of the limitation of the data, a simple F test was used to test if the lagged variables of GDP have explanatory power on CO_2 emissions or vice versa. Only a one period lag was used since the series were short.

The second study tested the hypothesis that CO_2 emissions are determined by economic scale, preferences, economic structure, technology, and energy input. GDP was used to represent economic scale. GDP-squared was used to represent the evolution of preferences. The capital-labour ratio was used to represent the structure of industrial production. The energy-labour ratio was used to represent the efficiency of energy use in production. A technological index was obtained using the Solow residual. All the variables were statistically significant with expected sign. The CO_2 emission-mechanism model explained 55% of the variation of the CO_2 emissions with economic scale, preferences, economic structure, energy input, and technology.

This work could be extended in four directions. First, there may be other explanatory variables that would improve the explanatory power of the model. For example, an industrial specific index could improve the explanatory power when cross-sectional data were used; an environmental policy variable could be important. Second, the variables used to represent the factors, economic scale, preferences, economic structure, energy efficiency, and technology, could be improved, especially for the technology indices. The technology indices used in this thesis were obtained using cross-sectional data. It would be better if long run time series data were used. Third, the model could be specified as varying parameter model in order to capture the change in preferences. Fourth, this method could be used to study other pollutants to obtain more evidence for the validity of a micro-foundation model. Of course, the improvement of data is very important.

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Appendix 1: Units of measurement for the variables

CO_2 emission and GDP data were obtained from Carbon Dioxide Report by the Canadian Industrial End-use Energy Data and Analysis Centre.

CO_2 emissions are measured in tonnes.

GDP is measured in millions of 1986 Canadian dollars.

The input data were obtained from the Statistics Canada productivity and input-output dataset, named KLEMS, from the Micro-Economics Analysis Division of Statistics Canada.

The value of capital, labour, energy, material, and service inputs are measured in thousands of 1992 Canadian dollars.

Appendix 2: Industry detail with SIC

Quarry and sand pit industries (8)
Tobacco products industries (12)
Rubber products industries (15)
Plastic products industries (16)
Clothing, hosiery industries (24)
Poultry, meat and meat prod. ind.(101)
Fruit and vegetable industries (103)
Dairy products industries (104)
Biscuit industry, Bread and other bakery products industry (107)
Veneer and plywood industries (252)
Pulp and paper industries (271)
Primary steel industries (291)
Steel pipe and tube industry (292)
Iron foundries (294)
Non-ferrous metal smelting and refining ind. (295)
Aluminum rolling, casting and extruding ind. (296)
Copper and alloy roll., cast. and extr. ind. (297)
Oth. roll., cast & extr. non-ferr. met. prod. ind.(299)
Motor vehicle industry (3231)
Motor vehicle parts and accessories ind. (325)
Hydraulic cement industry (3521)
Glass and glass products industries (356)
Industrial chemicals industries n.e.c.(371)
Gold mines (611)
Iron mines (617)
Asbestos mines (621)
Salt mines (625)