Long-run Changes in the Emission Intensities of Japan, the United States, and the United Kingdom : A DEA Approach

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Long-run Changes in the Emission Intensities of Japan, the United States, and the United Kingdom: A DEA Approach

Masayuki Shimizu*

Abstract: Using the emission intensity index, this study examines long-run changes in environmental performance by applying a Data Envelopment Analysis (DEA) approach. The analysis of time-series data from 1890–1992 reveals important implications for Japan, the United States, and the United Kingdom. This study confirms that the emission intensity indices of all three countries were at their highest before the Second World War. Thus, environmental performance deteriorated before the Second World War and improved after it. Furthermore, the emission intensity indices were high at low-income levels. Therefore, progressive improvements in income levels led to better environmental performance and economic development.

Key words: Carbon and Sulfur Emissions, Emission Intensity Index, Environmental Performance

JEL codes: Q53, Q54, Q56

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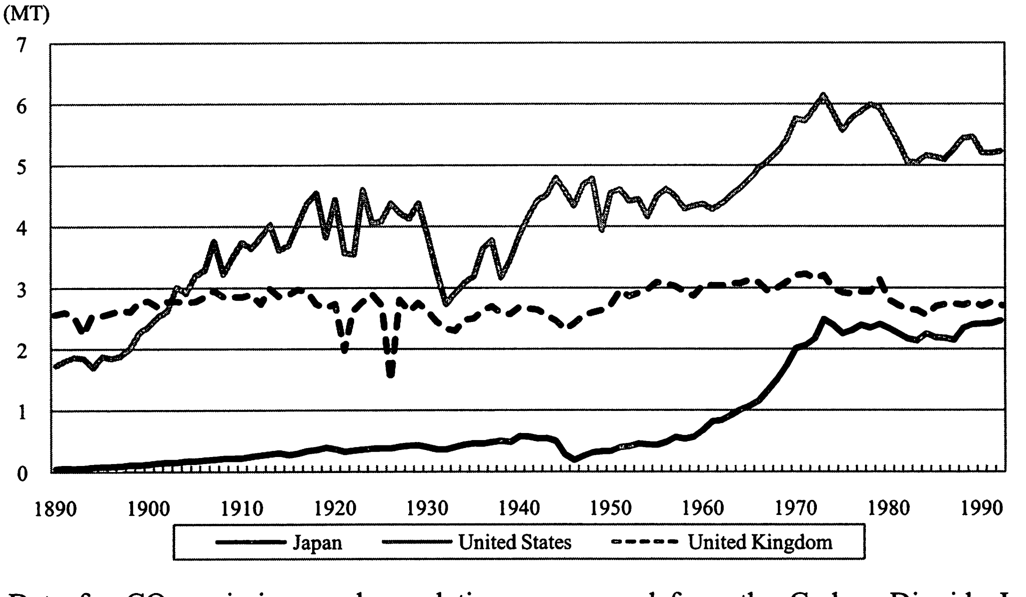
I. Introduction

This study estimates the emission intensity index as a measure of environmental performance for Japan, the United States, and the United Kingdom. Employing the time-series data of carbon and sulfur emissions, the emission intensity indices are estimated using a Data Envelopment Analysis (DEA) approach, thus revealing the long-run trends of environmental performance in these countries from 1890–1992.

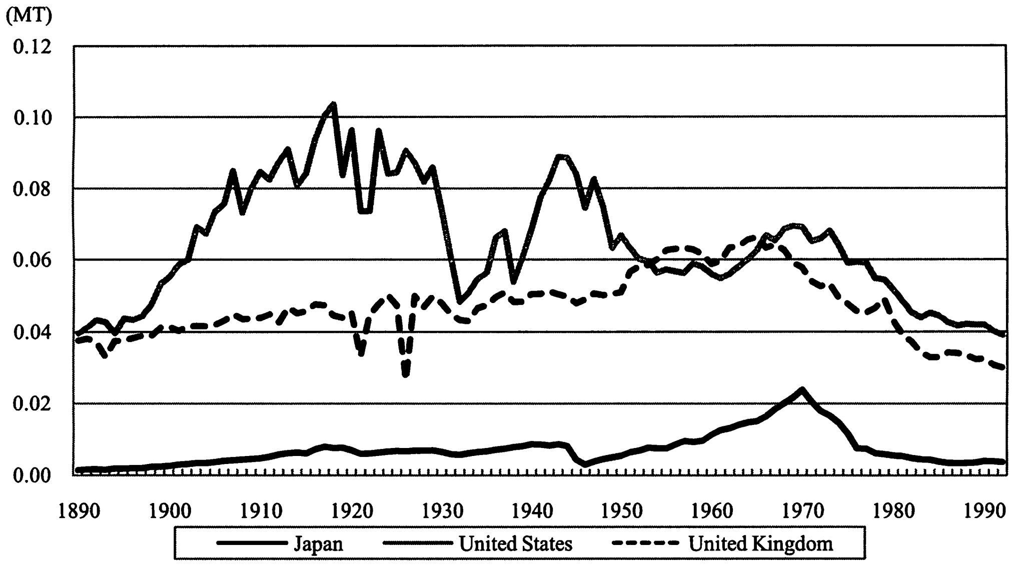
The past few decades have seen an increase in studies related to environmental issues due to the concerted measurement and collation of environmental data. For example, many countries maintain databases of long-term environmental data and aggregated sectoral data at the national level. The Carbon Dioxide Information Analysis Center (CDIAC) has been estimating long-term time-series data on carbon dioxide (CO_2) emissions since the 18th century. Furthermore, the Organization for Economic Cooperation and Development (OECD)/International Energy Agency (IEA) have been estimating sectoral CO_2 emissions data since 1971. Stern (2005, 2006) estimated long-term time-series data for sulfur emissions since 1850. Furthermore, the European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) have been estimating sectoral data for sulfur dioxide (SO_2) emissions since 1970.

Figure 1. Changes in Carbon Emissions Per Capita, 1890–1992



Sources: Data for CO_2 emissions and population are sourced from the Carbon Dioxide Information Analysis Center and Maddison Historical Statistics, respectively.

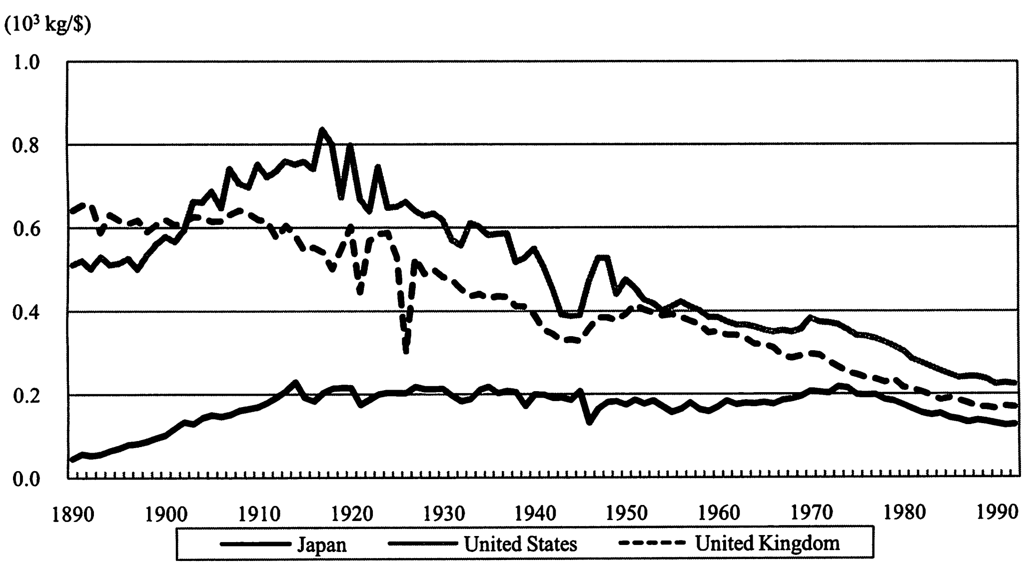
Figure 2. Changes in Sulfur Emissions Per Capita, 1890–1992



Sources: Data for sulfur emissions and population are sourced from Stern (2005, 2006) and Maddison Historical Statistics, respectively.

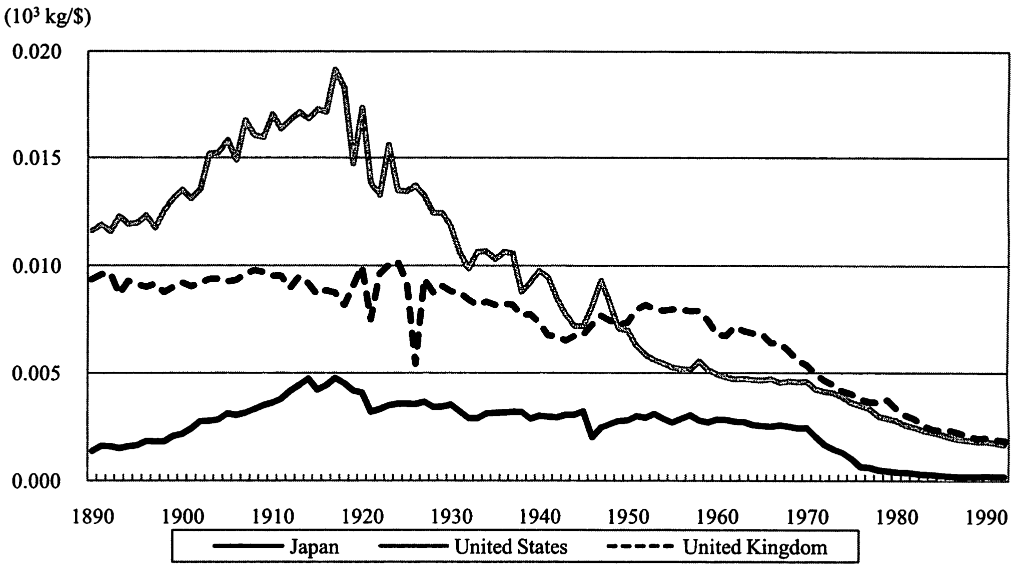
These data allow calculation of the typical indicators of environmental pollution, namely pollutant emissions in absolute and per capita terms, which represent the real impact on the environment. Figures 1 and 2 show the long-run changes in carbon and sulfur emissions per capita in Japan, the United States, and the United Kingdom from 1890–1992. These indicators show that the United States has been the largest emitter of carbon and sulfur emissions among the three abovementioned countries. Furthermore, since the 1970s, carbon emissions per capita showed on a plateau, while sulfur emissions per capita decreased.

Figure 3. Changes in Carbon Emissions Intensities, 1890–1992



Sources: Data for CO_2 emissions and GDP (1990 International/Geary–Khamis dollars) are sourced from the Carbon Dioxide Information Analysis Center and Maddison Historical Statistics, respectively.

Figure 4. Changes in Sulfur Emissions Intensities, 1890–1992



Sources: Data for sulfur emissions and GDP (1990 International/Geary–Khamis dollars) are sourced from Stern (2005, 2006) and Maddison Historical Statistics, respectively.

It is also possible to study the relationship between environmental pollution and economic activity through an indicator known as "emission intensity," which is expressed as the pollutants emitted per unit Gross Domestic Product (GDP). In other words, environmental pollution is a result of economic activity, the extent of which may help us measure environmental performance. According to Figures 3 and 4, for Japan and the United States, the emission intensities of carbon and sulfur emissions moved from increasing to decreasing trends, while those for the United Kingdom showed fairly uniform decreasing trends. Notably, both emission intensities showed decreasing trends before the Second World War. Therefore, this result presents different trends compared to those of carbon and sulfur emissions per capita.

This study assumes that desirable outputs, such as GDP, and undesirable outputs, such as environmental pollutants, are jointly produced by economic activity. In addition, while many types of environmental pollutants are emitted as a result of economic activity, this study assumes that several pollutants are emitted simultaneously. Therefore, in this study, the emission intensity index simultaneously accounts for multiple pollutants. The index is estimated using a DEA approach, which is advantageous in that it does not specify the functional forms in estimation techniques for two or more outputs.

To estimate the emission intensity index, this study employs the method applied by Zaim (2004), which in turn is based on an environmental performance index developed by Färe and Grosskopf (2003). The environmental performance index of Färe and Grosskopf (2003) is constructed using two quantity indices, one of desirable outputs and the other of undesirable outputs. In this approach, the quantity indices of desirable and undesirable outputs are represented by the rate of expansion in GDP and the rate of contraction in environmental pollutants, respectively, when compared to a certain standard year. As the final form, the environmental performance index is expressed as the ratio between the quantity index of desirable outputs and the quantity index of undesirable outputs, which is applied in the tradition of the Hicks–Moorsteen productivity index. The emission intensity index proposed by Zaim (2004) is defined as the reciprocal of the environmental performance index developed by Färe and Grosskopf (2003).

Färe and Grosskopf (2003) estimated the environmental performance indices of 24 OECD countries using a time-series data set covering the period 1971–1990. These indices simultaneously accounted for CO_2, sulfur oxides (SO_X), and nitrogen oxides (NO_X) emissions. The results indicated that the average environmental performance indices had successfully expanded for the studied countries. Using a cross-section data set, Färe *et al.* (2004) estimated the environmental performance indices for 17 OECD countries in 1990. These indices simultaneously accounted for CO_2, SO_X, and NO_X emissions. They found that France and Sweden had the best environmental performance. Similarly, Yörük and Zaim (2006) estimated the environmental performance indices for 27 OECD countries using a cross-section data set covering the period 1983–1998. This index simultaneously accounted for CO_2 and water pollutant (WP) emissions. The results indicated that Poland, Hungary, and Luxembourg were the best performers. Furthermore, Shimizu and Moriwaki (2012) estimated the environmental performance indices using cross-section data of 88 countries for 2008 and time-series data of 66 countries from 1990–2008. This index simultaneously accounted for CO_2, SO_2, and NO_X emissions. The results clearly showed that the environmental performance indices of low- and middle-income countries differ drastically by region.

On the other hand, Zaim (2004) estimated the emission intensity index of U.S. manufacturing sectors using a time-series data set. Yörük and Zaim (2008) estimated the emission intensity index of 28 OECD countries using a cross-section data set covering the period 1983–1998. This index simultaneously accounted for CO_2 and NO_X emissions, CO_2 and WP emissions, and NO_X and WP emissions. The results indicated that Poland and Hungary were the best performers.

As described above, previous empirical studies focused solely on the study period from the 1970s to the 2000s and did not consider the period before the Second World War. Thus, this study tries to extend the analysis period and estimates the long-run emission intensity indices for Japan, the United States, and the United Kingdom from 1890–1992. The results reveal trends of long-run environmental performance and also reveal the levels of environment and production efficiency in Japan, the United States, and the United Kingdom.

II. Model

This section explains the emission intensity index used by Färe and Grosskopf (2003) and Zaim (2004). Let the production factors (inputs) be represented by $x = (x_1, \ldots, x_N) \in R^N_+$, desirable outputs by $y = (y_1, \ldots, y_M) \in R^M_+$, and undesirable outputs by $b = (b_1, \ldots, b_J) \in R^J_+$. Then, the production technology T can be represented as follows:

$$T = \{(x, y, b): x \text{ can produce } (y, b)\},$$

which assumes the characteristics of weak disposability and nulljointness. Weak disposability is expressed as follows:

$$\text{If } (x, y, b) \in T \text{ and } 0 \leq \theta \leq 1, \text{ then } (x, \theta y, \theta b) \in T.$$

This means that if undesirable outputs are reduced, desirable outputs are reduced simultaneously at the same rate. The nulljointness is expressed as follows:

$$\text{If } (x, y, b) \in T \text{ and } b = 0, \text{ then } y = 0.$$

This means that if desirable outputs are produced, undesirable outputs are also necessarily emitted. In addition to the two properties of technology T, this study imposes closedness and convexity.

Next, to construct the quantity index of desirable and undesirable outputs, this study defines the output distance function D_y in desirable outputs as follows:

$$D_y(x, y, b) = \inf\{\theta: (x, y/\theta, b) \in T\}.$$

This shows the extent by which desirable outputs can be increased if undesirable outputs and factor inputs are kept constant. Then, D_y is homogeneous of degree +1 in y. Similarly, the input distance function D_b in undesirable outputs is defined as follows:[1]

$$D_b(x, y, b) = \sup\{\lambda: (x, y, b/\lambda) \in T\}.$$

This shows the extent by which undesirable outputs can be reduced if desirable outputs and factor inputs are kept constant. Then, D_b is homogeneous of degree +1 in b.

In the quantity index approach used by Färe and Grosskopf (2003), the quantity index of desirable outputs Q_y can be defined using D_y as follows:

$$Q_y(x^0, b^0, y^k, y^l) = \frac{D_y(x^0, y^k, b^0)}{D_y(x^0, y^l, b^0)},$$

which compares desirable outputs y^l and y^k, given inputs x^0 and undesirable outputs b^0. Thus, Q_y shows to what extent observation k expands the desirable outputs relative to observation l, which holds inputs and undesirable outputs in observation 0. Therefore, the expansion in desirable outputs for observation l is greater than that for observation k, and consequently, observation k is substantially more efficient than observation l. Thus, the production efficiency of desirable outputs for observation k is higher than that for observation l.

On the other hand, the quantity index of undesirable outputs Q_b can be defined using D_b as follows:

$$Q_b(x^0, y^0, b^k, b^l) = \frac{D_b(x^0, y^0, b^k)}{D_b(x^0, y^0, b^l)},$$

which compares undesirable outputs b^l and b^k, given inputs x^0 and desirable outputs y^0. Thus, Q_b shows to what extent observation k contracts the undesirable outputs relative to observation l, which holds inputs and desirable outputs in observation 0. Therefore, the contraction in undesirable outputs for observation l is greater than that for observation k, and consequently, observation k is substantially more efficient than observation l. Thus, the environmental efficiency of undesirable outputs for observation k is higher than that for observation l.

Following Zaim (2004), the emission intensity index EI is derived as follows:

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[1] Usually, the input distance function is expressed by $D_x(x, y) = \sup\{\lambda: (x/\lambda, y) \in T$, which holds desirable outputs as fixed and contracts the inputs as much as possible.

$$EI^{k,l}\left(x^0,y^0,b^0,y^k,y^l,b^k,b^l\right) = \frac{Q_b(x^0,y^0,b^k,b^l)}{Q_y(x^0,b^0,y^k,y^l)},$$

which is constructed using two quantity indices of desirable and undesirable outputs.[2] This ratio of the two quantity indices is represented as the emission intensity. Thus, a lower value indicates a good index and consequently, better environmental performance.

This study computes both the output and the input distance function using DEA.[3] Let the $k = (1, \ldots, K)$ index be represented by the year in the sample. For each year $k' = 1, \ldots, K$ in each studied country, the output and input distance function is solved using two linear programming problems as follows:

$$\left(D_y\left(x^0,y^{k'},b^0\right)\right)^{-1} = \max\theta \qquad \left(D_b\left(x^0,y^0,b^{k'}\right)\right)^{-1} = \min\lambda$$

$$\text{s.t.} \qquad\qquad\qquad \text{s.t.}$$

$$\sum_{k=1}^{K} z_k y_m^k \geq \theta y_m^{k'} \quad m=1,\ldots,M \qquad \sum_{k=1}^{K} z_k y_m^k \geq y_m^0 \quad m=1,\ldots,M$$

$$\sum_{k=1}^{K} z_k b_j^k = b_j^0 \quad j=1,\ldots,J \qquad \sum_{k=1}^{K} z_k b_j^k = \lambda\, b_j^{k'} \quad j=1,\ldots,J$$

$$\sum_{k=1}^{K} z_k x_n^k \leq x_n^0 \quad n=1,\ldots,N \qquad \sum_{k=1}^{K} z_k x_n^k \leq x_n^0 \quad n=1,\ldots,N$$

$$z_k \geq 0 \quad k=1,\ldots,K, \qquad z_k \geq 0 \quad k=1,\ldots,K.$$

The strict equality on the undesirable output constraints is assumed to impose weak disposability, while the nulljointness is assumed as follows:

$$\sum_{k=1}^{K} b_j^k > 0 \quad j=1,\ldots,J$$

$$\sum_{j=1}^{J} b_j^k > 0 \quad k=1,\ldots,K.$$

This study estimates the emission intensity index using time-series data. A feasible solution is needed for the two linear programming problems. To address this issue, following Färe *et al.* (2004), this study sets the hypothetical reference year to reflect the minimum desirable outputs and the maximum undesirable outputs and inputs.[4] Thus, this study assumes that observation l is observation 0, which then

[2] These two quantity indices satisfy some properties, such as homogeneity, time reversal, transitivity, and dimensionality. See Färe and Grosskopf (2003).

[3] These two distance functions are the reciprocals of Farrell's efficiency measures.

[4] In this regard, Färe *et al.* (2004) referred to a hypothetical reference country for minimum desirable and undesirable outputs and maximum inputs in the cross-section analysis. The time-series analyses conducted by Färe and Grosskopf (2003) and Zaim (2004) employed the initial year in their respective data sets as the reference year. However, when this study chooses the initial year as the reference year, the solution is not feasible. Thus, like Färe *et al.* (2004), this study applies a hypothetical reference year.

refers to the above hypothetical reference year. The emission intensity index is obtained by comparing the selected year with the hypothetical reference year.

III. Data

This study uses country-level time-series data sourced from Maddison's Statistics, the EU KLEMS database, the CDIAC database, and Stern (2005, 2006). The data span the period 1890–1992. However, employment data availability for the three countries have limited. This study uses employment data for Japan and the United Kingdom for the following years: 1890, 1913, 1929, 1938, 1950, 1960, and 1970–1992. On the other hand, this study uses employment data for the United States for the following years: 1890, 1913, 1929, 1938, 1950, 1960, 1973, and 1977–1992. Therefore, this study estimates the emission intensity index based on limited time-series data. Moreover, this study also estimates the emission intensity index using interpolated employment data. Some unavailable employment data are interpolated using the average annual growth rate and the geometric mean. Moreover, due to data availability issues, this study also excludes the period from 1939–1949 (i.e., the period during the Second World War and some years after it). The details of the limited time-series data appear in Table 1.

Table 1. Data Description of Output and Input Variables

	GDP (1990 International/Geary–Khamis millions dollars)		
	Japan	United States	United Kingdom
Mean	1,348,550	3,815,190	665,863
Std. dev.	729,181	1,868,715	224,934
Min	40,556	214,714	150,269
Max	2,422,245	5,985,152	944,610
	Employment (thousands)		
	Japan	United States	United Kingdom
Mean	53,566	96,009	25,627
Std. dev.	12,480	31,993	3,340
Min	20,305	23,842	14,764
Max	66,309	128,290	28,858
	Capital stock (1990 International/Geary–Khamis millions dollars)		
	Japan	United States	United Kingdom
Mean	3,205,661	8,682,327	981,336
Std. dev.	2,183,420	3,976,794	443,603
Min	27,713	652,931	124,858
Max	7,296,834	13,377,454	1,652,482
	Carbon emissions (thousand metric tonnes of carbon)		
	Japan	United States	United Kingdom
Mean	217,200	1,072,175	155,109
Std. dev.	100,710	375,983	18,474
Min	1,844	109,647	96,349
Max	306,425	1,350,173	180,219
	Sulfur emissions (thousand metric tonnes of sulfur)		
	Japan	United States	United Kingdom
Mean	817	10,333	2,316
Std. dev.	607	2,223	484
Min	55	2,497	1,408
Max	2,487	14,421	3,212

Desirable outputs refer to real GDP at 1990 prices sourced from Maddison Historical Statistics. In addition, GDP per capita (1990 prices) data are obtained from the abovementioned source. Undesirable outputs refer to carbon (CO_2) and sulfur emissions from the CDIAC database and Stern (2005, 2006), respectively. These emissions result from fossil fuel burning and processing of certain raw materials. Employment data from 1890–1960 and from 1970–1992 are sourced from Maddison (1991) (as number of persons engaged) and the EU KLEMS database, respectively. Capital stock refers to real gross stock of fixed nonresidential capital at 1990 prices (Maddison, 1995a, 1995b).

IV. Estimation Results

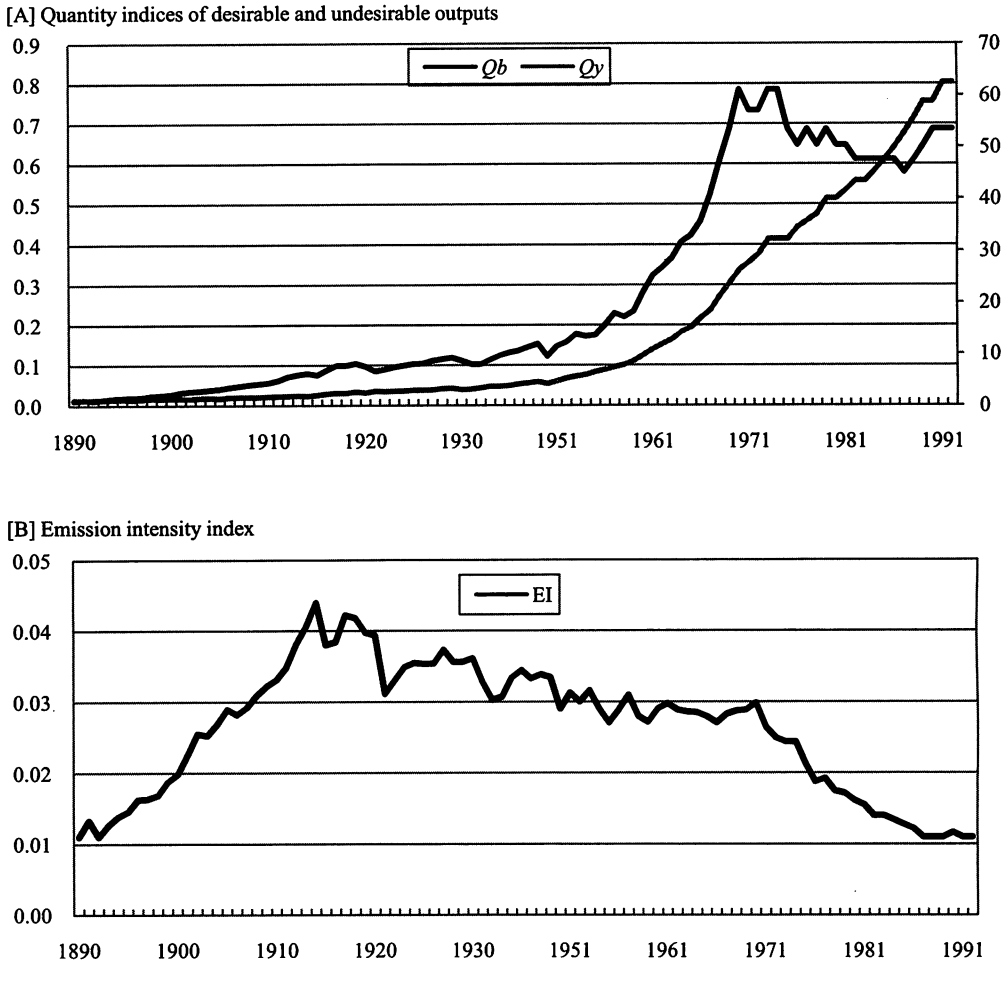
Table 2 reports the estimation results of the emission intensity indices calculated using the quantity indices of desirable and undesirable outputs. As mentioned previously, the estimations use limited time-series data. Furthermore, Figures 5, 6, and 7 present the long-run changes in the emission intensity indices from 1890–1992, which are re-estimations using interpolated employment data. These emission intensity indices simultaneously account for carbon and sulfur emissions in Japan, the United States, and the United Kingdom.

Table 2. Estimation Results of Emission Intensity Indices

	Japan			United States			United Kingdom		
	Q_b	Q_y	*EI*	Q_b	Q_y	*EI*	Q_b	Q_y	*EI*
1890	0.012	1.000	0.012	0.040	1.000	0.040	0.753	1.000	0.753
1913	0.078	1.767	0.044	0.145	2.410	0.060	0.964	1.494	0.645
1929	0.122	3.155	0.039	0.248	3.928	0.063	0.676	1.672	0.404
1938	0.158	4.348	0.036	0.226	3.723	0.061	0.604	1.980	0.305
1950	0.125	3.968	0.032	0.430	6.780	0.063	0.676	2.315	0.292
1960	0.293	9.259	0.032	0.533	9.533	0.056	0.717	3.014	0.238
1970	0.800	25.000	0.032	-	-	-	0.964	3.985	0.242
1971	0.800	26.316	0.030	-	-	-	1.139	4.070	0.280
1972	0.800	28.571	0.028	-	-	-	1.128	4.212	0.268
1973	0.857	30.303	0.028	0.952	16.473	0.058	1.150	4.496	0.256
1974	0.800	30.303	0.026	-	-	-	1.097	4.435	0.247
1975	0.706	31.250	0.023	-	-	-	1.092	4.430	0.246
1976	0.667	32.258	0.021	-	-	-	1.155	4.530	0.255
1977	0.706	33.333	0.021	1.000	18.024	0.055	1.202	4.630	0.260
1978	0.667	35.714	0.019	1.053	19.051	0.055	1.150	4.794	0.240
1979	0.706	37.037	0.019	1.053	19.699	0.053	1.246	4.928	0.253
1980	0.667	38.462	0.017	1.026	19.699	0.052	1.155	4.843	0.239
1981	0.667	40.000	0.017	1.000	20.202	0.050	1.221	4.783	0.255
1982	0.632	41.667	0.015	0.930	19.814	0.047	1.233	4.855	0.254
1983	0.632	41.667	0.015	0.952	20.641	0.046	1.330	5.029	0.264
1984	0.667	43.478	0.015	0.976	22.143	0.044	1.301	5.152	0.252
1985	0.632	45.455	0.014	1.000	23.001	0.043	1.442	5.335	0.270
1986	0.632	47.619	0.013	1.000	23.808	0.042	1.434	5.568	0.257
1987	0.600	50.000	0.012	1.053	24.649	0.043	1.451	5.839	0.249
1988	0.632	52.632	0.012	1.111	25.662	0.043	1.460	6.128	0.238
1989	0.667	55.556	0.012	1.111	26.551	0.042	1.516	6.265	0.242
1990	0.706	58.824	0.012	1.081	27.035	0.040	1.497	6.284	0.238
1991	0.706	58.824	0.012	1.081	26.974	0.040	1.497	6.201	0.241
1992	0.706	58.824	0.012	1.111	27.860	0.040	1.478	6.210	0.238

The results for Japan (Table 2 and Figure 5) show that the quantity index of undesirable outputs increased dramatically since the Second World War. This result implies that compared to the hypothetical reference year, the emission of undesirable outputs was inefficient, and thus, Japan's environmental performance worsened rapidly until the 1970s. However, after the 1970s, this index showed a decreasing trend, indicating that Japan made efforts to improve its environmental performance. On the other hand, the quantity index of desirable outputs also showed a rapid increase, indicating that the production of desirable outputs was efficient compared to the hypothetical reference year. Moreover, an inspection of both indices shows that the emission intensity index peaked in the 1910s, suggesting that Japan's environmental performance deteriorated before the Second World War and gradually improved after that. Notably, Japan recorded high environmental performance since the 1970s due to improvements in both environmental and production efficiency.

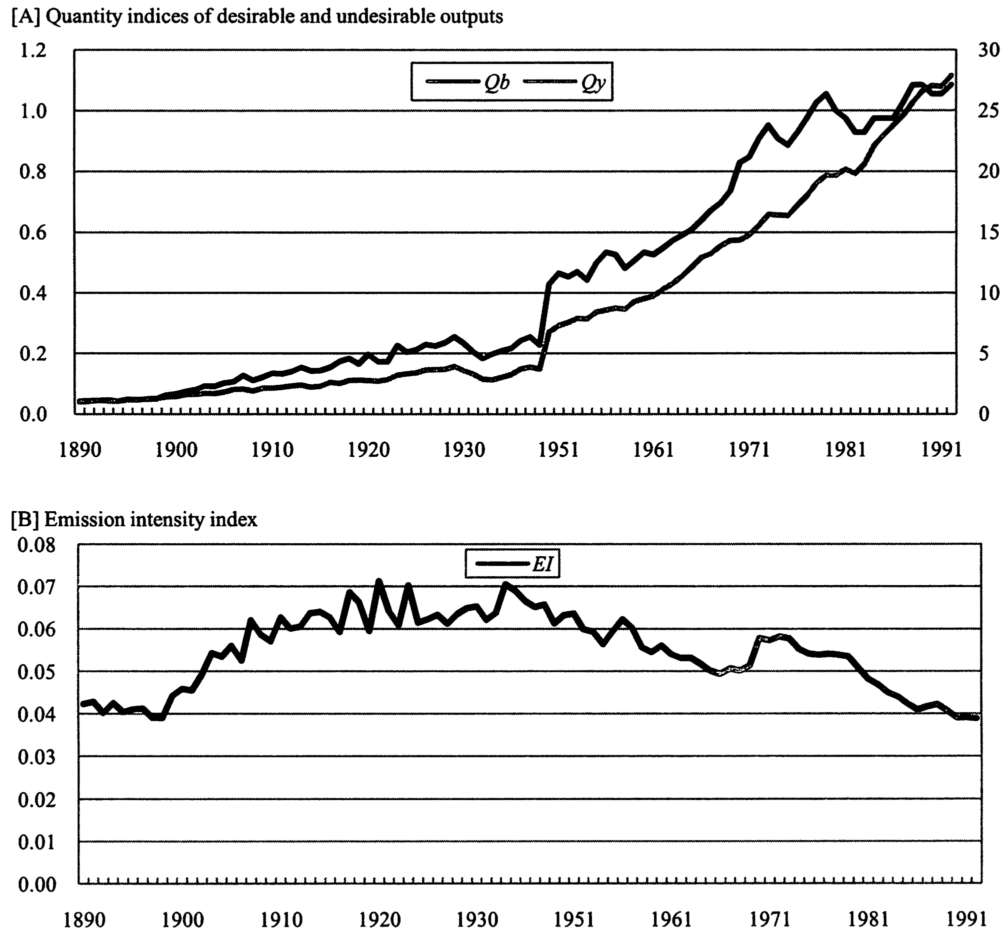
Figure 5. Long-run Changes in Japan's Emission Intensity Index, 1890–1992



Note: In Figure [A], the left axis denotes the quantity index of undesirable outputs, and the right axis, the quantity index of desirable outputs.

Similar to the results for Japan, those for the United States show that the quantity indices of both desirable and undesirable outputs increased sharply since the Second World War (Table 2 and Figure 6). The data for the United States do not show a clear decreasing trend in the quantity index of undesirable outputs. Thus, the emission of undesirable outputs was inefficient compared to the hypothetical reference year, indicating severe environmental pollution. However, the emission intensity index peaked before the Second World War and then recorded a decreasing trend. Therefore, the environmental performance of the United States continually improved since the Second World War. In this regard, this result may indicate an improvement in the country's production efficiency.

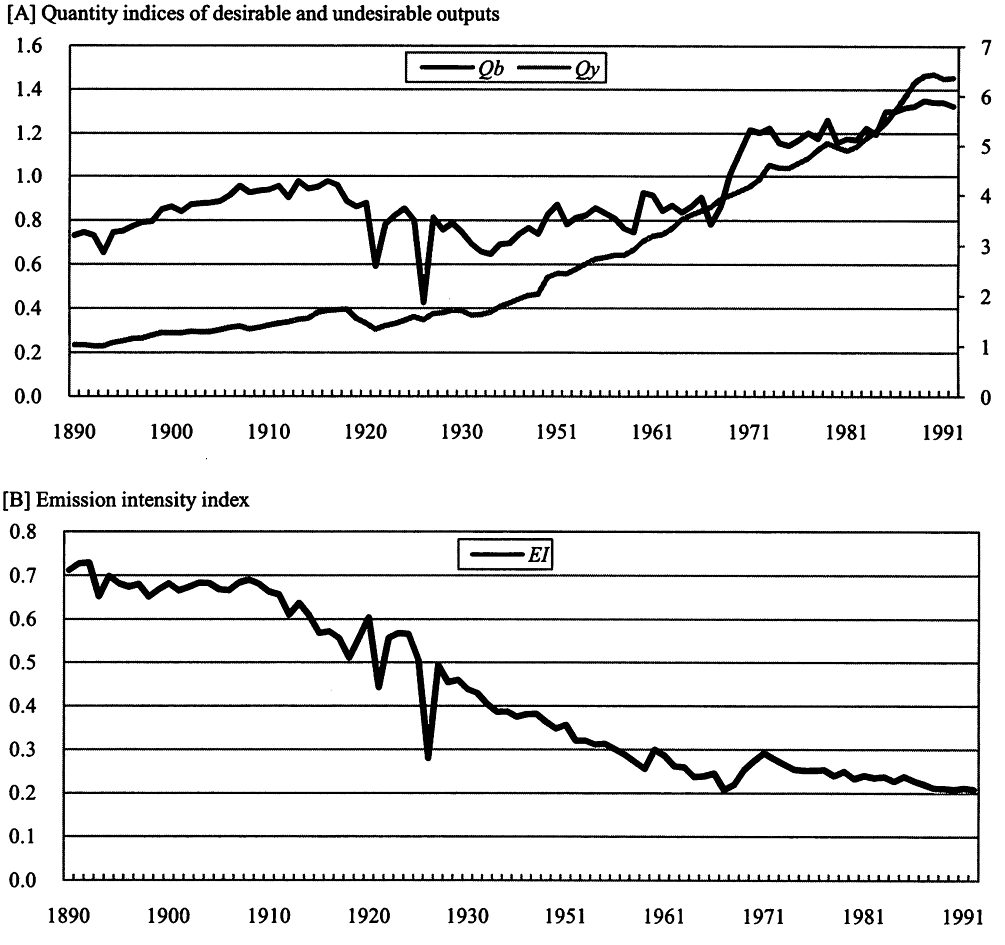
Figure 6. Long-run Changes in the Emission Intensity Index of the United States, 1890–1992



Note: The note for Figure 5 also applies to Figure 6.

On the other hand, the results for the United Kingdom differ from those of Japan and the United States in that the emission intensity index shows no increasing trend before the Second World War (Table 2 and Figure 7). This is because the quantity index of undesirable outputs did not increase sharply. This result implies that the emission of undesirable outputs became gradually inefficient. Thus, the United Kingdom was an early promoter of environmental protection and sustainable development. However, the environmental performance of the United Kingdom declined consistently since the 1910s.

Figure 7. Long-run Changes in the Emission Intensity Index of the United Kingdom, 1890–1992

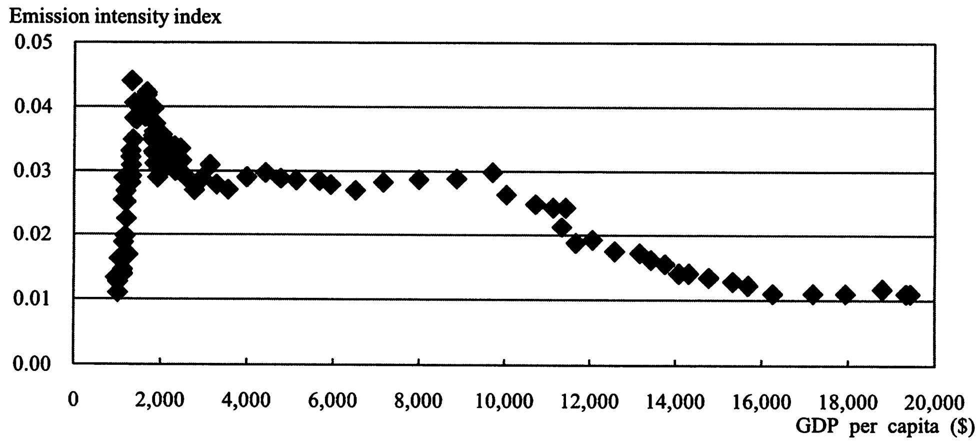


Note: The note for Figure 5 also applies to Figure 7.

The estimation results for Japan, the United States, and the United Kingdom show that the emission intensity indices for the first two countries moved from an increasing to a decreasing trend. However, as their highest emission intensities were recorded before the Second World War, their environmental performance deteriorated before the War and then improved. This trend was mainly prompted by improvements in their production efficiencies. Notably, Japan recorded a gradual improvement in environmental efficiency since the 1970s.

Figures 8, 9, and 10 show the relationships between the emission intensity index and economic development measured as GDP per capita for Japan, the United States, and the United Kingdom, respectively. There is a common overall trend in that the emission intensity index is high at low income levels. Notably, unlike the United States, the emission intensity index of Japan records a clear peak at lower income levels. Due to the short estimation period, it is not possible to observe such a peak for the United Kingdom. Nevertheless, the progressive improvement in income levels deteriorated the environmental performance of the countries in their initial phases of development. Later, once the emission intensity indices peaked, their environmental performance improved.

Figure 8. Relationships between Emission Intensity Index and GDP Per Capita for Japan



Sources: Data for GDP per capita (1990 International/Geary-Khamis dollars) are sourced from Maddison Historical Statistics.

[OLS]

$EI = 0.03879 - 0.00002y + 3.51\mathrm{e}{-09}y^2 - 2.42\mathrm{e}{-13}y^3 + 5.65\mathrm{e}{-18}y^4 + 0.00069t$

(9.04) (-3.84) (3.66) (-3.79) (3.91) (4.99)

$n = 92 \quad R^2 = 0.6597 \quad DW = 0.13143$

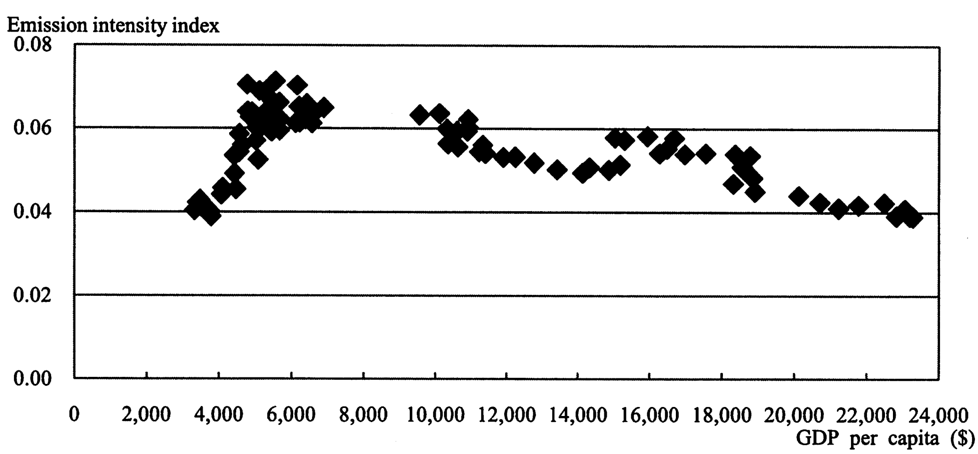
[GLS (Prais–Winsten)]

$EI = 0.02668 - 0.00001y + 2.04\mathrm{e}{-09}y^2 - 1.41\mathrm{e}{-13}y^3 + 3.27\mathrm{e}{-18}y^4 + 0.00048t$

(4.33) (-2.48) (2.43) (-2.60) (2.67) (3.34)

$n = 92 \quad R^2 = 0.2062 \quad DW = 1.77938$

Figure 9. Relationships between Emission Intensity Index and GDP Per Capita for the United States



Sources: Same as that for Figure 8.

[OLS]

$EI = -0.02763 + 0.00003y - 4.29\mathrm{e}{-09}y^2 + 2.19\mathrm{e}{-13}y^3 - 3.92\mathrm{e}{-18}y^4 + 0.00034t$

(-2.45) (6.64) (-7.28) (7.03) (-6.78) (3.85)

$n = 92 \quad R^2 = 0.7993 \quad DW = 0.86747$

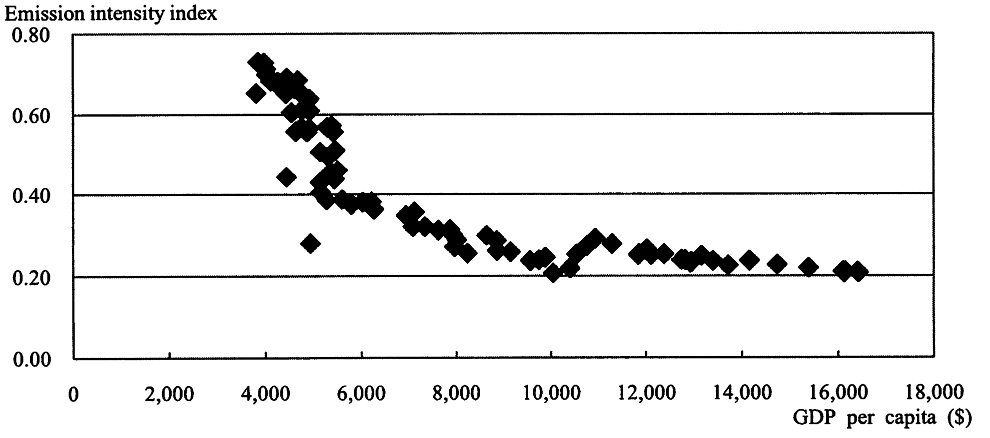
[GLS (Prais–Winsten)]

$EI = 0.00670 + 0.00002y - 2.42\mathrm{e}{-09}y^2 + 1.21\mathrm{e}{-13}y^3 - 2.11\mathrm{e}{-18}y^4 + 0.00042t$

(0.46) (2.72) (-3.07) (2.92) (-2.79) (2.92)

$n = 92 \quad R^2 = 0.6158 \quad DW = 2.22353$

Figure 10. Relationships between Emission Intensity Index and GDP Per Capita for the United Kingdom



Sources: Same as that for Figure 8.

[OLS]

$$EI = 0.14232 + 0.00034y - 6.48e\text{-}08y^2 + 5.01e\text{-}12y^3 - 1.31e\text{-}16y^4 - 0.00815t$$
$$(0.36) \quad (1.95) \quad (-2.55) \quad (3.09) \quad (-3.50) \quad (-6.15)$$

$n = 92$ $R^2 = 0.9582$ $DW = 1.38425$

[GLS (Prais Winsten)]

$$EI = -0.01855 + 0.00041y - 7.43e\text{-}08y^2 + 5.57e\text{-}12y^3 - 1.43e\text{-}16y^4 - 0.00860t$$
$$(-0.03) \quad (1.69) \quad (-2.15) \quad (2.55) \quad (-2.87) \quad (-4.42)$$

$n = 92$ $R^2 = 0.9279$ $DW = 2.04778$

Country-specific estimation results of the regression analyses using time-series data appear below Figures 8, 9, and 10. *EI* denotes the emission intensity index (the dependent variable), while *y* and *t* denote the real GDP per capita and the time trend (the independent variables).[5] The results of the Durbin–Watson test in the estimation of the ordinary least squares (OLS) parameters show a first-order autocorrelation. To deal with the serial correlation, this study also estimates the generalized least squares (GLS) applying the Prais–Winsten transformation.

The results show that the estimated parameters of GDP per capita are significantly positive, and its quadratic terms are significantly negative for the United States and the United Kingdom. In addition, their cubic terms are significantly positive, and their quartic terms, significantly negative. This suggests the existence of the Environmental Kuznets Curve (EKC), which means that the relationship between the emission intensity index and GDP per capita has an inverted U-shape. The estimation results for Japan, however, do not support the existence of the EKC. Therefore, the inverted U-curve shape in the United States and the United Kingdom indicates that environmental performance deteriorates in the initial phase, improves in the second phase, then deteriorates again in the third phase, and improves again in the fourth phase.

[5] Values in parentheses are robust *t*-statistics. *n* is the number of observations, R^2 is the coefficient of determination, and *DW* is the Durbin–Watson statistic.

V. Conclusions

The results of this study showed that the emission intensity indices were at their highest before the Second World War for all three countries. This suggests that in their initial phases of development, the production efficiencies of all three countries improved accompanied by deterioration in their environmental efficiencies. In other words, environmental performance was the worst before the Second World War when income levels were relatively low. Furthermore, this study also confirmed that as income levels increased to some degree in the later phases of development, environmental performance improved with economic development. Notably, in Japan, this study showed that environmental performance was the highest since the 1970s due to improvements in both environmental and production efficiency.

In future research, it would be worthwhile to examine the EKC for the United States and the United Kingdom (the existence of the EKC could not be proved for Japan during the period under study) and verify whether the same conditions also prevailed in other developed countries before the Second World War. Applying a panel data model will increase the robustness of the EKC analysis and help pinpoint the turning point or apex of the EKC.

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