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ORIGINAL ARTICLE

Monitoring environmental sustainability in Japan: an ESGAP assessment

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Abstract

This paper assesses the environmental sustainability of Japan by applying the environmental sustainability gap (ESGAP) framework, which builds on the concepts of strong sustainability, critical natural capital, environmental functions, and science-based reference values. The assessment is carried out using two indices of environmental sustainability (Strong Environmental Sustainability Index (SESI) and Strong Environmental Sustainability Progress Index (SESPI)) that provide a snapshot and a trend perspective on environmental sustainability performance and on progress toward it. The results reveal that Japan has not experienced significant changes in terms of aggregate environmental sustainability throughout the 2011–2017 period, but this is primarily a consequence of the mutually offsetting movements of different indicators. The country performs best for the human health and other welfare indicators, but worst for the sink function indicators such as the per-capita CO_2 emissions and the eutrophication of fresh water. The indices also expose the main policy areas that Japan needs to strengthen to improve its environmental performance. They include issues such as tropospheric ozone pollution, which has long been discussed in scientific literature but never been a primal policy focus of the government until very recently.

Keywords ESGAP · Environmental sustainability · Strong sustainability · Composite indicators · Japan

Introduction

Environmental metrics are widely used at different stages of the policy cycle, from agenda setting to monitoring and evaluation. Nonetheless, there are hundreds of metrics used to characterize the environment (and sustainable development more broadly) (Pintér et al. 2012), so selecting a set that is conceptually relevant, coherent, resonant, and adequate for the geographical context in which it will be used is of utmost relevance for good environmental policymaking. To assess whether a country is environmentally sustainable, relevant indicators need to show whether the functions provided by natural capital (i.e., the different elements that form the natural environment) will be maintained over the long term (Usubiaga-Liaño and Ekins 2021b).

The environmental sustainability gap (ESGAP) framework and its indices (Usubiaga-Liaño and Ekins 2021a, 2021b, 2022) were proposed to respond to the lack of adequate aggregate metrics to monitor environmental sustainability at the national level. The framework presents several sustainability metrics that are based on the concepts of strong sustainability, critical natural capital, environmental functions, and science-based reference values. The Strong Environmental Sustainability Index (SESI) and the Strong Environmental Sustainability Progress Index (SESPI) provide, respectively, a snapshot perspective on whether environmental sustainability conditions are met in a country, and a trend perspective on whether progress is being made toward those conditions. The ESGAP framework has been implemented for Europe (Usubiaga-Liaño and Ekins 2021a, 2022), New Caledonia (Comte et al. 2023), Vietnam (Thang et al. 2021), and Kenya (Otieno et al. 2021). This paper is

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another effort of implementing the ESGAP framework by applying it to Japan.

Japan has the world's third-largest GDP (IMF 2022) and the second-largest population among OECD members (UNDESA 2022). The environmental sustainability of the country is relevant not only at the local and national scale, but also at the global level. Also, in parallel with almost three decades of economic stagnation and deflation, the country has suffered from the most pronounced aging of its population in the world, which has caused an enormous impact on the relationships between nature and humans. This is a situation that will likely affect other countries in the coming decades. Measuring the environmental sustainability of Japan can therefore provide a good example in this context.

The postwar environmental policies in Japan experienced the first turning point when the country faced severe pollution problems during high economic growth since the 1950s. These events led to the adoption of legislation on pollution control and the establishment of the Environmental Agency. As global warming and other global issues such as depletion of the ozone layer, deforestation, and loss of biodiversity became major concerns, Japan reorganized its environmental policy framework through the legislation of the Basic Environment Law in 1993. In the international arena, Japan acted as a host for the adoption of the Kyoto Protocol in 1997, which was followed by the establishment of national global warming countermeasures, and the reorganization of the Environmental Agency into the Ministry of the Environment with strengthened mandates. The current focus of the national environmental policies is set on decarbonization, circular economy, and decentralization and harmony with nature, as well as the reconstruction after the Great East Japan Earthquake and the nuclear power plant accident in 2011 (Ministry of the Environment 2022a).

Progress in these and other environmental priorities has been monitored through several metrics and indicator systems in Japan.[1] In its most comprehensive annual environmental report, Japan describes the situation in various policy-relevant areas and regularly reports on several environmental indicators that address climate change, air and water pollution, biodiversity, and the use of natural resources (Ministry of the Environment 2022a). While this type of comprehensive report is a valuable source of information, some authors argue that using composite indicators or indices could make the information more digestible to the general public and other non-technical audiences (Saisana and Saltelli 2011). In this context, Japan's environmental performance has been the subject of academic interest on various fronts. For instance, several national and international organizations have attempted to evaluate Japan's sustainability through single composite indicators since the 1970s.

The earliest of these is Net National Welfare (NNW), proposed by the Economic Council of the Japanese Government in 1971 (Economic Council 1973). It is a flow-based measurement of welfare that deducts, from consumption in the national accounts, environmental maintenance costs, expenditures to remedy pollution damage, and loss related to urbanization. More recent efforts, especially those of capital-based measurement, are Genuine Saving (or Adjusted Net Saving) (Hamilton and Clemens 1999; Pearce and Atkinson 1993; Tokimatsu et al. 2011; World Bank 2011). They were followed by the latest efforts to estimate the Inclusive Wealth Index of the country for both the national level (Managi et al. 2018; Dasgupta et al. 2022; Sato et al. 2014) and the local level (Ikeda et al. 2017; Ikeda and Managi 2019).

Although the use of monetary aggregates in sustainability assessment is still common, these metrics have important limitations in respect of environmental sustainability because they implicitly accept that the loss of natural capital can be compensated by equivalent increases in other types of capital (an approach known as weak environmental sustainability) (Usubiaga-Liaño and Ekins 2021b). Moving away from monetary metrics, indices such as the Environmental Performance Index (EPI) (Wendling et al. 2020) or the Ecological Footprint (Lin et al. 2016) are also regularly computed for Japan. However, both have limits to represent environmental sustainability if this is to be understood from a perspective of strong sustainability. For instance, many indicators of the EPI measure performance against policy targets and frontrunners rather than against environmental sustainability conditions (i.e., the conditions required to maintain the functions of natural capital), while the Ecological Footprint is limited in its environmental scope, among other shortcomings (van den Bergh and Grazi 2014, 2015).

Against this background, this paper applies the ESGAP framework to Japan to assess the country's environmental sustainability. In doing so, it seeks to identify the functions of natural capital that are threatened in Japan and assess whether current trends will likely contribute to improve or worsen the situation. Both these research objectives are assessed through the computation of SESI and SESPI. While this work builds on the basic concepts and methodologies of ESGAP cited above, the paper provides several novel contributions. First, to the authors' knowledge, there are no previous strong sustainability assessments for Japan in the scientific literature. Second, this is the first attempt to implement the ESGAP framework in a non-European developed country. Third, Japan has a very well-established statistical system with long time series, which allows an expansion of the time frame used in previous studies.

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[1] See Usubiaga-Liaño and Ekins (2021b) for a general review of environmental sustainability metrics.

Finally, the paper goes beyond the previous ESGAP literature by providing a method to quantify the contributions of individual components of the indices to the evolution of the index. One of the striking features of sustainability indices based on the concept of strong sustainability is their attempt to capture the limited substitutability between different capitals or between other functions of natural capital. In the case of the ESGAP framework, this is embedded in the aggregation process of SESI and SESPI, as explained later. However, this unique aggregation process makes it difficult to evaluate the contributions of each component to the evolution of the index, in contrast to linearly aggregated indices where the contribution of a component is proportional to the amount of change. Here, we apply, with certain modifications, a technique of economic analysis typically used to decompose the contributions of capital, labor, and total factor productivity to GDP growth. Through this technique, we can address questions such as how individual elements contribute to the total changes of the index, how the limited substitution capacity between different forms of natural capital affects such contributions, and what causes a discrepancy between the sustainability of the country captured in the index and that recognized by policymakers. This exercise thereby expands the capacities of SESI and SESPI to monitor the status of and progress toward environmental sustainability.

The sections below are structured as follows. Sect. "The ESGAP framework" summarizes the main features of the ESGAP framework. The following section describes the methodology. Sects. "Results" and "Discussion" present and discuss the main results, respectively. The final section concludes the paper.

The ESGAP framework

In the ESGAP framework, environmental sustainability requires the maintenance of critical environmental functions and, consequently, the maintenance of the capacity of natural capital to provide those functions (Ekins et al. 2003). The environmental functions of natural capital are grouped into four main categories (Ekins et al. 2003):

- *Source functions* represent the capacity of natural capital to sustain the supply of biotic and abiotic natural resources.
- *Sink functions* represent the capacity of natural capital to neutralize wastes without incurring ecosystem change or damage.
- *Life support functions* refer to the capacity of natural capital to maintain ecosystem health and function.
- *Human health and welfare functions* represent the capacity of natural capital to provide other services to humans, very often of a non-economic kind, which maintain health and contribute to human well-being in different ways.

The ESGAP framework uses environmental sustainability principles to define the conditions under which the functions of natural capital can be maintained over time (see Table S1 in the supplementary material). The framework derives, from these principles, a set of reference values termed 'environmental standards,' which represent environmental sustainability conditions that are primarily science based. These can differ from environmental policy targets, which are determined through actual policy processes with a higher degree of normative judgment, where, beyond pure scientific evidence, other factors such as technological, economic, and political feasibilities are considered.

The ESGAP framework comprises three main metrics: the Strong Environmental Sustainability Index (SESI), the Strong Environmental Sustainability Progress Index (SESPI), and the monetary environmental sustainability gap (Usubiaga-Liaño and Ekins 2021b). This paper deals with the first two indices. SESI is an index designed to measure a country's absolute performance against environmental standards across different environmental and resource issues related to the functions of natural capital (Usubiaga-Liaño and Ekins 2021a). It is a single integrated metric calculated by normalizing, weighting, and aggregating individual indicators corresponding to the four environmental function categories. SESI provides a snapshot, at a specific point in time, of a country's absolute performance against environmental standards. SESPI, in contrast, presents a temporal perspective by measuring progress over time. Specifically, it evaluates the rates of improvements a country has experienced compared to those required to achieve environmental sustainability within a given time frame. Through such comparison, SESPI gives a sense of whether enough progress is being made toward environmental sustainability (Usubiaga-Liaño and Ekins 2022).

Methodology

Strong Environmental Sustainability Index (SESI)

Indicator selection

We follow Usubiaga-Liaño and Ekins (2021a) regarding the criteria for indicator selection, thereby considering relevance, statistical and methodological soundness, and data quality in the selection process. This process, which is documented in the supplementary material, led to the selection of 18 indicators from an initial list of 33. The final indicator set consists of 18 indicators, as shown in Table 1. The list

Table 1 List of selected indicators

Function	Principle	Topic	Indicator
Source	Renew renewable resources	Biomass	Forest utilization rate Fish stocks within safe biological limits
		Freshwater	Population not under water stress
	Use non-renewable resources prudently	Soil	Area with tolerable soil erosion
Sink	Prevent global warming and the depletion of the ozone layer	Earth system	Per-capita CO_2 emissions Per-capita consumption of ozone-depleting substances
	Respect critical loads for ecosystems	Terrestrial ecosystems	Land exposed to safe ozone level
		Freshwater ecosystems	Eutrophication of freshwater bodies Freshwater bodies in good chemical status
		Marine ecosystems	Eutrophication of marine water bodies Marine water bodies in good chemical status
Life support	Maintain biodiversity and ecosystem health	Terrestrial and freshwater ecosystems	Proportion of unthreatened species
Human health and welfare	Respect standards for human health	Human health	Population exposed to safe levels of outdoor air pollutants Population using clean fuels and technologies for cooking Tap water bodies that meet the drinking quality criteria
	Conserve landscape and amenity	Other welfare	Recreational waters that meet the good quality criteria Urban population residing in areas with satisfactory green space Natural and mixed world heritage sites that have a good conservation outlook

Table 2 Choices made in the construction of SESI

Step	Description
Data treatment	No outliers were identified. The period 2011–2017 was chosen as the greatest common divisor with a few data gaps filled by minimum operations of linear interpolations and value extensions described in the supplementary material
Normalization	The goalpost method is used. This is similar to the min–max method, but instead of using frontrunners and laggards as the max and the min, it uses values defined by the user. In this case, the maximum value represents full compliance with an environmental standard, while min represents no compliance
Weighting	Equal weights are used in the absence of an adequate method to determine the relative importance of the different environmental issues. Weights should be context specific
Aggregation	A geometrical mean is used to represent the limited substitution capacity between the functions of natural capital

of the basic information, including data providers and environmental standards, is shown in Table 4 in the appendix. Each indicator and standard are further described in the files in the supplementary material.

The indicators are placed in a four-layer structure that aggregates the indicator scores to topics, the topics to environmental sustainability principles, the latter to environmental functions, and finally environmental functions to a single index score. The structure is shown in Fig. S1 in the supplementary material.

Calculation of SESI

We convert the indicators into SESI by following the approach developed by Usubiaga-Liaño and Ekins (2021a), which was guided by a comprehensive manual on composite indicators (OECD & JRC 2008). The approach used here consists of four steps: data treatment, normalization, weighting, and aggregation. The approach is summarized in Table 2 and further explained in the supplementary material.

SESI uses a weighted geometric mean for aggregating the normalized scores of the indicators into a single index, which can be formulated as follows. In the equation, l, k, j, and i represent the individual components of each layer, i.e., functions, principles, topics, and indicators. Thus, SESI is the weighted geometric mean of the function scores W_l with α_l weights. The lower level represents a sequence of weighted geometric means of the $NI_{l,k,j,i}$ normalized scores, where N is the number of indicators in each layer.

Table 3 Choices made in the construction of SESPI

Step	Description
Data treatment	The same raw data is used as in SESI
Normalization	The goalpost method is used, where the maximum value represents the trends required to achieve environmental sustainability by 2030 and the minimum value represents the same but with the opposite sign
Weighting	Equal weights are used without an adequate method to determine the relative importance of the different environmental issues. Weights should be context specific
Aggregation	A geometric mean is used to represent the limited substitution capacity between the functions of natural capital

$$\begin{aligned}\mathrm{SESI} &= \prod_{l=1}^{4} W_{l}^{\alpha_l} = \prod_{l=1}^{4}\prod_{k=1}^{N_l} W_{l,k}^{\alpha_l\alpha_{l,k}} = \prod_{l=1}^{4}\prod_{k=1}^{N_l}\prod_{j=1}^{N_{l,k}} W_{l,k,j}^{\alpha_l\alpha_{l,k}\alpha_{l,k,j}} \\ &= \prod_{l=1}^{4}\prod_{k=1}^{N_l}\prod_{j=1}^{N_{l,k}}\prod_{i=1}^{N_{l,k,j}} NI_{l,k,j,i}^{\alpha_l\alpha_{l,k}\alpha_{l,k,j}\alpha_{l,k,j,i}}\end{aligned} \tag{1}$$

Decomposition of the contribution of each component to changes in SESI values

How do individual components of SESI contribute to the total change of the index score? How different are those contributions? Since SESI is aggregated through weighted geometric means in a nested four-level structure, the contribution of each component to changes in index scores is not as straightforward as if a weighted arithmetic mean were used. We therefore propose a different method. We utilize here a linear approximation of natural log to a rate of change in SESI in year t:

$$\frac{SESI_t - SESI_{t-1}}{SESI_{t-1}} \fallingdotseq \ln\left(1 + \frac{SESI_t - SESI_{t-1}}{SESI_{t-1}}\right) = \ln SESI_t - \ln SESI_{t-1}. \tag{2}$$

Following Eqs. (1), (2) can be rewritten as:

$$\begin{aligned}\frac{\mathrm{SESI}_t - \mathrm{SESI}_{t-1}}{\mathrm{SESI}_{t-1}} &\fallingdotseq \sum_{l=1}^{4} \alpha_l\left(\ln W_{l,t} - \ln W_{l,t-1}\right) \\ &= \sum_{l=1}^{4}\sum_{k=1}^{N_l} \alpha_l\alpha_{l,k}\left(\ln W_{l,k,t} - \ln W_{l,k,t-1}\right) \\ &= \sum_{l=1}^{4}\sum_{k=1}^{N_l}\sum_{j=1}^{N_{l,k}} \alpha_l\alpha_{l,k}\alpha_{l,k,j}\left(\ln W_{l,k,j,t} - \ln W_{l,k,j,t-1}\right) \\ &= \sum_{l=1}^{4}\sum_{k=1}^{N_l}\sum_{j=1}^{N_{l,k}}\sum_{i=1}^{N_{l,k,j}} \alpha_l\alpha_{l,k}\alpha_{l,k,j}\alpha_{l,k,j,i}\left(\ln NI_{l,k,j,i,t} - \ln NI_{l,k,j,i,t-1}\right).\end{aligned} \tag{3}$$

The contribution of function l, principle k, topic j, and indicator i to the rate of change of the index, $\theta_{l,t}$, $\theta_{l,k,t}$, $\theta_{l,k,j,t}$, and $\theta_{l,k,j,i,t}$, can therefore be approximated by

$$\begin{aligned}&\theta_{l,t} \fallingdotseq \alpha_l\left(\ln W_{l,t} - \ln W_{l,t-1}\right), \\ &\theta_{l,k,t} \fallingdotseq \alpha_l\alpha_{l,k}\left(\ln W_{l,k,t} - \ln W_{l,k,t-1}\right), \\ &\theta_{l,k,j,t} \fallingdotseq \alpha_l\alpha_{l,k}\alpha_{l,k,j}\left(\ln W_{l,k,j,t} - \ln W_{l,k,j,t-1}\right), \text{ and} \\ &\theta_{l,k,j,i,t} \fallingdotseq \alpha_l\alpha_{l,k}\alpha_{l,k,j}\alpha_{l,k,j,i}\left(\ln NI_{l,k,j,i,t} - \ln NI_{l,k,j,i,t-1}\right).\end{aligned} \tag{4}$$

Strong Environmental Sustainability Progress Index

To calculate SESPI, Usubiaga-Liaño and Ekins (2022) propose a similar process to that used by Eurostat to measure progress toward the SDGs (Eurostat 2020), but use linear trends instead of exponential trends. Thus, for each indicator underlying SESPI, the ratio between observed trends (calculated as the linear trend between two data points) and desired trends (calculated as the linear trend required to reach environmental sustainability conditions in 2030) is normalized. The process of constructing SESPI is summarized in Table 3 and further described in the supplementary material. To compute observed trends, a five-year step was chosen, where $t_0 = 2012$ and $t_1 = 2017$. Consequently, the desired trends were computed from 2017 to 2030.

Results

SESI

The solid line in Fig. 1 represents the evolution of the scores at index and function level. In contrast, the dotted line in the index-level figure represents the index score computed using an arithmetic instead of a geometric mean. A discrepancy between the two mainly indicates to what extent components with lower scores are penalized in the aggregation process and thereby represents a consequence of the limited substitution capacity captured in SESI. From the figure, we notice that the scores are roughly ten points lower than the

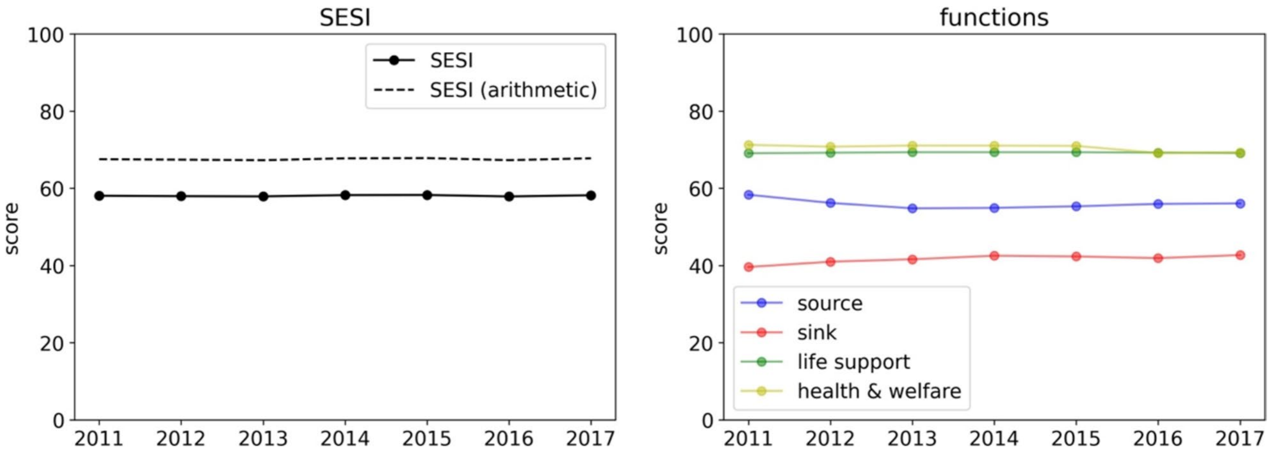

Fig. 1 Index- and function-level scores for SESI

reference values. This indicates the existence of the components in lower layers exhibit extremely lower scores and thereby significantly drag down the index-level scores when using a geometric mean.

The SESI score has remained around 58 points between 2011 and 2017. Therefore, judging by the aggregated score, Japan seems to have experienced neither significant improvement nor significant deterioration in terms of environmental sustainability throughout the 2011–2017 period. At the level of functions, scores have changed between − 2.25 and 3.09 points in the period studied. Nonetheless, as shown next, huge differences across lower-layer components exist in both their score level and their change. Results at the level of sustainability principle and environmental topic are shown in Fig. S3 in the supplementary material.

In 2017, Japan obtained the highest score for the human health and other welfare function (69), mainly because of its high performance in human health indicators. The exception in human health would be outdoor air pollution, where around 23% of the population is still exposed to particulate matter levels above those recommended by the World Health Organization. Other welfare functions, which include indicators on bathing waters, green coverage and World Heritage sites show a mixed performance. Japan also obtained 69 points for the life-support function, although this function only contains a single indicator on threatened species, so it requires careful interpretation. In the source function, Japan obtains 56 points. While the indicators representing the exploitation of forest and fish resources scored over 90, water scarcity and soil erosion indicators had normalized scores between 43 and 55. The sink function is the only component that exhibits much lower values (40–43 in the 2011–2017 period). For this function, the unsustainability of CO_2 emission levels and the eutrophication of freshwater systems are the main factors leading to a low score. Finally, although the index-level scores are pretty stable, we can observe considerable variations in some lower-layer components, as shown in Fig. S2 in the supplementary material. Ozone pollution in terrestrial ecosystems and fish resources are the indicators that have improved the most, while water stress and outdoor air pollution represent those that have worsened the most.

Figure 2 decomposes the changes seen in SESI at the level of function and indicator. Since the net effect is the same when using functions and indicators, it is only shown in the graph for functions. As in previous cases, the patterns in blue represent the source function, red the sink function, green the life support function, and orange the human health and welfare function.

SESI has increased by 0.14 points between 2011 and 2017, with variations in both directions in between. This is primarily a consequence of the mutually offsetting movements of different components. At the function level, the sink function has driven the score upward, but negative changes in the source, and human health and welfare functions have compensated. The score of the life support function has remained almost constant. This shows that underlying the relatively unchanged index are much more significant changes in some of its components.

The effect of indicators can be grouped into three categories depending on their direction: the ones mostly with an upward trend, the ones mainly with a downward trend, and those fluctuating due to a random factor. The joint evolution of these indicators is shown in the indicator-level graph of Fig. 2. Fish resources (source function) and ozone pollution in terrestrial ecosystems (sink function) are examples of those with an upward trend. Thus, fish resources have been continuously improving after a significant deterioration in 2013; similarly, low-level ozone pollution exhibits improvements in most of the period, especially in the first half. In contrast, outdoor air pollution (human health and welfare function) belongs to the downward-trend category. The

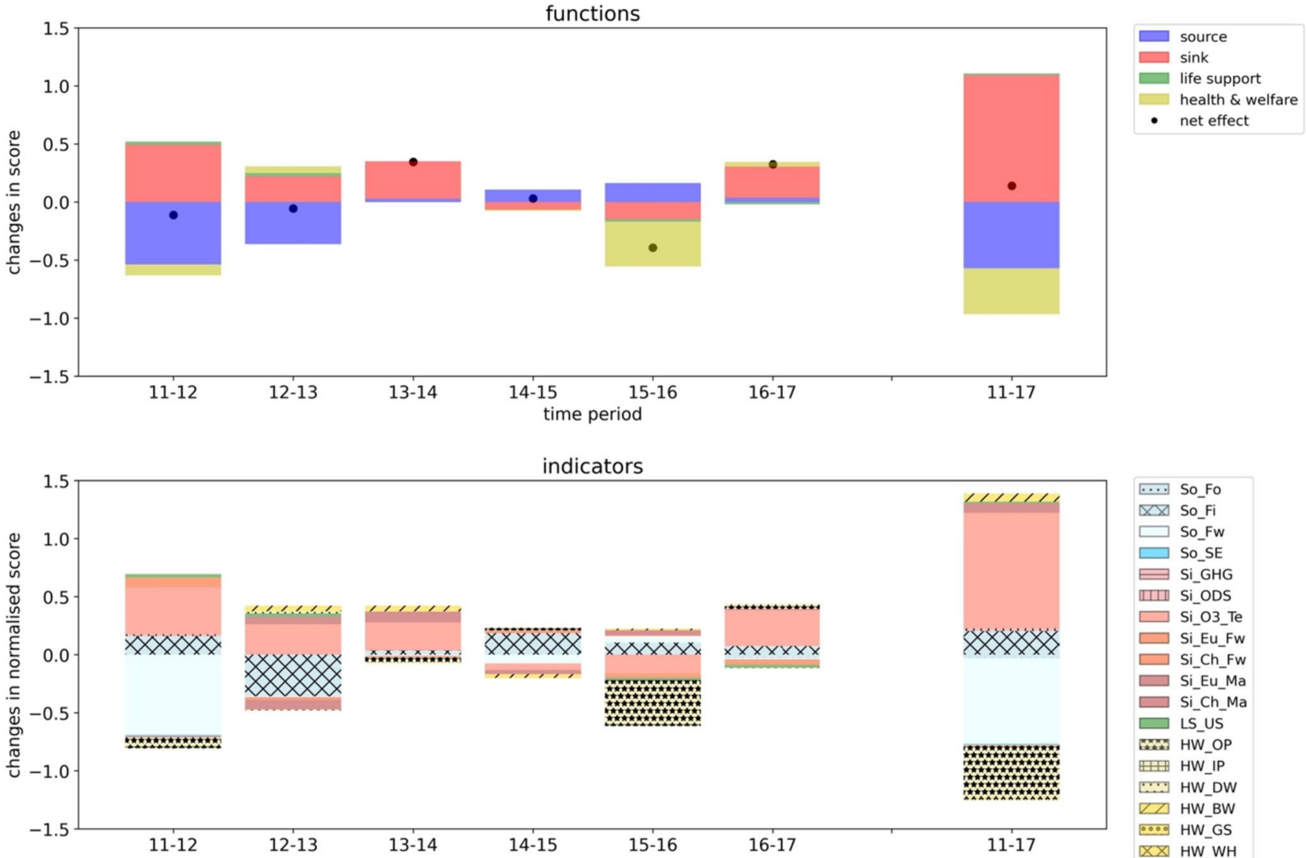

Fig. 2 Decomposition of changes in SESI at the level of function and indicator. Note: forest resources (So_Fo); fish resources (So_Fi); water stress (So_Fw); soil erosion (So_SE); per-capita CO_2 emissions (Si_GHG); per-capita ODS consumption (Si_ODS); ozone pollution (Si_O3_Te); eutrophication of fresh water (Si_Eu_Fw); chemical status of fresh water (Si_Ch_Fw); eutrophication of marine water (Si_Eu_Ma); chemical status of marine water (Si_Ch_Ma); unthreatened species (LS_US); outdoor air pollution (HW_OP); indoor air pollution (HW_IP); drinking water (HW_DW); bathing water (HW_BW); green coverage (HW_GS); World Heritage (HW_WH)

country experienced a worsening condition of population exposure to $PM_{2.5}$ from 2011. It significantly contributed to the negative growth of the index in 2016. Water stress (source function) belongs to the category describing fluctuations, since it largely depends on the weather conditions as well as the water use of society. In fact, the indicator offsets entirely the positive contributions of the low-level ozone pollution and the fish resources indicator in 2012. This is a reversal of the significant improvement in 2011, when the Kansai Rinkai Area experienced richer precipitation than other years close to 2011.

Finally, the two indicators that significantly drag down the score level of the aggregated index, the per-capita CO_2 emissions and the condition of World Heritage sites, have made no contributions to the change of the index, since their normalized scores have remained constant throughout the period. Nonetheless, had they changed, they would have significantly affected the index movement because their low performance penalizes index scores when using a geometric mean in the aggregation process.

Figure 3 shows the hypothetical contributions of each indicator for a one-point improvement from the 2017 score. In other words, it shows which areas have the highest potential to improve the index score. If the 2017 score is less than five (the minimum value assigned to avoid the geometric mean collapsing to zero), the contribution is calculated for the improvement from five. A reduction in the per-capita CO_2 emissions would have the most significant impact on the index. A one-point improvement can make 10–30 times as big a contribution as the indicators such as fish resources, water stress, ozone pollution, and outdoor air pollution, analyzed above. The contribution of the World Heritage sites is also significant, but much lower than the per-capita CO_2 emissions. In contrast, soil erosion and unthreatened species exhibit relatively high values mostly because they are the only indicators in the topic and principle (and function for unthreatened species) that they belong to and thereby get bigger weights than some other indicators in layers with multiple indicators. However, their contributions to changes in SESI are

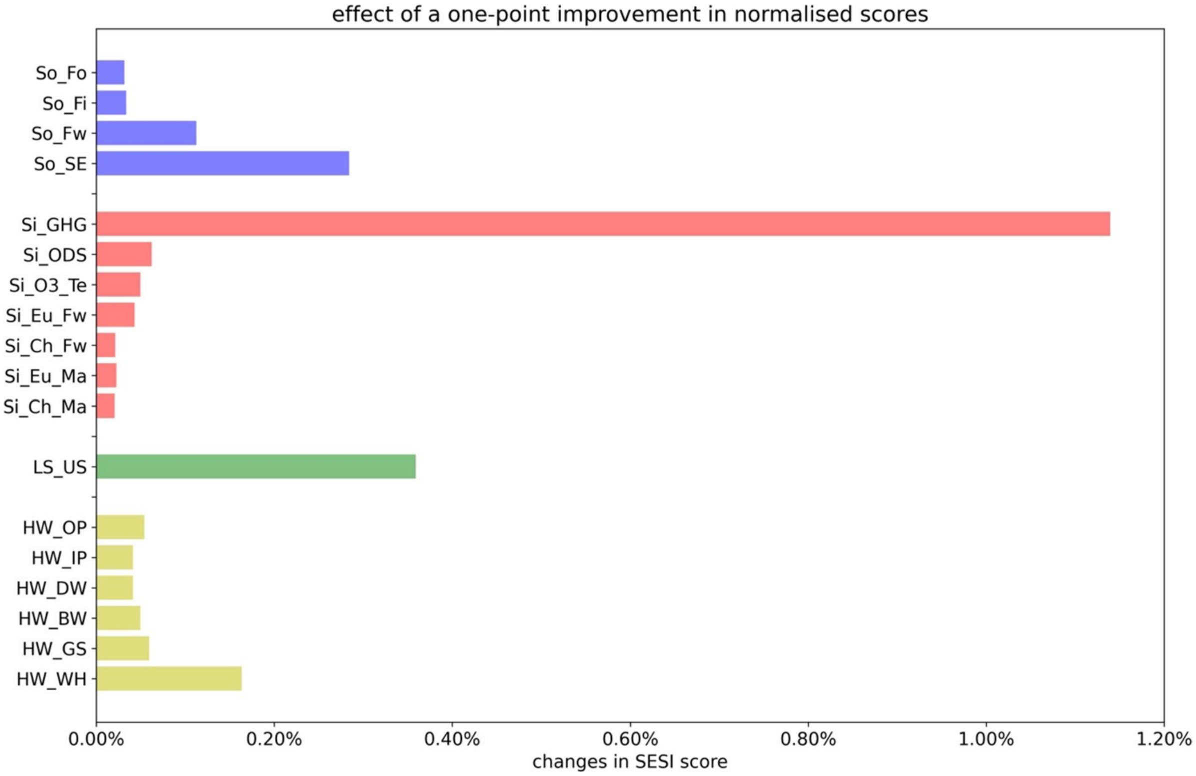

Fig. 3 Hypothetical contribution of one-point improvement to the 2017 index score. Note: forest resources (So_Fo); fish resources (So_Fi); water stress (So_Fw); soil erosion (So_SE); per-capita CO_2 emissions (Si_GHG); per-capita ODS consumption (Si_ODS); ozone pollution (Si_O3_Te); eutrophication of fresh water (Si_Eu_Fw); chemical status of fresh water (Si_Ch_Fw); eutrophication of marine water (Si_Eu_Ma); chemical status of marine water (Si_Ch_Ma); unthreatened species (LS_US); outdoor air pollution (HW_OP); indoor air pollution (HW_IP); drinking water (HW_DW); bathing water (HW_BW); green coverage (HW_GS); World Heritage (HW_WH)

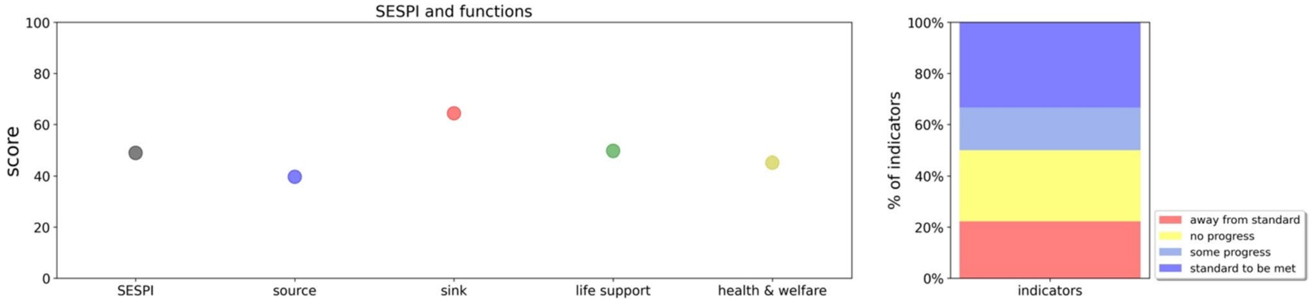

Fig. 4 SESPI scores at the index and function levels, and progress at the indicator level. Note: the right-side graph shows the proportion of the indicators whose score corresponds to "moving away from the environmental standard", "no progress," "improving trend," and "trend compatible with reaching environmental standard by 2030"

negligible, since the normalized scores remained constant or almost constant throughout the studied period.

SESPI

Figure 4 shows the scores of SESPI and its functions over five years. The normalized values of individual indicators are shown in Fig. S2 in the supplementary material. Japan scores 49 points in SESPI, primarily driven by the progress made in sink indicators, where all the indicators except those for freshwater systems show progress toward sustainability. Source and human health and welfare functions offer mixed performance. In the first case, the negative trends in forest exploitation rates drag the score down, while in the latter case, outdoor air pollution is moving in the wrong direction. The case of forest resources is noteworthy, since it has a normalized score close to 100 over the period studied, but the exploitation has continuously increased from 26.0% in 2003 to 70.5% in 2017 primarily reflecting the increase in annual harvest in this period. All in all, as shown on the right side of the figure, half of the indicators show negative (normalized score < 45) or no progress (normalized score between 45 and 55) toward environmental sustainability. In the other half, 33% describe trends largely compatible with reaching the environmental standards by 2030 (normalized score > 95), while the remaining 17% are moving in the right direction, but not at the required speed (normalized score between 55 and 95).

Discussion

Environmental sustainability in Japan

The use of SESI to provide a snapshot of Japan's environmental sustainability has shown a very diverse performance between environmental functions. For instance, Japan obtains a higher score in human health and welfare and life support functions than other environmental functions. The high performance in life support function is opposed to European countries (as shown in Usubiaga-Liaño and Ekins (2021a)), but this needs qualifications on several grounds since SESI only has one indicator for this function. In this vein, some candidate indicators measuring the life support function were excluded in the relevance assessment process, since we could not find any science-based environmental standards for the conservation status of ecosystems in Japan (Table S2 in the supplementary material). We instead included the indicator for the proportion of unthreatened species in terrestrial and freshwater ecosystems, although the equivalent indicator of marine ecosystems is excluded since a Red List of marine species started to be published in 2017 (Ministry of the Environment 2017) and is not sufficient to ensure an intertemporal comparability. The number of threatened species investigated in a Red List captures some aspects of ecosystem health, but it does not directly measure ecosystem function and the general conservation status of a species and habitats, especially at the local scale, for which a careful interpretation of this indicator is warranted.

In this context, the crises of ecosystems in Japan have been investigated and reported in quite some detail in the reports of the Ministry of the Environment and the Biodiversity Center of Japan as well as in various academic literature. For example, Monitoring Site 1000, a comprehensive ecosystem monitoring project of the Center, has collected and analyzed quantitative and qualitative data since 2003 in more than 1,000 sites belonging to eight types of ecosystems: alpine region, forest and grassland, Satoyama landscape, inland waters, sand beaches, coastal waters, coral reef, and small islands (Biodiversity Center of Japan 2022). Recent reports of the project reported the deteriorating conditions and future risks in the non-negligible proportion of the ecosystems in line with the four biodiversity crises classified in the National Biodiversity Strategy of Japan: crisis caused by human activities including development, crisis caused by reduced human activities, crisis caused by artificially introduced factors such as invasive alien species or chemical substances, and crisis caused by changes in the global environment (Ministry of the Environment 2012). Introducing indicators that could accurately represent the effects of these phenomena would likely change the dynamics of SESI and SESPI.

In the source function, the exploitation of fish and forest resources is close to being sustainable, something that does not happen in the case of freshwater and soil resources. Nonetheless, the exploitation rate of forest resources has increased steadily since 2011, which could, if sustained over time, put the renewability of forest resources at stake.

When it comes to different pollution processes, Japan currently exhibits, in line with virtually every country in the world, a CO_2 emission level largely incompatible with the remaining 1.5 ºC budget. In regional pollution processes, freshwater ecosystems are quite affected by eutrophication. Beyond that, most freshwater and marine systems are in good chemical condition.

While policies address most of the environmental topics covered in SESI, the case of tropospheric ozone pollution appears as an exception. The improvement in ozone pollution experienced between 2011 and 2017 could have significantly changed the evolution of the index score if it were not for the opposite contributions of different components. Nonetheless, ozone pollution of terrestrial ecosystems has never been a primal policy focus of the Japanese government until very recently. The government has had an environmental standard for photochemical oxidants in the atmosphere since 1973, but this standard is designed to protect human health (Ministry of the Environment 1996). Different factors could explain the lack of attention to the environmental consequences of tropospheric ozone pollution. A possible explanatory factor is the time lag of the policy discussions against scientific discussions. The problem of ozone contamination on vegetation and crops has long been discussed in scientific literature in Japan since the 1970s (Watanabe et al. 2017; Yonekura and Izuta 2017). In this respect, the policy relevance of this indicator is almost indisputable. But it was in 2022 that the government decided to start examining scientific insights on the impact of photochemical oxidants on vegetations and corresponding environmental standards (Ministry of the Environment 2022b). There might be several reasons for this lag and exploring them is beyond the scope of the paper, but this could be a factor for the disconnect between science-based environmental standards and relevant policy discussions.

In any case, it is essential to note that the reason for tropospheric ozone pollution to have such an important role in the evolution of SESI is related to its low initial value and to the structure of the index. As stated earlier, without consensus and scientific evidence on the relative importance between different environmental functions, we adopted equal weights to all components belonging to the same topic, principle, and function. As a result, ozone pollution acquires twice as significant weight as other indicators belonging to the principle of critical loads and equal weight as indicators belonging to the human health and welfare function. But obviously, no empirical evidence supports that or any other weighting choice.

Population aging and environmental sustainability

As mentioned in the introduction, Japan has suffered from the most severe population aging in the world. This, together with other socioeconomic changes such as the increased dependency on imported crops and woods, has caused an enormous impact on the relationships between nature and humans and on the ecosystems mainly through the contraction of human activities in rural areas. For instance, negative impacts on ecosystems extension and quality have been reported due to the declining utilization and maintenance of forest ecosystems and agroecosystems in Satochi–satoyama areas,[2] which constitutes about 40% of the country and provides a range of relevant ecosystem services (Ministry of the Environment 2010, 2021). On the positive side, it is reported that increasing abandoned farmlands provide preferred habitats for some threatened species (Osawa et al. 2013). But on the negative side, the reduced human interventions in formerly managed forests in such areas, for example, lead to structural homogenization, stand aging, canopy closures, and replacement or invasion of vegetation, which can be followed by decreasing biodiversity and ecosystem services (Oono et al. 2020). Also, the expansion of uninhabited areas and reduced vegetation management generate negative impacts on the biodiversity of vascular plants and Rhopalocera in some regions (NIES 2020). The increased disservice from wild animals is another issue. The number of active hunters of younger generations has kept declining or stagnated in Japan especially since the 1990s, and it is likely that this has been one of the drivers that led to the rapid increase of wild dears and boars in rural areas (Ministry of the Environment 2021). The increased dear density has negatively impacted forest ecosystems, including vegetation degradation and biodiversity loss (Maesako et al. 2020; Okuda et al. 2012).

The problems related to the changing relationships between nature and humans are expected to become more and more serious as the country experiences severe depopulation in the coming decades. Unfortunately, the set of indicators proposed in the present paper only marginally and indirectly captures such issues, mainly through the indicator of unthreatened species. However, as mentioned earlier, the crises of ecosystems in Japan have been investigated and reported in quite some detail in the government reports and academic literature with rich datasets even on the local scale. We, therefore, expect further discussions on the invention of scientific environmental standards that can measure the above issues.

Comparisons with the ESGAP assessments in other countries

Although grounded on the same framework, the ESGAP indices are formulated as a standalone exercise for each country. One of the advantages of the ESGAP indices is that there is no need for comparison with other countries because it uses environmental standards in the normalization process that give meaning to the resulting index independently from how a country performs relative to others. In fact, there are considerable differences in environmental standards (and indicators) across countries and this is the case as well for Japan and European countries. For instance, for the tropospheric ozone pollution, Japan uses a different reference tree species to determine environmental standards. Likewise, Japan monitors different parameters in water bodies for the chemical status indicators. Thus, comparisons between countries are possible only when both the indicator and the standards used are the same, which is rarely the case given that data for most indicators are compiled differently following national legislations. While this may seem a drawback, it allows to adapt SESI and SESPI to the national context and data availability.

Limitations

The limitations of the indices used have been documented by Usubiaga-Liaño and Ekins (2021a, 2022), but some are worth mentioning again for a correct interpretation of the results. First, the rationale behind the environmental standards adopted differs across themes. For some, the

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[2] Satochi–satoyama is “an area consisting of farmlands, irrigation ponds, secondary forest, plantation forest, and grasslands surrounding human settlements, and is located between more natural, deep mountainous areas and urban areas of intensive human activities. The environments of Satochi–satoyama have been formed through various human interventions such as farming and forestry activities over a long history, where people have practiced land use in a dynamic mosaic-like pattern and cyclic resource use.” (Ministry of the Environment 2010).

environmental standard represents acceptable impacts on human health or ecosystems. For others, they can be precautionary expert guesses or safe distance from tipping points. In any case, the level of scientific consensus behind environmental standards differs, so they should be interpreted as a warning signal rather than as reference values that should not be crossed under any circumstances. In this line, the absence of environmental standards in some areas has resulted in policy-relevant themes being excluded from the indices. This is the case, for instance, of ecosystem health indicators or the extraction of abiotic materials. Beyond these issues, it is worth noting that the results from SESPI are more uncertain than those of SESI because of the limitations of calculating trends by linearly extrapolating two arbitrary data points. Using more extensive data series should help mitigate this effect.

Choices made during the construction of SESI and SESPI are also worth discussing. An example of the effects of using equal weights has been described in Sect. "Environmental sustainability in Japan", while the impact of different aggregation functions has been described in Sect. "SESI". Beyond the specific effects of these choices in this case study, it should be noted that other construction choices can lead to different results and insights. For this reason, it is critical to align the methodology behind the construction of any index with the conceptual framework so that the index captures the phenomenon it intends to represent as accurately as possible (Usubiaga-Liaño and Ekins, in review). This is the case in ESGAP, as described in Usubiaga-Liaño & Ekins (2021a, 2022).

Because of these limitations, this paper aims to showcase the potential of SESI and SESPI to monitor environmental sustainability and provide policy-relevant messages. Additional data and research on environmental standards will help refine these metrics.

Conclusion

This paper applied the ESGAP framework to Japan. It selected 18 indicators, each of which relates to the different environmental functions of natural capital, by examining the relevance, the statistical and methodological soundness, and the data quality of the candidate indicators. We calculated SESI for each of the years in the 2011–2017 period, and SESPI, which is based on trends.

The major findings are the following. As for SESI, first, the limited substitution capacity represented in the aggregation process of SESI plays a vital role in determining the score level of the index. Significantly, the zero performance of the indicator of per-capita CO_2 emission significantly drags down the index score, thereby showing a critical area that needs to be addressed to improve SESI. Also, the poor performance of the World Heritage indicator offsets the satisfactory performances of the human health-related indicators. Second, judging from the aggregated index alone, the country seems to have experienced neither significant improvement nor significant deterioration in terms of environmental sustainability throughout the period, but this is primarily a consequence of the mutually offsetting movements of different components. The indicators that can be a significant driving force for such movements can be grouped into (1) the ones mostly with an upward trend (fish resources and ozone pollution), (2) the ones mostly with a downward trend (outdoor air pollution), and (3) the ones with a more randomized movement (water stress). There existed a nontrivial potential that the country would have experienced much more significant changes in the index scores if there were not the contingent coincidences of the opposite contributions of these components. Finally, the two indicators that significantly drag down the score level of the aggregated index, the per-capita CO_2 emissions and the state of World Heritage sites, have made no contributions to the change of the index, since their scores did not vary throughout the period studied. But had they changed, they would have made relevant contributions to the index movement due to the effect of low scores in geometric means. Regarding SESPI, Japan shows a mixed performance, where half of the indicators show negative or no progress, while the other half are moving in the right direction. This suggests that additional efforts are needed to move toward environmental sustainability.

A fundamental limitation of this study is the shortage of biodiversity and habitat indicators (life support functions) due to the lack of environmental standards for ecosystem conditions in Japan. If the crises of the ecosystems, which have been repeatedly reported in the governmental reports as well as scientific literature, were incorporated correctly, it would have a relevant impact on the country's environmental sustainability. It would significantly change the dynamics of SESI and SESPI.

All in all, we show the potential of the ESGAP framework, and by extension of SESI and SESPI, to provide an overview of Japan's environmental sustainability situation and the progress made toward it. As more data becomes available and environmental standards are proposed, these indices can be compiled regularly and used to identify which environmental areas require more policy attention.

Appendix

See Table 4.

Table 4 Additional information for the selected indicators

Function	Principle	Topic	SES indicator [unit]	Data provider	Standard	References
Source	Renew renewable resources	Biomass	Forest utilization rate [%]	Forest Agency	Forest utilization rate that ensures non-decrease of stock level	Schulze et al. (2012)
			Fish stocks within safe biological limits [%]	Fisheries Agency, Fisheries Research and Education Agency (FRA)	Fish stocks within safe biological limits	FRA (2021)
		Freshwater	Population not under water stress [%]	MLIT	Freshwater withdrawal as a proportion of available freshwater resources	FAO and UN Water (2021)
	Use non-renewable resources prudently	Soil	Area with tolerable soil erosion [%]	ESDAC	Tolerable soil erosion rate	Huber et al. (2008), Jones et al. (2004), Verheijen et al. (2009)
Sink	Prevent global warming and the depletion of the ozone layer	Earth System	Per-capita CO_2 emissions [t per capita]	Ministry of the Environment	Per-capita CO_2 emissions consistent with the global climate targets	IPCC (2018)
			Per-capita consumption of ozone-depleting substances [t ODP]	UNEP Ozone Secretariat	ODS consumption is consistent with reducing the ozone hall	Usubiaga-Liaño and Ekins (2021a)
	Respect critical loads for ecosystems	Terrestrial ecosystems	Land exposed to safe ozone levels [%]	NIES	AOT40 corresponds to a critical level for the Japanese vegetation	Ishi et al. (2005), Kohno et al. (2005)
		Freshwater ecosystems	Eutrophication of freshwater bodies [%]	Ministry of the Environment	Good chemical status	Ministry of the Environment (2019b)
			Freshwater bodies in good chemical status [%]	Ministry of the Environment	Good chemical status	Ministry of the Environment (2019b)
		Marine ecosystems	Eutrophication of marine water bodies [%]	Ministry of the Environment	Good chemical status	Ministry of the Environment (2019b)
			Marine water bodies in good chemical status [%]	Ministry of the Environment	Good chemical status	Ministry of the Environment (2019b)
Life-support	Maintain biodiversity and ecosystem health	Terrestrial and freshwater ecosystems	Proportion of unthreatened species [%]	Ministry of the Environment	Conservation status better than Near-Threatened	Ministry of the Environment (2020)

Table 4 (continued)

Function	Principle	Topic	SES indicator [unit]	Data provider	Standard	References
Human health and welfare	Respect standards for human health	Human health	Population exposed to safe levels of outdoor air pollutants [%]	World Bank	Average annual PM2.5	WHO (2005)
			Population using clean fuels and technologies for cooking [%]	WHO	Population using clean fuels and technologies for cooking	WHO (2018)
			Tap water bodies that meet the drinking quality criteria [%]	Japan Water Works Association	Drinking water criteria	MHLW (2020)
	Conserve landscape and amenity	Other welfare	Recreational waters that meet the good quality criteria [%]	Ministry of the Environment	Bathing water criteria	Ministry of the Environment (2019a)
			Urban population residing in areas with not unsatisfactory green space [%]	Local governments	Green coverage ratio that people do not feel unsatisfactory	Iino et al. (1996), Nagayama et al. (1991), Takahashi and Noda (1975)
			Natural and mixed world heritage sites that have a good conservation outlook [%]	IUCN	Good conservation outlook	Osipova et al. (2014)

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in this paper, and that the research does not involve any human participants and/or animals.

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