ARTICLE IN PRESS

Economic Analysis and Policy ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Economic Analysis and Policy

journal homepage: www.elsevier.com/locate/eap

Full length article

Shadow prices and production inefficiency of mineral resources

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ARTICLE INFO

Article history:
Received 8 August 2016
Received in revised form 24 March 2017
Accepted 30 March 2017
Available online xxxx

JEL classification:
L61
Q31

Keywords:
Mineral resources
Production restriction
Sustainability
Shadow price

ABSTRACT

With the Millennium Development Goal focusing on the eradication of poverty in developing countries expiring in 2015, the international focus is shifting toward sustainable development. The sustainability of the natural resources that are used as energy sources and in the production of goods is a global issue that is not specific to developing nations. We contribute to the need for quantitative targets for natural resources by calculating the shadow prices and production inefficiency levels of 32 mineral resources by using a stochastic frontier analysis and panel data from 1980 to 2010 in 162 countries. In addition, we provide estimated shadow prices and production inefficiency levels up to 2020 with various levels of production restrictions. The results show the following: (1) The shadow prices and production inefficiency levels of major metals are generally higher in Asian countries than in non-Asian countries; (2) there is an upward trend in the inefficiency levels in Asian countries, whereas the inefficiency levels remain rather stable in non-Asian countries; (3) production restrictions do not guarantee an increase in shadow prices, but the magnitude of the impact of such restrictions seems to be larger in Asian countries compared to non-Asian countries; (4) production restrictions do not seem to affect production inefficiency; thus, they may not be effective in reducing gaps in production inefficiency between Asian and non-Asian countries.

1. Introduction

An increase in the consumption of minerals is inevitable, given the pace of economic development and modernization and the increase in production and energy consumption. Nevertheless, the current consumption patterns raise concerns from the perspective of the sustainability of mineral resources. In recent years, international efforts have been made to provide solutions for poverty on a global scale. The UN established the Millennium Development Goals (MDGs) in 2000, the main goal of which was to eradicate extreme poverty; thus, the targets were the poor in developing countries. With a deadline in 2015, the next goals mentioned are Sustainable Development Goals (SDGs), which were discussed at the United Nations Conference on Sustainable Development (Rio+20) in 2012. One issue with the MDGs was that quantitative targets

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http://dx.doi.org/10.1016/j.eap.2017.03.005

Please cite this article in press as: Tamaki, T., et al., Shadow prices and production inefficiency of mineral resources. Economic Analysis and Policy (2017), http://dx.doi.org/10.1016/j.eap.2017.03.005

were not established, which may have hindered the effectiveness of the global program, and researchers have claimed that the SDGs can be distinguished from the MDGs by focusing the discussion on the latest research on the issue of sustainability (Jung et al., 2000; Griggs et al., 2013).

In recent years, there has been a shift in terms of how to approach economic development and growth, and designing quantitative targets for sustainable development has become the focus in the latest debate. Dasgupta et al. (2015) noted that neither the SDGs nor their background documents explain how governments should judge whether the development programs they undertake to meet the goals are sustainable. Moreover, the authors indicated that economic growth should reflect growth in the Inclusive Wealth Index (IWI). At Rio+20, an Inclusive Wealth Report (Agarwala, 2012) was proposed as an aggregate measure that includes factors that may affect countries' development and sustainability. Gross Domestic Product (GDP) essentially measures short-term economic activities; in contrast, the IWI attempts to evaluate the stocks of other assets, such as physical capital (including infrastructure), human capital and natural capital.

The IWI uses the shadow prices of various types of assets. The shadow prices of mineral resources are essential for the establishment of global production targets for mineral resources that are limited in availability. Lin and Zhang (2011) estimated the shadow prices of various minerals using the Hotelling model (Hotelling, 1931). The model analyzes the optimal usage of mineral resources through the estimated maximization of producers' discounted present value of minerals; however, the estimation assumes perfect information about mineral reserves, which is difficult to grasp and quantify because new mining spots are continuously being discovered. Many studies have provided shadow price calculations for different capitals and assets using various estimation methods. Ishinabe et al. (2013), Mekaroonreung and Johnson (2012), Kumar et al. (2015) and Molinos-Senante et al. (2015) calculated the shadow prices of CO_2 emissions and greenhouse gas emissions. Furthermore, Lee and Zhang (2012), Du and Mao (2015), and Du et al. (2016) focused on China, which is the world's largest CO_2 producer and energy consumer, and estimated the shadow prices of CO_2 emissions to assess potential cost savings. In particular, Du et al. (2016) proposed a new meta-frontier method to investigate technical efficiency.

CO_2 emissions and the production of undesirable outputs often have negative impacts on the natural environment and the sustainable development of a society and economy. The shadow prices of undesirable outputs are usually derived from the market prices of desirable outputs using distance functions and duality theory, which can be further calculated using parametric or nonparametric efficiency models (Zhou et al., 2014). Existing studies on estimations of efficiency and shadow prices have used the non-parametric Data Envelopment Analysis (DEA) approach and the parametric Stochastic Frontier Analysis (SFA) approach.[1]

The parametric SFA approach constructs the production frontier and offers the benefit of taking statistical noise into account. This approach applies to the directional distance function but not to the Shephard distance function (Du and Mao, 2015). Many existing studies have explored the theoretical and application aspects of distance functions, and both the Shephard distance function and the directional distance function have been successively employed in shadow pricing estimations. Relevant studies include Färe et al. (2005), Murty et al. (2007), and Wei et al. (2013). The directional distance function was developed to enable asymmetric changes in input and output vectors, which is favorable for modeling production technologies (Chung et al., 1997; Färe and Grosskopf, 2000). In application, some of the studies estimating shadow prices have mainly focused on single polluting industries, such as electricity, paper and pulp, and agriculture, but shadow pricing for multiple sectors and multiple regions has also been studied. Moreover, regarding the shadow price calculations of input resources, He et al. (2007) estimated the shadow price of water, and Misra and Kant (2007) employed a parametric linear programming approach to estimate a deterministic input distance function characterizing the production structure of Joint Forest Management (JFM) organizations in the Gujarat state of India. The distance function includes economic, biological and social outputs as well as neo-classical (land, labor, and capital) and non-neo-classical (social, political, institutional, and organizational) factors. The results are used to calculate the production efficiency and shadow prices of the neo-classical and non-neo-classical factors for different village-level JFM organizations.

Natural resources such as oil, natural gas and coal have received broad attention as crucial energy resources for growth. Despite the importance of mineral resources in industrialization and manufacturing and the fact that metals have the highest growth rate in terms of natural resource extraction of the resource categories,[2] there are few studies that focus on mineral resources (Behrens et al., 2007). Goal 12 of the SDGs is to 'ensure sustainable consumption and production patterns,' and one of the main targets is to achieve 'the sustainable management and efficient use of natural resources' by 2030.[3] Nonetheless, quantitative studies on the shadow prices or efficiency of mineral resources are rather scarce. Therefore, we contribute to the discussion on optimal quantitative sustainable development targets by estimating the shadow prices of mineral resources, which can be used to estimate mineral capital for the IWI. Additionally, we demonstrate that the parametric SFA approach with a directional distance function can be used to calculate the production inefficiency of mineral resources. We estimate the effect of production restrictions on shadow prices and production inefficiency using panel data for 32 mineral resources

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[1] See, Sheng et al. (2015), Alfredsson et al. (2016) and Tamaki et al. (2016) for DEA approach and Nghiem et al. (2011), Zhou et al. (2014) and Du and Mao (2015) for SFA approach.

[2] Behrens et al. (2007) found that global used resource extraction grew from 40 billion tons in 1980 to 55 millions in 2002, the extraction of metals increased by 56%, and the extraction of fossil fuels increased by 30%.

[3] The Goal 12 targets of the SDGs are available at http://www.un.org/sustainabledevelopment/sustainable-consumption-production/.

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in 162 countries from 1980 to 2010 by combining data from various sources. Although every country's endowment and technologies are different, it is common and still useful to compare countries using the frontier efficiency method (see Henderson and Russell, 2005; Kumar and Managi, 2016).

As Scholz and Wellmer (2013) noted, concerns regarding the limited supply of mineral resources have been expressed since the 1970s, but a minority of economists took such a position until the beginning of the 21st century. We may observe a larger impact of mineral resource production and usage on economic development in Asian countries due to the rapid pace of urbanization and industrialization in heavily populated developing nations such as China and India, which have increased the demand for resources exponentially and have therefore impacted the price. According to a recent study on domestic material consumption (DMC) by Schandl and West (2010), global DMC doubled over the period from 1970 to 2005, and the Asia-Pacific region has accounted for 80% of the global growth. Moreover, previous studies have found that the Asian share of global used resource extraction has increased, and in particular, the domestic extraction of primary materials including construction and industrial minerals and metal ores disproportionally grew in China and India (Behrens et al., 2007; Schandl and West, 2010). In this study, we compare and discuss the results for Asian countries in comparison with non-Asian countries in terms of the shadow prices of minerals, production inefficiency, and the impact of production restrictions.

2. Model of shadow price

To calculate the shadow price, we use stochastic frontier analysis (SFA), which is a parametric method. Non-parametric methods, such as data envelopment analysis (DEA), assume that technology that is on the production frontier, and the most efficient decision-making unit is used for production. One of the main limitations of non-parametric approaches such as DEA is that they cannot accommodate noise in the data and they cannot provide the statistical properties of the estimates, and SFA can mitigate this issue (Nghiem et al., 2011). Moreover, SFA can estimate the production frontier with uncertainty, while DEA cannot.

Moreover, this study uses a quadratic flexible functional form as the directional output distance function, following Färe et al. (2005). One of its benefits is that it allows zero input, which means zero use of mineral resources. In addition, it can account for variation and/or changes in the decision-making unit's production technology. That is, the functional form can express technological improvement (deterioration) over time.

The production technology, denoted as $P(x)$, can be expressed using the equation below, where $x \in R_{+}^{M}$ is an input vector, $y \in R_{+}^{N}$ represents good output and $b \in R_{+}^{L}$ represents bad output.

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

In this study, we use GDP as a proxy for good output y and CO_2 emissions as the bad output b. As a set of inputs x, we use labor, capital and each mineral resource. Following Färe et al. (2005), we adopt four conditions (free disposability for inputs; null jointness; weak disposability for bad outputs; and strong disposability for good outputs). The free disposability condition means that if $x' \geq x$, then $P(x') \supseteq P(x)$. This condition implies that when inputs are increased, the output set does not shrink. The next assumption is the null jointness condition, which can be written as $(y, b) \in P(x)$ and $b = 0$ then $y = 0$. This assumption implies that bad output $b = 0$ only when good output $y = 0$; thus, to produce y, b is also produced. In addition, we assume that any proportional contraction of good and bad outputs is feasible; this assumption can be expressed as follows: $(y, b) \in P(x)$ and $0 \leq \theta \leq 1$ then $(\theta y, \theta b) \in P(x)$. This assumption is the weak disposability condition of good and bad outputs; it implies that a reduction in bad outputs can be made by a proportional reduction in good output. In addition, strong disposability of good outputs is assumed following the traditional axiom; that is, if $(y, b) \in P(x)$ and $(y', b) \leqslant (y, b)$, then $(y', b) \in P(x)$.

We define the directional distance function as follows:

$$D(x, y, b; g) = \max_{\beta}\{\beta : (y + \beta \cdot g_y, b - \beta \cdot g_b) \in P(x)\}.$$

Using this function, we seek the maximum β that can simultaneously reduce bad outputs and expand good outputs. $g = (g_y, -g_b)$ is a direction vector to set the distance between output $(y, b) \in P(x)$ and the production frontier. The output on the boundary of the production frontier is expressed as $(y + \beta \cdot g_y, b - \beta \cdot g_b) \in P(x)$. Moreover, given the special property of the function according to the derivation in Färe et al. (2005), the directional output distance function satisfies the translation property. It can be denoted as follows:

$$D(x, y + \alpha g_y, b - \alpha g_b; g_y, -g_b) = D(x, y, b; g_y, -g_b) - \alpha. \tag{1}$$

In our analysis, we use labor and physical capital, the production volume of each mineral resource and GDP as the good output y and CO_2 emissions as the bad output b. Similar combinations of input and output variables are used by Färe et al. (2005) and Kumar et al. (2015) to calculate the distance function. According to Chambers and Pope (1996) and Chambers et al. (1998), changes in productivity can be divided into technological advancements and changes in efficiency. Given that changes in efficiency can be shown as changes in the production frontier per year, we account for technological changes

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using a time trend t, as in Färe et al. (2005). Then, we can express the output-based distance function as follows:

$$D(x, y, b; g) = a_0 + \sum_{i=1}^{3} \beta_i x_i + a_1 y + a_2 b + \frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3} \beta_{ij} x_i x_j + \sum_{i=1}^{3} \delta_{i1} x_i y + \sum_{i=1}^{3} \delta_{i2} x_i b + \frac{1}{2} a_{11} y^2$$
$$+ a_{12} yb + \frac{1}{2} a_{22} b^2 + a_3 t + a_{13} yt + a_{23} bt + \sum_{i=1}^{3} \delta_{i3} x_i t + \frac{1}{2} a_{33} t^2$$

but, $\beta_{ij} = \beta_{ji}$, $a_1 - a_2 = -1$, $a_{12} = a_{21} = a_{22}$, $\delta_{i1} = \delta_{i2}$.

Using this distance function, we conduct the SFA to obtain the parameters. Following Kumbhakar and Lovell (2003), we set the following condition:

$$0 = D(x^k, y^k, b^k; g_y, -g_b) + \epsilon^k \tag{2}$$

where ϵ^k is an error term, and we assume the following properties: $\epsilon^k = \nu^k - \mu^k$, $\nu^k \sim N(0, \sigma_\nu^2)$, and $\mu^k \sim N^+(\mu, \sigma_\mu^2)$; hence, ν^k is the effects of statistical noise, and μ^k is the effects of the technical inefficiency error, respectively (Kumbhakar and Lovell, 2003).

By obtaining the input sets on the frontier, we take the distance on the frontier from the point in which all inputs are null. Then, we divide this distance by the distance from the output when all inputs are null to the actual set of inputs. Essentially, this process gives a productivity efficiency ratio between [0, 1]. The production efficiency is maximized when the ratio is 1. In most cases, the points are inside the frontier, indicating some inefficiency. However, note that some input sets produce more than the estimated frontier. In such a case, the efficiency is greater than 1, which is alternatively called super efficiency.

Following Färe et al. (2005), we assume the following property for the directional vector: $g = (g_y, -g_b) = (1, -1)$. From Eq. (1), we can construct the following:

$$D(x^k, y^k + \alpha^k, b^k - \alpha^k; 1, -1) = D(x^k, y^k, b^k; 1, -1) - \alpha^k.$$

By the condition above, Eq. (2) can be written as follows:

$$-\alpha^k = D(x^k, y^k + \alpha^k, b^k - \alpha^k; 1, -1) - \epsilon^k.$$

In this analysis, we use the condition $a^k = b^k$ to estimate the shadow price of each mineral resource. Färe et al. (2005) and Kumar et al. (2015) estimated the shadow price of an output, and Misra and Kant (2007) and Reig-Martınez et al. (2001) applied the method to the estimation of an input shadow price. Following the steps in Misra and Kant (2007) and Reig-Martınez et al. (2001), the shadow price of each mineral resource input for this analysis can be expressed as follows:

$$p_x = -\frac{\partial D(x, y, b; g)/\partial x}{\partial D(x, y, b; g)/\partial y}. \tag{3}$$

As noted above, x is composed of inputs: labor, physical capital and mineral resources. Theoretically, performing the calculation with all of the inputs, including multiple mineral inputs, is ideal. However, due to the large number of mineral resource inputs for the analysis, we face difficulties in terms of dimensionality. In addition, for the conversion unit across mineral ores that we use as inputs, the unit for mineral ores varies depending on the share of ore that is actually tradable in the market. Moreover, these shares differ across countries due to purity as well as the technical capacity to process ores. This relevant information is not made available in detail, so we cannot create an aggregate input for mineral resources. We also estimate the coefficient for each mineral ore separately for the following reasons: (1) Depending on the data, estimations with more than 3 inputs are obviously possible, but it did not make sense to randomly choose several inputs that do not share a common unit and run multiple estimations; (2) in addition, given that there is very little substitution for each mineral resource, theoretically estimated coefficients from the model with all mineral resource inputs would differ very little from the separately estimated coefficients.

3. Data and variables

To estimate the shadow prices and usage restrictions of 32 mineral resources, we constructed panel data for 162 countries in the period from 1980 to 2010. For the estimation of shadow prices, we combine data from various sources. The production volumes of minerals are taken from the Global Material Flows Database constructed by the Sustainable Europe Research Institute and the Vienna University of Economics and Business. The production volume of minerals is the main input in the estimation. Given that these data are available only until 2010, our analysis is limited to 2010. We coded mineral production volume as 0 if a country does not produce a particular mineral at all and do not consider these observations missing. In addition, we use labor and physical capital data from the Penn World Table and GDP and CO_2 emissions (kilo tons) from the International Monetary Fund's World Economic Outlook Database and the World Bank's World Development Indicators, respectively. GDP per year is based on the purchasing-power-parity (PPP) valuation of country GDP, and we use estimated GDP up to 2020 as provided in the database when calculating the effect of future production restrictions on minerals. Because similar official estimates of CO_2 emissions and input variables are unavailable, we use the results of time

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Table 1
Global total production volumes of mineral resources by decade from 1980 to 2010.

Production (Mt/year)	1980–1990	1991–2000	2001–2010	1980–2010
Antimony	851.08	1597.68	1941.53	1443.68
Arsenic	2003.87	1407.33	496.14	1325.08
Bauxite	81,923.95	117,751.03	182,379.85	125,886.20
Beryllium	1.36	6.04	3.76	3.65
Bismuth	3.02	4.20	4.34	3.83
Cadmium	15.73	18.80	19.34	17.88
Chromium	6287.04	9827.68	19,422.33	11,666.37
Cobalt	32.21	24.94	61.17	39.21
Copper	1,009,540.85	1,448,827.92	17,44,474.47	13,88,321.72
Germanium	0.01	0.03	0.07	0.04
Gold	408,809.49	856,504.56	858,731.52	698,363.39
Iron	651,002.61	990,322.59	1,734,339.43	1,109,924.16
Lead	49,165.66	52,955.08	58,647.39	53,446.67
Lithium	103.87	231.01	363.96	228.78
Magnesium	228.77	345.82	623.91	393.99
Manganese	34,980.37	76,303.00	105,385.16	71,021.47
Mercury	12,193.45	2917.67	653.65	5478.75
Molybdenum	18,951.00	52,182.63	74,727.51	47,663.30
Nickel	40,676.75	58,748.02	11,4917.90	70,454.95
Niobium & Tantalum	108.83	235.01	674.10	331.88
PGM	12,556.87	19,294.17	31,643.63	20,887.21
Rare earth	1312.34	2346.93	3784.98	2443.70
Selenium	1.47	2.07	2.81	2.09
Silver	145,561.40	166,292.49	276,326.53	194,431.15
Tellurium	0.12	0.17	0.14	0.14
Tin	312,433.39	296,311.64	474,085.07	359,378.53
Titanium	7126.99	9044.89	10,912.37	8966.76
Tungsten	21,431.93	18,593.39	31,177.37	23,659.96
Uranium	28,864.40	24,028.64	24,457.61	25,882.93
Vanadium	19.84	36.52	62.58	39.01
Zinc	117,762.45	152,330.70	233,291.53	166,180.94
Zirconium	1865.98	1478.33	1323.06	1565.80

series regression analyses to estimate CO_2 emissions levels from 2010 to 2020. Summary statistics of all output and input variables are provided in Appendix [A1].

Table 1 provides the average production volumes of the 32 target mineral resources in the 1980s, 1990s and 2000s. From 1980 to 2010, we observe a reduction in the production volume for some minerals such as arsenic and mercury, but, as a whole, mineral production has increased and is expected to continue growing. Production volume has increased for approximately 70% of the mineral resources. In particular, the production volumes of lithium and chromium have increased approximately 5-fold. In addition, for minerals with a high trade volume in the market, such as bauxite, copper, gold, chromium and nickel, the production volume has increased over the past two decades. This time trend indicates an increase in the demand for natural resources, particularly due to the exponential growth in resource demand in China.

4. Shadow prices and production inefficiencies: comparison between Asian and non-Asian countries

Labor and the other capital inputs as common inputs and the production volumes of targeted mineral resources are used to estimate the parameters of a distance function for each mineral resource. The results of the parameter estimations for each mineral resource are available in Appendix [A2]. The production volume variable is not always statistically significant in the parameter estimation model; however, it tends to be statistically significant in most cases.

After obtaining the parameters of the distance function for all mineral resources, using the method provided in Section 2, we estimated the shadow prices and production inefficiency of each mineral resource in a given year. The period-averaged shadow prices and production inefficiency of all 32 mineral resources are available in Appendix [A3]. Table 2 provides shadow prices and production inefficiency estimates for the 10 mineral resources with the largest aggregate market value for the periods from 1980 to 1990 and 1991–2000. We also calculate separate shadow prices and production inefficiency estimates for Asian countries and non-Asian countries.

For the 10 major mineral resources, the shadow prices in Asian countries are generally higher compared to the prices in non-Asian countries. Iron is particularly important because it has the largest market of all the mineral resources and Asian countries currently produce over 40% of the global production. For iron, the average shadow prices in Asian countries are consistently more than double those of non-Asian prices over the three decades that we analyze. For copper, the second-largest market of all the mineral resources, the shadow prices are higher in Asian countries by approximately 4.5–6 fold when compared to the shadow prices of non-Asian countries. For nickel, for which Asian countries produce more than 80% of the global production, the shadow prices in Asian countries are more than 5 times those in non-Asian countries during 2000–2010. These differences between the shadow prices of Asian countries and non-Asian countries are likely to

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Table 2
Estimated shadow prices and production inefficiency of major mineral resources from 1980 to 2010.

Mineral	Period	Asian share %	S.P (Asia)	S.P (NA)	S.P (all)	Relative S.P	P.I (Asia)	P.I (NA)	P.I (all)	Relative P.I
Iron	1980–1990	24.84	111.75	40.36	49.69	2.77	0.22	0.12	0.13	1.77
	1991–2000	30.75	113.71	44.78	52.11	2.54	0.23	0.13	0.14	1.80
	2001–2010	41.59	107.25	48.88	54.97	2.19	0.30	0.14	0.16	2.10
Copper	1980–1990	10.11	113.02	24.97	35.76	4.53	0.18	0.14	0.14	1.35
	1991–2000	9.46	141.75	20.15	33.76	7.03	0.22	0.13	0.14	1.65
	2001–2010	12.35	96.04	16.30	24.99	5.89	0.29	0.15	0.16	1.92
Gold	1980–1990	3.21	45.02	48.44	48.13	0.93	0.14	0.11	0.12	1.23
	1991–2000	4.58	35.87	41.11	40.72	0.87	0.15	0.12	0.12	1.25
	2001–2010	7.30	46.67	29.48	30.83	1.58	0.17	0.13	0.14	1.29
Silver	1980–1990	1.12	350.50	43.63	132.91	8.03	0.28	0.36	0.34	0.77
	1991–2000	0.84	436.38	41.04	173.63	10.63	0.36	0.41	0.39	0.89
	2001–2010	0.57	131.95	26.96	71.26	4.89	0.49	0.35	0.41	1.38
Zinc	1980–1990	5.50	85.34	29.00	36.58	2.94	0.21	0.12	0.13	1.75
	1991–2000	4.64	94.28	18.89	27.55	4.99	0.25	0.12	0.14	2.00
	2001–2010	5.61	107.82	18.40	31.86	5.86	0.35	0.20	0.22	1.73
Bauxite	1980–1990	8.02	115.48	24.27	48.30	4.76	0.34	0.39	0.38	0.86
	1991–2000	12.38	93.93	22.30	39.71	4.21	0.35	0.34	0.34	1.03
	2001–2010	23.63	67.87	19.57	30.80	3.47	0.42	0.32	0.34	1.33
Nickel	1980–1990	74.29	33.38	9.05	12.59	3.69	0.15	0.11	0.12	1.37
	1991–2000	74.89	34.03	8.93	12.10	3.81	0.20	0.10	0.11	1.97
	2001–2010	81.93	43.87	8.74	12.64	5.02	0.27	0.13	0.15	2.05
Manganese	1980–1990	35.59	–	–	–	–	–	–	–	–
	1991–2000	39.26	3.20	3.27	3.27	0.98	0.03	0.05	0.05	0.65
	2001–2010	40.90	7.24	8.55	8.45	0.85	0.09	0.09	0.09	0.92
Lead	1980–1990	8.64	14.92	15.23	15.21	0.98	0.07	0.07	0.07	0.91
	1991–2000	12.51	12.82	14.11	14.01	0.91	0.11	0.09	0.09	1.32
	2001–2010	24.38	12.18	12.89	12.84	0.95	0.11	0.12	0.12	0.95
Chromium	1980–1990	11.38	5.25	20.54	18.98	0.26	0.24	0.28	0.28	0.83
	1991–2000	17.04	37.44	20.96	24.79	1.79	0.33	0.34	0.34	0.96
	2001–2010	20.42	48.10	16.45	22.84	2.92	0.36	0.40	0.40	0.90

NA: Non-Asian countries. Asian share (%): The share of production by Asian countries in global production. S.P: Shadow Prices in (USD$/t). P.I.: Production Inefficiencies. Relative P.I: the ratio of the average P.I. of Asian countries to the average P.I. of non-Asian countries.

Asian countries: Bangladesh, Brunei Darussalam, Bhutan, China, Hong Kong (China), Indonesia, India, Japan, Republic of Korea, Lao People's Democratic Republic, Sri Lanka, Maldives, Malaysia, Nepal, Pakistan, Philippines, Singapore, Thailand, Taiwan, Vietnam.

Non-Asian countries: Albania, Argentina, Armenia, Antigua and Barbuda, Australia, Austria, Azerbaijan, Burundi, Belgium, Benin, Burkina Faso, Bulgaria, Bahrain, Bahamas, Bosnia and Herzegovina, Belarus, Belize, Bolivia, Brazil, Barbados, Botswana, Central African Republic, Canada, Switzerland, Chile, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Colombia, Comoros, Costa Rica, Cyprus, Czech Republic, Germany, Djibouti, Dominica, Denmark, Dominican Republic, Ecuador, Egypt, Spain, Estonia, Ethiopia, Finland, Fiji, France, Gabon, United Kingdom, Georgia, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Greece, Grenada, Guatemala, Honduras, Croatia, Hungary, Ireland, Iran (Islamic Republic of), Iraq, Iceland, Israel, Italy, Jamaica, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Cambodia, Saint Kitts and Nevis, Kuwait, Lebanon, Liberia, Saint Lucia, Lesotho, Lithuania, Luxembourg, Latvia, Morocco, Republic of Moldova, Madagascar, Mexico, The Former Yugoslav Republic of Macedonia, Mali, Malta, Mongolia, Mozambique, Mauritania, Mauritius, Malawi, Namibia, Niger, Nigeria, Netherlands, Norway, New Zealand, Oman, Panama, Peru, Poland, Portugal, Paraguay, Qatar, Romania, Russian Federation, Rwanda, Saudi Arabia, Sudan, Senegal, Sierra Leone, El Salvador, Serbia, Sao Tome and Principe, Suriname, Slovakia, Slovenia, Sweden, Swaziland, Syrian Arab Republic, Chad, Togo, Tajikistan, Turkmenistan, Trinidad and Tobago, Tunisia, Turkey, United Republic of Tanzania: Mainland, Uganda, Ukraine, Uruguay, United States, Uzbekistan, St. Vincent and the Grenadines, Venezuela, Yemen, South Africa, Zambia, Zimbabwe.

be associated with high regional demand for these mineral resources as a source of export income as well as their necessity in the manufacturing sector due to rapid urbanization in developing economies, especially in China and India.

When we compare the levels of production inefficiency between Asian and non-Asian countries, we observe higher inefficiencies in Asian countries for most of the major mineral resources. The relative production inefficiency, presented in the last column of Table 2, is calculated by dividing the average production inefficiency of Asian countries by the average of non-Asian countries for each mineral resource. We observe the highest discrepancies in iron, copper, zinc and nickel. For these mineral resources, recent production inefficiencies are almost 2 times higher in Asian countries. Furthermore, relative production inefficiencies in Asian countries have increased since 1980 for most major mineral resources. We provide relative production inefficiency by dividing the production inefficiency in Asian countries by that of non-Asian countries. The relative production inefficiency of iron and copper from the 1980s to 2000s increased from 1.77 to 2.10 and from 1.35 to 1.92, respectively. We also see similar increases for other major industrial metal ores such as bauxite and nickel. For gold and silver, we observe that the relative production inefficiency in Asia is relatively higher compared to the rest of the world, but the magnitude remained rather flat during the past three decades.

One possible explanation for why we observe flat or an increase in production inefficiency over time is increases in production costs. Because mineral resources are mined over time, the general assumption about the process is that high-grade quality ores that require less processing costs are mined first from the most convenient and least costly locations.

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Thus, as mining continues, the fixed cost for production increases because the ore must be mined from more difficult sites and because the ore that is mined requires more processing. Additionally, the technological improvements in processing technologies may vary across counties, and countries with relatively inefficient production methods have increased their share in the global market over time. This increase in processing costs and the shift in production share to less technologically efficient countries may not be fully represented by general technological advances in mining production.

The discrepancies in inefficiency should be alarming for Asian producers of mineral resources. The production and usage of mineral resources represent a large part of these countries' income and economic growth, but relative inefficiency implies relatively ineffective management of bad outputs, such as the emissions associated with resource production. In addition, Asian countries may be more vulnerable to the problem of falling ore quality, which is accompanied by higher social and environmental costs (Giurco and Cooper, 2012; Mason et al., 2011; May et al., 2012; Mudd and Ward, 2008; Mudd, 2010; Prior et al., 2013). The degradation of ore quality substantially increases mine waste and energy consumption during the production process, thereby increasing bad outputs during mineral resource production. In addition, because deeper drilling is needed for the production, the cost of mining mineral resources increases.

Increasing demand and consumption of mineral resources combined with economies of scale and the labor-intensive nature of the mining industry have contributed to increased mineral resource production and the degradation of ore quality. Among Asian countries, China's development has a large impact on both ends of consumption and production because of its size and available mineral resources. China consumed 8.2% of worldwide steel in 1990 but now consumes nearly half of the market. In addition, China's total consumption has increased. China is the leading consumer of every major commodity, with the exceptions of crude oil and natural gas (Brown, 2005; Scholz and Wellmer, 2013). On the demand side, as previous studies suggest, if China's urbanization and modernization process continues at an unprecedented scale, it will be accompanied by a dramatic increase in the consumption of mineral resources in addition to the consumption of water, land and energy (Shen et al., 2005; Roberts and Rush, 2012; Tan et al., 2016). The authors also suggested that China will face a serious shortage in the supply of resources, particularly of major industrial metals such as iron, steel, copper and aluminum, even with low estimates of urbanization growth.

Prior et al. (2013) indicated that countries such as Japan, South Korea and Taiwan have implemented metal recycling and extended producer responsibility programs that control the demand and consumption of metals needed for their large manufacturing sectors. These countries have invested in preparing for shortages and in technology that reduces environmental costs, including emissions reductions in the production and refining processes. However, such efforts are rather limited and delayed in developing countries, especially in China and India, which have large populations and consumption demand that will continue to grow if their high economic growth rates are sustained.

In sum, the shadow price estimates are relatively higher for Asian countries, and this result implies that the production of mineral resources has a relatively larger impact on economic development in Asian countries compared to non-Asian countries, even if we take into account the cost of the bad output of CO_2 emissions. However, given the upward trend in production inefficiency in Asian countries and their high relative production inefficiency compared with non-Asian countries, management strategies other than simply increasing production should be considered.

4.1. The effect of production restrictions

Given problems with the sustainability of ore grades and the increasing demands associated with further urbanization and industrialization, many countries are implementing metal recycling and extended producer responsibility programs to decrease the emissions and waste associated with metal usage. In addition to recycling, technology investments to find more efficient manufacturing processes that use less metal and searches for alternative resources have been adopted. By using estimates of GDP growth and emissions, we calculate the post—2010 shadow prices for three different cases in terms of production level: (1) the production volume remains the same in 2020 as in 2010; (2) the production volume decreases by 10% from 2010 to 2020; and (3) the production volume decreases by 20% from 2010 to 2020. For cases 2 and 3, we assume a linear decline in the production volume. Tables 3 and 5 provide estimates of the shadow prices and production inefficiencies for the major metals, respectively. The estimates of shadow prices and production inefficiency levels calculated using the three levels of production restrictions for all mineral resources are provided in Appendix [A4].

According to the results, a global production restriction would increase the shadow prices of iron, copper, silver, nickel and manganese. An increase in shadow prices implies that restricting production would increase the additional value of each unit of produced mineral resources and would increase the mineral resources' contribution to GDP. In the cases of zinc and lead, restrictions do not substantially affect shadow prices, and for gold, bauxite and chromium, restrictions lead to reductions in shadow prices. In sum, simple production restrictions do not provide consistent effects on the shadow prices of mineral resources; thus, it is dangerous to claim that production restrictions will increase the value of mineral resources in the near future.

When we estimate the shadow prices under various production restrictions for Asian and non-Asian countries, we see stark differences in the results. Decreasing the production of iron by 20% in the period between 2016 and 2020 would increase the shadow price in Asian countries by over 130%, but the same production restriction would increase the shadow price in non-Asian countries by only 12%. We observe a similar pattern of disproportional increases in shadow prices in Asian countries for silver and manganese. Moreover, for mineral resources such as copper and nickel, production restrictions

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Table 3
The effects of production restrictions on shadow prices (2005USD$/t).

Mineral	Period	Asia			Non-Asia			Global		
		2010	10%	20%	2010	10%	20%	2010	10%	20%
Iron	2011–2015	75.09	99.86	155.54	54.93	59.81	63.34	56.73	63.35	71.48
	2016–2020	85.34	121.61	199.76	62.99	67.09	70.62	64.78	71.45	80.93
Copper	2011–2015	214.63	192.08	171.12	77.48	75.49	74.18	95.77	91.7	88.75
	2016–2020	190.29	260.85	310.85	115.46	109.94	104.88	124.97	131.16	135.36
Gold	2011–2015	62.66	62.01	60.9	38.1	35.96	33.81	40.47	38.46	36.4
	2016–2020	94.15	35.37	34.34	46.23	42.88	40.54	50.23	42.35	40.11
Silver	2011–2015	77.1	114.34	108.93	21.37	26.72	24.82	27.73	36.77	34.47
	2016–2020	126.24	212.71	188.87	27.91	31.77	29.63	37.01	48.03	44.24
Zinc	2011–2015	27.78	28.47	29.13	22.12	22.29	22.41	22.63	22.85	23.02
	2016–2020	24.21	24.99	25.81	17.66	17.52	17.68	18.21	18.15	18.36
Bauxite	2011–2015	48.51	42.67	38.6	15.01	12.17	7.98	19.69	16.15	11.23
	2016–2020	69.78	76.53	65.91	16	10.22	8.11	21.29	16.52	13.12
Nickel	2011–2015	27.59	37.13	61.33	8.19	7.81	8.08	10.24	10.85	13.32
	2016–2020	59.53	71.21	87.28	9.78	9.16	9.3	14.85	15.58	17.46
Manganese	2011–2015	32.53	37.03	41.51	9.59	12.44	14.55	12.3	15.3	17.7
	2016–2020	31.11	40	47.04	11.31	14.45	16.81	13.49	17.31	20.19
Lead	2011–2015	18.72	18.73	19.42	19.45	19.12	18.59	19.38	19.08	18.69
	2016–2020	20.28	20.11	19.75	21.81	21.44	20.75	21.69	21.33	20.67
Chromium	2011–2015	4.53	3.71	3.54	4.04	3.75	3.39	4.1	3.77	3.42
	2016–2020	9.75	6.21	3.59	4.96	4.55	3.94	5.39	4.7	3.92

2010 columns are the estimated shadow prices for 2010.
10%—estimated shadow prices in the case of a 10% production cut from the production level in 2010.
20%—estimated shadow prices in the case of a 20% production cut from the production level in 2010.
For the list of Asian and non-Asian countries, see note for Table 2.

Table 4
Monetary impacts of production restrictions for 10 major mineral resources.

	Total reduction effect (million USD$)					
	Asia		Non Asia		All	
	10%	20%	10%	20%	10%	20%
Iron	83,796	273,221	44,538	93,860	97,146	220,078
Copper	35,030	83,539	89,417	171,846	123,813	256,636
Gold	1,540	2,985	18,468	34,824	20,061	37,907
Silver	186	333	5,199	9,691	7,578	13,984
Zinc	257	531	2,407	4,854	2,682	5,422
Bauxite	2,737	4,738	856	1,297	1,958	3,023
Nickel	4,270	10,996	194	292	1,304	2,786
Manganese	1,528	3,561	524	1,220	1,285	2,995
Lead	250	493	485	939	746	1,447
Chromium	15	19	54	94	67	114

10%—in the case of a 10% production cut from the production level in 2010.
20%—in the case of a 20% production cut from the production level in 2010.
For the list of Asian and non-Asian countries, see note for Table 2.

increase the shadow prices in Asian countries by over 63% and 47%, respectively, whereas the shadow prices in non-Asian countries decrease by small percentages.

In some cases, production restrictions lead to a decrease in shadow prices in Asian countries, but in such cases, the changes in the shadow prices in Asian countries are much larger compared to those in non-Asian countries. For example, in the case of gold, the shadow price falls from 94.15 to 34.34 by restricting production by 20%. However, the same restriction decreases the shadow prices in non-Asian countries from 46.23 to 40.54. Similarly, in the case of chromium, a production restriction of 20% decreases the shadow price in Asian countries from 9.75 to 3.59, but the same restriction reduces the shadow price in non-Asian countries from 4.96 to 3.94. Overall, regardless of whether the production restrictions affect shadow prices positively or negatively, the magnitudes of the restriction effects are relatively larger in Asian countries.

These results indicate that in Asian countries, production restrictions can be useful for evaluating mineral resources as assets and for determining the sustainability of mineral resource production and its effect on economic development, but they should be used with caution. In contrast, the relatively small changes in shadow prices in non-Asian countries imply that production restrictions may not be an effective means to increase shadow prices, which are already relatively low compared to Asian countries.

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Table 5
The effects of production restrictions on production inefficiency.

Mineral	Period	Asia			Non-Asia			Global		
		2010	10%	20%	2010	10%	20%	2010	10%	20%
Iron	2011–2015	0.34	0.34	0.33	0.16	0.16	0.16	0.17	0.17	0.17
	2015–2020	0.37	0.37	0.37	0.18	0.19	0.19	0.20	0.20	0.20
Copper	2011–2015	0.39	0.39	0.40	0.22	0.23	0.25	0.25	0.25	0.28
	2016–2020	0.41	0.43	0.44	0.22	0.23	0.25	0.25	0.25	0.28
Gold	2011–2015	0.24	0.24	0.24	0.13	0.13	0.14	0.14	0.14	0.15
	2016–2020	0.22	0.20	0.21	0.13	0.13	0.14	0.14	0.13	0.14
Silver	2011–2015	0.3	0.3	0.3	0.15	0.16	0.16	0.16	0.17	0.17
	2016–2020	0.33	0.34	0.35	0.17	0.18	0.18	0.18	0.19	0.20
Zinc	2011–2015	0.32	0.32	0.32	0.15	0.15	0.15	0.17	0.17	0.17
	2016–2020	0.35	0.35	0.35	0.19	0.19	0.19	0.20	0.20	0.20
Bauxite	2011–2015	0.47	0.46	0.32	0.25	0.25	0.15	0.28	0.28	0.16
	2016–2020	0.47	0.48	0.33	0.28	0.28	0.17	0.29	0.30	0.18
Nickel	2011–2015	0.26	0.27	0.3	0.13	0.13	0.13	0.15	0.15	0.15
	2016–2020	0.32	0.33	0.34	0.16	0.16	0.16	0.18	0.18	0.18
Manganese	2011–2015	0.29	0.28	0.28	0.16	0.16	0.15	0.17	0.17	0.17
	2016–2020	0.28	0.29	0.29	0.16	0.16	0.16	0.18	0.18	0.18
Lead	2011–2015	0.32	0.32	0.32	0.15	0.15	0.15	0.17	0.17	0.17
	2016–2020	0.36	0.36	0.36	0.17	0.17	0.17	0.18	0.18	0.18
Chromium	2011–2015	0.29	0.29	0.27	0.15	0.15	0.15	0.16	0.16	0.16
	2016–2020	0.32	0.33	0.30	0.18	0.18	0.18	0.19	0.19	0.19

2010 columns are the estimated production inefficiency in 2010.
10%—production efficiency in the case of a 10% production cut from the production level in 2010.
20%— production efficiency in the case of a 20% production cut from the production level in 2010.
For the list of Asian and non-Asian countries, see note for Table 2.

Using the calculated shadow prices with production restrictions in Table 3, we calculate the monetary value of the surplus through production restrictions. Table 4 provides the production volumes of major metals, the shadow prices and the estimated monetary surplus in the cases of 10% and 20% production restrictions. The full list for all metals with a production volume with reductions and reduction effects is available in Appendix [A5]. The figures provide some idea regarding how production restrictions may improve and sustain a country's currently unaccounted for wealth in the near future through reductions in consumption and in the production of mineral resources. For mineral resources such as iron and copper, which are expected to increase in value with a reduction of production volumes and with relatively high shadow prices compared to other mineral resources, restrictions have a large impact in terms of wealth. The estimates can be used to discuss the optimal taxation of mineral resources that will induce changes in production and demand and incentives to invest in more efficient production processes. In this paper, constant production restrictions are used to calculate the shadow prices and monetary surplus; however, the optimal restrictions can be calculated to maximize the future monetary surplus (Fujii and Managi, 2015).

We also provide results on production inefficiency under various production restrictions. As shown in Table 5, overall, production restrictions do little to change the production inefficiencies in both Asian and non-Asian countries. The only visible exception is bauxite, whereby production restrictions of 20% decrease inefficiencies in both Asian and non-Asian countries from 0.47 to 0.33 and from 0.28 to 0.17, respectively, when we compare the average inefficiencies in the period between 2016 and 2020. One of the possible reasons that we observe little effect of output restrictions on production inefficiency is that the other inputs, such as physical and labor capitals, are relatively more important determinants of production efficiency compared to minerals. Hence, production inefficiency is not completely unaffected by changes in production but is not very sensitive to such changes. In sum, production restrictions seem to affect shadow prices, especially in Asian countries; however, they have a weak effect on production inefficiency. The results indicate that production restrictions do not help to reduce the difference in inefficiency levels between Asian and non-Asian countries; thus, Asian countries should seek other strategies to decrease their discrepantly high relative levels of production inefficiency.

5. Conclusion

In this paper, we provided shadow price estimates from 1980 to 2010 and explored the impact of production restrictions on shadow prices and production inefficiency for 32 mineral resources. We used panel data for 162 countries that combine available data on mineral production, CO_2 emissions, GDP and other production inputs, such as the labor population and physical capital. We provide estimates of shadow prices and production inefficiency levels for the period between 1980 and 2010 and future estimates up to 2020 with production restrictions for each mineral resource. We observe a general downward trend in shadow prices for mineral resources, particularly mineral resources with large markets. When we consider the exponential increase in the demand for mineral resources, technological improvements in the production

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process and the increased efforts to recycle and reuse over the past few decades, this downward trend seems to be relatively mild.

Because the SDGs endeavor to establish quantitative goals for the sustainable management and efficient use of natural resources while ensuring sustainable consumption and production, the shadow price is a useful quantitative tool, as it also reflects variations in consumption and production patterns, which are crucial for discussing sustainability and resource markets. The results indicate that shadow prices are disproportionally higher in Asian countries compared to non-Asian countries. In addition, the relative prices have remained consistently higher in Asian countries throughout the past three decades. The results may reflect the impact of the large-scale urbanization process that is occurring in many heavily populated developing countries in the Asian region, such as China and India. Given that the transition from agrarian economies to industrial, mineral-based economies in developing countries is in only the early to middle stages, we expect to continue to see consistent disparities between Asian and non-Asian countries (Schandl and West, 2010).

Not only are Asian economies relatively more dependent on mineral resources compared to their counterparts, their general production inefficiencies are much larger than non-Asian countries. Of the 10 major mineral resources that are the focus of our analysis, the inefficiency levels in Asian countries were higher for 8 mineral resources, and the relative inefficiency was as much as double the inefficiency level of non-Asian countries in the post—2000 period. In particular, the relative production inefficiency of Asian countries has increased for major industrial mineral resources such as iron, copper and nickel. This high relative inefficiency in Asian countries can be partly explained by the low ore grades of the major mineral resources in Asian countries as well as the relatively high share of production by countries that have less advanced production technologies, which may lead to relatively high costs in terms of capital and environmental costs.

The quantification of production efficiency is important because it allows one to establish a measurable goal for the efficient use of natural resources and to evaluate possible mechanisms that may impact it. In this paper, we consider the effect of production restrictions on shadow prices and find that such restrictions do have a significant impact on the shadow prices of the major mineral resources, especially in Asian countries. Production restrictions can have either positive or negative effects on shadow prices, and given that the greater swings in shadow prices due to such restrictions are expected in Asian countries, production restrictions may be an effective policy to encourage the sustainable management of resources in Asian countries, particularly for the mineral resources for which we have found a positive impact on shadow prices.

On the other hand, production restrictions seem to have a limited impact on production inefficiency. Therefore, reducing major mineral resource production will not help Asian countries reduce their relatively high production inefficiency levels. This result calls for policy considerations other than production restrictions. In particular, policies that incentivize investment in technological improvements and that lay the foundation for technological sharing on a global scale could enhance overall production efficiency. Additionally, to achieve sustainable development, countries need to consider a rather long-term strategy in terms of resource governance, which effectively combines population and urbanization targets with production and consumption policies through effective tax and subsidy policies and technological investments. Such strategic policies would reduce the social and environmental costs that are associated with mineral resource production.

There are several ways to improve the accuracy and robustness of the shadow price estimations. First, if the mineral resource reserve data are extended further to cover more mineral resources and the level of precision of the estimated reserves is improved, we could use the Hotelling model to estimate shadow prices. Second, considering the trade volume between countries for each mineral resource in the calculation of shadow prices would improve the shadow price estimations, but such detailed trade data for all mineral resources are currently unavailable. Third, we use ore-based data, but there are ore-grade variations across countries. Thus, the same unit of metal ore may not be converted to a refined metal that is sold in the market. Ore-grade variations may partially explain the discrepancies in production inefficiencies between Asian countries and non-Asian countries. Therefore, more detailed data on the ore grades of the mineral resources in various countries would also improve the accuracy of the shadow price and inefficiency estimates.

Acknowledgment

This research is supported by the Ministry of Education, Culture, Sports, Science and Technology in Japan (MEXT) under a Grant in Aid for Specially Promoted Research 26000001. Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of the MEXT.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.eap.2017.03.005.

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Please cite this article in press as: Tamaki, T., et al., Shadow prices and production inefficiency of mineral resources. Economic Analysis and Policy (2017), http://dx.doi.org/10.1016/j.eap.2017.03.005