The Dematerialization of Natural Resources and Resource Efficiency During 1990 to 2010

Jue YANG[1*] and Shunsuke MANAGI[2]

[1*]*Economic Research Center, Fujitsu Research Institute,*
16-1, Kaigan 1-chome, Minato-Ku, Tokyo 105-0022, Japan
[2] *Departments of Urban and Environmental Engineering, School of Engineering, Kyushu University,*
744 Motooka, Nishi-ku, Fukuoka, 819-0395, Japan
**email: yang.jue@jp.fujitsu.com*

Abstract

Various indicators have been developed for measuring the physical metabolism of economies and assessing the pressure on natural systems of material throughput. Among them, resource efficiency, which can represent the progress toward dematerialization, has become a popular indicator since the early 1990s. Improved resource efficiency, however, may not save resources, but result in even greater consumption through the so-called 'Jevons paradox.' This paper first compares countries' achievement of relative decoupling and absolute decoupling from four types of natural resources over the 1990−2010 period. We then apply a panel analysis to identify the interaction between the improvement of resource efficiency and economic growth. Based on the results, we further estimate the impacts of efficiency improvement, taking rebound effects into account in the short run. The results show that almost one in three countries achieved absolute good decoupling during the last two decades. Among the four types of natural resources we examined in this study, fossil fuel, ores and biomass exhibited a strong relationship between efficiency and economic growth, but industrial minerals did not. Higher resource efficiency can contribute to economic growth and dematerialization, while the development of technology may lead to a rebound effect in the short run. Finally, we analyze implications of our findings for post-2015 SDG designation as setting various targets based on the priority between renewable and nonrenewable resources and levels of resource efficiency across different scales of countries.

Key words: decoupling, dematerialization, rebound effects, resource efficiency

1. Introduction

The UN Sustainable Development Summit adopted a final document named 'Transforming Our World: the 2030 Agenda for Sustainable Development' on Sep. 25−27, 2015 in New York. The draft contains 17 goals and 169 proposed targets designed for sustainable development (UN, 2015a). Among them, improving resource use efficiency was included as target 12.2, 'By 2030, achieve the sustainable management and efficient use of natural resources.' Without a numerical goal, however, it is unclear how the improvement of resource use efficiency can be assessed at the global scale and national level. Adding numerical goals into the international agenda could effectively help governments think about what level of effort they should make, how much it may cost and whether they can afford it. Thus, the next issue should be setting indicators and a framework for estimating the achievement of resource use efficiency. Various types of indicators have been developed for assessing resource use. In a technical report published by BIO Intelligence Service (BIO, 2012) in May 2015, two indicators were proposed for estimating efficient use of materials: domestic material consumption (DMC) or DMC/ capita and material footprint (MF) or MF/capita. The feasibility of adopting these two indicators is ranked as BBB, which indicates they cannot be easily applied by many nations (UN, 2015b). As Wiedmann *et al.* (2015) noted in their review, DMC or DMC/ capita, which is based on a material flow accounting approach has been used as a leading indicator by the European Commission and United Nations Environment Program. MF, which represents the global allocation from raw material extraction to the final demand, contains information on the industrial structure of the given economy as well as its trade relationship with other countries. Grasping MF, however, requires detailed information about all the sectors in each country, which is still difficult to gauge for most developing countries. To further compare the achievement of resource use efficiency using MF, a set of international regulations would be required. Other studies have focused on resource use efficiency or intensity. The intensity concept has been applied to different types of resources and environmental impacts, e.g., energy intensity or CO_2 intensity (Canadell *et al.*, 2007).

For developing countries, investigating the drivers of higher resource use efficiency and the costs of dematerialization at the country level is a crucial issue. UNEP (2011) provides a new concept for assessing resource use, so-called 'resource decoupling.' It is not used for stopping the growth of resource use, but for further defining relevant relationships between economic growth and resource productivity improvement.

Another issue for setting numerical goals is the so-called 'rebound effect,' which use to describe increases in resource use after improvements in efficiency through technology or regulations. This occurs because improved efficiency can result in lower costs of resource use and economic growth, which increases the demand for resources.

This paper aims at grasping resource efficiency and estimating the impacts of efficiency improvements on economic growth, taking rebound effects into account for about 130 countries during the last two decades. We focus on four types of resources: industrial minerals, fossil fuel, ores and biomass. As Pothen and Schymura (2015) summarized, there are three perspectives for investigating the drivers of material use and efficiency improvement in the literature: country level-based index decomposition analysis, structural decomposition analysis, and econometric methodology, e.g., cross-sectional analysis and panel analysis. In this paper, we use cross-sectional analysis and panel analysis for investigating the relationship between resource efficiency and economic growth.

In Section 2, we present a brief overview of achievements in decoupling resource use from economic growth across different income groups over the 1990−2010 period. We then explore the interaction between resource efficiency and economic growth in Section 3. We further examine the impacts of improving resource productivity, taking rebound effects into account in the short run. Our findings are then discussed in Section 4 and conclusions presented in Section 5.

2. The Achievement of Relative Decoupling and Absolute Decoupling from Natural Resources

As stated in 'Decoupling Natural Resource Use and Environmental Impacts from Economic Growth'(UNEP, 2011), the OECD was the first international body to adopt the concept of resource decoupling (2001), and defines it as 'breaking the link between environmental bads and economic goods.' UNEP (2011) redefined it as the 'rate of primary resource use per unit of economic activity.' In 'Decoupling Natural Resource Use and Environmental Impacts from Economic Growth,' UNEP further defined relative decoupling and absolute decoupling. Relative decoupling of resources means that the growth rate of use of the environmentally relevant resources in question is lower than the growth rate of a relevant economic indicator such as GDP (Mudgal *et al.*, 2010), while absolute decoupling means resource use decreased but the economic growth rate did not. Thus, absolute reduction in resource use is more difficult to achieve. It can occur only when the growth rate of resource productivity exceeds the growth rate of the economy.

In this study, we first grasp the achievement of decoupling resource use from economic growth by calculating relative and absolute decoupling. We focus on industrial minerals, fossil fuel, ores and biomass, because these four types of resources are used more generally, with less country specificity.

The data used in this study are from two sources: the World Bank database (World Bank, 2013) and Sustainable Europe Research Institute (SERI) material flows (SERI, 2014). Both of these datasets have been widely used in social science studies.

2.1 Total Use of Natural Resources

To investigate decoupling, we chose the total Gross Domestic Product (GDP) based on purchasing power parity in constant 2011 international dollars of about 130 countries to represent economic growth at the global scale. We plotted the total resource use growth and GDP growth during the period between 1990 and 2010 (Fig. 1). The data of year 1990 are set at 100 as a baseline. The figure shows that the growth of resource use, especially fossil fuel and mineral use, was higher than economic growth in the early 1990s. After 1997, however, ore became the only resource to continue a higher growth rate of usage with GDP. From 2001, the GDP growth rate was much faster compared to mineral use, fossil fuel use and biomass use. Generally speaking, during the last two decades, both resource use and the economic base have been increasing, and a relative

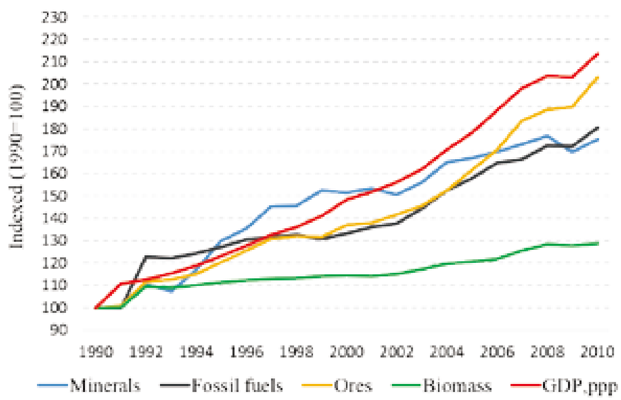

Fig.1 Resource use and GDP.

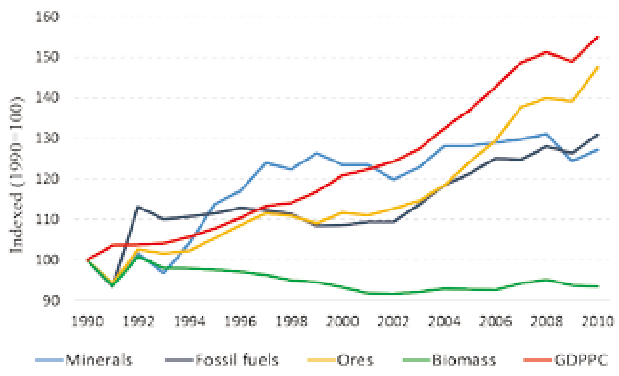

Fig.2 Per capita resource use and GDP per capita.

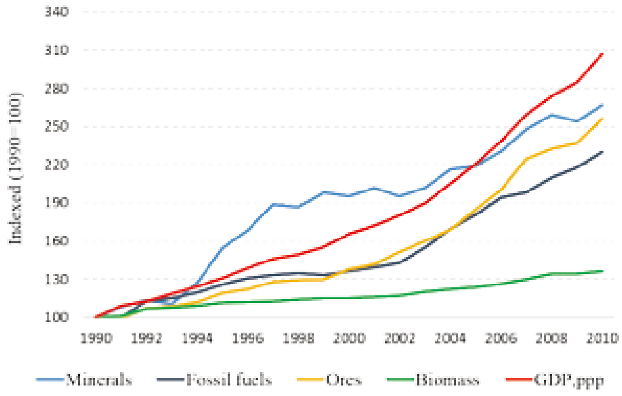

Fig.3 Resource use and GDP growth of developing countries.

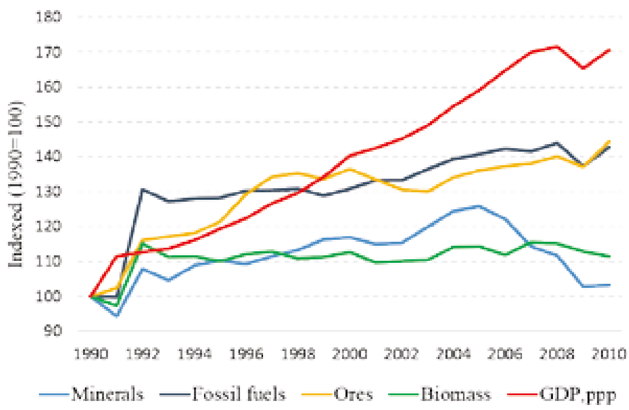

Fig.4 Resource use and GDP growth of developed countries.

decoupling has been achieved in the recent 10 years. Ore use, however, has risen faster than the GDP since 2006. In the dataset, ores, which represent the extraction of major metals and minerals in countries, and include iron, antimony, copper, lead, nickel, zinc, uranium and gold, are highly correlated with urbanization and industrialization. Developing countries probably contribute to the rapid growth of ores.

Because of the rapid population growth during the past two decades, comparing per capita resource consumption and economic growth is also crucial.

Figure 2 shows per capita resource use and GDP during 1990 to 2010 at the global scale. The curves of mineral, fossil fuel and ores use are very similar to the curves in Fig.1. The per capita growth rates of these three resources are lower than GDP per capita, especially after year 2001, which indicates relatively good resource decoupling from economic growth. It is notable that per capita biomass use has shown a downward trend since 1992. A kind of absolute decoupling seems to have been achieved for biomass use. The biomass use here includes biomass food (e.g., sugar crops), biomass animals (e.g., marine fish catch), biomass feed (e.g., crop residue straw), biomass forestry (e.g., wood), and other types (e.g., natural rubber). Per capita minerals use has also changed little since 2004. Here, we only use industrial minerals data from SERI, because data on construction minerals consist of estimated values based on countries' income level. Again, however, ores have shown rapid growth during the past five years. A possible reason is that with industrializations and urbanization, the rate of modern energy accessibility is increasing and there may have been a shift from biomass use for energy to fossil fuel use and from biomass wood use for housing to ore use.

To confirm our thoughts, we further investigated the differences across the developing and developed world. Levels of countries' development is created based on the UN 2012 classification. Figure 3 shows the relationship between resource use and economic growth for developing countries. Compared to Fig.2, all four types of resource use have been increasing more gently. Mineral use was much higher than GDP growth until 2003, while biomass use has continued increasing, but at a much lower speed compared to the growth of GDP, since 1991.

If we look at the resource use of developed countries, however, we see a totally different tendency (Fig. 4).

In the case of developed countries, the growth rate of resource use has become lower than economic growth in total since 1999. Especially for mineral and biomass use, absolute decoupling was achieved in the period 2004–2008. The growth rates of ore and fossil fuel use in the 2000s slowed compared to that of the 1990s, and relative decoupling seems to have been achieved. Environmental regulations designed for improving resource use and technology may have contributed to the decoupling.

2.2 Comparison of Countries

To get a better grasp of patterns of resource use and achievement of decoupling, we examined the relationship between economic growth and resource use across different income groups. The income groups of countries are from the classification of the World Bank's Gross National Income (GNI) per capita.

Figures 5 to 8 represent the relevant relationship during the 1990s and 2000s. We use the resource use growth rate as the horizontal axis, and the GDP growth rate as the vertical axis in the figures. The growth rates here are the growth rates of the total values during the

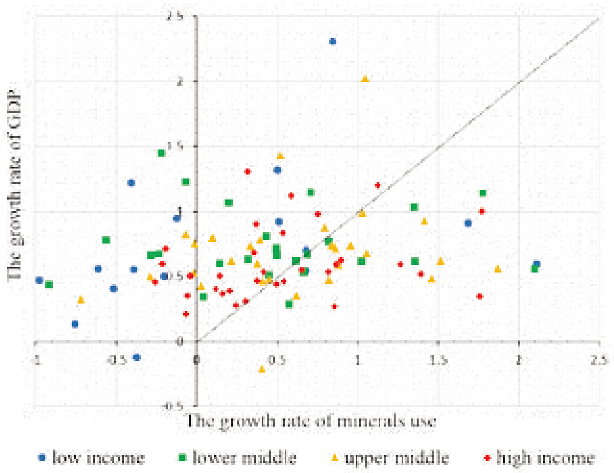

Fig.5 Decoupling of mineral use from economic growth (N=109).

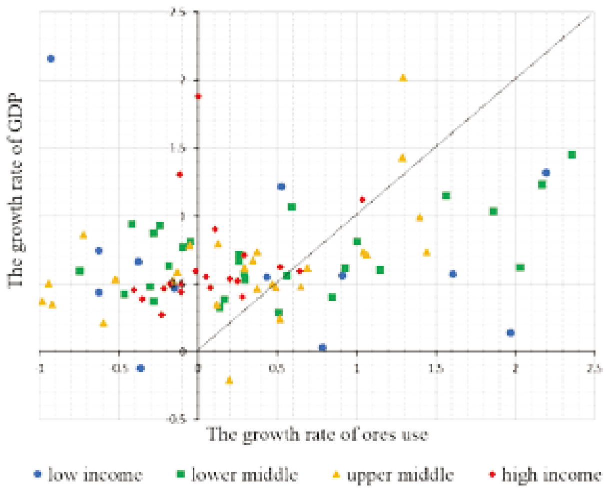

Fig.6 Decoupling of ore use from economic growth (N=95).

1990s and 2000s, which measure the changes for the past 20 years. The nodes representing countries in the figures are colored according to the countries' income levels. For instance, low-income countries are colored blue; lower-middle-income countries, green; upper-middle-income countries, orange; and high- income countries, red. We can distinguish four types of resource use situations in each figure: nodes in the first quadrant can be defined as representing weak decoupling (both resource use and GDP growth rate are positive); nodes in the second quadrant indicate absolute good decoupling (while the economy grows, resource use decreases); nodes in the third quadrant indicate relative bad/ good decoupling (while the economy grows, resource use decreases); and nodes in the fourth quadrant indicate absolute bad decoupling (when the economy and resource use are both decreasing). We have further added a 45 degree line in the first quadrant. The space between this 45 degree line and the vertical axis is the relative good decoupling zone, because economic growth outpaces the growth of resource use. The space between the 45 degree line and the horizontal axis could be defined as the weak decoupling zone. Our goal for most of the countries would be for them to enter the relative good decoupling zone or the second quadrant. Figure 5 shows the relationship between mineral use and GDP growth rate across countries. Among the 130 countries, 109 countries were extracting minerals, so the total observations here were 109. Countries with different income levels were mixed together and most of them were located in the first quadrant, which indicates weak decoupling from mineral use for the past 20 years. There are some countries, however, in the second quadrant, which means they have already achieved absolute good decoupling. They are Hungary, Poland, Uruguay, Armenia, Yemen and Uganda. Most of these countries are not big mineral suppliers. There is only one country located in the fourth quadrant, Jamaica. Jamaica has been a big minerals exporting country since the 1970s, and is now suffering a serious economic crisis

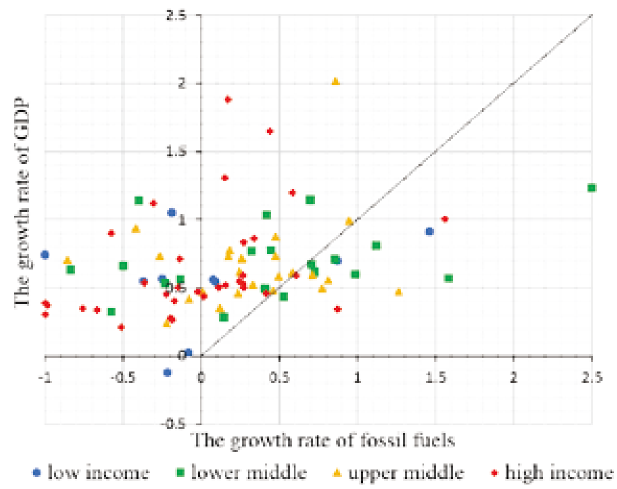

Fig.7 Decoupling of fossil fuel use from economic growth (N=92).

and environmental pressure (Harris & Omoregie, 2008). Thus, its economic growth rate is negative while its resource use growth rate is positive. For Jamaica, the goal for sustainable resource use should be to shift from the fourth quadrant to the first quadrant.

Figure 6 shows the state of decoupling from ore use. Due to limited data, only 95 observations were available. Compared to the previous figure, here we can see a clearer cluster of income groups. Almost all the high-income countries are located in the relative good decoupling zone and the second quadrant, while lots of low-income and lower-middle-income countries are located in the weak decoupling zone. Upper-middle-income countries are variously located in the figure. There is a kind of pattern here in that ore use is highly similar in the case of rich countries. Combining what we found in Fig.4, that developing countries have been contributing the largest amount of the ore use recently, the results here are understandable. Again, Jamaica is the only country located in the fourth quadrant. Jamaica is also one of the biggest producers of bauxite and alumina, but exporting ores has no longer been able to

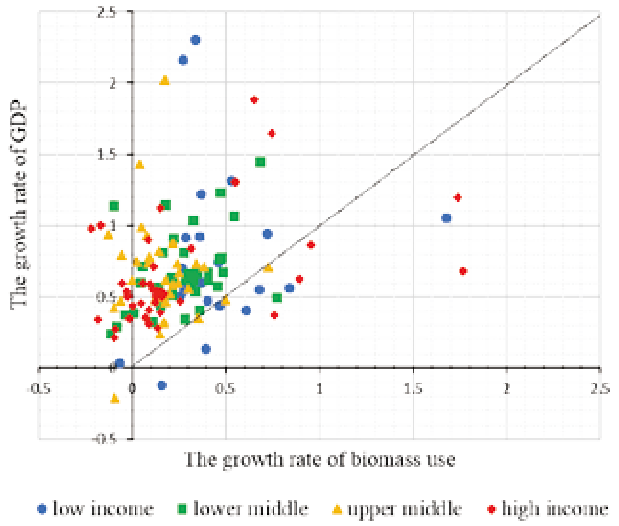

Fig.8 Decoupling of biomass use from economic growth (N=129).

support its economy since the 1980s.

Figure 7 is a scatterplot of fossil fuel use and GDP growth. One third of the countries are located in the second quadrant. We find a different tendency of low-income countries compared to the previous figure. Most low-income countries are located near the vertical axis. A possible reason is most low-income countries do not possess fossil fuels and are more dependent on exports. No countries are located in the fourth quadrant here. With higher extraction of fossil fuels, the GDP growth rate also increases. Countries like Cote d'Ivoire, Senegal and Israel, however, face unstable political situations that result in low economic growth, despite increasing fossil fuel prices and exports.

Figure 8 shows the relationship between biomass use and economic growth. There are fewer countries located in the second quadrant, and they range along the horizontal axis from −0.5 to 2.5.

The figure demonstrates that more countries have achieved relative good decoupling in the case of biomass use. With population growth, it may be difficult to reach an absolute decoupling from biomass use. Except for Croatia, Estonia, Israel and Kuwait, most of the high-income countries have achieved relative good decoupling. Developing countries like Cambodia and Liberia, have achieved high growth rates and low biomass use growth rates. Less than one third of the countries have achieved absolute good decoupling. The remaining two thirds of the countries have the potential to improve their relationship between resource use and economic growth. We find, however, that countries with unstable political situations or large debts seem to experience inefficient economies.

3. Mechanism of Interaction between Improved Resource Efficiency and Economic Growth

In this section, we consider the empirical determinants of relative and absolute good decoupling using a panel analysis. We first create a panel dataset for exploring the factors impacting the efficiency of resource use. Then we examine the effects of resource use efficiency on countries' income growth.

3.1 Cross Country Analysis of Resource Efficiency

There are abundant studies that have investigated the inter-effects between resource use and economic growth, especially on energy, emissions and economic growth. As Soytas and Sari (2009) summarized, these studies can be divided into two areas. One uses the Environmental Kuznets Curve (EKC) hypothesis, which assumes an inverted U-shaped relationship as well as quadratic and cubic relationships between per capita income and environmental pollutants (Stern, 2004; Fujii & Managi, 2013). The other area focuses on identifying the Granger causality link between energy consumption and economic growth or employing cointegration models (Ozturk, 2010). Recently, a combined approach using both methods for investigating the dynamic relationships between resource use and economic growth has been applied (Zhang & Cheng, 2009). We have simply followed their findings and tried to capture the tendencies for the last 20 years. Our model for estimation has the following form:

$$lnefficiency_{i,t} = \alpha_0 + \alpha_1 \, lnGDP_i^{1990} + X\beta + c_i + \varepsilon_{i,t} \quad (1)$$

where the indices t and i represent time and country, respectively. There are two periods in our dataset: the 1990s and 2000s. The dependent variable resource efficiency is the ratio of the sum GDP to the total domestic resource use for the last two decades, divided by population. Higher values represent better efficiency. We use the GDP of year 1990 for controlling the initial income level of each country. $\boldsymbol{X}$ denotes the matrix of variables used for investigating their impacts on resource efficiency. The average values of each decade are used for the variables in $\boldsymbol{X}$. CAP is the gross domestic fixed capital investment, which is proportional to the GDP. It includes land improvements, plant, machinery and equipment purchases, and the construction of roads and railways, which may affect resource use in a given country. CPI is the consumer price index, which represents changes in the cost of goods and services. It is also worth considering that changes in costs may impact changes in the demand side of resource use. The GDP deflator is the annual change in the GDP implicit deflator, which shows the rate of price changes in a given country. We assume it would also be an important factor affecting resource use. The number of patents is employed for capturing improvements in technology in a given country. Renewable energy as a share of energy use is used to examine its impacts on fossil fuels and biomass use. 'ε' is the error vector. Fixed effect and random effect are examined using Hausman tests.

Table 1 presents the results of the panel analysis. Labor is the only variable that is relevantly consistent in the four models. Countries with large populations, such as China

Table 1 Resource efficiency in the panel analysis.

	Model I minerals	Model II fossil fuels	Model III ores	Model IV biomass
GDP1990 (logged)	−0.063	0.095	1.167**	−0.138
	0.178	0.502	0.388	0.137
CAP	−0.017	−0.116+	−0.094*	−0.024+
	0.02	0.059	0.042	0.013
CPI(logged)	0.091	0.982+	0.593+	−0.103
	0.169	0.559	0.346	0.15
Labor(logged)	−0.757**	−0.790+	−1.212**	−0.333**
	0.145	0.452	0.335	0.117
Patent(logged)	0.006	0.083	−0.294	0.175*
	0.082	0.296	0.18	0.079
GDP deflator	−0.033	−0.385	−0.206	0.006
	0.068	0.404	0.137	0.069
Trade (%)	0.007**	−0.005	0.013+	0.002
	0.002	0.01	0.007	0.003
Renewable (%)	0.020**	0.028	0.007	−0.004
	0.005	0.018	0.012	0.004
Period	0.013	−1.009+	−1.213*	0.14
	0.223	0.57	0.481	0.154
constant	15.029**	11.056	−6.134	8.945**
	2.82	8.616	6.296	2.342
N	178	144	149	188
R2	0.615***	0.522**	0.147***	0.579**
Model type	Random effect	Fixed effect	Random effect	Fixed effect
Hausman test	0.3244	0.0147	0.5699	0.0371

Note : The first column is the coefficient; the second column is the robust standard error.
+=p<.1; *= p<.05; **= p<.01; ***= p<.001.

and India, have lower resource efficiency. The income level in 1990 shows a positive effect on the efficiency of ore use only, indicating that the level of development may not so important in improving resource efficiency.

As we showed in the previous section, the growth of ore use shows a different tendency compared to the other three types. It is a more income-oriented resource. The result of trade shows that a country more dependent on exports seems to have a lower efficiency of mineral use. The renewable energy share also has a positive effect on the efficiency of mineral use. There are a large number of developing countries with less access to modern energy that have high renewable energy shares. Thus, it is not simple income level but the structure of the economy and the level of human development that affect efficiency. The number of patents only impacts biomass use.

3.2 Panel Analysis of the Relationship between Resource Efficiency and Economic Growth

Here we apply a dynamic panel analysis of the relationship between resource efficiency and economic growth. We focus on whether resource efficiency in previous times has had an impact on the GDP per capita in subsequent times.

Our model for estimation has the following form:

$$lnGDPpc_{i,t} = \alpha_0 + \alpha_1\, lnefficiency_{i,t\text{-}1} + X\beta + c_i + \varepsilon_{i,t} \quad \textbf{(2)}$$

where X includes variables that have been examined in the existing studies. CPI, patents, GDP deflator and renewable energy share are used in the analysis, along with life expectancy, legal origin (LaPorta *et al.*, 2008), regions (Barro & McCleary, 2003) and a geographic variable, tropical area (Center for International Development, 2001). Table 2 shows the results of the panel analysis. Year dummies are omitted in the table. We can see that the previous efficiencies of resource use have a positive effects on economic growth except for the case of mineral use. The CPI index, renewable energy share and Islam have negative impacts on GDP per capita which have been confirmed by previous studies. There are various methods of dealing with the effects of technologies. Here we simply use the number of patents and find positive effects on three of the four resource types.

Table 2 The impacts of efficiency on economic growth.

	Model I minerals	Model II fossil fuels	Model III ores	Model IV biomass
Efficiency minerals	0.008			
	0.005			
Efficiency fossil		0.035**		
		0.005		
Efficiency ores			0.012**	
			0.004	
Efficiency biomass				0.154**
				0.01
Life expectancy	0.0002	1.13E+05	0.0003	1.36E+05
	0.0004	3.83E+05	0.0003	0.0003
Islam	−0.017*	−0.009	−0.013+	−0.016*
	0.007	0.008	0.008	0.007
Legal origin	−0.001	0.002	0.0003	−0.002
	0.004	0.004	−0.004	0.003
Tropical area	0.001	−0.009	0.005	0.003
	0.01	0.011	0.011	0.01
CPI (logged)	−0.024**	−0.012	−0.024**	−0.019**
	0.008	0.008	0.008	0.007
Patent (logged)	0.009	0.022**	0.021**	0.012*
	0.006	0.006	0.006	0.005
GDP deflator	−0.002	0.005*	−0.003+	−0.006**
	0.002	0.002	0.002	0.002
Trade (% of GDP)	0.0003	0.001**	0.0003	−0.0002
	0.0002	0.0003	0.0003	0.0002
Renewable energy (%)	−0.006**	−0.005**	−0.007**	−0.004**
	0.001	0.001	0.001	0.001
Constant	9.279**	9.162**	9.204**	9.421**
	−0.066	0.075	0.075	0.057
N	1501	1222	1237	1538
R2	0.697**	0.725**	0.700**	0.733**
BIC	−2377.87	−2009.71	−1986.47	−2654.75

Note : The first column is the coefficient; the second column is the robust standard error. *= p<.05; **= p<.01; ***= p<.001.

3.3 Rebound Effects

In 1865, William Stanley Jevons first put forward the possibility that energy-efficiency improvements would increase rather than reduce energy consumption. Later, abundant studies have debated the existence and the possible amount of rebound effects. Recently, researchers have concentrated especially on the macro-economic side of the issue, using neoclassical growth models, econometric evidence and general equilibrium models (Dimitropoulos, 2007). In this study, we conducted a panel analysis focusing on the effects of improved resource efficiency on resource use in the subsequent years.

Our model for estimation has the following form:

$$lnResourceuse_{i,t+1} = \alpha_0 + \alpha_1\, lneffgrowth_{i,t} + X\beta + c_i + \varepsilon_{i,t} \quad \textbf{(3)}$$

where *lnResourceuse* is the total use of resources and *lneffgrowth* is the growth rate of efficiency at time $t-1$.

Table 3 shows the results of the rebound effects test

Table 3 Rebound effects of efficiency improvement.

	Model I Mineral use(t+1)	Model II fossil fuels use(t+1)	Model III Ores use(t+1)	Model IV Biomass use(t+1)
Efficiency growth of minerals	−0.083**			
	0.011			
Efficiency growth of fossil fuels		−0.014**		
		0.002		
Efficiency growth of ores			−0.014+	
			0.008	
Efficiency growth of biomass				−0.257**
				0.031
CPI(logged)	0.119**	0.084*	0.224**	−0.025*
	0.045	0.041	0.065	0.01
Patent(logged)	−0.024	0.136**	0.175**	−0.008
	0.032	0.032	0.049	0.007
GDP deflator	−0.002	−0.009	−0.009	0.004+
	0.01	0.011	0.013	0.002
Trade (% of GDP)	0.004**	−0.001	−0.004+	−0.001**
	0.001	0.001	0.002	0.0003
Renewable energy (%)	0.001	−0.036**	−0.019**	−0.002+
	0.005	0.005	0.007	0.001
Constant	6.684**	9.363**	6.841**	10.701**
	0.351	0.364	0.621	0.078
N	1424	1156	1172	1460
R2	0.115**	0.155**	0.062**	0.119**
Model type	Fixed effect	Fixed effect	Random effect	Fixed effect

Note : The first column is the coefficient; the second column is the robust standard error.
* = p<.05; ** = p<.01; *** = p<.001. (+ = p<.1)

in the short run. A higher growth rate of efficiency at the macro level has a negative impact on total domestic resource use. The number of patents, however, has significant positive impacts on resource use. This may indicate that improvement of resource efficiency at the micro level has a rebound effect on resource use. The rebound effects are around 13.6% on fossil fuel use and 17.5% on ore use, which are under 30%, as most researchers in the energy field have found. Other variables such as CPI and trade have different impacts on resource use. For instance, CPI positively affects mineral, fossil fuel and ore use, but is negatively related to biomass use. It is thought that higher prices directly affect demand from households.

4. Discussion

We investigated the relationships among resource use growth, economic growth and the efficiency of resource use in the previous sections. Only one third of the countries examined have achieved absolute good decoupling, and two thirds of the countries could achieve a better decoupling by improving the efficiency of their resource use. Our panel models provide evidence that improved efficiency could contribute to economic growth with no rebound effect on future resource use at the macro level.

It is unclear, however, how detailed a sustainable development goal should be designed and whether it can be adopted in international negotiations. Establishing a resource-efficient economy is a big environmental and macroeconomic challenge for most developing countries, especially for emerging economies. At the practical level, basically there are three means of improving resource efficiency: (1) installing treatment technology in the resource use sector or searching for substitutes for rare resources; (2) promoting reuse, recycling and reduction of resource use; and (3) adjusting the industrial structure. All these efforts require considerable inputs (including human and social capital) in the long run. At present, economic activity is still very materials-intensive in emerging economies. Their extensive economic growth depends on the low cost of resource use. Targets can hardly be adopted if they may cost them too much. It is critical to clarify whether a higher resource efficiency could cover the costs of improving the efficiency of resource use.

Table 4 Countries with the lowest resource efficiency.

	Mineral	Fossil fuels	Ores	Biomass
1	India	China	South Africa	Uganda
2	China	India	Chile	Vietnam
3	Vietnam	Russia	Zambia	Kenya
4	Morocco	Indonesia	United States	Niger
5	United States	United States	Papua New Guinea	Indonesia
6	Russia	Nigeria	Australia	Mozambique
7	Turkey	South Africa	Democratic Republic of the Congo	United States
8	Mexico	Poland	Ukraine	Nepal
9	Poland	Iran	Russia	Mali
10	Brazil	Vietnam	Kazakhstan	Russia

Table 4 shows countries with the smallest average values of per capita efficiency of resource use during the past two decades. The United States and Russia appear in all four resource categories. Major countries like Vietnam (3), India (2), China (2), Indonesia (2) and Poland (2), also appear more than once in the table. For these countries, the total costs could be much higher than for other countries. Negotiation with these countries would probably be very difficult. Among these countries, however, Indonesia, Chile, Turkey, Mexico and Vietnam have weak decoupling. As we found in Section 2, the levels of resource efficiency and decoupling vary across income groups and countries at the same income levels. We suggest designing SDGs without setting definite values for resource efficiency, but goals that can encourage countries to achieve a better decoupling. For instance, improving resource efficiency from a relative good decoupling to absolute decoupling. Since income level does not play a major role in efficiency improvement, other factors such as institutions and trade relationships may be more important for most developing countries. We also find a shift from renewable resource use (e.g., biomass) to nonrenewable resource use (e.g., ores). Thus, we should set orders of priority for different types of resources and levels of targets for various statuses of countries.

5. Conclusions

Sustainable development goals for dematerialization of absolute material use of limited resources by increasing resource efficiency are urgently required. This paper investigates the relationship between resource use and economic growth by grasping decoupling levels and using an interaction analysis of minerals, fossil fuels, ores and biomass. We further examine the rebound effects on resource use and analyze implications of the findings for SDG designing. This paper provides evidence towards designing resource-related sustainable development goals. Our results also indicate that not only do the income level and economic plight impact the efficiency of resource use, but also the economic structure, the political situation and the degree of human development inside the country have effects. Our analysis, however, is simple and has limitations. Future research will be needed to estimate the rebound effects in the long run with micro and macro data combined. As stated in the UNEP Report (UNEP, 2011), that said, "UNEP's International Resource Panel will be addressing the challenges of applying the concept of decoupling more comprehensively in separate reports, including applications to water, land and soil, and other key natural resources," the impacts of efficiency improvement of other resources use should also be investigated in the future.

Acknowledgements

We acknowledge the Project on Sustainability Transformation beyond 2015 from the Ministry of the Environment, Japan, for providing funding for this research.

References

Barro R.J. and R.M. McCleary (2003) Religion and economic growth across countries. *American Sociology Review*, 68: 760−781.

BIO Intelligence Service, Institute for Social Ecology and Sustainable Europe Research Institute (2012) *Assessment of resource Efficiency Indicators and Targets*. Final report prepared for the European Commission, DG Environment. <http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/report.pdf>

Canadell, J.G., C. Le.Quere, M.R. Raupach, C.B. Field, E.T. Buitenhuis, P. Ciais, T.J. Conway, N.P. Gillett, R.A. Houghton, and G. Marland (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *PNAS*, 20, 18866−18870.

Dimitropoulos, J. (2007) Energy productivity improvements and the rebound effect: an overview of the state of knowledge. *Energy Policy*, 35: 6354−6363.

Fujii, H. and S. Managi (2013) Which industry is greener? An empirical study of nine industries in OECD countries. *Energy Policy* (57): 381−388.

Harris, M. and S. Omoregie (2008) Post-mining deterioration of bauxite overburdens in Jamaica: storage methods or subsoil dilution? *Environmental Geology*, 54(1): 111−115. doi: 10.1007/s00254-007-0798-3

LaPorta R., L.-d.-S. Florencio and S. Andrei (2008) The economic consequences of legal origins. *Journal of Economic Literature*, 46: 285−332.

Mudgal, A., S.H. Anderson, C. Baffaut, N.R. Kitchen and E.J Sadler (2010) Effects of long-term soil and crop management on soil hydraulic properties for claypan soils. *Journal of Soil and Water Conservation*, 65(6): 393−403.

Ozturk, I. (2010) A literature survey on energy-growth nexus. *Energy Policy*, 38: 340−349.

Pothen, F. and M. Schymura (2015) Bigger cakes with fewer ingredients? A comparison of material use of the world economy. *Ecological Economics*, 109: 109−121.

SERI (2014) *Global Material Flow Database*. Technical Report.

Soytas, U. and R. Sari (2009) Energy consumption, economic growth, and carbon emissions, challenges faced by an EU candidate member. *Ecological Economics*, 68(6): 1667−1675.

Stern, D.I.(2004) The rise and fall of the environmental Kuznets curve. *World Developmen*t, 32: 1419−1439.

UN (2015a) Zero draft: Outcome document to adopt Post-2015 Development Agenda. <http://www.un.org/youthenvoy/2015/06/zero-draft-outcome-document-adopt-post-2015-development-agenda/>

UN (2015b) Technical report by the Bureau of the United Nations Statistical Commission (UNSC) on the process of the development of an indicator framework for the goals and targets of the post-2015 development agenda-working draft. <https://sustainabledevelopment.un.org/content/documents/6754 Technical% 20report% 20of% 20the% 20UNSC% 20Bureau %20%28final%29.pdf >

UNEP (2011) *Decoupling Natural Resource Use and Environmental Impacts from Economic Growth*, a Report of the Working Group on Decoupling to the International, Resource Panel.

Wiedmann, T.O., H. Schandl, M. Lenzen, D. Moran, S. Suh, J. West and K. Kanemoto (2015) The material footprint of nations. *PNAS*, 112(20): 6271−6276.

World Bank (2013) *World Development Indicators*. World Bank, Washington D.C. < http: / / data.worldbank.org/ data-catalog/ world-development-indicators>

Zhang, X.P. and X.M. Cheng (2009) Energy consumption, carbon emissions, and economic growth in China. *Ecological Economics*, 68: 2706−2712.

Jue YANG

Jue YANG is a senior associate at the Economic Research Center at Fujitsu Research Institute (FRI), Japan. She received her M.Sc. in policy and planning science in 2008 and her Ph.D. in environmental science from the University of Tsukuba, Japan, in 2011.
In 2008, she joined the National Institute for Environmental Studies, Japan as an assistant fellow and in 2011 became a research associate. From 2012, she became a postdoctoral fellow at the Graduate School of Environmental Studies, Tohoku University. She joined Fujitsu Research Institute in April, 2015. Her current research interests include sustainability and inequality, the formation of environmental regulations, and the formation of environmental regimes.

Shunsuke MANAGI

Shunsuke MANAGI is a professor of technology and policy at Kyushu University, Japan. He received his Ph.D. in Environmental and Natural Resource Economics from the University of Rhode Island in 2004. He is an editor of *Environmental Economic and Policy Studies* and on the editorial boards of six journals, including associate editor of *Resource and Energy Economics*, a lead author for the Intergovernmental Panel on Climate Change, and author of *Technology, Natural Resources and Economic Growth: Improving the Environment for a Greener Future*, published by Edward Elgar Publishing Ltd. He has authored 12 books and more than 100 academic journal papers. He has been published in peer reviewed journals such as the *Journal of Environmental Economics and Management; Journal of Economic Dynamics and Control;* and *Land Economics.*

(Received 31 May 2015, Accepted 20 October 2015)