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TECHNICAL REPORT

Development of a method for downscaling ecological footprint and biocapacity to a 1-km square resolution

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Abstract

In this study, we propose a method for downscaling ecological footprint (EF) and biocapacity (BC) to a 1-km square resolution for a spatially flexible analysis of environmental burden balance. To conduct EF downscaling (by land type and consumption category) for all terrestrial areas of Japan, the grid population was multiplied by the scaled EF per capita based on the consumption expenditures and income statistics available at the municipal level. The BC of each land type was estimated following the land-use map. Subsequently, a balance analysis between EF and BC showed the spatial distribution of EF, BC, and the environmental load excess ratio (EF/BC). The values of the environmental load excess ratio significantly varied between grids, and the spatial distributions differed depending on the land type. An example of multiscale balance analysis at municipal and prefectural scales by the developed dataset showed the different distributions of the environmental load excess ratio due to the scale of spatial boundaries and demonstrated its contribution to designing interregional cooperative policies from a multilayered perspective. The established high-resolution dataset can be utilized practically for flexibly analyzing the multilayered spatial boundaries to fill the scale mismatch between natural resources and administrative boundaries. The downscaling method proposed in this study can be applied beyond Japan if similar sets of statistics and land-use information are available, which will significantly improve the spatial resolution of the analysis.

Keywords Ecological footprint · Biocapacity · Localization · Grid resolution · Scaling

Introduction

Background

To achieve sustainable development, humans must live within the boundaries of ecosystem stocks (natural capital) and the flows the stocks generate (ecosystem services). The ecological footprint (EF), an environmental indicator developed in the early 1990s (Rees 1992; Wackernagel and Rees 1996), has received global attention as a useful sustainability indicator. EF is the total "area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the wastes that the population produces" (Rees 2000). In other words, EF is an environmental indicator that converts various human-induced ecological burdens, such as resource consumption and CO_2 emissions, into consumed land areas. As a counterpart to EF, biocapacity (BC) is an indicator that represents the amount of biologically productive land and sea areas available to provide ecosystem services or nature's regenerative capacity (Borucke et al. 2013). Moreover, these indexes are proposed

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to have two basic contributions (Nakano and Wada 2007). First, they enable a quantitative assessment of the balance between the capacity of the ecosystem service supply (BC) and human demand (EF). Second, they show how much the economic activities in a particular country or region environmentally burden other regions through the importation and exportation of goods and services (Nakano and Wada 2007; van Vuuren and Bouwman 2005).

The EF and BC datasets at the global and national scales are being continuously developed by the Global Footprint Network (GFN 2021). Measuring the EF at various smaller spatial scales (i.e., subnational, prefectural, municipal, and community) is a significant and widespread research theme (Ujihara et al. 2008; Kuzyk 2012; Cano-Orellana and Delgado-Cabeza 2015; Suzuki and Tanabe 2016; Luo et al. 2018; Galli et al. 2020), because spatially revealing the EF distribution is difficult, unlike BC whose distribution is tied to land types. However, van den Bergh and Verbruggen (1999) highlighted that EF estimation following geopolitical and cultural boundaries (e.g., national or subnational administrative boundaries) is somewhat arbitrary from an environmental viewpoint. This could be an inherent weakness of the EF, because its calculation depends heavily on statistics developed according to administrative boundaries, such as countries, provinces, and municipalities. If the EF can be calculated for areas defined from an ecological perspective (i.e., larger connected ecosystems or river catchments by hydrological or ecological boundaries), it can be useful for designing sustainable and integrative management at bioregion scales at which ecosystem functions are interconnected.

Moreover, it is also necessary to analyze the spatial evolution and pattern of EF using a high-resolution dataset and geographic information system. Such analysis should provide profound implications of the spatial distribution of ecological security and optimize the coordination of urban spaces (Lu et al. 2019). Kuzyk (2012) argued that questions regarding local sustainability could be addressed at an increasingly local level as EF data become finer. However, studies developing such an EF dataset at a high resolution are limited. Given the significant effect of spatial dimensions on the sustainability assessment process and territorial management policies (Barrahmoune et al. 2019) and the aspiration to achieve sustainability through multilevel environmental governance (Newig and Fritsch 2009), breaking the limitations of existing studies on the spatial flexibility of the EF is worthwhile. Thus, in this paper, we develop a novel method for downscaling EF and BC in high spatial resolutions. The appropriate approach will be reviewed in the next section.

Review of methodologies for estimating local EF

Two approaches have been applied to construct EF datasets at scales below the national scale (GFN 2009). The early "bottom-up" (component) approach calculated the EF of all individual products consumed by the local population and summed them. Its analysis was detailed and flexible, but measuring the exact footprint intensity of all activities and products was challenging (GFN 2009). Many studies have applied the bottom–up approach, such as Barthelmie et al. (2008), who applied it for a town in Canada, focusing on carbon footprint, and Luo et al. (2018) who applied it to 18 provinces in Midwestern China, and Yokawa et al. (2008).

Later, a "top-down" (compound) approach was applied. This approach first calculates the EF data at the national level in the National Footprint Accounts (NFA) and then derives subnational footprints based on local populations (GFN 2009). The top–down approach can ensure comparability with other countries or regions. Nevertheless, it can be less responsive to regional policy shifts if the scaling data do not reflect specific local conditions (Chapman et al. 2017; Świąder et al. 2020). Examples of existing studies that have applied the top–down approach are Cano-Orellana and Delgado-Cabeza (2015, for 771 municipalities in the Andalusian region, Spain), Suzuki and Tanabe (2016, for 47 prefectures in Japan), Galli et al. (2020, for six cities in Portugal), and Tsuchiya et al. (2021, for 47 prefectures in Japan). These studies commonly applied the downscaling of national EF data using the consumption land-use matrix (CLUM) provided by the GFN and considering subnational and local consumption characteristics.

To balance the advantages and disadvantages of the existing approaches for EF derivation, some studies have proposed a hybrid approach integrating the bottom–up and top–down approaches. Kuzyk (2012) analyzed the EF of housing components for residential postal code areas in the city of Calgary based on the initial EF value derived from the national data and the variation in EF estimated using the bottom–up approach. Furthermore, Świąder et al. (2020) estimated the total EF for the city of Wrocław in Poland by summing the carbon footprint using the bottom–up approach, and the remaining EF components were determined using the top–down approach.

We selected the top–down approach to establish a high-resolution dataset of EF for two reasons. First, only the top–down approach is recognized as a "standards-compliant" approach by the Ecological Footprint Standards 2009 (GFN 2009). The top–down approach makes EF data

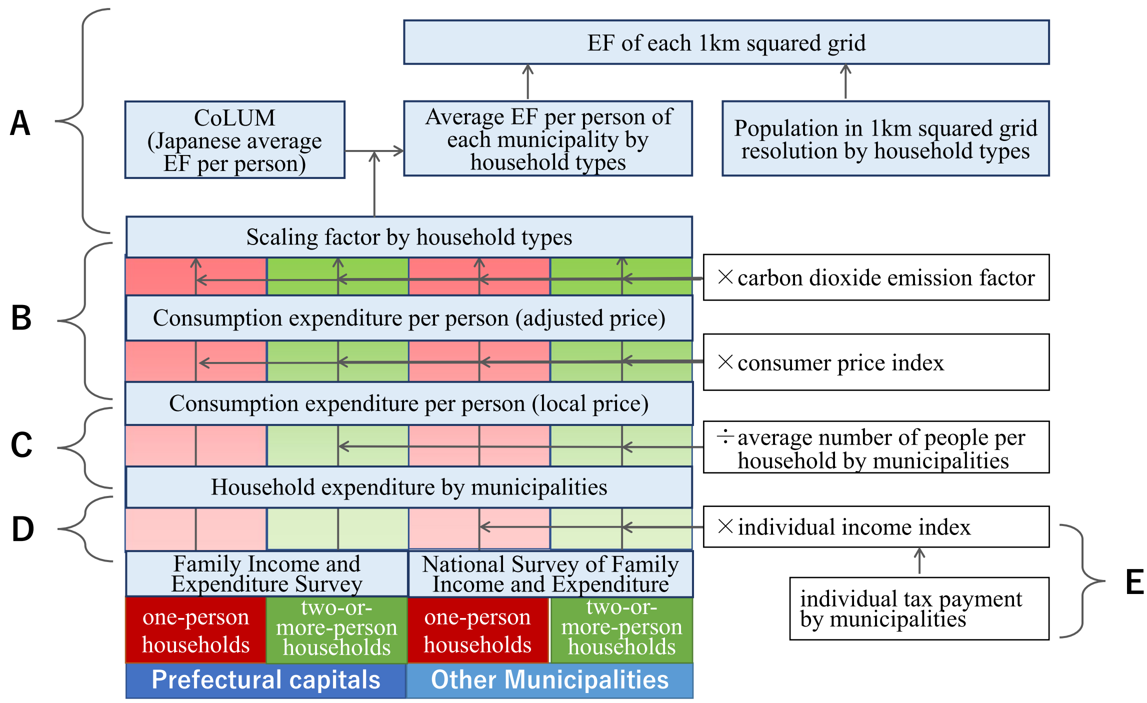

Fig. 1 Flowchart showing the method for downscaling the national-level EF to a 1-km grid level

comparable as a "common language" (Wackernagel et al. 2006) for discussing environmental impacts of human activities in different areas. Additionally, it makes hidden and externalized impacts apparent and can generate global thinking (Klinsky et al. 2010; Kuzyk 2012).

Second, data are available for the top–down approach. To flexibly enable EF analysis at any scale, a grid-based high-resolution dataset must be established for not only a few selected areas and extensive spaces. Only top–down estimation can be adopted because of the difficulty in obtaining the detailed data required to specify the absolute amount of resource consumption in each grid. Although the downscaled data using the top–down approach are less responsive in reflecting regional policies (Świąder et al. 2020), they can be used to flexibly explore the appropriate spatial boundaries where natural resources can be circulated.

Objective of this study

In this study, we propose a top–down-based method for downscaling the EF indicators in high resolution for spatially flexible EF analysis. We seek to establish an EF dataset at a 1-km resolution for all of Japan based on the national CLUM provided by the GFN. A detail of the method is described in the following section, and the balance analysis between EF and BC and their spatial distribution is shown by the established data at a 1-km resolution (Sect. "Results"). This study should provide a functional and practical approach for other countries to realize a spatially flexible analysis of environmental burdens.

Materials and methods

The GFN has calculated the EF and BC for each land type, such as cropland, grazing land, forestland, fishing grounds, and built-up land (Lin et al. 2018). In addition, carbon footprint has been established as a category of EF, different from BC, which mainly accounts for carbon uptake capacity as a subcategory of forest BC (Borucke et al. 2013). EF and BC are expressed in global hectares (gha). A gha is a globally comparable and standardized accounting unit that expresses biologically productive hectares with the world's average biological productivity for a given year (Wackernagel and Rees 1996). Using the GFN classifications, we estimated the EF and BC according to the same land typology and unit (i.e., gha) for each 1-km grid in Japan.

Estimation of EF at 1-km grid resolution

The proposed method in this study is summarized by multiplying the population at a 1-km grid resolution by the scaled EF per capita for municipalities based on consumption expenditure and income (Fig. 1). Using multiregional input–output (MRIO) assessments, GFN divided the national EF into consumption categories that induced EF

Table 1 Data sources for downscaling EF and BC in Japan

Data	Data year	Description	Data provider
CoLUM	2011	COICOP Land-Use Matrix (CoLUM)	GFN
Population	2010	Population in 1-km squared grid by number of people per household	Grid Square Statistics of 2010 Population Census, SBJ
Household expenditure	2009, 2010	Yearly average of monthly receipts and disbursements per household by city group, district, and city with prefectural government (two-or-more-person households)	Family Income and Expenditure Survey, SBJ
	2009	Yearly average of monthly receipts and disbursements per household (one-person households)	
	2009	Monthly receipts and disbursements per household by area (two-or-more-person households)	National Survey of Family Income and Expenditure, SBJ
		Monthly receipts and disbursements per household by sex and area (one-person households)	
Consumer price index	2007	Subgroup Index for Selected Areas (City Groups, Districts, Major Metropolitan Areas, and Cities with Prefectural Governments)	Consumer Price Index, SBJ
Carbon dioxide emission factor	2010	Actual emission factor for each electric utility in FY 2010	Ministry of Environment: MOE, Japan
Number of people per household, number of household	2010	Households, household members and members per household, by type of household, type of institutional household and size of household for Japan, prefectures, shi, machi, mura, and municipalities in 2000	2010 Population Census, SBJ
Amount of individual tax payment	2010	Total amount of tax payment and the number of individual tax payers (taxation on per capita basis and income basis)	Survey of Municipal Taxation Status, MIC
Land-use map	2009	Land-use subdivision mesh data in 100 m squared grid	Digital National Land Information, MLIT

(GFN, official homepage). The divided dataset is provided as a CLUM in the form of EF per capita (gha/person). In this study, we used the Japan CoLUM (COICOP Land Use Matrix) version 2011 based on the NFA 2017 edition as the primary dataset (GFN 2017a). The CoLUM is a dataset very similar to CLUM; it follows The Classification of Individual Consumption According to Purpose (COICOP; United Nations 2018) and comprises three dimensions: the short-lived consumption directly paid for by households (divided into 43 consumption categories; Appendix 1), short-lived consumption directly paid for by the government, and long-lasting consumption also called gross fixed capital formation (houses, roads, and machines). The calculation procedure in Fig. 1 was driven by the dataset listed in Table 1 regarding World Wide Fund for Nature (WWF) Japan (2016), Galli et al. (2020), and Tsuchiya et al. (2021), who utilized the CoLUM to conduct EF downscaling following the top–down approach.

The primary CoLUM dataset represents the average EF per capita of Japanese residents. To reflect the regional differences in consumption level, scaling factors (SFs) were created for all 1741 municipalities (B–D of Fig. 1). They were multiplied using the Japanese EF average to calculate the scaled EF (gha/person) (A in Fig. 1). By multiplying the scaled EF using the population of each grid (Statistics Bureau of Japan: SBJ 2012), the total EF (gha) of each grid induced by the residents' consumption was calculated (A in Fig. 1). The EF calculation was conducted for each land type for 383,389 1-km square grids covering the entire land area of Japan, as shown in Eq. (1)

$$EF_{i,j,k} = \sum_{l=1}^{2} \left(P_{i,l} * \sum_{m=1}^{45} \left(ef_{j,m} * SF_{k,l,m} \right) \right). \quad (1)$$

Here, $EF_{i,j,k}$ is the EF (gha) of land type j (1–6, including land carbon uptake) at grid i (1–383,389), belonging to municipality k (1–1741, for each city, town, village, and special ward). $P_{i,l}$ is the population of one household type l ($l=1$ [one-person household] or 2 [two-or-more-person households]) at grid i. $ef_{j,m}$ is the national average value of

EF per capita (gha/person) of land type j caused by the consumption category m (1–46). Finally, $SF_{k,l,m}$ is the scaling factor of municipality k for each household type l and consumption category k.

The SFs for the consumption categories of short-lived consumption directly paid for by households ($m = 1$–43) were calculated using Eqs. (2) and (3) (B in Fig. 1)

$$SF_{k,l,m} = \left(ce_{k,l,m}/CPI_{k,m}\right)/ce_{\text{Japan,ave},m} \ldots (m \neq 11, 44, 45), \tag{2}$$

$$SF_{k,l,m} = \{(ce_{k,l,m}/CPI_{k,m})/ce_{\text{Japan,ave},m}\} * (CEF_k/CEF_{ave}) \ldots (m = 11), \tag{3}$$

$$SF_{k,l,m} = 1 \ldots (m = 44, 45). \tag{4}$$

Here, $ce_{k,l,m}$ and $ce_{\text{Japan,ave},m}$ [JPY/person] represent per capita consumption expenditure in municipality k of household type l and the national average value of per capita consumption expenditure (including both household types) for consumption category m. $CPI_{k,m}$ is the consumer price index of consumption category m in municipality k (SBJ 2008). $CPI_{k,m}$ was multiplied to adjust the price differences between municipalities.

The category of "electricity, gas, and other fuels" was designated using $m = 11$. The EF induced by electricity use differs depending on the energy source used for power generation. Ten major electric power companies monopolized the electricity supply to assigned prefectures in Japan. Even after the liberalization of the electricity supply in 2016, most households still buy electricity from those ten companies (Electricity and Gas Market Surveillance Commission 2021). Thus, the carbon dioxide emission factor, CEF_k [t-CO_2/MWh] (MOE 2012), was based on one company that supplies electricity to the prefecture where municipality k belongs[1] among the ten electric power companies. The ratio of CEF_k to the national average value (CEF_{ave} [t-CO_2/MWh]) allowed the EF of energy consumption to be localized by reflecting local power supply characteristics.

The SFs of short-lived consumption directly paid for by the government ($m = 44$) and long-lasting consumption ($m = 45$) were set as 1 for all municipalities and all land types. This is due to the difficulty of evaluating regional differences in the environmental burden induced by governmental consumption and gross fixed capital formation.

In Japan, two statistical surveys have been conducted on consumption expenditures using consumption categories: the Family Income and Expenditure Survey (SBJ 2010) and the National Survey of Family Income and Expenditure (SBJ 2009), which were used to calculate $ce_{k,l,m}$. The Family Income and Expenditure Survey aims to grasp the actual circumstances of household income and expenditures. Moreover, the provided data are aggregated for prefectural capital and regional blocks. The National Survey of Family Income and Expenditure is a comprehensive survey of household income and expenditures, durable consumer goods, and household assets, of which the prefectural average data are published. Both surveys summarize the household expenditure data for one-person and two-or-more-person households; in the Family Income and Expenditure Survey, the household expenditures of one-person households are available only as the national average value. Thus, the $ce_{k,l,m}$ of prefectural capitals was estimated using the Family Income and Expenditure Survey, and those of the other municipalities were calculated mainly using the National Survey of Family Income and Expenditure. Appendices 1 and 2 show the correspondence of the consumption categories between the CoLUM, household expenditure data, and consumption price index data.

Consumption expenditure estimation for prefectural capital

The per capita consumption expenditure of the prefectural capitals ($ce_{\acute{k},l,m}$) was estimated using Eqs. (5) and (6) (C in Fig. 1)

$$ce_{k',l=1,m} = he_{k',l=2,m} * he_{Japan,l=1,m}/he_{\text{Japan},l=2,m}, \tag{5}$$

$$ce_{k',l=2,m} = he_{k',l=2,m}/NP_{k',l=2}. \tag{6}$$

Here, $he_{k',l,m}$ and $he_{\text{Japan},l,m}$ [JPY/household] represent a household expenditure of prefectural capital $\acute{k}$ and the national average value for consumption category m of household type l; the data were sourced and established based on the Family Income and Expenditure Survey (SBJ 2010). $NP_{k',l=2}$ [persons/household] is the average number of people per household in households with two or more persons in prefectural capital $\acute{k}$; the data were obtained from the 2010 Population Census (SBJ 2011).

Consumption expenditure estimation for other municipalities

Since the household expenditure data for municipalities were available only for prefectural capitals, the per capita consumption expenditure of other municipalities was estimated from the prefectural average value for household

[1] Japan's administrative division structure comprises 47 prefectures; each prefecture is divided into municipalities. Several neighboring prefectures are grouped and called regional blocks by geographical condition, and eight regional blocks cover the whole of Japan.

Table 2 Correspondence of land-use types and utilized factors

Land-use type by NFA	Land-use type by MLIT	Yield factor	Equivalence factor
Cropland	Paddy field, other agricultural land	1.97	2.53
Grazing land	Uncultivated land, golf course	2.16	0.46
Forest land	Forest	1.37	1.29
Marine fishing grounds	Sea area, beach	0.78	0.37
Inland fishing grounds	Rivers, lakes, and marshes	1.00	0.37
Infrastructure	Built-up area, road, railroad, others	1.97	2.53

expenditures. Furthermore, the individual income index which represents the income level for each municipality was used for the estimation following Eqs. (7)–(9) (C and D of Fig. 1). Given the observed positive correlation between disposable income level and consumption expenditure (Ministry of Health, Labor, and Welfare: MHLW 2015), the consumption expenditure level was assumed to be linked to the individual income level

$$ce_{k\neq k',n,l=1,m} = he'_{n,l=1,m} * II_k, \tag{7}$$

$$ce_{k\neq k',n,l=2,m} = \left(he'_{n,l=2,m}/NP_{k,l=2}\right) * II_k, \tag{8}$$

$$he'_{n,l,m} = \left(he_{n,l,m} * NH_{n,l} - he_{k',n,l,m} * NH_{k',n,l}\right)/\left(NH_n - NH_{k',n,l}\right). \tag{9}$$

Here, $h'e_{n,l,m}$ [JPY/household] represents a prefectural average of household expenditures, excluding the prefectural capital for consumption category m of household type l. II_k is the individual income index of municipality k showing regional differences in the income level. $Np_{k,l=2}$ [persons/household] is the average number of people per household of households with two or more persons in municipality k. $h'e_{n,l,m}$ was estimated from $he_{n,l,m}$ and $he_{k',n,l,m}$ [JPY/household], representing an average value of household expenditures of prefecture n and household expenditure of prefectural capital k' belonging to prefecture n, as cited from the Family Income and Expenditure Survey (SBJ 2010) and the National Survey of Family Income and Expenditure (SBJ 2009). $NH_{n,l}$ and $NH_{k',n,l}$ [households] are the number of households of household type l in prefecture n and prefectural capital k' belonging to prefecture n. The data were obtained from the 2010 Population Census (SBJ 2011).

To estimate the individual income index of each municipality, municipal tax payment per person was used as the approximate variable reflecting the difference between individual income levels, because Japan's inhabitant tax is levied according to the income amount. Thus, the individual income index II_k was estimated using the average number of municipal tax payments per person in each municipality, as shown in Eqs. (10)–(12) (E in Fig. 1)

$$II_{k,n} = tp_{k,n}/tp_n, \tag{10}$$

$$tp_{k,n} = TP_{k,n}/NTP_{k,n}, \tag{11}$$

$$tp_{n=\dot{n}} = \sum_k tp_{k,n=\dot{n}}/NM_{n=\dot{n}} \ldots (\dot{n} = 1 \sim 47). \tag{12}$$

Here, tp_n and $tp_{k,n}$ [JPY/person], respectively, show the average number of individual tax payments of prefecture n and municipality k belonging to prefecture n. $TP_{k,n}$ [JPY] is the total individual tax payment in municipality k, and $NTP_{k,n}$ [persons] is the number of individual taxpayers of municipality k. These data were cited from the Survey of Municipal Taxation Status (Ministry of Internal Affairs and Communications, Japan 2010). The utilized data included taxation based on per capita and income. NM_n [municipalities] is the number of municipalities belonging to prefecture n, and it was utilized to estimate the average number of individual tax payments in prefecture n.

Estimation of BC at a 1-km grid resolution

The BC in a 1-km grid resolution was estimated from the land-cover maps by referring to the existing research that calculated the local BC (Lu et al. 2019; Galli et al. 2020). The utilized dataset was Land Use Subdivision Mesh data provided by the Ministry of Land, Infrastructure, Transport, and Tourism (MLIT 2009). In the data, one of 12 types of land use was assigned for every 100 m square grid, and all grids covering territorial areas of Japan were targeted. The areas of each type of land use were aggregated into 1-km square grids. Twelve types of land use were merged into six land types whose BC were summarized by the GFN, as shown in Table 2. The BC of the six land types in the 1-km resolution was estimated using Eq. (13)

$$BC_{i,j} = A_{i,j} * JYF_j * EQF_j. \tag{13}$$

Here, $BC_{i,j}$ is the BC [gha] of land type j at grid i. JYF_j [wha (world average ha) /ha] is the Japanese national yield factor of land type j, representing the local productivity of the land. EQF_j [gha/wha] is the equivalence factor that is a productivity-based scaling factor for converting the areas of different land types into the standard gha unit. JYF_j and EQF_j were multiplied using the area of each land type j at grid i ($A_{i,j}$ [ha]). The utilized value of the national yield and equivalence factors in Table 2 were cited from the NFA 2017 edition provided by GFN (2017b).

Analysis using the established dataset

Statistical analysis of scaled EF per capita

The mean, variance, median, and quartile were calculated using consumption categories and household types to grasp the municipalities' statistical distribution of EF per capita. The results are shown by a scatter plot and a boxplot. For each consumption category, the difference in the mean value of the EF per capita between household types was tested using a paired t test. For each household type, the differences in the means and variances between consumption categories were tested using multiple comparison procedures using the Steel–Dwass method and F test.

The distribution of total EF per capita of municipalities was projected on the map, and the difference of the mean and deviation between household types was tested using a t test and an F test. To explore the relationship between regional characteristics and EF per capita, the differences in the statistical distribution of EF per capita were evaluated for three categories of municipalities (i.e., metropolitans, mid-sized municipalities, and small-sized municipalities) as determined by population size. Referring to the categories by MLIT (2017) and the Family Income and Expenditure Survey, municipalities holding populations of over 200,000 and special wards in Tokyo were included as metropolitans. Municipalities holding populations of more than 50,000 and less than 200,000 were categorized as mid-sized municipalities. The difference in the mean EF per capita between municipal categories was tested using a t test for both household types.

Analysis of the environmental load excess ratio

Given the advantage that the EF and BC indexes can measure ecological overshoot status, the environmental load excess ratio (r) was calculated at a 1-km grid resolution using Eq. (14) (Ujihara et al. 2008)

$$r_{i,j} = EF_{i,j}/BC_{i,j}. \quad (14)$$

Here, $r_{i,j}$ is the environmental load excess ratio of land type j at grid i. The grid with $r=0$ indicates a nonresidential area, whereas $0<r\leq 1$ indicates that the grid has an ecological surplus with more BC than EF. Grids with $1<r$ fall into an ecological overshoot with an ecological deficit.

Besides grid resolution, r was calculated for the municipality and prefecture levels to highlight the change in the balance between EF and BC at different spatial boundaries. The municipal r value was derived using Eq. (15), and the same aggregating calculation was conducted for the prefectures

$$r_{k=\dot{k},j} = \sum_i EF_{i,j,k=\dot{k}} / \sum_i BC_{i,j,k=\dot{k}} \left(\dot{k} = 1 \sim 1,741\right). \quad (15)$$

Finally, the balance distribution between the EF and BC was analyzed by calculating the proportion of grids (i.e., the area ratio) according to the r value for each prefecture.

Results

Distribution of per capita EF

Figure 2 shows the statistical distribution of EF per capita after the scaling procedure for municipalities by consumption category and household type.

The mean values of the EF per capita were significantly greater for one-person households than for two-or more-person households for all consumption categories (significance level: 0.1%). For both household types, the mean EF values of "food and nonalcoholic beverages," "housing, water, electricity, gas, and other fuels," and "transportation" were significantly higher than those of other consumption categories (significance level: 0.1% significant differences were detected between all categories except between "furnishings, household equipment, and routine household maintenance" and "communication" for both household types and between "housing, water, electricity, gas, and other fuels" and "transportation" for two-or-more-person households). Furthermore, the standard deviations of "housing, water, electricity, gas, and other fuels" and "transportation" were greater than those of "food and nonalcoholic beverages," and the differences in variances were significant (significance level: 0.1%). The possible reason is that consumption in those two categories vastly differs by region because of the differences in climate classifications and urbanization levels.

Figure 3 shows the spatial distribution of the EF per capita (total value of all consumption categories) of each municipality according to household types. Table 3 summarizes the statistical distribution, including the analysis by municipal category. The mean of the total EF per capita of one-person households was significantly higher than that of two- or more-person households (significance level: 0.1%). Furthermore, total EF per capita was observed to have almost a twofold difference in maximum

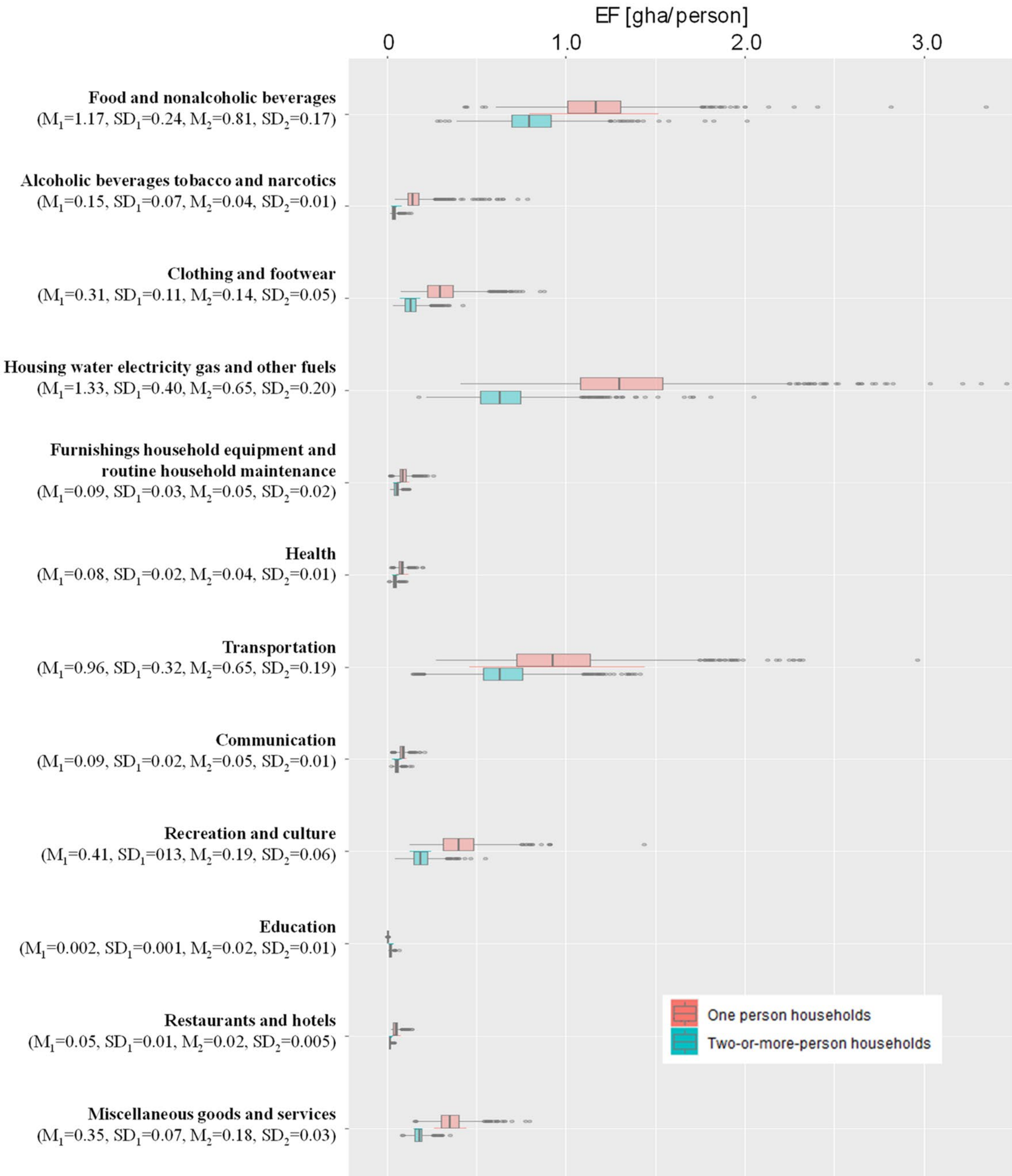

Fig. 2 Box plots of EF per capita for 1741 municipalities using the consumption category (M_1: mean value of one-person households, SD_1: standard deviation of one-person households, M_2: mean value of two- or more-person households, SD_2: standard deviation of two-or-more-person households, vertical lines in the middle of boxplot: the median of the dataset, left and right edges of the boxes: interquartile ranges, the far end of the horizontal lines (whiskers): the minimum and maximum values)

between municipalities. The Kyusyu and Shikoku regions (yellow circles in Fig. 3) seemed to have smaller differences between municipalities than others. Nevertheless, many prefectures were observed to have large differences according to the municipality, even within the same prefecture.

Small municipalities showed significantly lower mean EF per capita than larger ones (significance level: 0.1%). This

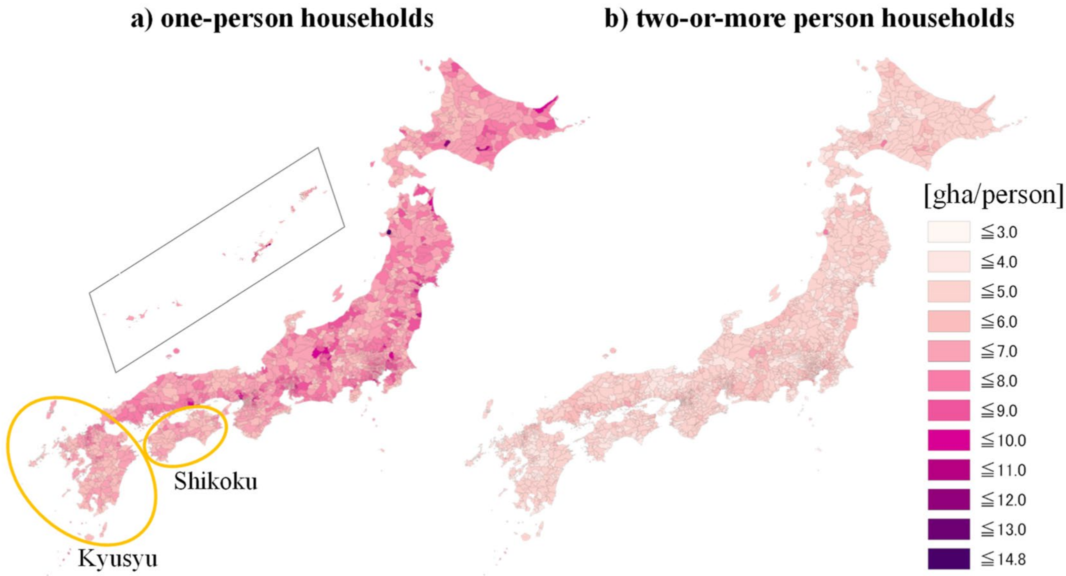

Fig. 3 Total EF per capita by municipality

Table 3 Statistical distribution of total EF per capita of municipalities

	One-person households			Two-or-more-person households		
Mean [gha/person]	6.58			4.42		
Standard deviation	1.03			0.60		
	Metropolitans	Mid-sized municipalities	Small Municipalities	Metropolitans	Mid-sized municipalities	Small municipalities
The number of municipalities	132	412	1197	(same as left)		
Mean [gha/person]	7.11	7.15	6.32	4.81	4.75	4.26
Standard Deviation	0.83	0.96	0.97	0.45	0.57	0.55
P value (tested between "Metropolitans")		0.66	($p < 0.0001$)		0.23	($p < 0.0001$)
P value (tested between "Mid-sized municipalities")			($p < 0.0001$)			($p < 0.0001$)

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

result corresponds with the previous studies which observed that more urbanized areas had increased EF per capita (Rashid et al. 2018; Tsuchiya et al. 2021). Over 80% of the Japanese population lives in municipalities categorized as metropolitan or mid-sized municipalities (SBJ 2016); thus, an increased EF per capita in urban areas significantly increases the EF for all of Japan.

Distribution of EF, BC, and environmental load excess ratio

Figure 4 shows the total spatial distribution of BC, EF, and *r* at a 1-km grid resolution.

High BC values were widely distributed in plain areas. The values obtained by multiplying the yield and equivalence factors were highest in croplands and built-up lands (Table 2), which are located in plain areas. In the EF map, the gray area indicates the nonresidential area. It accounts for 53% of all grids covering terrestrial areas in Japan. The EF per 1-km-square grid is distributed following the population distribution; the EF value is higher when closer to the center of the metropolitan area. Figure 4c shows that the distribution of *r* grids with bluish colors has an ecological surplus, and those with reddish colors show areas of ecological deficit. Furthermore, areas under ecological overshoot were observed widely in residential areas, except for the fringes

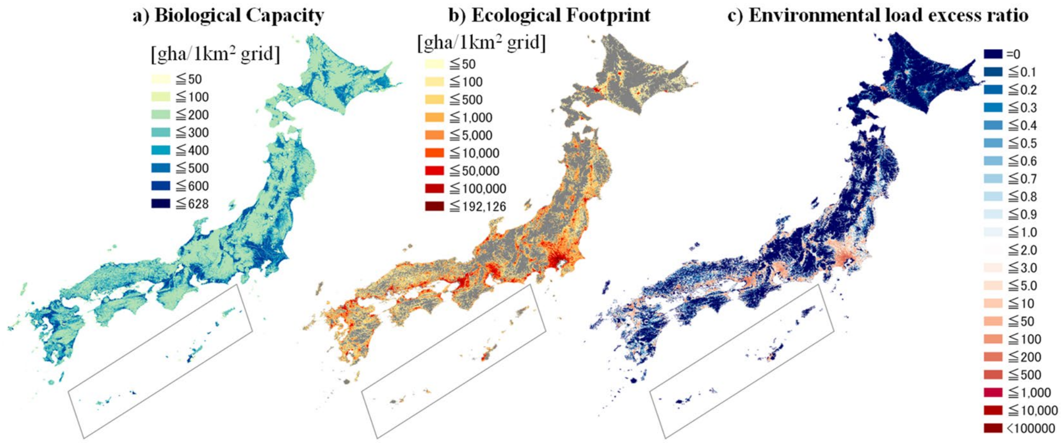

Fig. 4 Distribution of BC (total of all land types), EF (total of all consumption categories and land types, including carbon footprint), and *r* at a 1-km grid resolution

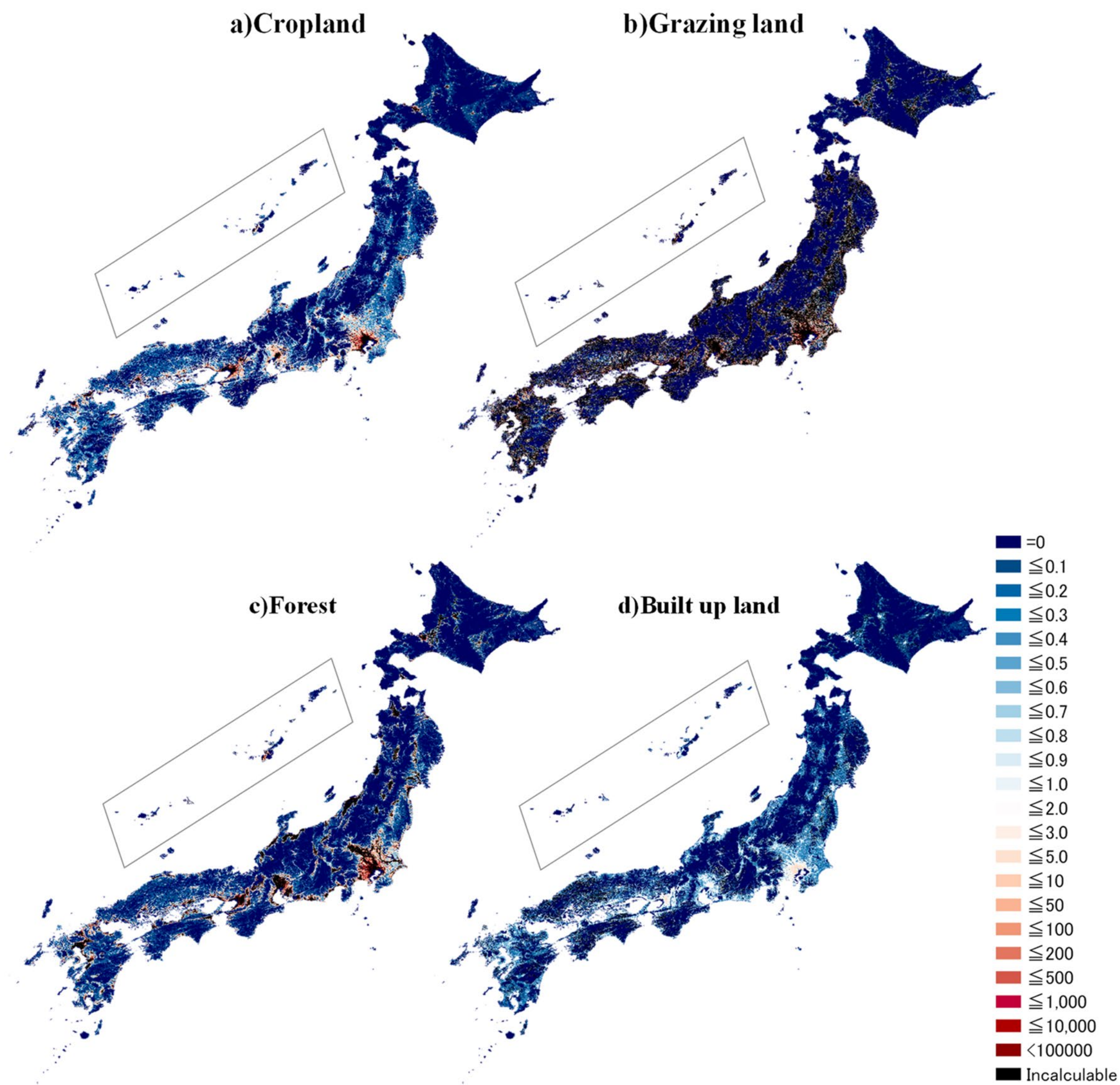

Fig. 5 Distribution of *r* by land type at a 1-km grid resolution

Table 4 The ratio of grids according to the r value (denominator: the number of residential grids)

Area ratio [%]	Total	Cropland	Grazing land	Forest land	Built-up land
$0<r\leq 1$	43.0	68.3	15.6	61.0	71.5
$1<r\leq 10$	40.9	17.3	13.2	14.6	11.2
$10<r\leq 100$	14.8	5.0	7.6	6.9	0.0
$r>100$	1.3	9.5	63.6	17.5	17.2

and regions with high agricultural production. Grids with $r>1$ accounted for 27% of the total number of grids.

Figure 5 shows the distribution of r by land type. Table 4 summarizes the ratio of grids according to the r value (the denominator is the number of residential grids). It is noted that the r value of fishing grounds is not shown here, because the BC of marine fishing grounds was significantly underestimated using data focusing on the terrestrial area of Japan. This point will be argued further in the section "Discussion". The black grids in Fig. 5 indicate the areas where EF is greater than 0, but BC does not exist; thus, r is not calculable.

The spatial distribution of r differed between land types (Fig. 5, Table 4). The r value of cropland increased as the area approached the urban centers, but over half of the residential grids did not overshoot. This might be because cropland can exist near urban areas, such as suburban areas. For grazing lands, the black grids (EF existing without BC) were widely distributed in residential areas (the area ratio with $r<1$ was 15.6%). Although areas holding grazing lands were limited, people consumed goods from grazing land, such as meat, regardless of where they lived. For forestlands, the national EF total was lower than the total BC (WWF Japan 2009). However, large parts of the urbanized area fell into an ecological deficit. This is because forests do not tend to encroach on residential areas, unlike croplands. The EF and BC locations seemed to be the most matched for the built-up land. Black grids can also be observed in other areas, such as mountainous areas. This might result from the land-use map at 100 m resolution, which may overlook scattered small residential areas in mountainous areas.

Analysis of the environmental load excess ratio at municipal and prefectural boundaries

Figure 6 shows the distribution of r calculations for municipalities and prefectures. The upper maps show r for the total of all land types, including carbon footprint, which is aggregated from Fig. 4c, and the lower maps are examples of croplands, which can be compared with Fig. 5a.

For all land types, 22.5% of municipalities had $r<1$, located mainly in Hokkaido (indicated in Fig. 6) and partially in the inland areas of the Japanese archipelago. For croplands, 51.4% of municipalities had $r<1$, widely distributed throughout Japan, excluding the areas around metropolitan areas. In the municipalities at the center of metropolitan areas, such as Tokyo and Osaka, r was significantly greater than 1. These results enabled us to specify the municipalities with nationwide surplus EF and BC.

However, when r was aggregated for the prefectures, all the prefectures were under ecological deficits ($r>1$) for all the land types. This was because all prefectures included municipalities with a population concentration and r that was significantly greater than 1. This result showed almost no room for exchanging surplus BC beyond prefectures when all land types and carbon footprint were summarized. Moreover, it confirms that the problem is the unbalanced environmental load and its absolute volume. Nevertheless, the difference in r between the prefectures can be grasped by this result. For croplands, the prefectures with $r<1$ could be found in Hokkaido, the Tohoku region, and some parts of the Sea of Japan side of western Japan, which differed significantly from that of Tokyo ($r=161$).

This result can be used to design the spatial boundary or interregional relationship in which the balance between EF and BC can be achieved from a multilevel perspective. For example, many municipalities near the Tokyo metropolitan area are falling into an ecological deficit regarding croplands. Some municipalities have ecological surpluses within the Kanto region, where Tokyo belongs. However, when it is aggregated by the prefectural boundary, all prefectures of Kanto result in an ecological deficit. This reveals that the municipalities with cropland $r<1$ in the Kanto region cannot afford the municipalities of Tokyo metropolitans beyond prefectural boundary; instead, the municipalities in the Tohoku region can be candidates to support the cropland demand of metropolitans remotely, because almost all of the areas in Tohoku have ecological surplus even on a prefectural scale. Hence, multiple-scale balance analysis of EF and BC using a developed dataset enables us to design practical cooperative policies between regions from a multilayered perspective.

Figure 7 shows the area proportion according to the r value for each prefecture (the denominator is the number of grids belonging to each prefecture). There were large differences between prefectures in the distribution of areas holding ecological surplus (i.e., EF > BC) and deficits (i.e., EF < BC). Furthermore, the prefectures where the area proportion with $r>1$ was highest were the suburbs of Tokyo (Chiba and Saitama). In the central prefectures of major

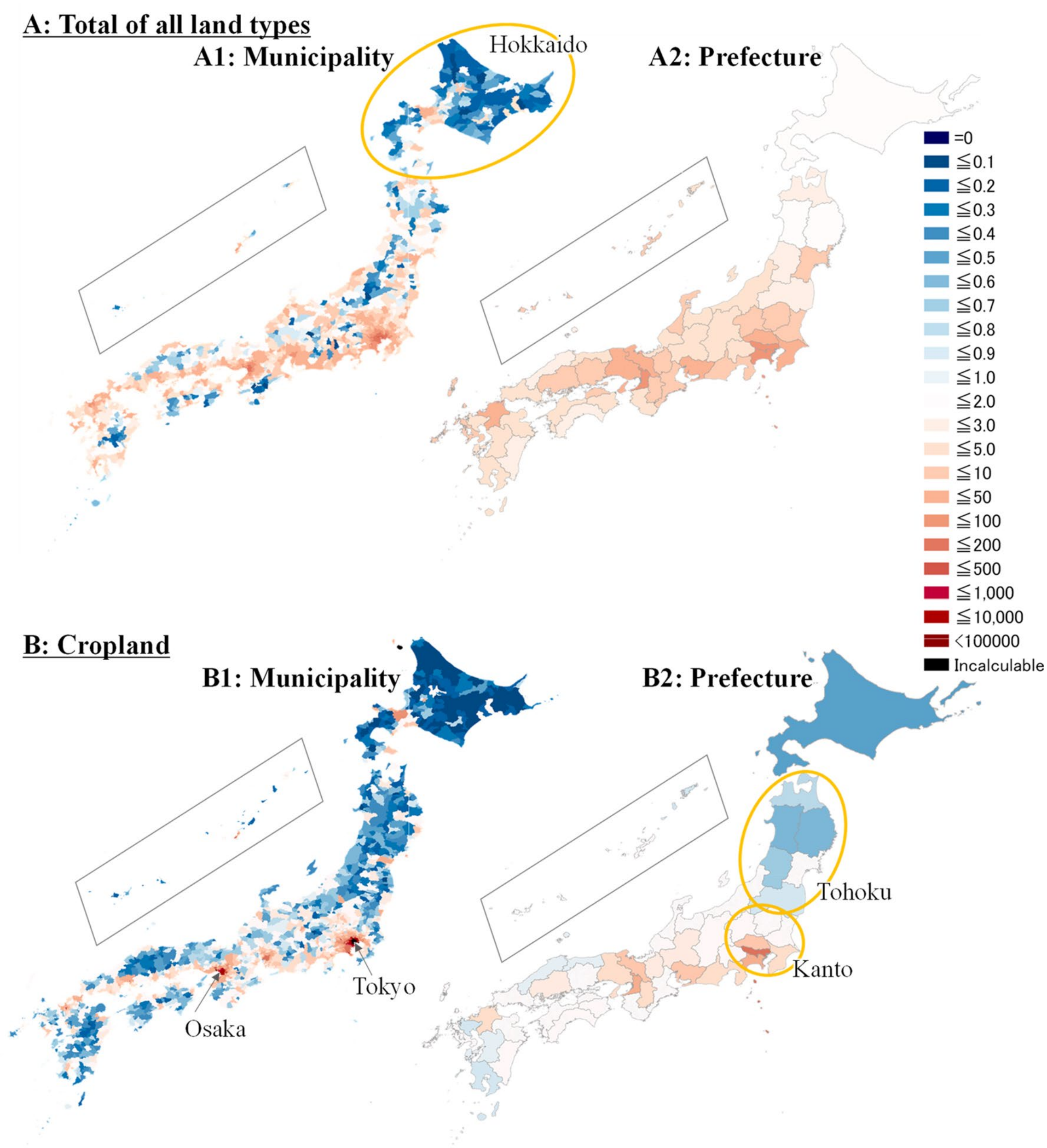

Fig. 6 Distribution of *r* at the municipal and prefectural levels [A: *r* in all land types aggregated from Fig. 4c for municipalities (A1) and prefectures (A2), B: *r* in all croplands aggregated from Fig. 5a for municipalities (B1) and prefectures (B2)]

metropolitan areas, such as Tokyo, Osaka, and Kanagawa, the area proportion with $r > 10$ was the highest.

Discussion

Significance of the method

In this study, we proposed a top–down-based method for downscaling the EF at a 1-km square resolution for the entirety of Japan. The proposed method is summarized by multiplying the population in 1-km square grids using the scaled EF per capita for municipalities based on consumption expenditures and income level. This downscaling method has two advantages. First, the required data are easily available compared with conventional research attempting to localize the EF for municipalities or communities (e.g., Kuzyk 2012; Cano-Orellana and Delgado-Cabeza 2015). Furthermore, the applicability of this method can be expanded to other countries and regions. Even if the actual

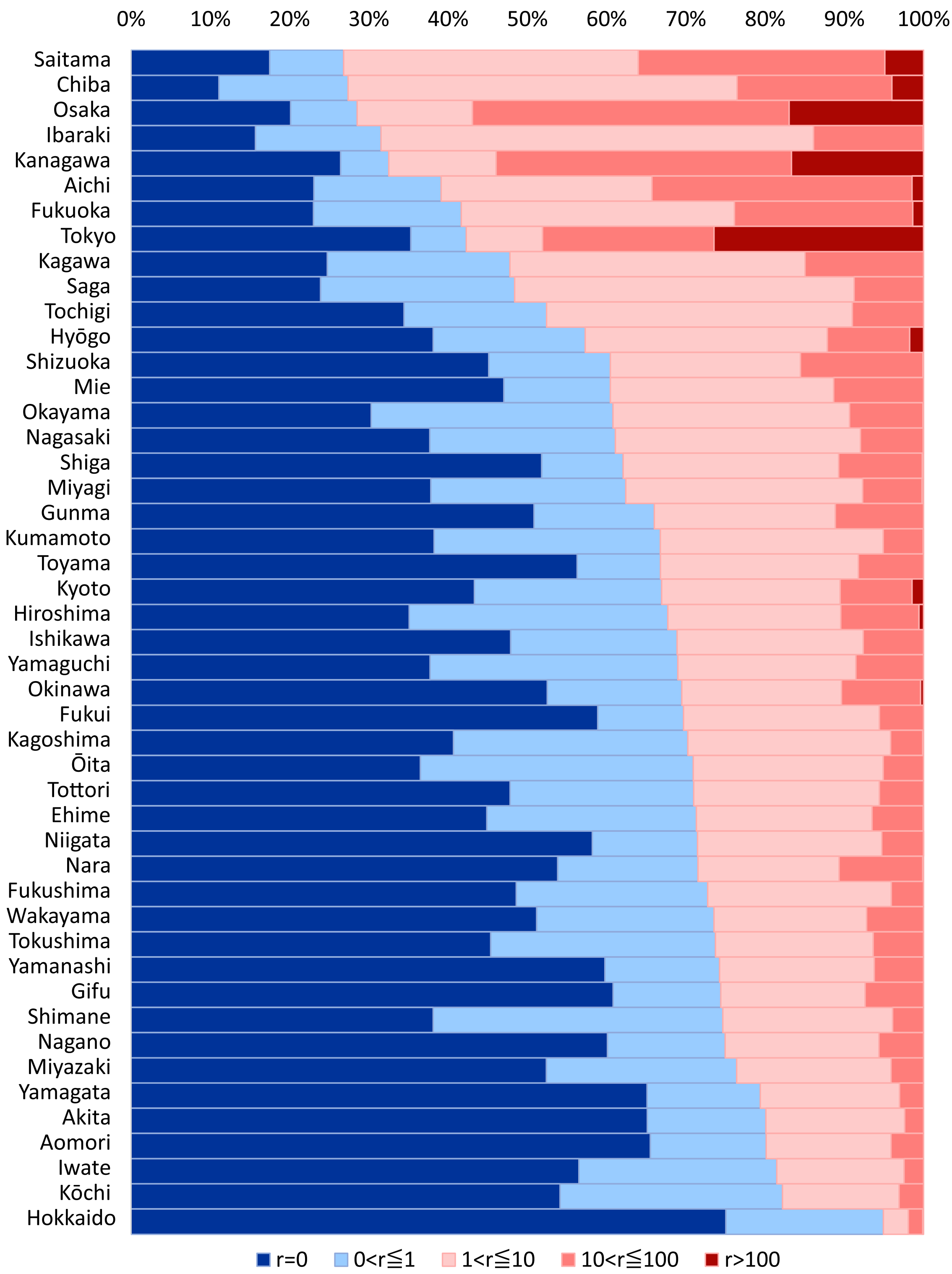

Fig. 7 Area proportion according to r value (sorted according to the proportion with $r < 1$)

consumption data of all municipalities are unavailable, the estimation can be conducted using proxy indicators. In the Japanese case, local consumption expenditure was estimated using the individual income index obtained from the tax payment data of the municipalities. However, as Galli et al. (2020) used an indicator of per capita purchasing power in each municipality, the available approximate variables can be selected when this method is applied to other countries.

Although nationwide high-resolution population data might not be available in all countries, it can be estimated from open sources, such as high-resolution land-cover maps (Silva et al. 2013) or nighttime light datasets (Yu et al. 2018).

Second, despite the simplicity of this method, it reflects the findings of Baabou et al. (2017) and Tsuchiya et al. (2021) that areas (prefectures or cities) with higher average incomes had a higher EF per capita. Given the causal relationship, it is rational to estimate the consumption level in each municipality by breaking down the prefectural consumption expenditure data based on the municipal income level. However, local lifestyles and industrial characteristics vary significantly among municipalities within the same prefecture. Thus, the proposed method for estimating the EF per capita for each municipality is an excellent approach that reflects these differences.

This method is especially recommended for application in Asian countries, which, similar to Japan, suffer from issues of disjuncture between the urban areas' overconsumption of natural resources and rural areas' richness in ecosystems but delayed development (McGee 2008). The approach to reassessing the spatial and integral interdependent relationships between urban and rural areas based on scientific evidence is being expanded from Japan to these countries (IGES: Institute for Global Environmental Strategies 2021). Following this movement, the proposed method's high-resolution EF and BC datasets can contribute to the spatially flexible balance analysis between environmental burdens and capacities, including urban, peri-urban, and rural areas in Asian countries.

Two areas not addressed in the present study require further research. They should be considered for methodological advancement: integrating the BC of marine fishing grounds and refinement of areas covered by each land-use type within a 1-km square grid. Although defining where to allocate the BC of marine fishing grounds is difficult, the idea is to expand the target area to grids covering an exclusive economic zone and allocate the BC to the municipality or prefecture with the closest coastline to each grid (Hori et al. 2016). Accurate land-use aggregation can be realized using vegetation inventories as the primary data (Shoyama 2021).

Utility of the developed dataset

The developed dataset of EF and BC at a 1-km square resolution enables a balanced analysis of the environmental burdens at any spatial scale. This is a significant contribution, given that the localized EF data established for Japan so far was just for prefectures (Suzuki and Tanabe 2016; Chin et al. 2016; WWF Japan 2019). Although only one example of balance analyses in multiple municipal and prefectural scales was shown in this paper (the section "Analysis of the environmental load excess ratio at municipal and prefectural boundaries"), the different distribution of *r* by the scale of spatial boundaries could be shown quantitatively for the entirety of Japan. It could provide the foundation for the practical designing of interregional cooperative policies from a multilayered perspective. This would lead to the realization of the interregional cap and trade program of environmental burdens proposed by Ujihara et al. (2008). Furthermore, advanced spatially flexible balance analysis, not along administrative boundaries but at the river basin or community scales, is a greatly expected research expansion, demonstrating the full potential of the developed data.

A spatially flexible analysis of EF and BC is becoming essential in Japan. In the Fifth Basic Environment Plan, the Ministry of the Environment (MOE) proposed a new concept, the Circulating and Ecological Sphere (CES) (MOE 2018). The CES is a spatial–environmental system where "each region demonstrates its strengths by utilizing its unique geographic and socio-economic characteristics, thereby building a self-reliant and decentralized society where different resources are circulated within each region" (MOE 2018). CES premises on multilayered circular regions connected by the supply and demand of ecosystem services and aims to establish new rural–urban linkages that enable a minimized environmental impact (Ortiz-Moya et al. 2021). Nevertheless, no standard approach has been developed to identify the spatial scale of the CES effectively; building CES is attempted practically for various spatial scales, from community to prefectural scale (MOE 2020). To realize CES, it is essential to assess and discuss the spatial boundaries in which natural and socio-economic resources can circulate. Furthermore, the spatial scale of the CES could vary according to the types of resources (indicated as multilayered circular regions). The established high-resolution dataset in this study is ideal for exploring appropriate multilayered boundaries to create CES. Thus, the dataset should be utilized proactively at the decision-making stage for CES establishment, and it would induce contributions to realize the multilevel governance essential for sustainability (Ostrom and Janssen 2004) throughout the CES framework.

However, this dataset must be carefully utilized when discussing the appropriate spatial scale for balancing the EF and BC, because it is only a visualization of the relationship between the EF attributed to the final consumption by residents of each grid and the BC of that grid. Nakano and Wada (2007) argued that the localized EF by gha "is a hypothetical area, not an actual area." Furthermore, Barrahmoune et al. (2019) and Chapman et al. (2017) wrote about the limited aptitude of global accounting to answer regional research or policy questions. Even if the *r* value of one grid is 1, it does not mean that the grid residents have a self-sufficient way of life or that the BC of the grid is fully utilized. Moreover, it does not express the place and mode of production for each consumed good and service. Thus, this dataset must be used to assess the heterogeneity of the spatial distribution of EF and BC to present potential management actions to be taken on each geographic scale (Barrahmoune et al. 2019) and to explore comprehensive and coordinated development (Lu et al. 2019) for living in harmony with nature.

As a related argument, van den Bergh and Verbruggen (1999) demonstrated the "anti-trade bias" of the EF. The comparison between the local EF and BC implies that some form of self-sufficiency is the most desirable situation. Given this concern, it must be emphasized here that this study does not suggest a self-sufficient lifestyle within a 1-km grid. As van den Bergh and Verbruggen (1999) argued, it is necessary to recognize the positive impact of the spatial concentration of people and the advantages of regions related to endowments of environmental and ecological resources, which can be grasped from our developed EF and BC dataset. The recognition induces the design of appropriate institutions for the sustainable trade of commodities and resources between regions (van den Bergh and Verbruggen 1999). Additionally, it enables spatial matching of consumption, production, and resource use, as is the aim of CES. This dataset can be useful for showing the invisible and externalized environmental burden created by the people of each grid and the unutilized resources there.

One of the next research agendas is the spatial and flexible balance analysis of EF and BC, using the developed dataset for the actual regions that can be established as CES. The scenario analysis of future EF is also a meaningful challenge, for which this developed dataset can be integrated with projection methods, such as a system dynamics model (Wei et al. 2013), a scenario-based projection model of the future population distribution (Hori et al. 2021; Kumagai et al. 2021), determinant analyses of EF and the environmental load excess ratio (Pata 2021; Pata and Isik 2021), or a method for exploring lifestyle pathways to reduce the footprint (Koide et al. 2021). Furthermore, research expressing the EF and BC by local hectares, which reflects actual local land productivity, should be considered (Nakano and Wada 2007; Wiedmann and Lenzen 2007). For further development of the EF dataset, analysis of the EF flow throughout the supply chain across municipalities using an input–output analysis utilizing the MRIO database of all Japanese municipalities (Wakiyama et al. 2020) is a significant challenge. This enables the design of institutions for sustainable trade between regions, considering the transformation of production modes and distribution systems.

Conclusion

This study proposed a top–down-based method for downscaling EF and BC to a 1-km square resolution for a spatially flexible analysis of the balance of ecological burden. The downscaling of EF was conducted for all terrestrial areas of Japan, and local EF was estimated based on the national CoLUM of Japan by land type and consumption category. The proposed method can be summarized as to multiply the grid population by the scaled EF per capita for municipalities based on consumption expenditure and income levels. In the result of EF per capita scaling, large differences between municipalities were indicated, even within the same prefectures. The BC of each land type was estimated from the land-use map in a 100-m square resolution, the national yield factors, and equivalence factors. The balance analysis between EF and BC showed the spatial distribution of EF, BC, and the environmental load excess ratio (r). The r values significantly varied between grids, and the distribution differed depending on the land type. An example of multiscale balance analysis at municipal and prefectural scales could show the different distributions of r by the scale of spatial boundaries and enable the practical design of interregional cooperative policies from a multilayered perspective. The established high-resolution dataset can be used to flexibly analyze multilayered spatial boundaries for implementing the CES of Japan. The proposed method used relatively high availability data compared to the conventional studies. This method should be applied to other countries and regions.

Appendix 1. Forty-three consumption categories of CoLUM and the correspondence between household expenditure data and consumption price index data

	Household expenditure	CPI
1. Food and nonalcoholic beverages		
1.1 Food	3~11	5
1.2 Nonalcoholic beverages	12	15
2. Alcoholic beverages, tobacco and narcotics		
2.1 Alcoholic beverages	13	16
2.2 Tobacco	60	60
3. Clothing and footwear		
3.1 Clothing	32~37, 39	33
3.2 Footwear	38	36
4. Housing, water, electricity, gas and other fuels		
4.1 Actual rentals for housing	17/2	19
4.2 Imputed rentals for housing	17/2	19
4.3 Maintenance and repair of the dwelling	18	20

	Household expenditure	CPI
4.4 Water supply and miscellaneous dwelling services	23	25
4.5 Electricity, gas other fuels	20,21	21
Direct household consumption (Heating)	22	24
5. Household furnishings, equipment and maint		
5.1 Furniture, furnishings, carpets etc.	25/2, 27	26
5.2 Household textiles	26	28
5.3 Household appliances	25/2	27
5.4 Glassware, tableware, and household utensils	28	30
5.5 Tools and equipment for house and garden	29	31
5.6 Goods and services for household maintenance	30	32
6. Health		
Social protection		
6.1 Medical products, appliances, and equipment	41,42,43	39
6.2 Out-patient services	44/4	42
6.3 Hospital services	44/4	42
7. Transportation		
7.1 Purchase of vehicles	47/3	45
7.2 Operation of personal transport equipment	47/3	45
7.3 Transport services	46	44
7.4 Direct household consumption (transportation)	47/3	45
8. Communication		
8.1 Postal services	48/3	46
8.2 Telephone and telefax equipment	48/3	46
8.3 Telephone and telefax services	48/3	46
9. Recreation and culture		
9.1 Audio-visual, photo, and info. Processing equipment	51/2	52
9.2 Other major durables for recreation and culture	51/2	52
9.3 Other recreational equipment etc.	52	53
9.4 Recreational and cultural services	54/4	55
9.5 Newspapers, books, and stationery	53	54
9.6 Package holidays	54/4	55
10. Education		
10. Education	49	47
11. Restaurants and hotels		
11.1 Catering services	14,15	17
11.2 Accommodation services	54/4	55
12. Miscellaneous goods and services		
12.1 Personal care	57	57
12.3 Personal effects nec	58,59	56
12.4 Social protection	44/4, 54/4	42
12.5 Insurance	44/4	42
12.6 Financial services nec	–	1
12.7 Other services nec	61	61

Appendix 2. Consumption categories of household expenditure data and consumption price index data

Household expenditure			CPI		
All items		1	**All items**		1
Food		2		All items, less fresh food	2
	Cereals	3		All items, less imputed rent	3
	Fish and shellfish	4		All items, less food (less-alcoholic beverages) and energy	4
	Meat	5	**Food**		5
	Dairy products and eggs	6		Cereals	6
	Vegetables and seaweeds	7		Fish and shellfish	7
	Fruits	8		Meat	8
	Oils, fats, and condiments	9		Dairy products and eggs	9
	Cakes and candies	10		Vegetables and seaweeds	10
	Cooked food	11		Fruits	11
	Beverages	12		Oils, fats, and seasonings	12
	Alcoholic beverages	13		Cakes and candies	13
	Eating out	14		Cooked food	14
	Charges for board	15		Beverages	15
Housing		16		Alcoholic beverages	16
	Rents for dwelling and land	17		Meals outside the home	17
	Repairs and maintenance	18	**Housing**		18
Fuel, light, and water charges		19		Rents for dwelling and land	19
	Electricity	20		Repairs and maintenance	20

Household expenditure			CPI		
	Gas	21	**Fuel, light and water charges**		21
	Other fuel and light	22		Electricity	22
	Water and sewerage charges	23		Gas	23
Furniture and household utensils		24		Other fuel and light	24
	Household durables	25		Water and sewerage charges	25
	Interior furnishings and decorations	26	**Furniture and household utensils**		26
	Bedding	27		Household durable goods	27
	Domestic utensils	28		Interior furnishings and decorations	28
	Domestic nondurable goods	29		Bedding	29
	Domestic services	30		Domestic utensils	30
Clothes and footwear		31		Domestic nondurable goods	31
	Japanese clothing	32		Domestic services	32
	Clothing	33	**Clothing and footwear**		33
	Shirts and sweaters	34		Closing	34
	Underwear	35		Shirts and sweaters and underwear	35
	Cloth and thread	36		Other clothing	36
	Other clothing	37		Footwear	37
	Footwear	38		Services related to clothing	38

Household expenditure			CPI		
	Services related to clothing	39	**Medical care**		39
Medical care		40		Medicines and health fortification	40
	Medicines	41		Medical supplies and appliances	41
	Health fortification	42		Medical services	42
	Medical supplies and appliances	43	**Transportation and communication**		43
	Medical services	44		Public transportation	44
Transportation and communication		45		Private transportation	45
	Public transportation	46		Communication	46
	Private transportation	47	**Education**	Education	47
	Communication	48		School fees	48
Education	49		School textbooks and reference books for study	49	
Reading and recreation		50		Tutorial fees	50
	Recreational durable goods	51	**Culture and recreation**	Culture and recreation	51
	Recreational goods	52		Recreational durable goods	52
	Books and other reading materials	53		Recreational goods	53
	Recreational services	54		Books and other reading materials	54
Other living expenditure		55		Recreational services	55
	Miscellaneous	56	**Miscellaneous**	Miscellaneous	56

Household expenditure			CPI		
	Personal care services	57		Personal care services	57
	Toilet articles	58		Personal care goods	58
	Personal effects	59		Personal effects	59
	Tobacco	60		Tobacco	60
	Other miscellaneous	61		Other miscellaneous	61
	Pocket money (of which, detailed	62	**Fresh food**		62
	Social expenses	63	**Energy**		63
	Remittance	64			

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