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Decoupling Status of Metal Consumption from Economic Growth*

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The decoupling statuses of the consumption of 22 kinds of metals from economic growth were analyzed. Metals were Fe, Al, Cu, Cr, Zn, Mn, Pb, Ni, Co, Sn, Sb, Si, Mo, W, Li, In, Ga, Ag, Au, Pt, Pd and rare earths. The relations between the per capita annual consumption of each metal and per capita GDP were approximated by a two-steps linear formula of $y_M = a_{M,1} X$ ($X < c_M$) and $y_M = a_{M,2} X + b_{M,2}$ ($X > c_M$), where y_M is the annual consumption of a metal M, and X is GDP per capita. Metals which had only a single relation of $y_M = a_{M,1} X$ were judged to be in a state of coupling. When $a_{M,1} > a_{M,2}$, the state was judged to be decoupling. Furthermore, a metal was judged to be in a state of absolute decoupling when $a_{M,2} < 0$. The metals which tended to exhibit characteristics of absolute decoupling were Au, Sn, Zn and W, while Cu and Pb were borderline. While Fe, Al, Ni, Mo, Sb, Ag, Pd are decoupling from per capita GDP, Si and Pt are still coupled with economic growth. In the cases of Co, Li, In, Ga and rare earths, a new coupling relation with economic growth has developed over the past several years.
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1. Introduction

The expansion of economic development around the world in recent years is increasing concerns about its sustainability. This is especially true for the utilization of materials, which is one of the fundamental aspects that have supported economic activities. However, most of these materials are derived from natural resources and massive energy inputs are required to process them into usable products; furthermore, after the profitable characters are utilized, they become waste products in the environment. Thus, they can not only have benefits, but they can also have environmental impacts, and be a factor that exerts pressure on sustainability.

It cannot be denied that if world economic growth becomes more connected with the quantitative increase in materials utilization, it will lead to limitations on the capacity to supply resources and further deterioration of the global environment. Against this backdrop, a turnaround is required from the paradigm which holds that economic growth is closely related to the quantitative increase of material consumption. This is called “decoupling.” When a state of decoupling has been achieved, economic growth can occur without an increase and sometimes even with a decrease in quantitative material consumption. In this state, sustainability can be established by eliminating increases in adverse environmental effects and averting resource depletion.

It is pointed out that decoupling is not an issue of the future, it began in the OECD countries with the oil shocks of the 1970s. Between 1980 and 2000, the production of steel in Japan remained at about the same quantitative level, but in terms of GDP it nearly doubled. At the same time, better steel products came into use in automobiles, buildings, and other fields. While decoupling started for some materials like this way, the demand of silicon has also been rising as the economy grows, becoming difficult to secure raw materials. The present paper looks at different metals and examines their decoupling status from the perspectives of economic growth and increasing quantitative consumption. The findings will be used in an attempt to not only provide basic data that will help to predict future materials consumption, but also to identify important metals and other materials that will be the subject of new technological development for decoupling.

2. Decoupling of Economy and Environment and Associated Indexing

Although the English word “decoupling” is generally used to mean “separating,” here it is used in a stricter sense to refer to the separation of economic growth from environmental degradation. In other words, it is used to indicate economic growth that is not directly tied to environmental degradation. At the 2001 OECD Environmental Ministers’ Meeting, the term was defined as “the decoupling of environmental pressure from economic growth.”

In April 2004, the OECD gathered reports[1] related to decoupling indices. If the following relation is materialized within a fixed period, then decoupling is considered to have been achieved:

$$\text{(Increase rate of environmental pressure)} \\ < \text{(Growth rate of economic driving force)} \quad (1)$$

Figure 1 is a synthesis of figures used in the reports that show annual changes in GDP (Gross Domestic Product), DMI (Direct Material Investment) and SOx emissions based on 1980 as the index year. If we interpret GDP as being the driving force of an economy, then SOx emissions show a negative (decreasing) tendency when GDP shows a positive, increasing trend. This is judged to be a state of decoupling. A state of decreasing environmental load during a growing economy is called “absolute decoupling.” In contrast, increases in DMI tended to be dependent on increases in the GDP, so it is not headed toward absolute decoupling. However, based on eq. (1), it can be considered to be in a somewhat weak state of decoupling.

These OECD reports include various decoupling indicators, such as climate changes, atmospheric pollution, water

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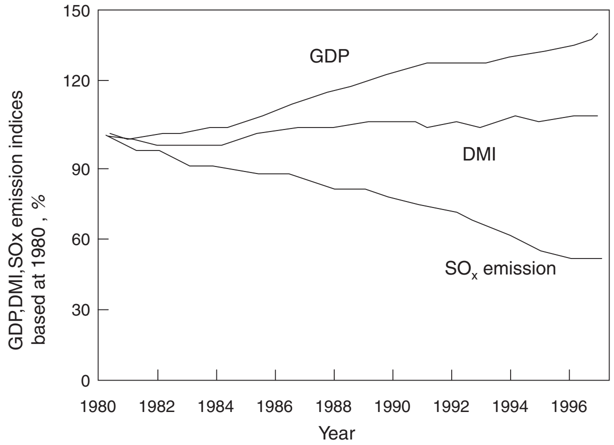

Fig. 1 Indices change of SOx emission, DMI and GDP.

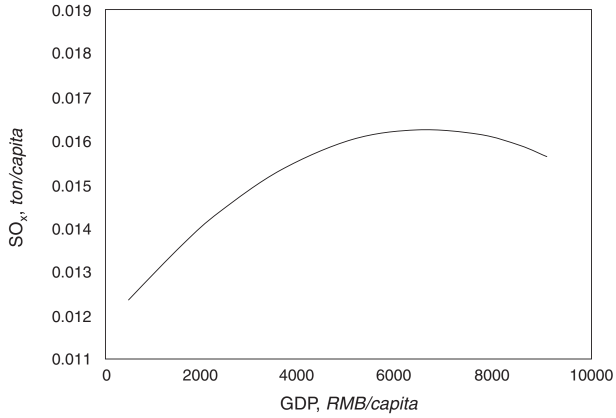

Fig. 2 An Environmental Kuznetz Curve of SO_2 emission per capita v.s. GDP per capita at China.

quality, traffic and transportation, and agriculture, among others. One typical example on the resource side is Japan's resource productivity,[2)] which is being treated as a target for promoting a sound circulation society in the country. The following is an explanation.

$$\text{(National resource productivity)} = \frac{\text{(Gross Domestic Product)}}{\text{(Amount of inputs of natural resources and their associates)}} \tag{2}$$

While "national resource productivity" is expressed as the ratio of absolute values, in the OECD reports there are some examples of it being indexed as the rate of change based on a fiscal year, as shown in Fig. 1. The method for expressing this rate of change is generally called "elasticity analysis." Looking at the case of energy, we find it expressed as follows:

$$\text{(Energy elasticity)} = \frac{\text{(Rate of energy increase)}}{\text{(GDP growth rate)}} \tag{3}$$

The relation with eq. (1) is that if the elasticity value is 1 or less, then it is equivalent to a state of decoupling.

A similar expression to the decoupling index is the Environmental Kuznetz Curve. The Kuznetz Hypothesis holds that the relationship between economic growth as economists have maintained it to be and income disparity forms an upside-down U curve, and some have argued that the relationship between economic growth and changes in environmental quality shows a similar tendency. Figure 2 shows an example by Ninomiya[4)] of SOx occurrence in China. Plotting per capita GDP(x) against per capita SOx(s) gives us the following equation:

$$S = -1.2 \times 10^{-10} X + 1.36 \times 10^{-6} \tag{4}$$

As Yamashita[5)] and Matsuoka[6)] have pointed out, whether or not the Environmental Kuznetz Curve has generality is a subject for future repeated corroboration and debate. However, the equation that describes per capita environmental pressure factors vis-à-vis per capita GDP is effective for gaining an understanding of the state of decoupling. For example, in the 1992 World Development Report, upside-down U patterns for SOx emissions, and steadily increasing pattern for CO_2 emissions, volume of waste products, etc., have been used to make comparisons between countries having different levels of per capita GDP.[7)] At that time, the concepts of decoupling were still in the development stage, so focused mostly on trends rather than indices. However, in the present paper this method is used in an attempt to describe the state of decoupling.

3. Method for Indexing Decoupling

By expressing the indexing of different types of decoupling with numerical equations as was done in the previous section, let us attempt here to generalize, compare and find differences. First, let us examine the absolute expression (f) such as for Japan's resource productivity that was shown with eq. (2). We can derive the following equation,

$$f = z/g \tag{5}$$

where f is resource productivity, z is the environmental pressure factor, and g is the economic factor.

It should be noted that in the case of indicators used to define resource productivity in Japan, z is the amount of natural resource inputs and g is the gross domestic product, but there is an inverse relationship with the other absolute indicators so the figures become difficult to interpret. In addition, when k is used for the elastic value notation in Equation (3), z_o, and g_o are used for the environmental pressure factor and economic factor of a standard year, respectively, and the respective amounts of changes over a fixed period are denoted as Δz and Δg, then we can derive the following relationship:

$$k = \frac{(\Delta z/z_o)}{(\Delta g/g_o)} \tag{6}$$

When $k < -1$, there is decoupling; when $k < 0$, there is complete decoupling. In addition, using y to express the correlation per person used in the graph that takes into consideration the Environmental Kuznetz Curve, y generally is a function of x, as follows:

$$y = \text{func}\ (x) \tag{7}$$

However, as in the previously mentioned case of SOx emissions in China, parameters y and x are the per capita value of the environmental pressure factor z (that is, SOx) divided by population p, and the economic factor g (that is, GDP) divided by population, respectively:

$$y = z/p, \quad x = g/p \tag{8}$$

The absolute ratio notation is effective for making comparisons between different countries, and the elastic value notation is also effective for static analyses such as comparisons of the level of decoupling that have been reached during different periods. Therefore, by thinking of consumption of metals as one environmental pressure factor in the present paper, and by deriving the relational function func $_{\mathrm{M}}$() between per capita consumption y_{M} of each metal M and per capital GDP: x, we can understand the state of decoupling.

Concerning the function form, Ninomiya *et al.* considered the Environmental Kuznetz Curve and assumed a quadratic function of an upside-down U going through the origin. However, this paper makes no prior assumptions about the Environmental Kuznetz Curve, and describes the relations as the following progressive linear relation:

$$y_{\mathrm{M}} = a_{\mathrm{M},1}\,x + b_{\mathrm{M},1} \quad (x < c_{\mathrm{M},1}) \tag{9}$$
$$y_{\mathrm{M}} = a_{\mathrm{M},2}\,x + b_{\mathrm{M},2} \quad (c_{\mathrm{M},1} < x < c_{\mathrm{M},2}) \tag{10}$$
$$y_{\mathrm{M}} = a_{\mathrm{M},3}\,x + b_{\mathrm{M},3} \quad (c_{\mathrm{M},2} < x < c_{\mathrm{M},3}) \tag{11}$$
$$\ldots$$

It should be noted that since no more than about 50 data sets since 1950 are being approximated, there is no sense in expanding the progression endlessly, so the two-step linear approximation was stopped at the second level in eq. (10). In addition, for this purpose, $c_{\mathrm{M},2}$ is treated as infinity.

Potential objects of analysis were annual changes and differences between countries. In order to reflect continuous economic and technological conditions, it was decided to choose annual changes in one country. Since data from Japan were the easiest to obtain, it was decided to derive the correlationship. It should be noted that in the discussion, consideration is given to annual changes in several other countries and differences in steel consumption between countries in order to confirm that there were no large discrepancies in the analysis resulting from annual trends in just one country.

The metals targeted for analysis were steel, aluminum, gold, silver, copper, nickel, lead, zinc, tin, platinum, palladium, antimony, silicon, gallium, indium, cobalt, molybdenum, chrome, lithium, manganese, tungsten, and rare earths. Trends in annual consumption were derived from data for up to 2004 listed in the Mineral Resource Databook.[8) Figures for the population and GDP of Japan were a composite of domestic and foreign sources for each year examined, including Kyoto University's Pacific Rim Database, United Nations statistics, and the Bank of Japan's "Annual Report of Economic Statistics." These materials were also used to obtain the amount of steel consumption, the population and GDP data for China, South Korea, the United States, Canada, Australia, and Malaysia that were used in the discussion.

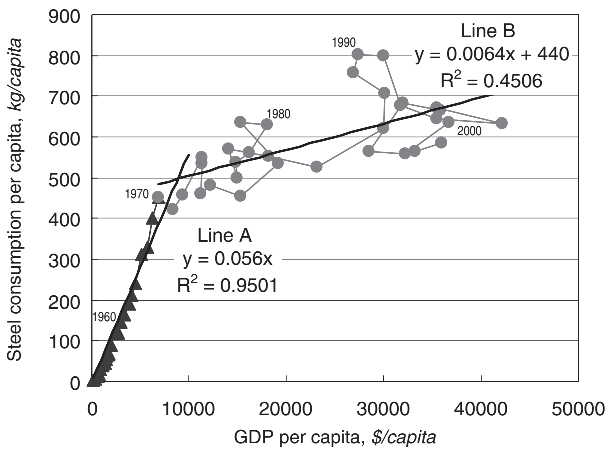

Fig. 3 The relation between steel consumption per capita and GDP per capita in Japan.

4. Results

The relation in Fig. 3 was derived by plotting the value for steel consumed in Japan since 1945 divided by the Japanese population (per capital steel consumption) on the y-axis, and the GDP divided by population (per capita GDP) on the x-axis. Until 1970, the per capita energy consumption showed a roughly linear increase vis-à-vis per capita GDP, but this increase tended to soften from about 1970 onward. Using 1970 as the pivot point and approximating with the two lines, we can express the value for 1970 and earlier as

$$y_{\mathrm{Fe}} = 0.056\,x \tag{12}$$

and can be approximated as a line (Line A) that goes through the origin. The value for 1970 onward can be approximated as Line B, as follows:

$$y_{\mathrm{Fe}} = 0.0064\,x + 440 \tag{13}$$

In the period up to and including 1970, we can approximate using equations of (5) derived by (8) and (12)

$$f \fallingdotseq 0.056 \tag{14}$$

For this period, Equation (6) is always expressed as follows:

$$k = 1 \tag{15}$$

In other words, in the section where Line A is pertinent, the increase in steel consumption is closely tied with the increase in GDP, and there is no decoupling, that is, consumption is coupled with economic growth.

On the other hand, from 1970 onward, the slope of Line B is a positive 0.0064, indicating that there is no absolute decoupling because there is not a definite trend of steel consumption declining as GDP increases. However, it is considered to be a weak decoupling. The reason is followings. In the following equation which is the absolute notation of Equation (5), the absolute ratio decreases with the GDP growth

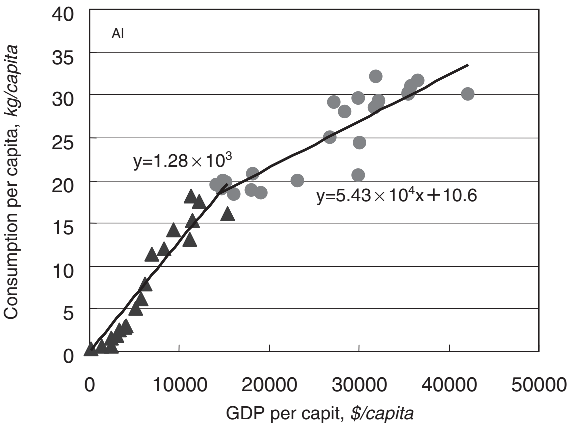

Fig. 4-1 Metal consumption per capita v.s. GDP per capita: Aluminum

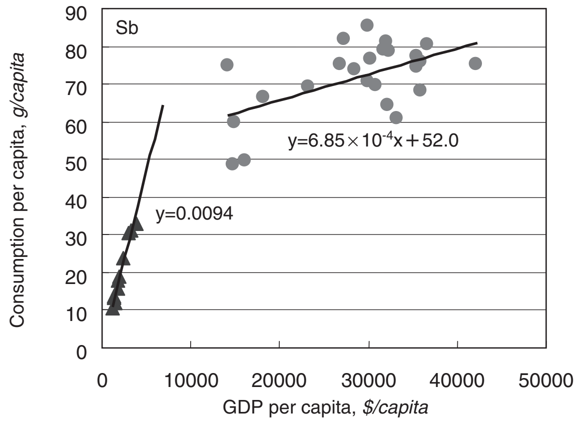

Fig. 4-4 Antimony

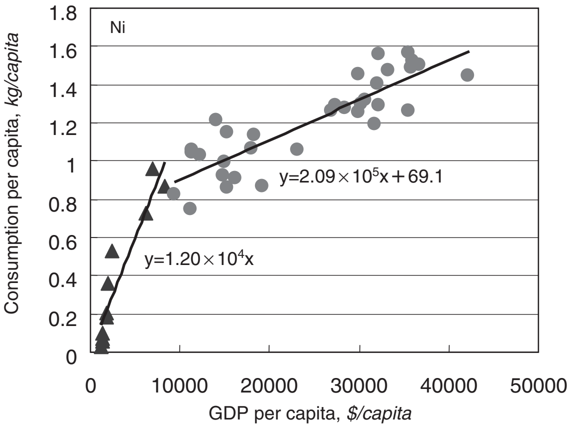

Fig. 4-2 Nickel

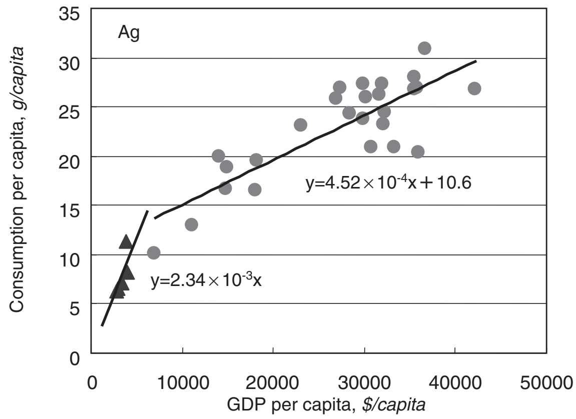

Fig. 4-5 Silver

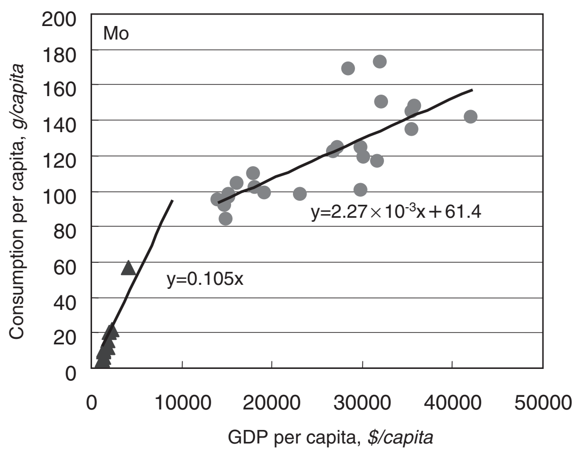

Fig. 4-3 Molybdenum

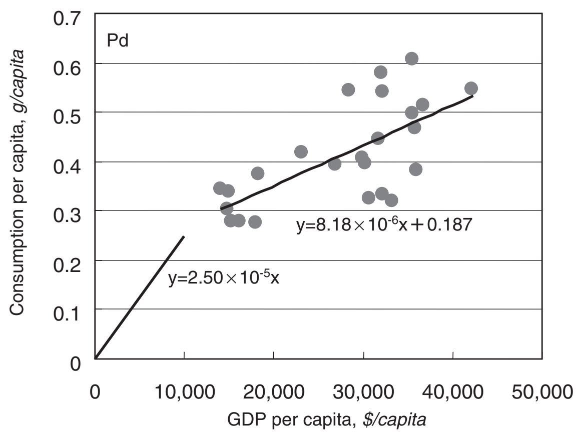

Fig. 4-6 Palladium

$$f = 0.0064 + 440/g \tag{16}$$

The relation between per capita GDP (x_o) for a random year and an elastic value k can be expressed as

$$k = \frac{x_o}{x_o + 68750} \tag{17}$$

in which $0 < k < 1$ signifies that a weak decoupling is occurring.

The following graphs from Fig. 4-1 to Fig. 4-21 are the analytical results for the various types of metals. Included in the group showing the same type of weak decoupling as steel are aluminum, nickel, molybdenum, antimony, silver, and palladium. Among these, it was not possible to obtain data on palladium when it was in a state of coupling. However, because the slope of the regression line of Line B does not traverse the origin, palladium was considered to be in a state of decoupling at 2004. Assuming that Line A intersects with Line B at a per capita GDP of US $10,000 where most metals tend to make the transition from coupling to decoupling, the

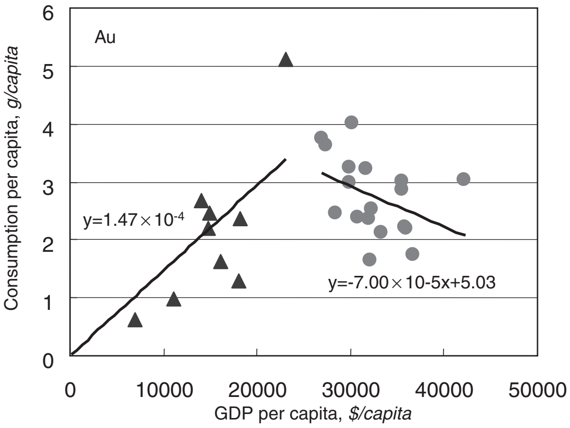

Fig. 4-7 Gold

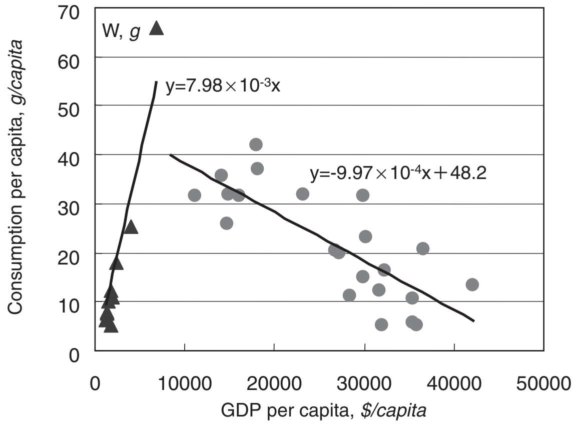

Fig. 4-10 Tungsten

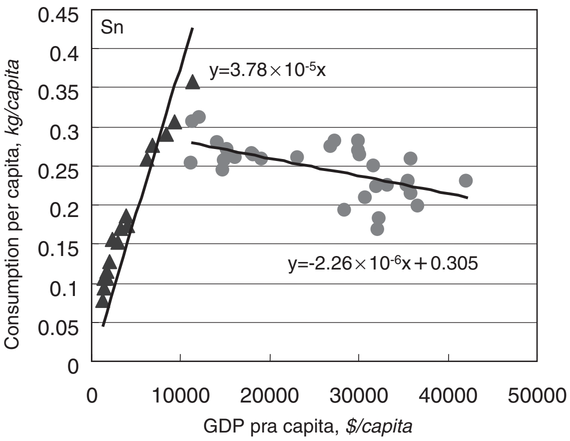

Fig. 4-8 Tin

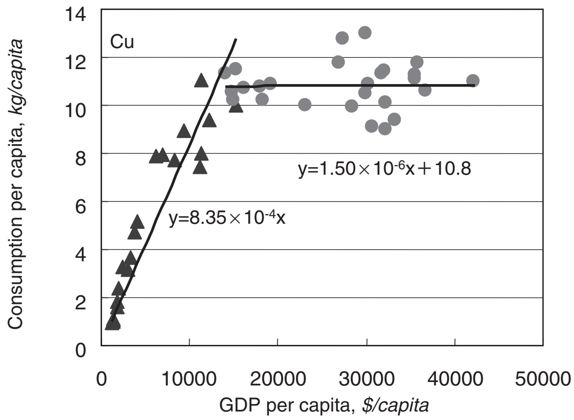

Fig. 4-11 Copper

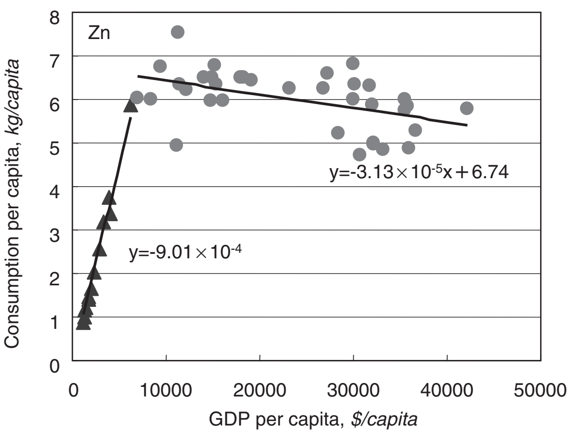

Fig. 4-9 Zinc

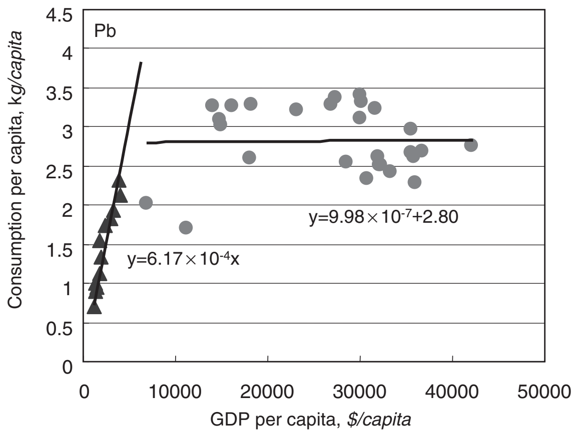

Fig. 4-12 Lead

slope of Line A, which corresponds to a state of coupling, was estimated.

Metals for which absolute decoupling was occurring were gold, tin, zinc, and tungsten. Gold was particularly noteworthy in that its transition to decoupling was at a per capita GDP of about US $25,000, a much higher economic level than the other metals. In addition, after decoupling, copper and lead had no dependency on per capita GDP, and they could be considered to be bordering on absolute decoupling. For chrome and manganese, which have many applications as steel components, there was incomplete data, so it was not clear whether they were in a state of transition toward decoupling, but since the current trends show a negative slope, they were judged to be in a state of absolute decoupling, and a relation for decoupling was estimated in the same way it was for palladium.

On the other hand, metals that could not be extricated from a state of coupling were platinum and silicon. Including the

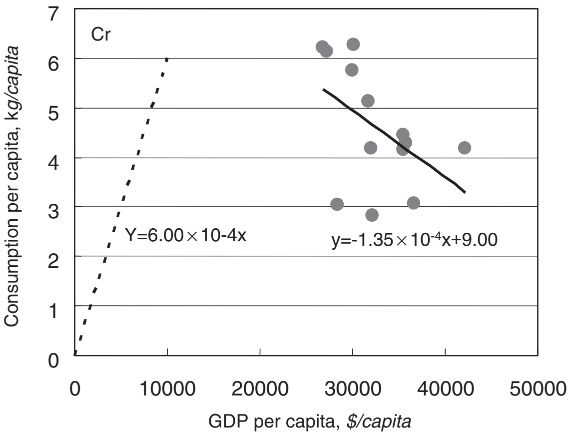

Fig. 4-13 Chrome

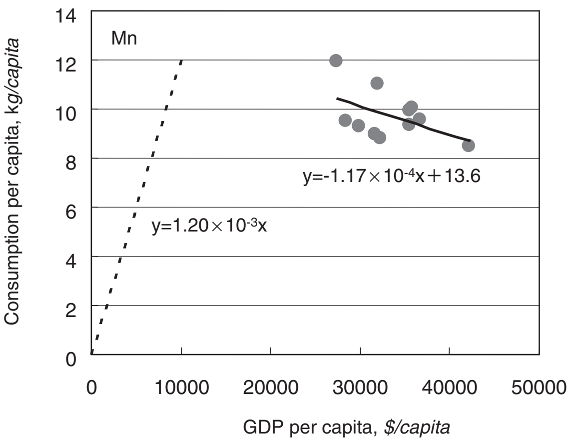

Fig. 4-14 Manganese

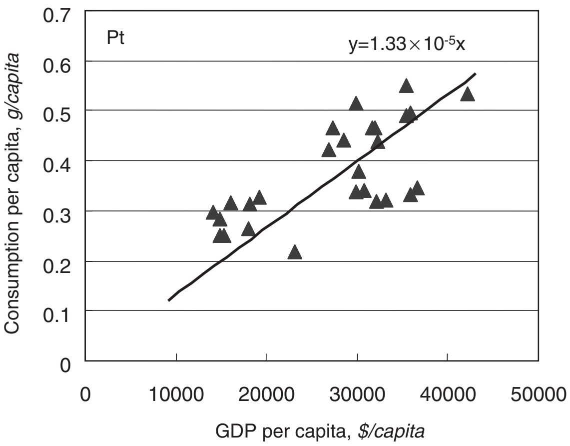

Fig. 4-15 Platinum

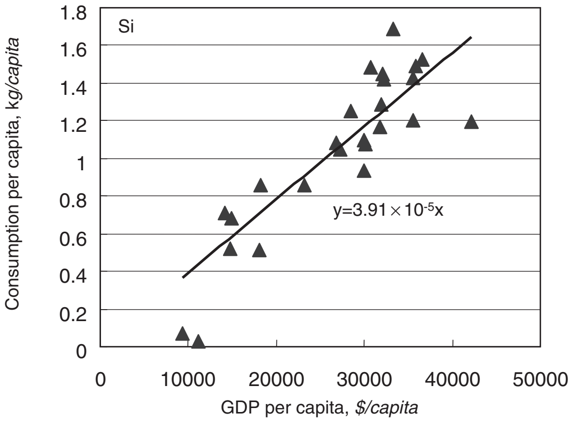

Fig. 4-16 Silicon

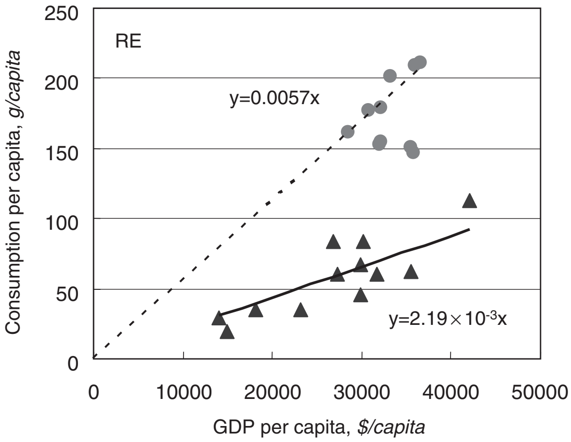

Fig. 4-17 Rare earth

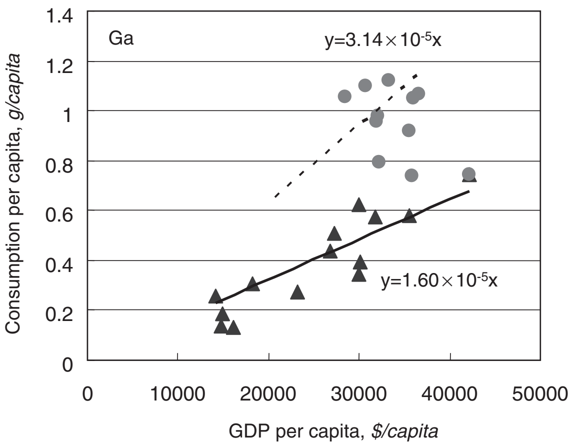

Fig. 4-18 Gallium

2004 data, it was possible to approximate a linear line that traverses the origin for per capita consumption of these two metals, and it appears that coupling has been continuing to the present. In addition, the relation between per capita GDP and per capita consumption of cobalt, lithium, gallium, indium and rare earths has been rapidly rising. As a result, in addition to the bold line in the figure which shows the coupling relationship in the past, a new (broken) line traversing the origin has been added to show a new coupling relationship, its slope was estimated. While changes in the slope correspond to changes in elastic value, in the cases of gallium and rare earths it is double, and in the case of indium is has reached 8-fold. This is because these metals are typical elements used in new technologies such as indium-containing transparent electrodes, GaAs elements containing gallium, lithium batteries, and rare earth magnets. It appears that

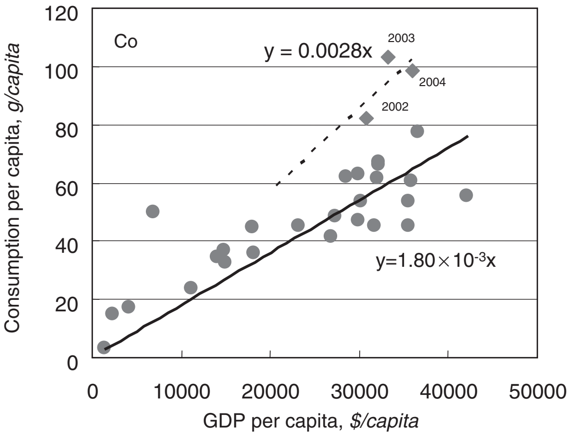

Fig. 4-19 Cobalt

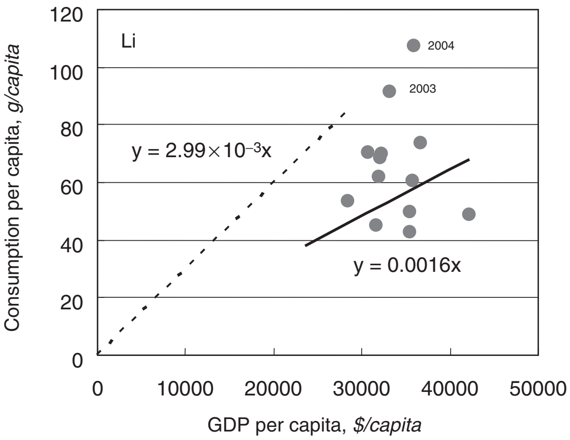

Fig. 4-20 Lithium

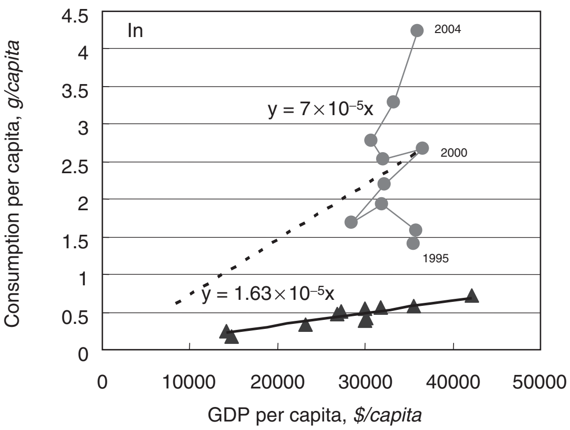

Fig. 4-21 Indium

technological development is leading to new functions and new needs, which in turn is leading to the emergence of new forms of coupling relationships.

5. Discussion

The results of the investigations of each metal were compiled to determine the coefficients of the approximation lines A and B, and the transitional per capita GDP values for each of these metals as x-coordinates of the respective intersections of lines A and B (Table 1). Here, Type I is reaching a state of absolute decoupling, while Type I' is borderline decoupling, Type II shows weak signs of decoupling, Type III shows a state of coupling, and Type III' designates a shift toward a new state of coupling in recent years. Types I and I' (absolute decoupling and borderline decoupling) include numerous metals such as gold, copper, zinc, lead, tin, etc., that have been used for a long time and may even be in danger of depletion. Alternative technologies are being developed for many of these metals, such as tin-free steel, and "the right material for the right purpose" is progressing. Type II metals, which are in a state of weak decoupling, are being put to new uses after the development of public infrastructure. For example, fields of application are expanding for iron, which is being used in steel plates for automobiles, and aluminum, which is used in aluminum siding and automobile engines, so it appears that they will not reach a state of absolute decoupling. Demand for silicon and platinum is rising in high value-added applications in IT industries such as semiconductors, high-value added catalysts, etc., so their state of coupling is being supported by high GDP.

Table 1 Linier coefficient of Approximated Decoupling Relations and Transition GDP.

Type	metal	unit	Line A	Line B		Transition GDP$/capita
			$a_{M,1}$	$a_{M,2}$	$b_{M,2}$	
I	Au	g/capita	0.00015	−0.000069	5.16	23,900
I	Sn	Kg/capita	0.000048	−0.0000023	0.3	8,300
I	Zn	Kg/capita	0.0009	−0.000031	6.7	7,200
I	W	g/capita	0.008	−0.0001	48.2	5,400
I	Cr	Kg/capita	0.0006	−0.00014	9.0	12,200
I	Mn	Kg/capita	0.0012	−0.00012	13.6	10,300
I'	Cu	Kg/capita	0.00084	0	11.0	13,200
I'	Pb	Kg/capita	0.00062	0	2.8	4,600
II	Fe	Kg/capita	0.070	0.0066	336	10,700
II	Al	Kg/capita	0.0013	0.00054	10.6	13,800
II	Ni	Kg/capita	0.00012	0.000021	0.69	7,100
II	Mo	g/capita	0.0105	0.0023	61.4	10,700
II	Sb	g/capita	0.0094	0.00069	52.0	9,800
II	Ag	g/capita	0.0023	0.00045	10.6	5,600
II	Pd	g/capita	0.000025	0.0000082	0.19	11,300
III	Pt	g/capita		0.000013	0	—
III	Si	Kg/capita		0.000039	0	—
III'	Co	g/capita	0.0018	0.0028	0	—
III'	RE	g/capita	0.0022	0.0057	0	—
III'	Ga	g/capita	0.000016	0.000031	0	—
III'	Li	g/capita	0.0016	0.0030	0	—
III'	In	g/capita	0.000016	0.0007	0	—

Furthermore, there are materials that are being used support quality of life at new levels, such as lithium and cobalt for lithium batteries and nickel-hydrogen batteries, indium for transparent electrodes, gallium for LED, rare earths for fluorescent/magnetic materials used for visual information, mobile technology, automatic control. These are now giving rise to new coupling relationships.

Efforts have been made to trace these decoupling relationships to Japan's economic development. Determining whether or not these relationships can be used in other countries can be useful for predicting future resource demand, including in

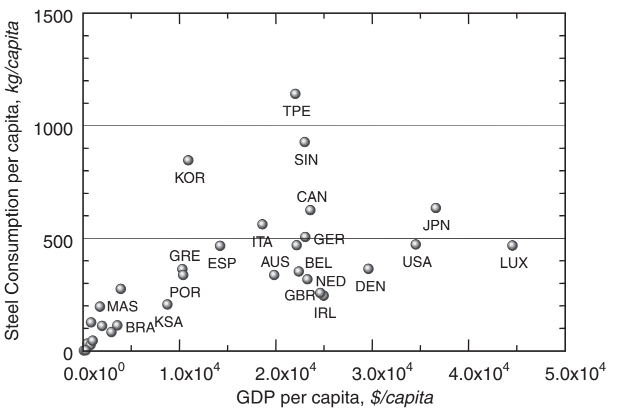

Fig. 5 The relation between steel consumption per capita and GDP per capita of various countries.

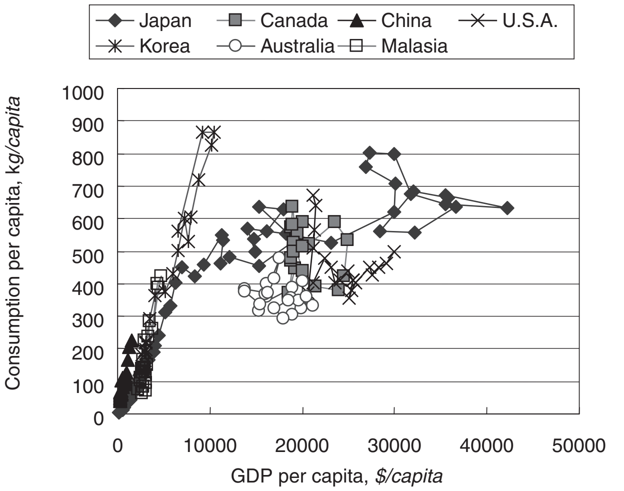

Fig. 6 Changes in the relation between steel consumption per capita and GDP per capita.

countries whose economies are rapidly growing. Thus, an attempt was made to investigate the possibilities. Figure 5 shows the relationship between per capita GDP of various countries and per capita steel consumption. It should be noted that the country abbreviations used here are the official abbreviations of the International Olympic Committee. Although there are some countries such as Taiwan (TPE), Singapore (SIN) and South Korea (KOR) which have exceptionally high per capita steel consumption, we can see that other countries except for these countries are in a state of weak decoupling, resembling the basic one shown in Fig. 3.

Figure 6 shows an overlay of the Japanese graph of transition over time (Fig. 3) with the cases of several other countries (China, Canada, United States, Australia, South Korea, Malaysia). Using this figure, we can get a more clear understanding of the state of decoupling and temporal transitions in these countries by juxtaposing the data with the graph of the state of decoupling in Japan. Particularly in the exceptional case of South Korea, we can see that the data fit fairly neatly with Line A.

Regression analysis was conducted on the data from all countries (except for Taiwan and Singapore; $\diamond$ in Figure 6) with the same weights. The results are shown in Fig. 7. Looking at the case of iron, it appears that the state of

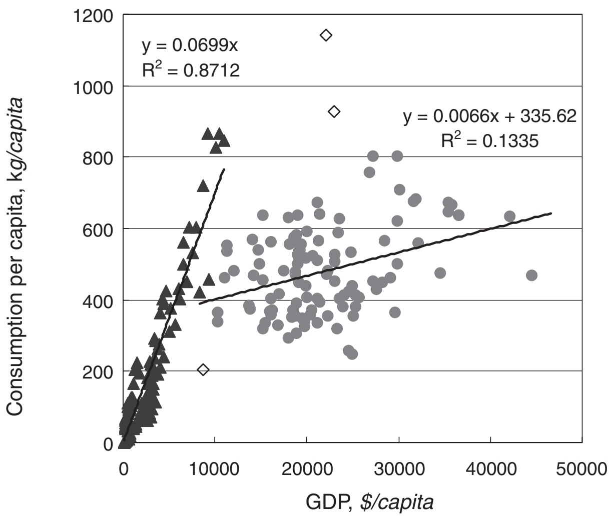

Fig. 7 Extraction of two liner relation form data in Figs. 5 and 6.

decoupling in Japan can be used as a rough approximation to create and examine models for showing the mutual relationship between GDP and metal consumption.

6. Conclusions

This study examined the relation between economic growth and the consumption of certain metals. As a result, it was found that gold, zinc, tin and tungsten were approaching a state of absolute decoupling, and copper and lead were nearing the threshold of absolute decoupling. Metals showing a state of weak decoupling were iron, aluminum, nickel, molybdenum, antimony, silver, and palladium. Meanwhile, silicon and platinum could not be extricated from coupling, and cobalt, rare earths, lithium, gallium, and indium were entering a new state of coupling with a higher absolute ratio.

In addition, these relations can be approximated with two-step linear lines with the limit expressed as transitional per capita GDP ($GDPC_{M,1}$), as follows:

$$y_M = a_{M,0}\,x \qquad (x < c_{M,1})$$
$$y_M = a_{M,1}\,x + b_{M,1} \qquad (c_{M,1} < x)$$

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