Article

Annual Nationwide Eco-Efficiency Assessment of Japanese Municipalities Based on Environmental Impact and Gross Regional Product

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Abstract: It is important for enterprises to decide their environmental policies after carefully examining their future paths based on the relationship between the environment and the economy. This study focused on Japanese minimum administrative divisions (municipalities) and attempted to quantify the annual environmental efficiency of production activities within each division according to the theory of life-cycle impact assessment (LCIA). Included in the LCIA process is "integration," which is the methodology whereby a number of environmental loads that affect various impact categories, such as global warming, air pollution, and land use, are integrated into an assessment result represented by a simple indicator. First, annual environmental impact assessments were conducted for all Japanese municipalities based on statistical information that was reliable, verifiable, and comparable. Next, the environmental efficiency of productivity for each division was conceptualized by dividing the gross domestic product (GRP) by the environmental damage amounts calculated by the theory of LCIA. Assessment results for each municipality were placed on a map of Japan in order to visualize the regionality of each indicator. The findings revealed in this study will aid public administrators in their decision-making process with respect to environmental policies.

Keywords: LCIA method; local government; statistical information; gross regional product; environmental accounting

1. Introduction

Recent international frameworks such as the Sustainable Development Goals (SDGs) and the Paris Agreement have been enacted to promote global cooperation toward achieving environmental conservation. At the same time, more and more companies have begun to recognize the importance of creating environmental policies after carefully examining their future plans and considering their business activities in relation to the environment and the economy. In this context, the United Nations in 2012 published "The System of Environmental-Economic Accounting (SEEA)" [1], an international standard framework that integrates economic and environmental information. In Japan, the Ministry of the Environment published "Environmental Accounting Guidelines 2005" [2], which lays out a system by which an organization reports its environmental activities in monetary terms; these guidelines have been widely adopted and utilized by Japanese companies. The revised version, "Environmental Reporting Guidelines 2018" [3], describes a unified principle of environmental conservation applicable to all domestic organizations and seeks to promote environmental accounting more aggressively. It has therefore become increasingly important for

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enterprises in Japan to recognize, quantitatively measure, and express their own environmental impacts in order to build a more sustainable society.

In recent years, not only have many companies around the world introduced environmental accounting into their business practices, but many public agencies, including local governments, have also begun to incorporate this approach as part of their financial accounting practices. Indeed, there are examples ranging from local to national governments: Eurobodalla Shire in Australia publishes annual statistics on its sustention of assets related to environmental conservation [4]; Washington State in the U.S. publishes both a strategic plan and a draft budget for a statewide environmental project every two years [5]; and the statistical department of the United Kingdom publishes annual environmental reports on the entire nation based on the SEEA framework [6]. However, compared with private companies and national governments, it may be more difficult for local governments to measure the environmental loads of their own administrative divisions in an objective way because such an assessment must be conducted over a wide geographical area and requires the expertise of specialists in many kinds of environmental fields, yet local governments often lack the resources necessary to do so. To date, no country has established a unified system of environmental accounting at the local government level; as a consequence, environmental accounting has not been adopted by local governments as widely as private companies.

In Japan, the trend of enterprises self-reporting their environmental activities both quantitatively and monetarily emerged in the early 1990s, with many private companies becoming early adopters. Some local governments also proactively introduced the practice; for example, the cities of Yokosuka and Sabae now publish environmental accounting reports on an annual basis using one-of-a-kind methods [7-8]. However, whereas private companies can make use of the "Environmental Accounting Guidelines 2005," no official environmental accounting guidelines for public agencies have been provided by the government of Japan, so local governments must devise their own individual methods to assess their local environmental conditions.

Studies on environmental accounting by governments from local to the national level have been conducted in the fields of economics and accounting. Ball examined the modality of environmental accounting through an analysis of local councils in the United Kingdom in the 2000s [9]. Qian et al. proposed the ideas to improve the environmental accounting conducted by the government of New South Wales in Australia with respect to waste management [10-12]. Muller et al. provided a framework for evaluating the economic damage related to air pollution emitted by each industry in the U.S [13]. In addition, some studies have surveyed and analyzed the actual environmental management conditions, of specific local governments around the world [14-16]. However, the examples provided by these studies have shown that calculations of environmental loads in certain areas are limited in that they focus on only a single environmental category. By fusing environmental accounting practices with the knowledge of environmental science, it may be possible to establish a new framework that integrates a number of categories to comprehensively assess the environmental loads of a given area.

Life-cycle impact assessment (LCIA) is one aspect of research in the field life-cycle assessment, whereby environmental loads throughout the life cycle of products and services are measured in a quantitative way. Included in the LCIA process is "integration," which is the methodology whereby a number of environmental loads that affect various impact categories, such as global warming, air pollution, and land use, are integrated into an assessment result represented by a simple indicator. Assessment methods that include the theory of integration, such as ExternE [17] and EPS [18], have already been developed. Additionally, other studies that have measured the environmental loads of spatial scopes, such as countries and regions, have reported results using several values, including carbon footprint and land footprint [19-23]. However, a methodology incorporating these approaches for environmental accounting has not been established on a global scale, nor are there any international standards. It is therefore possible that the LCIA may prove beneficial in helping to construct a unified methodology for environmental accounting of local governments, which they can use to make informed decisions concerning local environmental policies.

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This study focused on minimum administrative divisions (municipalities) in Japan and, using the LCIA method, attempted to comprehensively measure environmental loads emitted in each division during a certain period. This study leverages the assessment theory Life-Cycle Impact Assessment Method Based on Endpoint Modeling 2 (LIME2) [24, 25], which was developed in 2010. This is an endpoint-type LCIA method and can be used to calculate environmental impacts that reflect environmental conditions and knowledge unique to Japan. LIME2 incorporates the abovementioned "integration" theory of LCIA and calculates assessment results in monetary units called the "Eco-index Yen" (unit: Japanese yen) while integrating the environmental loads of several impact categories. Naturally, it is impossible to understand everything happening within each division therefore, the aim of this study was to capture the circumstances of local governments with respect to environmental accounting as comprehensively as possible within the range of LIME2, using statistical information available in Japan. In addition, this study aimed to conceptualize environmental efficiency and compare the assessment results with the area, population, and gross regional product (GRP) of each administrative division. Through comparative examination of the environmental efficiencies of Japanese municipalities based on these indicators, this study sought to provide new insights to aid public administrators in their decision-making process with respect to environmental policies.

2. Methodology

2.1. Research Approach

This study used LIME2 to assess the environmental loads of administrative divisions (i.e., municipalities) in Japan. The assessment results were divided by the area and population of each municipality to quantify environmental efficiency during a given period. In addition, the environmental efficiency of productivity was conceptualized for each administrative division by dividing the annual GRP by the annual values of environmental loads. These results were placed on a map of Japan to visualize the regionality of these concepts. The basic assessment points are described below.

First, the period for assessment is defined as one year, based on the assumption that assessment results will correspond to the fiscal years of local governments as well as the enterprises in their administrative division, which will allow for definitive comparisons of industrial and environmental statistics. For the purposes of this assessment, the year 2015 was chosen because a comparatively large number of relevant statistical investigations were conducted that year.

Second, the counting scope for assessing environmental loads is defined in accordance with the role of the local government. According to Japanese law, local governments shall autonomously and comprehensively carry out public administration mainly for the purpose of improving the welfare of local residents. Thus, this study defines the counting scope of environmental loads as all operations carried out within the area of the administrative division and within the range for which the required statistics are available, based on the assumption that municipalities have responsibilities providing them a broad perspective of the current circumstances throughout their divisions. This includes not only the public-works operations led by municipalities, but also the operations of private companies and households. Incidentally, it excludes household and transport statistics when calculating the environmental efficiency of productivity.

2.2. LIME2 Model

This section provides a summary of the LIME2 assessment method developed by Itsubo and Inaba [24, 25]. LIME2 is an endpoint-type LCIA method developed in Japan and is based on environmental conditions and knowledge unique to Japan. LCIA systems generally comprise two processes, characterization and integration. Characterization is a process for measuring the environmental impacts of products and services throughout their life cycles on a specific impact category. Integration is a process for obtaining an assessment result for a single indicator, by integrating the environmental impacts of several impact categories. The assessment theory of LIME2

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includes both of these processes and shows their assessment results as the cost of environmental impacts over a certain period with the monetary indicator Eco-index Yen (unit: Japanese yen), which is defined in this theory. The assessment framework of LIME2 is shown in Figure 1.

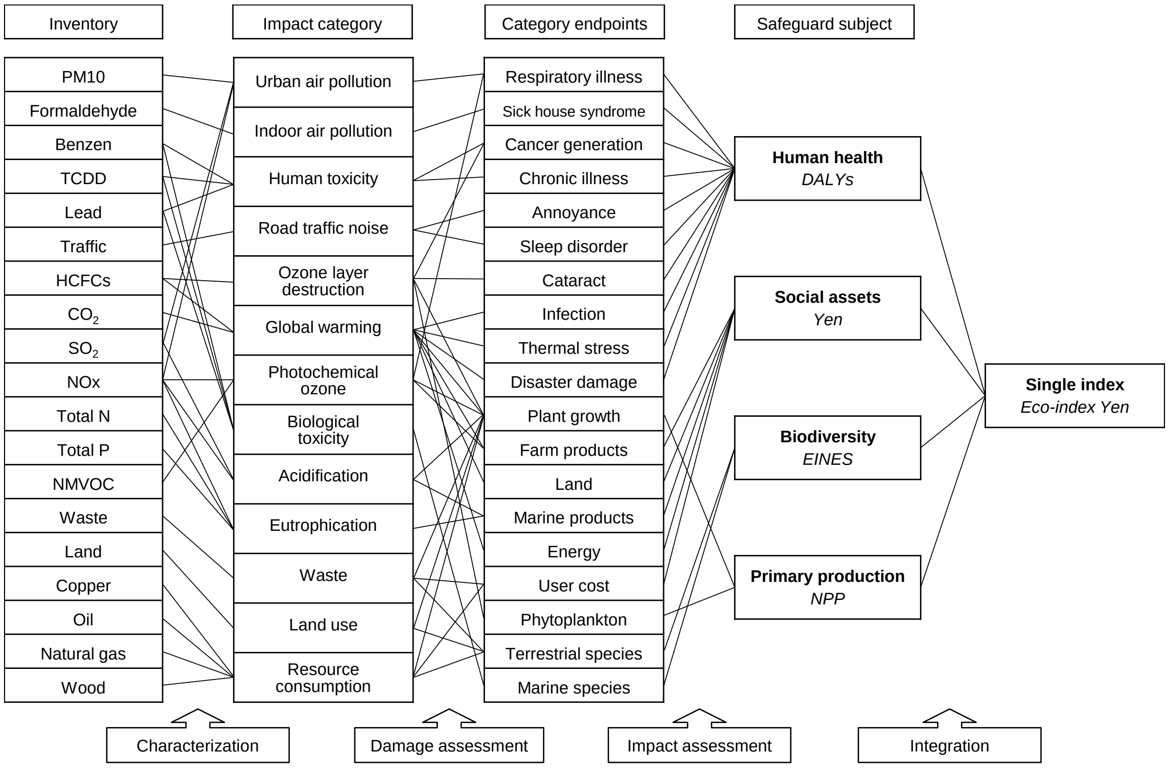

Figure 1. LIME2 assessment framework [14]

The LIME2 framework comprises 13 impact categories (e.g., urban air pollution and global warming), with one or more inventories designated for each impact category. The assessment proceeds as follows. First, each impact category is characterized according to an inventory. Second, damage assessments are conducted to measure the impact of each impact category on each category endpoint (e.g., respiratory illness and disaster damage). Third, for each category endpoint, impact assessments are performed for 4 safeguard subjects: human health, social assets, biodiversity, and primary production. Finally, the results of these impact assessments are integrated into a single indicator.

In LIME2, the stated preference method is used to evaluate the economic impact of environmental loads. The stated preference method is a concept from economic science, whereby certain values are derived from the value judgements of a number of individuals. It is for measuring abstract values when making comparisons between different subjects. Through the process of integration in LIME2, the assessment results of the 4 safeguard subjects are weighted by conjoint analysis based on a questionnaire survey of people's values. The assessment results are converted into a monetary value that can be viewed as a reflection of Japanese environmental values. By using this approach, the environmental loads of several inventories become comparable. For all inventories, LIME2 has integration factors that were calculated to reflect each step in the assessment procedure. The single indicator is directly obtained by multiplying the integration factors with corresponding inventory data and summing these values. The calculation formula is as follows.

$$SI = \sum_{X} Inv(X)?\ IF\ \ X) \qquad (1)$$

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SI : Single indicator (Eco-index yen) [yen] $Inv(X)$: Inventory of substance X [kg]
$IF(X)$: Integration factor of substance X [yen/kg]

In LIME2, environmental impacts are calculated according to where environmental loads are emitted within Japan. Even if a product that is produced in Japan is exported and consumed in another country, the assessment calculation does not change because the environmental loads resulting from production have an impact domestically. In contrast, the impact category "resource consumption" takes into account products imported into Japan. LIME2 can assess the environmental impact of consuming certain natural resources. However, because Japan relies heavily on imports of natural resources from other countries, the environmental impact on other countries are calculated according to the data on Japan's average annual imports of natural resource.

The integration factors of two impact categories, photochemical ozone and atmospheric pollution, are provided by regions in Japan in order to calculate the environmental impact as a reflection of each environmental condition, such as climate. But this study used the integration factors provided as a standard value for all regions in Japan to assess all impact categories uniformly because one purpose of this study was to assess all administrative divisions based on the same conditions in order to compare the results according to differences in inventory data from this study alone.

2.3. Identification of Environmental Load Location

This section describes the locational perspective of environmental load. It is necessary to standardize the method for calculating the individual transboundary movement of products between divisions in order to measure environmental loads emitted from spatial objects, which is the purpose of this study. For example, if environmental loads have trended downward in a certain division which is home to various manufacturing facilities, this outcome should not be interpreted as the sole effort of the municipality because the divisional cooperation of industry has been established in modern society.

Several studies have discussed who is responsible for the environmental loads related to certain categories. For example, Gallego et al., Rodrigues et al., Lenzen et al., and Marques et al. used interindustry analyses to examine the sharing of responsibility for greenhouse gas (GHG) emissions between producers and consumers of certain products [26-32]. There are some other studies that discussed the responsibilities of GHG emissions [33, 34]. In addition, Cordier et al. analyzed the shared environmental responsibilities for marine ecosystems [35]. In these studies, the researchers basically created a framework of environmental responsibility by classifying emitters as either producers (places of production) or consumers (places of consumption).

However, it might have proved difficult to apply this framework to the assessment concept of this study, in which the environmental loads of various impact categories from various operations were targeted. While it may be possible to draw clear distinctions between producers and consumers of agricultural crops and manufacturing products throughout their life cycles, it is difficult to classify the environmental responsibilities of service industries such as GHG emissions and land use for medical services and educations. Accordingly, a different approach was taken for the assessment conducted in this study, with a focus on the environmental responsibilities of administrative units at the level of municipalities.

Thus, this study tentatively proposed two principles for assessing Japanese divisions: territorial occurrence and territorial benefit. Territorial occurrence is defined as the environmental loads emitted through the life cycle of a product or service, which includes production, consumption (operation), and disposal, and is counted in the administrative divisions where these loads were emitted. In contrast, territorial benefit is defined as the environmental loads in the administrative division that benefitted from the product or service; in this way, an accurate assessment of the environmental impact of the product or service is achieved. For example, when a product is produced in area A and consumed in area B, the environmental loads emitted through the production of the product are counted in area A under the former principle and in area B under the latter. Furthermore, when an inhabitant lives in area C and is treated at a hospital in area D, the environmental loads emitted through the treatment are counted in area D under the former principle and in area C under the latter.

An assessment based on the principle of territorial benefit is ideal for correctly capturing the individual effort and responsibility of each municipality. For such an assessment, it is necessary to prepare inventory data reflecting the transboundary movement of products and services coverage for all divisions domestically and internationally. However, it is not easy to clarify industrial structure numerically at the municipal level in Japan. Accordingly, the principle of territorial occurrence was chosen for this study because of its precision with respect to assessment results and the availability of required data. This allowed for a focus on the practical calculation of environmental loads in administrative divisions nationwide. Moreover, the value of environmental loads based on this principle appeared to be comparable to the value of GRP for each administrative division because GRP is counted in the divisions where the added values are produced. Development of an assessment method based on the principle of territorial benefit will be a challenge for the future.

2.4. Assignment of Responsibility for Environmental Loads among Municipalities

This section describes the responsibility of municipalities for the environmental load assessment results in this study, which should be defined because LIME2 shows the calculated results as a monetary indicator. LIME2 is supposed to be utilized in Japan. However, the area affected by environmental impacts, such as regions within Japan, Japan as a whole, and the entire world, differ between each impact category. For example, the impact area of respiratory illness caused by air-pollution substances is limited to a certain region where these particles are suspended in the atmosphere. In contrast, the impact area of global warming caused by GHG is the entire world. The assessment theory of LIME2 is based on individual impact areas according to each impact category. Therefore, the assessment results based on this method include environmental loads that affect foreign countries in part or in total, so it may be excessive for Japanese municipalities to interpret these results as their individual responsibilities. It is necessary to arrange these concepts in order to apply this method to municipalities.

This study takes the position that the Japanese government has complete responsibility for the environmental loads emitted within Japanese territory. To explain municipalities' responsibilities for their impact on foreign countries, Japan is a member of several international organizations, including the United Nations, and is recognized as a nation with a great responsibility for the global environment as a leading member of the international community. As such, the Japanese nation must take full responsibility for environmental loads caused by operations within Japanese territory that have impacts on the global environment.

Accordingly, this study defines all environmental loads calculated in Japan as being counted toward the total damage on environmental assets both at home and abroad, where responsibility belongs to the Japanese government. Here, environmental assets are interpreted as the 4 safeguard subjects mentioned above: human health, social assets, biodiversity, and primary production. The assessment results expressed as a monetary unit is called the "damage amount on environmental assets" in this study. Based on this interpretation, municipalities shall uniformly be responsible for individual damage amounts because they are part of the Japanese nation.

2.5. Data Inventory

This section describes the preparation of LIME2 inventory data from statistical information in Japan. The LIME2 assessment framework comprises 13 impact categories, each of which is made up of several inventory items. However, because it was not practical to prepare all these inventory data, it was necessary to select which items to include based on a consideration of the assessment purpose, availability for information, and accuracy of the collected data. Thus, the availability of statistical information for all inventory items at the level of Japanese municipalities was surveyed before starting the study.

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Publicly available statistical information that was uniformly collected or estimated by governmental agencies in Japan was used to ensure that the inventory data was reliable, verifiable, and comparable across all divisions in order to make a valid assessment of Japanese municipalities nationwide. Specifically, statistical information from the year 2015 was chosen. When data for 2015 was not available, data from the year closest to 2015 was used instead.

Japan consists of 47 prefectures, which in turn consist of 1,747 municipalities. This study prioritized the uniform use of statistical information across all Japanese municipalities, with an aim to provide useful knowledge to local governments throughout the country. When statistical information at the municipal level was unavailable, it was estimated based on information collected at the prefectural level. In the end, the statistical information of 6 municipalities (Shikotan, Tomari, Ruyobetsu, Rubetsu, Shana, and Shibetoro in Hokkaido) was insufficient and therefore removed from the assessments in this study. These survey results are shown in Table 1, which describes the inventory items for which data was available, the number of these inventory items, the government ministry that conducted the statistical investigation, the indicator for the assessment of municipalities in this study, and the minimum administrative unit for which data was available, according to all 13 impact categories.

Table 1. Survey results for availability of LIME2 inventory data of collected by Japanese administrative divisions

Impact category	Inventory (number) *	Ministry that conducted the investigation	Indicator for assessment	Administrative unit
Ozone layer destruction	Various chemicals (21)	Ministry of Economy, Trade and Industry [36]	Emission amount [kg]	Municipalities
Photochemical ozone	Various chemicals (58)			
Human toxicity	Various chemicals (99)			
Biological toxicity	Various chemicals (127)			
Eutrophication	Various chemicals (17)			
Global warming	Various chemicals (19)			
	CO_2 (1)	Ministry of the Environment [37]	Emission amount [kg]	Municipalities
Land use	Various types of land use (5)	Ministry of Land, Infrastructure, Transport and Tourism [38]	Current area [km^2]	Municipalities
Resource consumption	Coal, natural gas, crude oil (3)	Ministry of Economy, Trade and Industry [39]	Consumption amount [kg]	Prefectures
Acidification	SO_2, NO_2 (2)	Ministry of the Environment [40]	Emission amount [kg]	Prefectures, and some municipalities
Atmospheric pollution	SO_2, NO_2 (2)			
Waste	Various types of domestic waste (1)	Ministry of the Environment [41]	Disposal amount [kg]	Municipalities
Road traffic noise	Travel distances by type of car (4)	Ministry of Land, Infrastructure, Transport and Tourism [42]	Travel distance [km]	Prefectures, and some municipalities
Indoor air pollution	Various chemicals (-)	-	-	-

* the inventory items which data was available, and number of these inventory items

As shown in the rightmost column of Table 1, some inventory data was not available at the municipal level for the 4 impact categories: resource consumption, acidification, urban air pollution, and road traffic noise. As previously mentioned, the solution to this problem was to estimate from the prefectural data, using a method published by the Japanese Ministry of the Environment [43]. As shown in the sixth row of Table 1, the Ministry publishes statistical information about annual CO_2 emissions at the municipal level. In this study, the CO_2 emission data at the municipal level is

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estimated from the data at the prefectural level, based on proportion distribution using other indicators. The estimation formula is as follows.

$$Inv_{mun}(X) = Inv_{pre}(X) \text{ ? } \frac{D_{mun}}{D_{pre}} \qquad (2)$$

$Inv_{mun}(X)$: Inventory data at the municipal level
$Inv_{pre}(X)$: Inventory data at the prefectural level
D_{mun} : Other indicator for proportion distribution at the municipal level
D_{pre} : Other indicator for proportion distribution at the prefectural level

In its method, the Ministry used the indicators "shipment value of manufactured goods" in the manufacturing sector, "number of employees" in industrial sectors except manufacturing, "number of households" in the residential sector, and "number of automobiles owned in divisions" in the transportation sector, as the factors for "D" in Eq. (2). The Ministry explains that this is one of the simplest methods to estimate data at the municipal level from data at the prefectural level, and it is suitable for approximating the overall data for each administrative division in Japan [43].

Next, the points to note about statistical information shown in Table 1 are described below for each impact category. Regarding the CO_2 emissions in the global warming category, the Ministry of the Environment collects data on the 6 types of GHG emissions: CO_2, CH_4, N_2O, HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), and SF_6. The Ministry converts the greenhouse effects of these substances into the effect of CO_2, and their summations are published as the equivalent mass of CO_2. Accordingly, this study referred to this data as the emission of CO_2 and uniformly used the integration factor of CO_2 for these data. Incidentally, the 19 substances counted for global warming by the Ministry of Economy, Trade and Industry do not include these 6 types of GHG.

The data on land use comes from geographic information system (GIS) data published by the Ministry of Land, Infrastructure, Transport and Tourism. This data shows different types of land use, indicated as percentage per square kilometer. For this study, the data was converted for the administrative divisions of each municipality using ArcGIS (v 10.5) software. Assessment targets were limited to man-made land use types, such as paddy field, cropland, building site, road site, and other site (e.g., golf course).

LIME2 assesses waste according to type, including paper, plastic, metal, and so on. But the required data on disposal condition according to type published in Japanese statistical information is incomplete. Therefore, this study used the integration factor prepared as a standard for all types of waste for the total disposal amount of all types of waste by each municipality.

For indoor air pollution, LIME2 assesses environmental loads based on the mass of toxic chemical materials produced in residential houses during construction and inhabitation. While these inventory data are required for assessment, it is not easy to collect or estimate these data for all residential houses in each administrative division. Moreover, this category does not correspond with the concept of assessing all municipalities nationwide. Accordingly, this category was excluded as an assessment target.

2.6. Conceptualization of Environmental Efficiency

The environmental loads of individual municipalities were thought to be largely related to area and population size, with larger municipalities tending to have larger loads. Accordingly, this study attempted to conceptualize environmental efficiency by dividing the values derived from assessment results by the administrative areas and their populations in 2015. This made it possible to compare environmental loads separately from size and to examine the qualities of each municipality from various perspectives.

However, the damage amount per area and per capita was thought to tend to be higher in administrative divisions with more active industries. Therefore, it is still not appropriate to directly judge the environmental efficiency of municipalities based on these indicator alone. In order to measure this concept more accurately, the benefits realized from the processes resulting in these damage amounts must also be quantified and their rates must be calculated. This study therefore attempted to conceptualize the environmental efficiency of administrative divisions by using the indicator, GRP. This indicator is total amount of value added by all industries in a given division over a given period and is indicated by a monetary unit. Gross domestic product (GDP) is commonly used as the indicator at the national level, and GRP is the same indicator at a regional level within a country. It is one of the most representative indicators for this purpose and statistical information is available for each municipality in Japan. Accordingly, this study defined the unique index by dividing the value of GRP (unit: Japanese yen) by value of damage amount (unit: Japanese yen). This indicator is called the "environmental efficiency for productivity (unit: dimensionless)" in this study, and the calculation formula is as follows.

$$(\mathit{Environmental\ efficiency\ for\ productivity})\ [\text{-}] = \frac{(\mathit{GRP})\ [\text{yen}]}{(\mathit{Damage\ amount})\ [\text{yen}]} \qquad (3)$$

This study referred to the statistical information on GRP for each municipality published by Ministry of Economy, Trade and Industry. Because statistical research was not conducted in 2015, the data from 2016 was used instead. Furthermore, the indicator for normal GRP was used, which is based on commodity prices in 2016. It was also necessary to recalculate the damage amounts for certain sectors that were assessable by GRP indicators in order to make them correspond to both indicators for the assessment. Thus, the damage amount was limited to the amount for the industry sector (which includes the service industry) in all impact categories; the amounts for the household and transport sectors were excluded in this section. This damage amount indicator is called the "production damage amount". For example, the CO_2 emissions related to consumption of heating energy by households was not included in the damage amount for the global warming category. Additionally, the damage amounts for domestic waste and road traffic noise were excluded because these amounts were wholly caused by the household and transport sectors. The damage amounts for land use were also reluctantly excluded because they were impossible to classify for certain sectors due to the nature of the statistical information. Incidentally, it is preferable to use damage amounts under the principle of territorial occurrence in this section because the administrative division where the added value was counted is same division where the related environmental load was emitted.

In economics, "flow" is the amount that something changes over a given period of time and "stock" is the storage of something at a particular point in time. The indicators of GRP and production damage amount both measure the flow within administrative divisions, and thus environmental efficiency for productivity can be interpreted as an index of the relationship between the amount of change for both indicators over a given period.

3. Results

This chapter describes the assessment results for administrative divisions (i.e., municipalities) in Japan as calculated based on the abovementioned methods. The environmental load calculated by LIME2 is called the damage amount on environmental assets, as previously mentioned in the section 2.4. Though these calculations were originally performed in Japanese yen, the results are presented here in U. S. dollars (111.34 USD/JPY on 1 April 2019). For reference, the tables and figures showing the results in Japanese yen is included in the Supporting Information.

3.1. Total Damages for Entire Japan

Total damage amounts for entire Japan are shown in Figure 2 (The figure in Japanese yen is shown in Figure SI 1). The total damage amount was 76.6 billion USD (8.53 trillion yen). The impact category with the largest amount was global warming (25.3 billion USD, 2.82 trillion yen), followed by land use (20.9 billion USD, 2.33 trillion yen), domestic waste (11.1 billion USD, 1.24 trillion yen), biological toxicity (5.66 billion USD, 0.63 trillion yen), atmospheric pollution (5.48 billion USD, 0.61

trillion yen), and resource consumption (5.03 billion USD, 0.56 trillion yen). These 6 categories accounted for 96.1% of the total. Breakdowns of inventory data for 4 categories according to the total damage amount are shown in Figure 3 (The figure in Japanese yen is shown in Figure SI 2). Building sites accounted for 61.0% of the total land use. Likewise, styrene accounted for 91.9% of biological toxicity, SOx accounted for 88.8% of atmospheric pollution, and crude oil accounted for 78.4% of resource consumption. A single inventory accounted for over half of the total in each of these categories. Incidentally, nearly the entirety of global warming consisted of the inventory data collected by Ministry of the Environment on 6 types of GHG, including CO_2. Moreover, the entirety of domestic waste was accounted for by a single inventory data, as previously mentioned. As these results show, the environmental loads for Japan according to each category and each inventory become comparable as a single monetary indicator quantitatively.

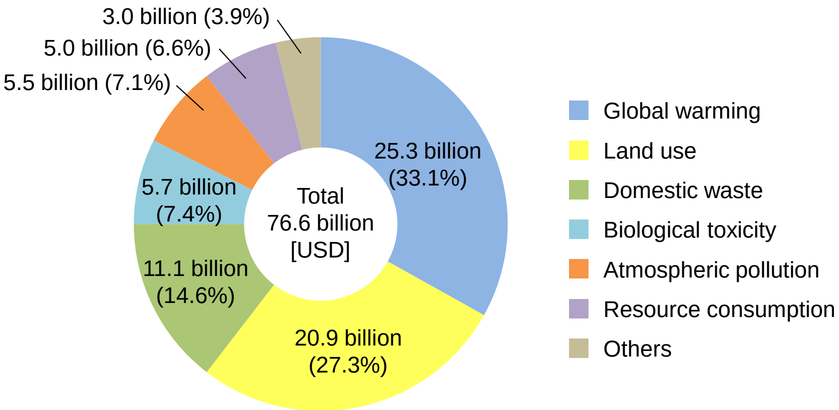

Figure 2. Total damage amounts for Japan by impact category

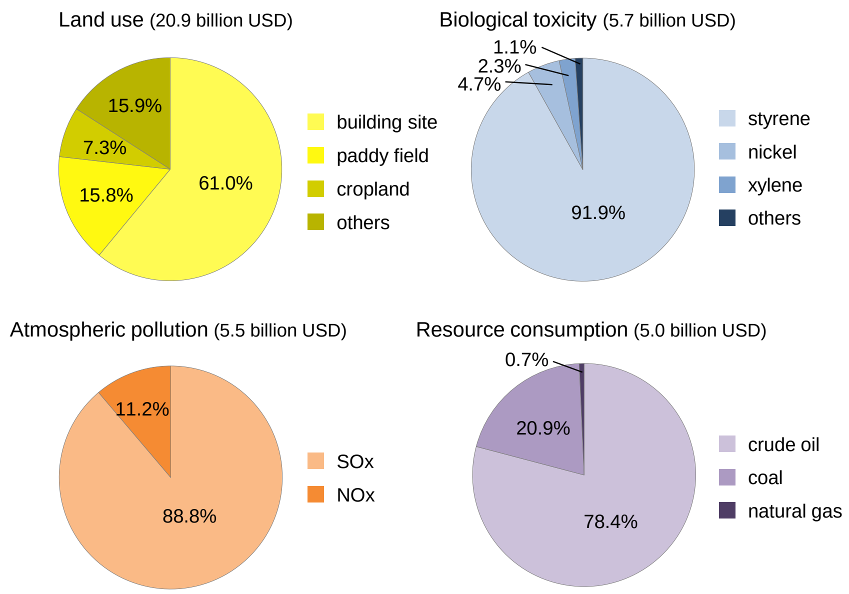

Figure 3. Breakdowns of inventory data for total damage amount by each impact category

3.2. Disaggregated Damages for Entire Japan

In this section, the damage amounts per unit area and per capita were calculated for all municipalities. The results are shown in Table 2, which lists the average, standard deviation, and variation coefficient for the damage amounts per unit area and per capita for all Japanese municipalities by each impact category (The table in Japanese yen is shown in Table SI 1). The variation coefficient was calculated by dividing the standard deviation by the average, and it shows the relative variation in the data.

The averages of total damage amount per unit area and per capita were calculated as 666 thousand USD/km² (74.2 million yen/km²) and 916 USD/capita (102 thousand yen/capita). The top

Table 2. Statistical value of damage amounts for municipalities

Impact category	Damage amount per area for municipalities			Damage amount per capita for municipalities		
	Average [USD/km²]	Standard deviation [USD/km²]	Variation coefficient [-]	Average [USD/capita]	Standard deviation [USD/capita]	Variation coefficient [-]
Ozone layer destruction	1.27×10^{3}	3.52×10^{4}	27.91	8.30×10^{-1}	2.06×10^{1}	24.78
Photochemical ozone	2.06×10^{3}	1.71×10^{4}	8.28	2.87×10^{0}	2.61×10^{1}	9.12
Human toxicity	3.85×10^{3}	4.20×10^{4}	10.91	2.60×10^{0}	2.26×10^{1}	8.70
Biological toxicity	6.06×10^{4}	3.60×10^{5}	5.94	5.46×10^{1}	5.14×10^{2}	9.41
Eutrophication	1.36×10^{-3}	2.88×10^{-2}	21.23	1.97×10^{-6}	4.89×10^{-5}	24.81
Global warming	1.86×10^{5}	4.82×10^{5}	2.59	2.31×10^{2}	3.06×10^{2}	1.33
Land use	1.30×10^{5}	1.31×10^{5}	1.01	4.19×10^{2}	5.27×10^{2}	1.26
Resource consumption	3.51×10^{4}	1.01×10^{5}	2.86	3.69×10^{1}	1.01×10^{2}	2.72
Acidification	3.87×10^{3}	8.84×10^{3}	2.28	6.75×10^{0}	7.03×10^{0}	1.04
Atmospheric pollution	5.92×10^{4}	2.01×10^{5}	3.40	4.75×10^{1}	6.37×10^{1}	1.34
Domestic waste	7.02×10^{4}	1.36×10^{5}	1.97	8.63×10^{1}	3.14×10^{1}	0.36
Road traffic noise	1.07×10^{4}	1.54×10^{4}	1.44	3.50×10^{1}	3.85×10^{1}	1.10
Total	6.66×10^{5}	1.61×10^{6}	2.41	9.16×10^{2}	1.92×10^{3}	2.10

Number of samples: 1741

three amounts per unit area were global warming (186 thousand USD/km², 20.7 million yen/km²), land use (130 thousand USD/km², 14.5 million yen/km²), and domestic waste (70.2 thousand USD/km², 7.82 million yen/km²). The top three amounts per capita were land use (419 USD/capita, 46.7 thousand yen/capita), global warming (231 USD/capita, 25.7 thousand yen/capita), and domestic waste (86.3 USD/capita, 9.61 thousand yen/capita). The wide range of differences between the average amounts per unit area and per capita in accordance with each impact category is due to the wide range of land area and populations of municipalities throughout Japan. The variation coefficients for ozone layer destruction, photochemical ozone, human toxicity, biological toxicity, and eutrophication were much higher than the total values, suggesting the damage amounts for these categories varied comparatively between municipalities. The inventories of these categories include the toxic chemical substances produced continually from specific industries, such as the heavy chemical industry. Therefore, there tended to be major disparities between municipalities according to the kinds of industries within their divisions.

3.3. Spatially-explicit Damages for Japanese Municipalities

In this section, the assessment results for all municipalities calculated in the previous section are shown in a map of Japan in order to visualize the regionality of environmental loads. The total damage amount per unit area and per capita for Japanese municipalities nationwide is shown in Figure 4 (The figure in Japanese yen is shown in Figure SI 3). Here, the damage amount for all municipalities is shown so that map colors represent 10% increments of cumulative frequency distribution. The damage amount per unit area tended to be higher in more densely populated areas. In particular, the rate was much higher in the three major metropolitan areas of Japan, including the national capital region (around Tokyo and Yokohama), the Kinki region (around Osaka), and the Chukyo region (around Nagoya). The rate was also higher in and around Fukuoka and Sapporo.

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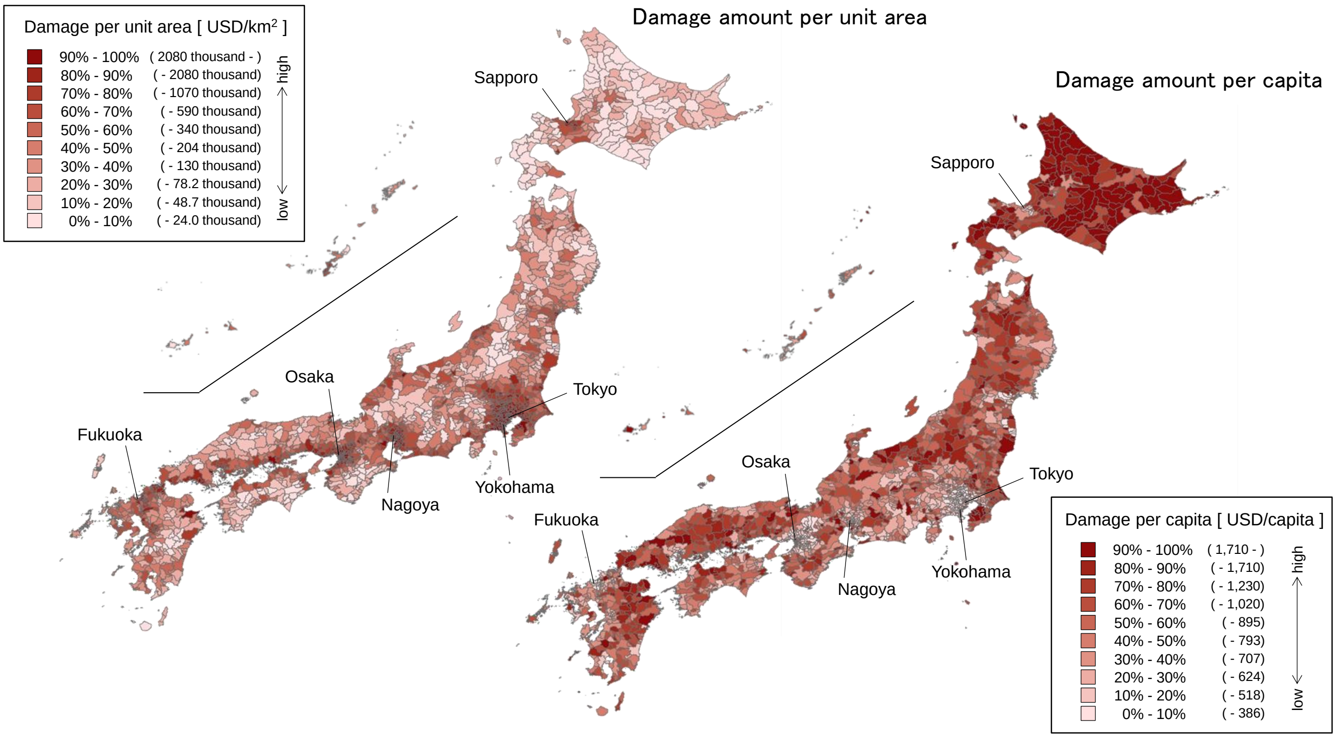

Figure 4. Assessment results for total damage amount by Japanese municipalities nationwide (left map, damage amount per unit area; right map, damage amount per capita)

In contrast, the rate was lower in sparsely populated areas, such as inland mountainous regions. This distribution is extremely similar to the distribution of population density in Japan, indicating a deep relationship between these indicators.

In contrast with the damage amount per unit area, the amount per capita tended to be lower in densely populated areas, such as parts of the three major metropolitan areas. At the same time, it tended to be higher in sparsely populated areas, such as inland mountainous regions. In some urban areas, the absolute damage amount was higher but the population tended to be concentrated at a rate higher than that of the damage amount. It therefore may be suggested that environmental efficiency was comparatively better around urban areas in Japan from the perspective of environmental loads per capita. However, agricultural crops and manufactured goods are produced outside of urban areas but are consumed in urban areas in Japan so it is essential that an assessment theory based on the principal of territorial benefit mentioned above be developed so that this hypothesis may be accurately verified.

The assessment results by impact category are shown on a map of Japan. The damage amounts per unit area and per capita by Japanese municipalities for the top 5 categories, shown in Figure 2 (global warming, land use, domestic waste, biological toxicity, and atmospheric pollution) are shown in Figure 5. The distributions of damage amount per unit area were very similar among the 4 categories global warming, land use, domestic waste, and atmospheric pollution. The rates for these categories tended to be higher in urban and suburban areas. Because the emissions of chemicals related to global warming and atmospheric pollution are comparatively large from not only the industrial sector but also the service and transport sectors, these damage amounts tended to be high in densely populated areas, regardless of the kind of industries located within these areas. Naturally, the damage amounts for land use and domestic waste also tended to be higher in densely populated areas. In contrast, the rate for biological toxicity was the only category to not show a relationship with population distribution on the map. The result of this category was not particularly biased nationwide because the damage amount for this category was largely affected by the specific industry located in a given area, regardless of its population.

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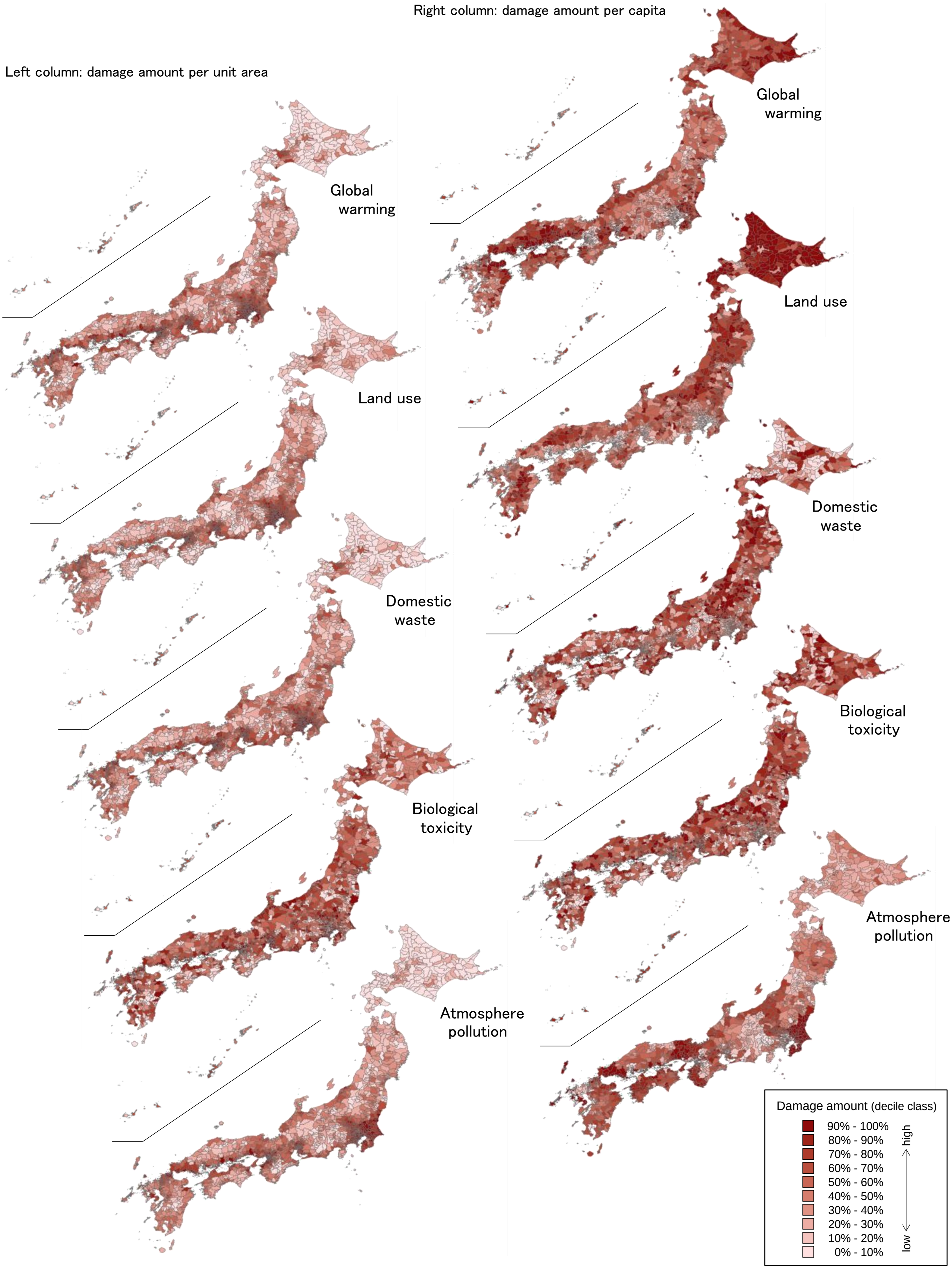

Figure 5. Assessment results for each impact category by Japanese municipalities nationwide (left column, damage amount per unit area; right column, damage amount per capita)

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Certain categories showed different distributions between damage amount per capita and the amount per unit area. In particular, the rates for global warming, land use, and atmospheric pollution were lower in the central parts of the three major metropolitan areas. This was reflected in the results that the populations were larger than the absolute damage amount for each category in these areas, as described above. But there were some exceptions in the suburbs of these areas. The rates for global warming and atmospheric pollution were higher in parts of the areas surrounding the national capital region and the Kinki region. These areas have some industries that actively support the local economies but the population is not as concentrated as in the heart of the metropolitan areas, and these reasons are reflected the results.

Taking a closer look at the amount per capita for each category, the rate for global warming tended to be higher in cold areas, such as Hokkaido (the northern island that includes Sapporo), in the coastal areas of western Japan, and in some suburban areas, as described above. In Hokkaido, heating energy consumption was larger in colder areas, including in the household sector. Heavy industry has been active in the coastal areas of western Japan for a long time. There are industrial zones in the coastal areas throughout the country, which is also reflected in the results for atmospheric pollution. The rate for land use was much lower in densely populated areas, in contrast with the amount per unit area, suggesting that environmental efficiency may be higher in more densely populated areas, particularly from the perspective of residential land use. The rate for domestic waste showed a different distribution for amount per capita than per unit area, but it did not show a particular relationship with population distribution on the map. As shown the rightmost column of Table 2, the variation coefficient of this category per capita was the lowest among all categories, indicating that the disparity for this rate was comparatively narrow across all municipalities nationwide. The rate for biological toxicity was the only category to show a similar distribution between amount per unit area and per capita. Because this category was affected by the specific industries in a given area, both distributions were independent from other categories.

3.4. Spatially-explicit Environmental Efficiency for Japanese Municipalities

In this section, the environmental efficiency based on the method described in the section 2.6 was calculated. The values of GRP per capita and environmental efficiency for productivity for all municipalities are shown in Figure 6 (The figure in Japanese yen is shown in Figure SI 4). These values are shown so that map colors represent 10% increments of cumulative frequency distribution. Here, the median value of environmental efficiency for productivity for all municipalities was calculated as 65.5. Accordingly, values higher than the median are represented by cold colors (blue) and lower values are represented by warm colors (red) for each administrative division on the map of Japan.

The GRP per capita tended to be higher in the Chubu region (the central part of Japan that includes Nagoya). This can be explained by the concentration of the automotive and the electronics industries in the region, and these industries contribute a large added value. Moreover, the rate tended to be higher in certain coastal areas around the national capital region and western Japan where heavy industries are concentrated.

The rate for environmental efficiency for productivity also tended to be higher in the Chubu region. In these areas GRP per capita was higher and production damage amount per capita was comparatively lower so the rate was higher than the national average. In particular, it was suggested that the automotive industry produced large benefits relative to its environmental loads. Similarly, the benefits produced by the electronics industry were large relative to the unit size of its products, so the value added is larger than the environmental loads. In contrast, the rate tended to be comparatively lower in certain coastal areas around the national capital region and western Japan because the GRP per capita was higher but the production damage amount per capita was also higher there. Heavy industries produce large benefits but their environmental loads are also large. The assessment results reflected the characteristics of these industries for each municipality.

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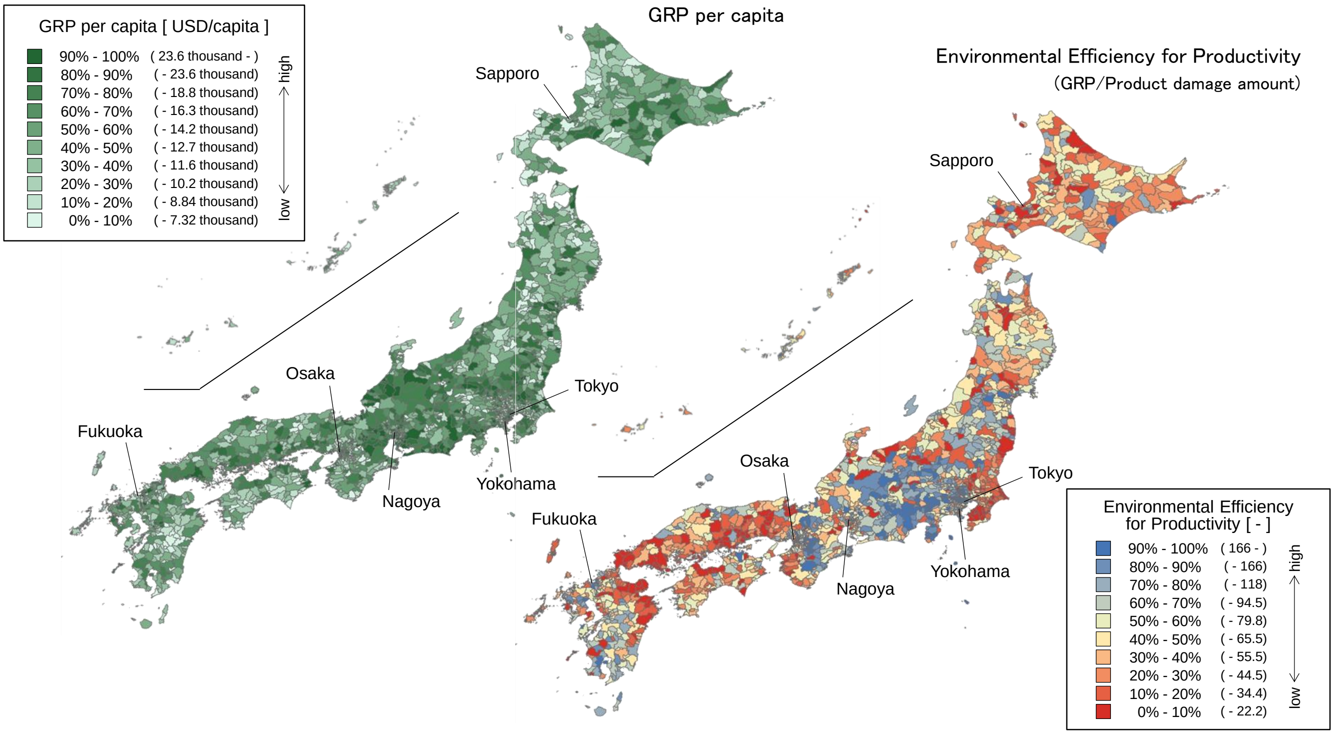

Figure 6. GRP per capita and environmental efficiency for productivity by Japanese municipalities nationwide (left map, GRP per capita; right map, environmental efficiency for productivity)

3.5. Assessment Results for Major Cities

This section focuses on the major municipalities that make up the urban areas of Japan and discusses their characteristics based on the assessment results calculated in the previous sections. In Tokyo, the capital of Japan, the main area where the nation's administrative functions are carried out is designated as a special ward. This area was treated as an administrative division for the municipality of Tokyo in this section. In addition, the 20 municipalities whose populations and economic scales are large are given a higher degree of autonomy than general municipalities in Japan. These municipalities are officially called government-designated cities. This study attempted to examine the current conditions of these 21 municipalities.

The assessment results of GRP per capita, production damage amount per capita, and environmental efficiency for productivity are shown in Table 3 along with the cumulative relative frequency for these indicators based on the assessment results for all Japanese municipalities (The table in Japanese yen is shown in Table SI 2). Cumulative relative frequency is an index that shows a position relative to all data in a constellation. Here, the top value for all municipalities is 100% and the bottom value is 0% for each indicator in Table 3. A graph that describes their assessment results is shown in Figure 7 (The figure in Japanese yen is shown in Figure SI 5). This graph shows the value of production damage amount per capita on the horizonal axis and the value of GRP per capita on vertical axis. Each point represents a municipality. Thus, the slope of the line connecting the plot with origin point shows the value of environmental efficiency for productivity for each municipality. Accordingly, the more upper left on the graph a point is, the higher its environmental efficiency for productivity.

As shown in Table 3 and Figure 7, the top three municipalities in terms of GRP per capita were Tokyo (52.8 thousand USD/capita, 5.88 million yen/capita), Osaka (46.2 thousand USD/capita, 5.14 million yen/capita), and Nagoya (32.2 thousand USD/capita, 3.58 million yen/capita). These municipalities are the central locations of the three major metropolitan areas. The results reflect the thriving economic conditions in these municipalities. Additionally, 15 of the 21 municipalities had 80% cumulative relative frequency or greater. This meant that these municipalities were in the top

Table 3. Statistical values of assessment results for 21 major municipalities in Japan

Municipality	GRP per capita [USD/capita]		Production damage amount per capita [USD/capita]		Environmental efficiency for productivity [-]	
Sapporo	1.80×10^4	(78.8%)	2.68×10^2	(65.6%)	67.2	(53.1%)
Sendai	2.66×10^4	(94.8%)	1.86×10^2	(47.8%)	143.1	(89.1%)
Saitama	1.94×10^4	(83.8%)	5.93×10^1	(4.8%)	327.0	(99.3%)
Chiba	2.15×10^4	(89.1%)	5.24×10^2	(84.9%)	41.1	(27.4%)
Tokyo (special ward)	5.28×10^4	(99.1%)	1.48×10^2	(38.5%)	355.0	(99.6%)
Yokohama	1.92×10^4	(83.2%)	2.20×10^2	(56.9%)	87.3	(68.0%)
Kawasaki	1.70×10^4	(75.0%)	4.37×10^2	(80.5%)	38.9	(25.2%)
Sagamihara	1.37×10^4	(57.2%)	1.39×10^2	(34.3%)	98.0	(74.7%)
Niigata	1.86×10^4	(81.2%)	2.06×10^2	(53.3%)	90.5	(70.4%)
Shizuoka	2.24×10^4	(90.4%)	1.04×10^2	(21.9%)	214.8	(96.6%)
Hamamatsu	2.08×10^4	(87.4%)	1.14×10^2	(25.8%)	182.2	(94.1%)
Nagoya	3.22×10^4	(97.0%)	3.39×10^2	(73.5%)	95.0	(72.8%)
Kyoto	1.99×10^4	(85.5%)	2.65×10^2	(65.3%)	75.3	(59.0%)
Osaka	4.62×10^4	(98.7%)	5.06×10^2	(84.0%)	91.4	(71.0%)
Sakai	1.62×10^4	(71.4%)	2.69×10^2	(65.7%)	60.4	(45.5%)
Kobe	2.15×10^4	(89.1%)	1.95×10^2	(49.9%)	110.6	(80.7%)
Okayama	1.95×10^4	(83.9%)	3.04×10^2	(70.0%)	64.0	(49.3%)
Hiroshima	2.26×10^4	(90.9%)	3.13×10^2	(71.2%)	72.4	(57.0%)
Kitakyushu	1.82×10^4	(79.5%)	4.43×10^2	(80.9%)	41.1	(27.4%)
Fukuoka	2.69×10^4	(94.9%)	8.49×10^1	(12.8%)	316.9	(99.2%)
Kumamoto	1.57×10^4	(68.9%)	1.90×10^2	(48.6%)	82.9	(64.9%)

* Cumulative relative frequency based on all municipalities is shown in parentheses beside each value

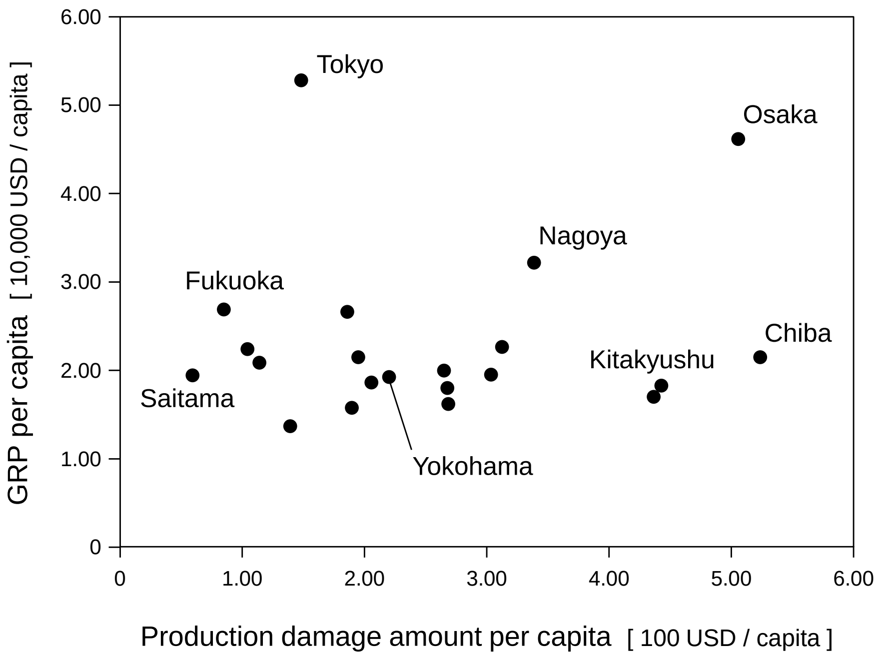

Figure 7. A graph showing assessment results for 21 major municipalities in Japan

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20% of all Japanese municipalities and that their productivity was comparatively higher than many of other general municipalities.

The top three municipalities in terms of Production damage amount per capita were Chiba (524 USD/capita, 58.3 thousand yen/capita), Osaka (506 USD/capita, 56.3 thousand yen/capita), and Kitakyushu (443 USD/capita, 49.3 thousand yen/capita). Chiba is located east of Tokyo in the national capital region, and Kitakyushu is located north of Fukuoka in Kyushu, which is the large island in the southwest part of Japan. Various industries supporting the local economy are active in these large urban areas. Accordingly, their results were comparatively higher from the perspective of environmental loads related to productivity.

The top three municipalities in terms of environmental efficiency for productivity were Tokyo (355.0), Saitama (327.0), and Fukuoka (316.9). In Tokyo, GRP per capita was high but the production damage amount per capita was comparatively low, so the environmental efficiency value for Tokyo was the highest of the 21 municipalities. Tokyo is also a hub of Japanese culture, and there are many large commercial facilities, entertainment facilities, and major media companies, such as broadcasters and publishing firms. The environmental loads of these businesses are low relative to their benefits, which is one of the reasons for Tokyo’s assessment results. Similarly, in Saitama and Fukuoka the GRP per capita was high and the production damage amount per capita was low. The main industries in these municipalities are service businesses and the assessment results seem to reflect these conditions. Additionally, 7 of the 21 municipalities had over 80% cumulative relative frequency, and 16 municipalities had over 50%.

4. Discussion

4.1. Usability of the Method in Practice

The assessment theory of LIME2 has the potential to be adopted by local governments. as an approach to environmental accounting. The ability of LIME2 to assess the environmental loads emitted in administrative divisions by a single monetary indicator provides public administrators with valuable information for comparing the effects of their measures across different environmental fields. Such information is expected to be useful for allocating environmental conservation funds for local governmental budgets. Moreover, this system provides residents with easy-to-understand information about their local environmental situation, thanks to assessment results described as a clear indicator that anyone can understand.

The assessment results of environmental efficiency related to productivity can be represented visually for every municipality in a 2D graph (e.g., Figure 7). This method makes it possible to quantify the environmental loads across all Japanese municipalities and to discern each municipality’s position relative to other municipalities. The LIME2 approach to environmental accounting is expected to be adopted by local governments throughout Japan and may reveal promising examples of best practices across the country.

4.2. Challenges of the Assessments

In this study, the data required for assessment came from statistical information collected by the Japanese government. However, not all of the inventory data were available at the municipal level as currently structured in Japan. Therefore, a simple estimation method was used for the required data at the municipal level. In the future, it will be necessary to collaborate with various statistics institutes in Japan and to obtain more detailed statistical information from the private sector to carry out a more accurate assessment that will lead to the adoption of the LCIA method of environmental accounting by local governments. Additional future considerations include the development of an assessment method based on the principle of territorial benefit, as described in section 2.3.

It must be noted that the inventory of industrial waste was reluctantly excluded as an assessment target in this study because the relevant data was not available at the prefectural level or by type of business, and consequently the required data at level of municipality could not be estimated in application on Eq. (2) in section 2.5. In most cases, the administrative divisions where

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industries operate are not the same as the divisions where their waste is disposed, particularly for industrial waste. These circumstances should therefore be noted in an assessment of municipalities such as this study. An assessment method based on the principle of territorial benefit is particularly desirable to address the issues with this category.

It was possible to capture the regionality of environmental efficiency for production nationwide, as described in section 3.4. However, these results were largely affected by the kind of industries operating in each area. As such, it will be a challenge for the future to calculate these amounts according to the type of business and will require more detailed statistical information. The results of such an assessment would allow for a comparison of environmental efficiency of industries across all municipalities.

4.3. Global Expansion of the Method

This study leveraged the framework and assessment theory of LIME2, which was chosen because of the advantages described in section 2.2. However, other LCIA methods used around the world, such as ExternE [17] and EPS [18], are also able to calculate different environmental impacts as a single indicator. In future stages of this study, assessments of the same concepts will be conducted for administrative divisions in every country by following LCIA methods that reflect climate conditions and by using data from local statistics institutions. Moreover, it may be possible to quantify the environmental efficiency of administrative divisions around the world using the same conditions by applying a global-scale LCIA method. In so doing, information useful to local governments can be more widely disseminated around the world.

Sustainable urban development is becoming a common challenge worldwide, as shown by Goal 11 of the SDGs (Sustainable Cities and Communities). In addition, the assessment method of this study is thought to be particularly useful to measure the status of efforts by local governments toward achievement of Goal 3 (Good Health and Well-being), Goal 12 (Responsible Consumption and Production), Goal 13 (Climate Change), and Goal 15 (Life on Land). It may also be expected to contribute to the achievement of Goal 17 (Partnership for the Goals) by promoting communication between local governments around the world through the sharing of information about assessment results because they are based on a common method. In the future, an assessment theory for measuring progress toward achieving targets by local governments will be developed by focusing on the framework of SDGs.

5. Conclusions

This study aimed to assess the environmental efficiency of Japanese municipalities by using LIME2. The representative conclusions are described below.

1. The total damage amount for Japan was 76.6 billion USD (8.53 trillion yen) in 2015. The six largest impact categories in terms of damage amount were global warming, land use, domestic waste, biological toxicity, atmospheric pollution, and resource consumption. Based on these results, priorities for planning environmental conservation strategies for the whole of Japan should be examined.
2. The damage amount per capita tended to be lower in densely populated areas, such as parts of metropolitan areas. This suggests that environmental efficiency may be higher in more densely populated areas, particularly from the perspective of residential land use, further suggesting the importance of appropriate urban planning and development.
3. The environmental efficiency for productivity tended to be higher in areas where industries that produced large benefits relative to their environmental loads, such as automotive and electronics industry, were active. This suggests that a best practice for municipalities may be identifying the environmentally efficient industries that operate in their divisions.
4. Of the 21 government-designated cities (including a special ward of Tokyo) in Japan, seven ranked in the top 20% and 16 ranked in the top 50% in environmental efficiency for productivity. This suggests that environmental efficiency was comparatively high in many of the municipalities located in large urban areas in Japan from the perspective of productivity.

5. The usability of this method for environmental accounting by local governments in Japan is suggested. By considering the same challenges described in section 4, attempts should be made to improveme this method in the future so that it can be utilized by local governments around the world.

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