The Environmental Kuznets Curve and Convergence of Sulfur Emissions in OECD Countries : Analysis Based on the Green Solow Model

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Abstract

This paper investigates the relationship between economic growth and the environment based on the Green Solow model. We observed the resemblance of the shapes of the environmental Kuznets curve between per capita GDP and sulfur emissions for 17 OECD countries. Using cross-national panel data, the convergence of sulfur emissions per capita for 25 OECD countries was analyzed. Overall, a conditional convergence in sulfur emissions per capita for the 25 OECD countries was confirmed. The speed of convergence in the neighborhood of the balanced growth path was estimated to be 16.7 percent a year during the period from 1950 to 1973 and 7.3 percent a year during the period from 1974 to 2000.

JEL Classification : O41, Q53, Q56

Keywords : Green Solow Model, Conditional Convergence in Emissions, Environmental Kuznets Curve

1. Introduction

Environmental degradation associated with economic activities is an important issue that society cannot ignore. Air pollution, in particular, is an actively discussed topic in the context of the global economy. When we consider such an issue, the fact that the state of the economy in a country changes with time needs to be noted. Thus, in an attempt to study the relationship between economic development and the environment, dynamic models need to be constructed. Then, arguments can be developed based on the constructed model. Hence, in this paper we examine the link between macroeconomic performance and environmental pollution from the viewpoint of a model of economic growth. From this we then aim to present new empirical evidence regarding pollutant emissions associated with long-term economic growth.

A major trend for empirical research in environmental economics has been the hypothesis of the environmental Kuznets curve (hereinafter, EKC).¹ In general, research into the EKC examines the inverted U-shaped relationship between per capita GDP and an environmental pollution index using regression analysis. Reports dealing with the EKC include Selden and Song [19], Holtz-Eakin and Selden [12], Grossman and Krueger [11], and Bhattarai and Hammig [6]. These researchers verified whether the hypothesis of the EKC was supported or not by utilizing various data sets.

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¹ See, for example, Stern [22], Dasgupta, Laplante, Wang and Wheeler [8], and Dinda [9] as review articles on the environmental Kuznets curve.

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Selden and Song [19] examined the emissions of sulfur dioxide (SO_2), suspended particulate matter (SPM), nitrogen oxide (NO_x) and carbon monoxide (CO). Holtz-Eakin and Selden [12] explored the amount of carbon dioxide (CO_2) emissions caused by fossil fuels and cement production. Grossman and Krueger [11] analyzed aspects of air and water pollution such as SO_2 density, SPM, and cadmium density in rivers. Bhattarai and Hammig [6] focused on the relationship between income and deforestation.

On the other hand, many recent theoretical studies have examined the relationship between economic performance and the environment in the context of models of economic growth. The major studies in the field include those of Gradus and Smulders [10], Aghion and Howitt [1], and Stokey [24]. Gradus and Smulders [10] suggested there is a tendency that when the deterioration of the environment has a negative effect on human capital formation, a country with lower level of tolerance of pollution should have higher rate of long-term economic growth. Aghion and Howitt [1] examined the existence of a growth path, such as an increase in the consumption level and environmental improvement in the context of a research and development (R&D) based endogenous growth model. Stokey [24] demonstrated a mechanism for the occurrence of the EKC, and noted that raising welfare in a country that has already experienced a certain level of economic development requires a reduction in emissions even if the level of production falls as a result.

It is noteworthy that in environmental studies related to economic growth, theoretical and empirical analyses have generally been conducted separately. One exception is Brock and Taylor [7], who constructed a model by extending Solow's [21] framework and called it the Green Solow model. Brock and Taylor [7] focused on 22 member countries of the Organisation for Economic Co-operation and Development (OECD), and examined the convergence properties of CO_2 emissions in those countries.² Using cross-sectional data, they found that the CO_2 emissions of these 22 OECD countries tended to converge to the same level in the long term.

In the present paper, we extend the discussion in Brock and Taylor [7], and examine the long-term properties of the relationship between economic growth and sulfur emission. The sulfur emission is seen as closely related to the economic activity of industry and represents an important index for determining air pollution.³ Moreover, this paper analyzes an interesting implication of Brock and Taylor's [7] model where the EKC is theoretically derived under certain conditions. Specifically, we investigate the empirical evidence of the EKC for 25 OECD member countries using long-term time series data. Though there are many reports on the EKC, as described in Osaka [18], most have verified using samples of cross-country data, while there are few reports considering long-term time series data by country. Therefore, it is of great interest to examine the EKC by applying time series data. To address this issue, we use a nonparametric regression method. As well, we apply a panel analysis method to test convergence in the sulfur emissions of the Brock and Taylor's [7] model, unlike the cross-section analysis they used. Consequently, we find that the present paper complements and extends earlier studies.

The results we obtain are as follows. We confirm the shape of a rough reversed-U relationship between per capita GDP and sulfur emissions for 17 countries: Austria, Belgium, Canada, Denmark, Finland, France, Ireland, Italy, Japan, the Netherlands, Norway, Republic of Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Using a panel analysis, we also find that there is conditional convergence of sulfur emission per capita for the 25 OECD countries studied.

² By extending the Green Solow model, Ohkuma and Noda [16] examined the convergence of CO_2 emissions in samples of developed and developing countries. They showed that when controlling for the determinants of the per capita CO_2 emission of each country on a balanced growth path, a country for which the per capita CO_2 emission level is initially far from the value on a balanced growth path has a higher growth rate of per capita CO_2 emissions.

³ See, for example, Okamoto and Ichikawa [17].

This suggests that each country's per capita sulfur emissions tend to approach that country's specific level on a balanced growth path and that per capita sulfur emissions are likely to take various values in the long-term.

The remainder of the paper is organized as follows. Section 2 gives a description of the basic setup of the Green Solow model and its implications. In Section 3, we examine the relationship between economic growth and the environment from an empirical perspective. Finally, in Section 4 we summarize the main results and conclude.

2. The Green Solow Model

Consider a closed economy in which the homogeneous good of $Y(t)$ at time t is produced by using physical capital of $K(t)$ at time t and labor by person-hours of $L(t)$ at time t , given the present state of technological knowledge $B(t)$ at time t . The aggregate production function is specified as

$$Y(t) = K(t)^\alpha [B(t)L(t)]^{1-\alpha}, \quad (1)$$

where α is a parameter and we impose the restriction $0 < \alpha < 1$.

In the present model, we simplify this by assuming that all representative agents participate in the labor market, and we normalize everyone's amount of working hours to one. Hence we can regard the amount of total labor as the total population of a country. Here we assume that the total population grows at an exogenous constant rate $n \geq 0$ over time, given the initial level $L(0) \equiv L_0$. We also assume that the initial level of technological knowledge is given as $B(0) \equiv B_0$ and that technological knowledge grows at an exogenous constant rate $g \geq 0$ over time. Therefore, the state of technological knowledge at time t is given by $B(t) = B(0)e^{gt}$. We call g the rate of progress of general technology.

Suppose that an exogenous constant fraction $\theta \in (0, 1)$ of the total output is required as the resource for environmental improvement activities. In this setting, θ can be interpreted as the index of the country's effort level for environmental improvement. For convenience, we refer to the difference between total output and the cost for abatement of pollutant emissions $(1 - \theta)Y(t)$ as the environmental cost-adjusted GDP. In the model, because of the care taken for the environment and technological progress related to emissions reduction, the amount of pollutants as production side effects can be reduced somewhat. Let $g_A \geq 0$ be the technological progress rate in environmental fields, which is given exogenously and is a constant value over time.

Here, the amount of pollutant emissions $Q(t)$ is defined by

$$Q(t) = \Omega(t)Y(t)(1 - \theta)^\varepsilon, \quad (2)$$

where $\Omega(t) = \Omega(0)e^{-g_A \cdot t}$ and ε is a positive parameter. Note that the term $\Omega(t)$ in Eq. (2) reflects the effect of technological progress in the reduction of emissions. Because $\theta Y(t)$ is used for the abatement of pollutant emissions, $(1 - \theta)Y(t)$ is available for consumption $C(t)$ or gross investment in physical capital $I(t)$. Here, we use the symbol s_k to denote the portion of environmental cost-adjusted GDP allocated to such an investment, and assume that $s_k \in (0, 1)$ is an exogenous constant over time. Then, the gross investment of the economy becomes $s_k(1 - \theta)Y(t)$. We also assume that the depreciation rate for physical capital is a constant $\delta > 0$ over time.

In the present model, the net increase in the physical capital stock is equal to the amount of gross investment in physical capital from which depreciation has been deduced. Therefore, the following relation holds.

$$\begin{aligned} \dot{K}(t) &= I(t) - \delta K(t) \\ &= s_k(1 - \theta)K(t)^\alpha [B(t)L(t)]^{1-\alpha} - \delta K(t), \end{aligned} \quad (3)$$

where $\dot{K} \equiv dK/dt$. Throughout this paper, a dot notation denotes a variable for which the deriva-

tive of the variable is given with respect to time. If we divide both sides of Eq. (3) by the effective amount of labor $B(t)L(t)$, after some manipulation, we obtain

$$\frac{\dot{\hat{k}}(t)}{\hat{k}(t)} = s_k(1-\theta)\hat{k}(t)^{-(1-\alpha)} - (n+g+\delta), \quad (4)$$

where $\hat{k}(t) \equiv K(t)/[B(t)L(t)]$. Using Eqs. (1), (2), and (4), we obtain

$$\frac{\dot{Q}(t)}{Q(t)} = \alpha s_k(1-\theta)\hat{k}(t)^{-(1-\alpha)} - [\alpha(n+g+\delta) - \chi], \quad (5)$$

where $\chi \equiv g+n-g_A$. From Eq. (5), it is apparent that the growth rate of pollutant emissions depends on the difference between $\alpha s_k(1-\theta)\hat{k}(t)^{-(1-\alpha)}$ and $\alpha(n+g+\delta) - \chi$.

Here we note that the balanced growth path is one denoting the state in which all variables grow at a constant rate. The Green Solow model implies that $c(t) \equiv C(t)/L(t)$, $k(t) \equiv K(t)/L(t)$, and $y(t) \equiv Y(t)/L(t)$ are consistent with the rate of progress of general technology g in the balanced growth path. Hence, if the growth rates of consumption per capita, physical capital stock per capita, and the amount of production in the balanced growth path are represented as g_c , g_k and g_y , respectively, then $g_c = g_k = g_y = g$.

We now consider a situation in which the growth rate in consumption per capita is a positive and the growth rate of pollutant emissions per capita is a negative in the balanced growth path. Brock and Taylor [7] defined such a situation as the sustainable growth path. The growth rate of pollutant emissions in the balanced growth path is given by

$$\frac{\dot{Q}(t)}{Q(t)} = g + n - g_A. \quad (6)$$

Eq. (6) indicates that if $g_A > g+n$, then the growth rate of pollutant emission is a negative value in the balanced growth path. On the other hand, if $g_A < g+n$, then the growth rate of emissions is a positive value. The dynamics of the model in the cases of $g_A > g+n$ and $g_A < g+n$ are shown in Figures 1 and 2, respectively.

In Figures 1 and 2, physical capital per unit of effective labor corresponding to the intersection of the $\alpha s_k(1-\theta)\hat{k}(t)^{-(1-\alpha)}$ curve and the $\alpha(n+g+\delta)$ line is represented by $\hat{k}_*$. Additionally, the physical capital per unit of effective labor corresponding to the intersection of the $\alpha s_k(1-\theta)\hat{k}(t)^{-(1-\alpha)}$ curve and the $\alpha(n+g+\delta) - \chi$ line is represented as $\hat{k}_{**}$.

From Figures 1 and 2, we ascertain relationships between the per capita output and pollutant emissions shown in Figures 3 and 4, respectively.

In Figures 3 and 4, $y_* \equiv B\hat{k}_*$ and $y_{**} \equiv B\hat{k}_{**}$. Note that the inverted U-shape association between per capita output and pollutant emissions shown in Figure 3 denotes the EKC. Generally, the hypothesis of the EKC implies that the environment tends to worsen in the early stages of

Figure 1. Dynamics of the Green Solow model when $g_A > g+n$

 Figure 2. Dynamics of the Green Solow model when $g_A < g + n$

 Figure 3. The relationship between emissions and output per capita when $g_A > g + n$

 Figure 4. The relationship between emissions and output per capita when $g_A < g + n$

economic development and, subsequently, after the economy has somewhat matured, the environment might improve concomitant with development. As shown in Figure 4, the Green Solow model suggests that the inverse U-shaped relation between per capita output and pollutant emissions is not a general property. In other words, there are various shapes in terms of the relationship between per capita output and pollutant emissions, depending on the relative values of the growth rates of the variable and the parameters. Hence, from the viewpoint of the Green Solow model, it is possible that statistical analysis may often not observe a U-shaped relation for the EKC. Thus, to investigate the link between economic growth and the environment, Brock and Taylor [7] proposed a different view from the traditional regression approach regarding the EKC hypothesis. Specifically, Brock and Taylor [7] presented an alternative method, applying the convergence

approach of Barro [2], Barro and Sala-i-Martin [3], [4], [5], Mankiw, Romer, and Weil [15], and others.

Based on the above discussion, we derive the convergence equation in emissions developed by Brock and Taylor [7]. In the balanced growth path, we find that $\dot{\hat{k}}(t)/\hat{k}(t)=0$. Further, from Eq. (4), the physical capital per unit of effective labor in the balanced growth path is derived as

$$\hat{k}_*(t) = \left[\frac{(1-\theta)s_k}{n+g+\delta} \right]^{\frac{1}{1-\alpha}}. \quad (7)$$

Therefore, if we define $\hat{y}(t) \equiv Y(t)/[B(t)L(t)]$, then the value of its natural logarithm $\ln \hat{y}_*(t)$ is given by

$$\ln \hat{y}_*(t) = \frac{\alpha}{1-\alpha} \ln s_k + \frac{\alpha}{1-\alpha} \ln(1-\theta) - \frac{\alpha}{1-\alpha} \ln(n+g+\delta). \quad (8)$$

Here, if we take a first order Taylor expansion of the right-hand side of Eq. (4) around $\ln \hat{k}_*$, then we obtain the following equation.

$$\frac{\dot{\hat{k}}}{\hat{k}} \cong -(1-\alpha)(n+g+\delta) \ln \left(\frac{\hat{k}}{\hat{k}_*} \right). \quad (9)$$

Using Eq. (9) and $\hat{y} = \hat{k}^\alpha$, we obtain

$$\frac{d \ln \hat{y}(t)}{dt} = -\lambda \cdot \ln \left[\frac{\hat{y}(t)}{\hat{y}_*} \right], \quad (10)$$

where $\lambda \equiv (1-\alpha)(n+g+\delta)$. Hence, we obtain $\lambda = -\partial(\hat{y}/\hat{y})/\partial \ln \hat{y}$. The term λ in Eq. (10) is often referred to as the convergence coefficient in the neighborhood of the balanced growth path, which determines the speed of convergence from $\hat{y}$ to $\hat{y}_*$ in the neighborhood of the balanced growth path. Solving Eq. (10) yields

$$\ln \hat{y}(t) = (1 - e^{-\lambda t}) \ln \hat{y}_* + e^{-\lambda t} \ln \hat{y}(0). \quad (11)$$

Recall that the relationship between pollutant emissions and GDP is given by Eq. (2). Dividing both sides of Eq. (2) by $L(t)$, the equation of term per capita is given by

$$q(t) = \mathcal{Q}(t)y(t)(1-\theta)^\varepsilon, \quad (12)$$

where $q(t) \equiv Q(t)/L(t)$. From Eqs. (10) and (12), we obtain

$$\frac{d \ln \hat{q}(t)}{dt} = -g_A - \lambda \cdot \ln \left[\frac{\hat{q}(t)}{\hat{q}_*(t)} \right], \quad (13)$$

where $\hat{q}(t) \equiv Q(t)/[B(t)L(t)]$ and $\hat{q}_*(t)$ denotes $\hat{q}(t)$ on the balanced growth path. Given $\mathcal{Q}$, from Eq. (13), the relation of $\lambda = -\partial(\hat{q}/\hat{q})/\partial \ln \hat{q}$ holds. Hence, we can also regard λ as the parameter reflecting the speed of convergence of pollutant emissions in the neighborhood of the balanced growth path.

Using Eqs. (8), (11), and (12), after some manipulation, we obtain

$$\begin{aligned} \ln \left[\frac{q(t)}{q(t-1)} \right] &= (g - g_A) + (1 - e^{-\lambda}) \left[\ln(B_0 \mathcal{Q}_0) + \left(\frac{\alpha}{1-\alpha} + \varepsilon \right) \ln(1-\theta) - (g - g_A) \right] \\ &\quad + (1 - e^{-\lambda})(g - g_A)t - (1 - e^{-\lambda}) \ln q(t-1) + (1 - e^{-\lambda}) \frac{\alpha}{1-\alpha} \ln s_k \\ &\quad - (1 - e^{-\lambda}) \frac{\alpha}{1-\alpha} \ln(n+g+\delta). \end{aligned} \quad (14)$$

Eq. (14) can be rewritten as

$$\begin{aligned}
\ln q(t) = & (g - g_A) + (1 - e^{-\lambda}) \left[\ln(B_0 \Omega_0) + \left(\frac{\alpha}{1 - \alpha} + \varepsilon \right) \ln(1 - \theta) - (g - g_A) \right] \\
& + (1 - e^{-\lambda})(g - g_A)t + e^{-\lambda} \ln q(t-1) + (1 - e^{-\lambda}) \frac{\alpha}{1 - \alpha} \ln s_k \\
& - (1 - e^{-\lambda}) \frac{\alpha}{1 - \alpha} \ln(n + g + \delta).
\end{aligned} \tag{15}$$

Eqs. (14) and (15) represent the convergence equations for emissions based on the Green Solow model. Here we describe the concepts of convergence in emissions. When we express as $q_t = q(t)$ and $q_{t-1} = q(t-1)$, from Eq. (14), we find that $\partial \ln(q_t/q_{t-1})/\partial \ln q_{t-1} = -(1 - e^{-\lambda}) < 0$. Note that $-(1 - e^{-\lambda}) < 0$ in Eq. (14) means $e^{-\lambda} < 1$ in Eq. (15), hence $\lambda > 0$. In Brock and Taylor [7], the tendency that a country with lower pollutant emissions per capita initially has higher growth rates for emissions afterward, is referred to as the “*absolute convergence in emissions*”. When all countries have identical values of the determinants of $\hat{y}_*$ and q_* , the pollutant emissions per capita for each country in the long-term converge to the same value. However, if such conditions are not satisfied, then the long-term values of each country’s emissions per capita are also different. On the other hand, we define the tendency for the emissions in a country to grow faster with increasing distance from the values on the balanced growth path as “*conditional convergence in emissions*”, under the condition that the determinants of $\hat{y}_*$ and q_* are controlled.

3. Statistical Analysis

3.1 Data

For an empirical investigation of the Green Solow model, we constructed a sample that consisted of 25 selected OECD countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

The data necessary for our statistical analysis are an index of pollutant emissions, real GDP per capita, the ratio of investment to environmental cost-adjusted GDP, and population (to calculate the population growth rate). As an index of pollutant emission data, we focus on sulfur emission and use Stern’s [23] data, which is measured in metric tons for each country. For the ratio of investment to environmental cost-adjusted GDP, as in Brock and Taylor [7], we use the investment share of real GDP per capita from the Penn World Table Mark 6.2, as a proxy. We also use the data of population and real GDP per capita (constant prices: chain series) from the Penn World Table Mark 6.2, respectively.

3.2 Characteristic Features between Per Capita GDP and Sulfur Emissions

Using the time series data of the 25 OECD countries, we investigate the relationship between real GDP per capita and sulfur emissions, and examine the implications from the viewpoint of the Green Solow model. The data periods for each country are as follows: Australia 1950–2002, Austria 1950–2002, Belgium 1950–2002, Canada 1950–2002, Denmark 1950–2002, Finland 1950–2002, France 1950–2002, Greece 1951–2002, Iceland 1950–2002, Ireland 1950–2002, Italy 1950–2002, Japan 1950–2002, Luxembourg 1950–2002, Mexico 1950–2003, the Netherlands 1950–2002, New Zealand 1950–2002, Norway 1950–2002, Portugal 1950–2002, Republic of Korea 1953–2000, Spain 1950–2002, Sweden 1950–2002, Switzerland 1950–2002, Turkey 1950–2001, the United Kingdom 1950–2002, and the United States 1950–2003.

To capture the properties of the relationship between real GDP per capita and sulfur emissions for each country, we run a local linear regression with the Epanechnikov kernel. Then, the bandwidth is selected according to the Silverman’s [20] method. In the present paper, we express bandwidth as symbol h . The results of local fitting with the scatter plot are shown in Figure 5.

Figure 5. The relationship between per capita GDP and sulfur emissions

From Figure 5, we can observe the shape of a rough reverse-U for 17 of the 25 nations : Austria, Belgium, Canada, Denmark, Finland, France, Ireland, Italy, Japan, the Netherlands, Norway, Republic of Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Recall that the Green Solow model implies that the environmental Kuznets curve exists, under the assumption that $g_A > g + n$. Hence, for these 17 countries, the Green Solow model suggests that $g_A > g + n$ holds, and we may regard the 17 countries as having economies with relatively a high technological progress rate in environmental fields. For Australia, Greece, Portugal and Turkey, we can observe a rough upward-sloping shape. Recall that such a relationship is similar to the graph shown in Figure 4, which represents the case of $g_A < g + n$. In the context of the Green Solow

Figure 5 The relationship between per capita GDP and sulfur emissions (Continued)

model, we can thus interpret that these 4 countries indicate a rough upward-sloping shape that has the relationship $g_A < g + n$. A clear pattern is not detected for the other 4 countries: Iceland, Luxembourg, Mexico, and New Zealand. That is, the Green Solow model cannot easily explain the dynamic state of these 4 countries.

3.3 Panel Analysis of Convergence in Sulfur Emissions

We examine the implications of the Green Solow model using a panel analysis technique. The idea for our analysis is similar to that in Islam [13].

Figure 5 The relationship between per capita GDP and sulfur emissions (Continued)

In the econometric analysis, we follow Mankiw, Romer and Weil [15] and Islam [13] assuming $g_i + \delta_i = 0.05$. Based on Eq. (15), we formulate the population regression equation for country i as

$$\ln q_{i,t} = \eta_i + \xi_t + \phi_1 \ln q_{i,t-1} + \phi_2 \ln s_{k,i,t} + \phi_3 \ln(n_{i,t} + 0.05) + u_{i,t}, \quad (16)$$

where

$$\eta_i \equiv (g - g_A) + (1 - e^{-\lambda}) \left[\ln(B_0 \Omega_0) + \left(\frac{\alpha}{1 - \alpha} + \varepsilon \right) \ln(1 - \theta_i) - (g - g_A) \right],$$

$$\xi_t \equiv (1 - e^{-\lambda})(g - g_A)t, \phi_1 \equiv e^{-\lambda}, \phi_2 \equiv (1 - e^{-\lambda})\frac{\alpha}{1 - \alpha}, \phi_3 \equiv -(1 - e^{-\lambda})\frac{\alpha}{1 - \alpha}.$$

In Eq. (16), η_i represents the individual effect, ξ_t denotes a time effect, and u_{it} express an error term. Here we assume that $E(u_{i,t})=0$, $Var(u_{i,t})=\sigma_u^2$, $Cov(u_{i,t}, u_{j,s})=0$ ($i \neq j$, $t \neq s$).

It has often been pointed out that first oil shock gave rise to structural changes in countries. For example, Lee and List [14] suggest the importance of considering the effects of structural change in long-term issues between macroeconomic performance and the environment. Hence, taking into account the influence of any structural change, we incorporate the coefficient dummy variables into Eq. (16) as follows:

$$\begin{aligned} \ln q_{i,t} = & \eta_i + \xi_t + \phi_1 \ln q_{i,t-1} + \phi_2 \ln s_{k,i,t} + \phi_3 \ln(n_{i,t} + 0.05) \\ & + \psi_1 D_{1t} \ln q_{i,t-1} + \psi_2 D_{2t} \ln s_{k,i,t} + \psi_3 D_{3t} \ln(n_{i,t} + 0.05) + v_{i,t}, \end{aligned} \quad (17)$$

where v_{it} represents an error term with $E(v_{i,t})=0$, $Var(v_{i,t})=\sigma_v^2$, $Cov(v_{i,t}, v_{j,s})=0$ ($i \neq j$, $t \neq s$), and $D_{m,t}$ ($m=1, 2, 3$) is defined by

$$D_{m,t} = \begin{cases} 0 & \text{if } 1 \leq t \leq \tau, \\ 1 & \text{if } \tau + 1 \leq t \leq T. \end{cases}$$

Considering structural changes, we estimate the parameters in Eq. (17), specifically, $D_{m,t}=0$ for the period from 1950 to 1973 and, $D_{m,t}=1$ for the period from 1974 to 2000.

In a Hausman test for the model of Eq. (17), we find that the random effect model is selected. Table 1 shows the estimation results of Eq. (17) excluding coefficient estimates in terms of individual effects and time effects.

As shown in Table 1, the estimated coefficients on $\ln q_{i,t-1}$ and $\ln s_{k,i,t}$ are estimated as significant at or below the 1 percent level, and the sign condition of each estimated coefficient is also

Table 1. Estimation results, 1950-2000

Dependent variable : $\ln q_t$	
$\ln q_{t-1}$	0.968 (0.006)
$\ln s_k$	0.053 (0.018)
$\ln(n+0.05)$	-0.047 (0.041)
$D_1 \ln q_{t-1}$	0.033 (0.009)
$D_2 \ln s_k$	-0.062 (0.029)
$D_3 \ln(n+0.05)$	0.271 (0.065)
R^2 (within)	0.962
Number of observations	1272
Hausman's χ^2 -statistic	44.76
p -value	0.860

Notes : 1) Standard errors are in parentheses.

2) The table shows the results excluding the estimated values in terms of individual effects and the trend variable.

Table 2. Estimation results, 1950–1973 and 1974–2000

Dependent variable : $\ln q_t$		
	1950–1973	1974–2000
$\ln q_{t-1}$	0.846 (0.022)	0.930 (0.012)
$\ln s_k$	0.152 (0.043)	0.104 (0.034)
$\ln(n+0.05)$	0.180 (0.111)	−0.313 (0.090)
R^2 (within)	0.853	0.962
Number of observations	598	674
Hausman's χ^2 -statistic	38.42	47.37
p -value	0.055	0.017

Notes: 1) Standard errors are in parentheses.

2) The table shows the results excluding the estimated values in terms of individual effects and the trend variable.

satisfied. The estimated coefficient on $\ln(n_{i,t}+0.05)$ satisfies the sign condition, but is not significant at or below the 5 percent level. Examining a test for the structural change in this case, we find the null hypothesis of $\psi_1=\psi_2=\psi_3=0$ is rejected at or below the 1 percent level: suggesting that structural change due to the first oil shock existed in the relevant period.

Hence, we separately analyze the samples of the first period (1950–1973) and the second period (1974–2000). Specifically, we consider the following equations.

$$\begin{aligned}\ln q_{i,t} &= \eta_i + \xi_t + \phi_1 \ln q_{i,t-1} + \phi_2 \ln s_{k,i,t} + \phi_3 \ln(n_{i,t}+0.05) + u_{1,i,t}, \quad (t=1, 2, \dots, \tau), \\ \ln q_{i,t} &= \eta_i + \xi_t + \hat{\phi}_1 \ln q_{i,t-1} + \hat{\phi}_2 \ln s_{k,i,t} + \hat{\phi}_3 \ln(n_{i,t}+0.05) + u_{2,i,t}, \quad (t=\tau+1, \tau+2, \dots, T),\end{aligned}$$

where $u_{1,i,t}$ and $u_{2,i,t}$ are the error terms that satisfy the same assumptions as u_{it} in Eq. (16). The results of the panel estimation are shown in Table 2.

In Table 2, the estimation results of individual and time effects are omitted, and only the consequences of the independent variables that have theoretically significant meaning are shown. From the Hausman test, the fixed-effect model was selected for both the first and the second period.

For the first period, the sign conditions of the coefficients on $\ln q_{i,t-1}$ and $\ln s_{k,i,t}$ are satisfied and estimated as significant at or below the 1 percent level. However, the estimated coefficient on $\ln(n_{i,t}+0.05)$ does not satisfy the sign condition, and is not significant at an appropriate level. On the other hand, in the case of second period, the sign conditions of the coefficients on $\ln q_{i,t-1}$, $\ln s_{k,i,t}$ and $\ln(n_{i,t}+0.05)$ are satisfied and are estimated as significant at or below the 1 percent level. Comparing the results of the first period to the second one, we find that the case of the second period overall gives better results.

We now examine the economic implications of the estimated coefficient on $\ln q_{i,t-1}$. In both the first and the second period cases, by the definition of the coefficient on $\ln q_{i,t-1}$, we can confirm that $\lambda > 0$, because the estimated coefficient of $\ln q_{i,t-1}$ is smaller than 1. Hence, when the determinants of sulfur emissions per capita are controlled, we find a tendency that sulfur emissions per capita converge towards a steady-state value for each country over time. Thus, the estimation results could be interpreted as evidence of the conditional convergence in terms of sulfur emissions per capita for the 25 OECD countries. Noteworthy is the speed of the convergence of sulfur emissions in the neighborhood of the balanced growth path, that is λ , for the two cases. From the

results in Table 2, we calculate the implied λ for each case. Consequently, we obtain 0.167 for the first period case, and 0.073 for the second. That is, the speed of convergence is 16.7 percent and 7.3 percent per year, respectively. Therefore, we find that the speed of convergence declines over time.

4. Conclusion

In the previous section, we analyzed from both theoretical and empirical perspectives the relationship between economic development and the environment using a modified version of the Green Solow model developed by Brock and Taylor [7].

The main results can be summarized as follows. We first investigated the hypothesis of the environmental Kuznets curve, an implication of the growth model presented here. The environmental Kuznets curve denotes an inverted-U relationship between the level of economic development and the level of environmental pollution. Using time series data of sulfur emissions of 25 OECD countries, we applied a nonparametric regression method and ascertained characteristic features between per capita GDP and sulfur emissions for each country. Consequently, we confirmed the shape of a rough reverse-U for 17 of the 25 countries: Austria, Belgium, Canada, Denmark, Finland, France, Ireland, Italy, Japan, the Netherlands, Norway, Republic of Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States. As noted earlier, in respect of research into the environmental Kuznets curve, there are few reports considering long-term time series data by country using a nonparametric regression method. Therefore, we believe this study makes a meaningful contribution to research in this area.

Second, using a panel analysis we analyzed the convergence properties of sulfur emissions per capita for the 25 OECD countries. As it has often been pointed out that first oil shock gave rise to structural changes in countries, we took into account the influence of any structural change. Hence, we separately estimated samples from the first (1950–1973) and the second (1974–2000) periods. Overall, we confirmed the conditional convergence of sulfur emission per capita for these 25 OECD countries. Thus, we found that each country's per capita sulfur emissions tend to approach that country's specific level on a balanced growth path. We also found that per capita sulfur emissions are likely to take various values in the long-term. Our results are in contrast to that of absolute convergence in terms of CO₂ emission per capita as reported in Brock and Taylor [7]. As well, we derived the estimates of the speed of convergence of sulfur emissions in the neighborhood of balanced growth path as follows: 16.7 percent per year in the case of the first period, and 7.3 percent per year in the case of the second period. The results suggesting that empirical evidence showed the speed of convergence declines over time.

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References

- [1] Aghion, P. and Howitt, P., *Endogenous Growth Theory*, Cambridge, The MIT Press, 1998.
- [2] Barro, R.J., "Economic Growth in a Cross Section of Countries," *Quarterly Journal of Economics*, Vol. 106, 1991, pp. 407–443.
- [3] Barro, R.J. and Sala-i-Martin, X., "Convergence across States and Regions," *Brookings Papers on Economic Activity*, No. 1, 1991, pp. 107–158.
- [4] Barro, R.J. and Sala-i-Martin, X., "Convergence," *Journal of Political Economy*, Vol. 100, 1992a, pp. 223–251.

- [5] Barro, R.J. and Sala-i-Martin, X., "Regional Growth and Migration : A Japan-United States Comparison," *Journal of the Japanese and International Economy*, Vol. 5, 1992b, pp. 312-346.
- [6] Bhattarai, M. and Hammig, M., "Institutions and the Environmental Kuznets Curve for Deforestation : A Crosscountry Analysis for Latin America, Africa and Asia," *World Development*, Vol. 29, 2001, pp. 995-1010.
- [7] Brock, W.A. and Taylor, M.S., "The Green Solow Model," *NBER Working Paper*, No. 10557, 2004.
- [8] Dasgupta, S., Laplante, B., Wang, H. and Wheeler, D., "Confronting the Environmental Kuznets Curve," *Journal of Economic Perspectives*, Vol. 16, 2002, pp. 147-168.
- [9] Dinda, S., "Environmental Kuznets Curve Hypothesis : A Survey," *Ecological Economics*, Vol. 49, 2004, pp. 431-455.
- [10] Gradus, R. and Smulders, S., "The Trade-off Between Environmental Care and Long-term Growth-Pollution in Three Prototype Growth Models," *Journal of Economics*, Vol. 58, 1993, pp. 25-51.
- [11] Grossman, G.M. and Krueger, A.B., "Economic Growth and the Environment," *Quarterly Journal of Economics*, Vol. 100, 1995, pp. 353-377.
- [12] Holtz-Eakin, D. and Selden, T.M., "Stoking the Fires? CO₂ Emissions and Economic Growth," *Journal of Public Economics*, Vol. 57, 1995, pp. 85-101.
- [13] Islam, N., "Growth Empirics : A Panel Data Approach," *Quarterly Journal of Economics*, Vol. 110, 1995, pp. 1127-1170.
- [14] Lee, J. and List, J.A., "Examining Trends of Criteria Air Pollutants : Are the Effects of Governmental Intervention Transitory?," *Environmental and Resource Economics*, Vol. 29, 2004, pp. 21-37.
- [15] Mankiw, N.G., Romer, D. and Weil, D.N., "A Contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics*, Vol. 107, 1992, pp. 407-437.
- [16] Ohkuma, S. and Noda, H., "On the Convergence of CO₂ Emissions," *Studies in Applied Economics*, Vol. 1, 2007, pp. 179-200.
- [17] Okamoto, S. and Ichikawa, Y., *Introduction to Environmental Study*, Second Edition, Tokyo, Sangyo Tosho (in Japanese), 2005.
- [18] Osaka, H., *An Econometric Analysis of Economic Development and Productivity in East Asian Region*, Tokyo, Taga Shuppan (in Japanese), 2005.
- [19] Selden, T.M. and Song, D., "Environmental Quality and Development : Is There a Kuznets Curve for Air Pollution Emissions?," *Journal of Environmental Economics and Management*, Vol. 27, 1994, pp. 147-162.
- [20] Silverman, B.W., *Density Estimation for Statistics and Data Analysis*, London, Chapman & Hall, 1986.
- [21] Solow, R.M., "A Contribution to the Theory of Economic Growth," *Quarterly Journal of Economics*, Vol. 70, 1956, pp. 65-94.
- [22] Stern, D.I., "Progress on the environmental Kuznets curve?," *Environment and Development Economics*, Vol. 3, 1998, pp. 175-198.
- [23] Stern, D.I., "Global Sulfur Emissions From 1850 to 2000," *Chemosphere*, Vol. 58, 2005, pp. 163-175.
- [24] Stokey, N.L., "Are There Limits to Growth?," *International Economic Review*, Vol. 39, 1998, pp. 1-31.